Economic Analysis of Property Rights: First Possession of Water in the American West*

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Abstract

We analyze the economic determinants and effects of prior appropriation water rights that were voluntarily implemented across a vast area of the US West, replacing common-law riparian water rights. We model potential benefits and test hypotheses regarding search, coordination, and investment. Our novel dataset of 7,800 rights in Colorado, established between 1852 and 2013 includes location, date, size, infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, and precipitation. Prior appropriation doubled infrastructure investment and raised the value of agricultural output beyond baseline riparian rights. The analysis reveals institutional innovation that informs contemporary water policy.

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1 Introduction

Property rights are fundamental institutions for economic decisions and outcomes. They contribute to long-run economic growth (Acemoglu et al., 2001, 2005; Mehlum et al., 2006; Rodrik, 2008; Dixit, 2009; Besley and Ghatak, 2009), facilitate greater investment when returns are uncertain or delayed (Besley, 1995; Jacoby et al., 2002; Galiani and Schargrodsky, 2010; Lin et al., 2010), allow for the development of markets (Greif et al., 1994; Dixit, 2009; Edwards and Ogilvie, 2012), and reduce rent dissipation associated with common-pool resources (Gordon, 1954; Scott, 1955; Wiggins and Libecap, 1985; Gaudet et al., 2001; Wilen, 2005; Costello et al., 2008).[1] Despite their importance, the determinants of how property rights initially emerge and how the process frames subsequent economic behavior have received little attention.[2] The reason is that voluntary major shifts in property institutions are rare, reducing empirical observation for analysis. Property regimes more commonly change involuntarily with revolution or military conquest, as was the case with the Russian revolution of 1917 or the expansion of the British Empire over native arrangements (Libecap et al., 2011).

It is costly to set up a property rights system and once in place, owners (individuals or group members, depending on the institution) form expectations about the range of designated uses, conditions for exchange, investment opportunities, time frames, delegation of associated costs and benefits and hence, the flow of net rents from the asset. The property rights structure also defines political and social positions in societies. Accordingly, any important change in property rights imposes uncertainty and potential losses on incumbent owners and aspiring ones across a variety of margins with significant distributional and efficiency consequences. For these reasons, individuals and organizations within societies, economies, and political structures develop stakes in the prevailing property rights system, suggesting the high costs of replacing them and explaining their observed durability.

In this paper, we exploit the empirical setting of the westward settlement of the American frontier as a laboratory for institutional innovation. Settlers moved west across the continent after native claims had been swept aside. Migrants, seeking ownership of natural resources—land, timber, gold and silver, proceeded ahead of formal state and territorial governments,

[1] The role of property rights in constraining rent dissipation in open-access resource has perhaps the largest literature. Other examples include Casey et al. (1995), Grafton et al. (2000), and Bohn and Deacon (2000).

[2] Demsetz (1967), Cheung (1970), Anderson and Hill (1975), and Barzel (1997) emphasize that property rights emerge when the marginal benefit of creating, defining, and enforcing those rights exceed the marginal costs of doing so, but do not examine the forms property rights take in different settings or why.

bringing with them basic legal norms but confronting unfamiliar conditions that required new arrangements for successful economic development. These institutions appeared spontaneously via local collective action and persist today, determining contemporary actors and molding markets and policy.

Our focus is on the abrupt, deliberate shift from common-law riparian water rights that dominated in the eastern US and granted use of surface water to adjacent land holders as shares based on contiguous acreage, to prior appropriation that assigned ownership of water based on time, as first-possession claims.[3] Prior appropriation granted the right to divert a fixed amount of water for beneficial use at sites distant from a stream. It became the basis for large-scale investment in irrigated agriculture and the subsequent economic development of the West. Prior appropriation displaced riparian rights across an immense area of some 1,808,584 mi^2 (17 western states and 2 Canadian provinces).[4] Most prior appropriation rights were established between 1850 and 1920 when water was valued primarily as an input to irrigated agriculture, and today 40 to 80% of western water use remains in agriculture (Brewer et al., 2008).[5] Examination of the economic gains attributable to prior appropriation makes clear why it was adopted so broadly and so quickly as well as why it has persisted even after initial conditions changed.[6]

Our empirical analysis of the economic advantages of prior appropriation relative to riparian water rights begins with a model for deriving testable hypotheses. For the empirical analysis we develop a novel data set that includes the location, date, and size of 7,800 water claims along with measures of infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, precipitation, and drought in Colorado, the state where prior

[3]First-possession ownership of natural resources has been criticized for encouraging a race among homogeneous agents that dissipates rents (Barzel, 1968, 1994; Lueck, 1995, 1998). This argument does not account for the ubiquity of first possession or its economic contribution. Indeed, when agents and the resource are heterogeneous, dissipation is reduced (Leonard and Libecap, 2015).

[4]Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, Wyoming, Alberta, and British Columbia. This system is often characterized by the phrase, "first in time, first in right." First possession in property rights allocation is discussed by Epstein (1978), Rose (1985, 1990), Ellickson (1993), and Lueck (1995, 1998).

[5]Prior appropriation water rights have been described by many, including Burness and Quirk (1979, 1980a,b), Johnson et al. (1981), Smith (2000), Howe (2005), Hanemann (2014), and Chong and Sunding (2006). Kanazawa (1996, 2015) explores the early development of prior appropriation in mining camps, but it developed largely from demands for irrigation in the semi-arid region west of the 100th meridian. Ostrom (1953) and Ostrom and Ostrom (1972) discuss the replacement of riparian rights by prior appropriation.

[6]Related to the economic advantages we examine, is the ability to move water from one place to another that is possible only at very high cost with a riparian rights system. This transfer ability was the basis for the implementation of the Reclamation Service (Bureau of Reclamation) in 1902 and its multiple water storage and transfer infrastructures, as well as the transport of water to Los Angeles, San Francisco and other urban centers from remote water sources (Pisani, 2002).

appropriation was most completely implemented initially. We find that i) search by early claimants generated positive externalities, lowering costs for subsequent claimants; ii) secure, recognized property rights facilitated coordination among large numbers of heterogeneous agents by reducing uncertainty and providing an instrument for exchange; iii) coordination led to substantially higher levels of infrastructure investment, which led to iv) long-run increases in income per acre in agriculture.

While valuable in much of Colorado, we find that formal prior appropriation water rights were less critical in those parts of Colorado where water users were in close-knit, small, older Hispanic communities and relied upon shared norms in farming and irrigation decisions (Ostrom, 1990). Finally, we provide new empirical estimates of the contribution of irrigated agriculture made possible by prior appropriation to economic development in the western US. We conclude by emphasizing that once prior appropriation was put into place, it provided an on-going framework for water allocation, use, and investment decisions. This framework remains today, channeling how contemporary water uses respond to new urbanization, environmental, and industrial demands. Our analysis extends the literatures on institutional change, property rights, first possession, and path dependency.

2 Background

The western frontier was immense and varied in terrain, quality, and potential value, leading to high information and coordination costs for resource claimants. Through most of the 19th century, natural resources in the American West—farmland, timberland, mineral land, rangeland, and water—were open for first-possession claiming (Kanazawa, 2015; Libecap, 2007).[7] Examination of various resources reveals how little early claimants knew about the location of the most promising mineral ore sites, timber stands, or agricultural lands. Most parties had little experience with western resources, and many California emigrants, for example, ultimately earned only their opportunity wage (Clay and Jones, 2008).

Settlers sought to establish property rights with very limited information and understanding of the necessary conditions for successful enterprises. In the case of water, frontier

[7]Frontier resources, land, minerals, timber, and water were generally allocated via first possession (Umbeck, 1977, 1981; Libecap, 1978, 2007; Libecap and Johnson, 1979; Reid, 1980; Zerbe and Anderson, 2001; McDowell, 2002; Clay and Wright, 2005; Stewart, 2009; Gates, 1968; Allen, 1991; Romero, 2002; Getches, 2009). The federal government attempted to sell lands early in the century at a floor price of between \$1.25 and \$2.50/acre, but given the vastness of the area and small size of the US Army, the government could not control or police entry as squatters moved ahead of the government survey and occupied properties under first possession. Kanazawa (1996) discusses the rapid shift from sales and land auctions to first possession in the distribution of federal lands in the early to mid-19th century.

migrants could observe relatively stable resource characteristics, such as topography, elevation, and stream location in their claiming decisions. Soil quality and variable stream flow due to drought, however, were not known. Variable stream flow was particularly critical because water claims could be made at a time of unusually high water supplies but provided insufficient water during drought. There was a general misunderstanding of the region's dry climate and of the potential for drought to dramatically shift production (Libecap and Hansen, 2002; Hansen and Libecap, 2004b,a).

The costs of establishing property rights to water were potentially high: learning about stream fluctuation, soil quality, and optimal farming techniques was time consuming and successful use of water required investment in major diversion infrastructure to move water from rugged and unproductive riparian terrain. The report on the Colorado Territory by Cyrus Thomas to the US Congress exemplifies the degree of heterogeneity and uncertainty facing potential claimants:

> I made an effort to ascertain what the average cost of ditching is to the acre, but found it next to an impossibility to do this. The difference in the nature of the ground at different points, the uncertainty in regard to the price of labor, the difference in the sizes of the ditches, would render an average, if it could be obtained, worthless. (Hayden, 1869, p. 150)

Each additional wave of settlers brought new competition but also created the potential for cooperation in the construction of critical diversion infrastructure.[8] These challenges had not presented themselves in settings where the riparian doctrine dominated—where land was more homogeneous with established ownership, the climate was better understood, farming practices were well established, and the terrain did not require water to be moved to distant irrigation sites. The riparian doctrine granted a right to a share of the water on a stream to any owner of land adjacent to the stream.[9] This property rights scheme, however, was ill suited to western water resources.

Figure 1 depicts the distribution of major streams and types of water rights in the United States to illustrate the dramatic nature of the shift in property rights regimes for water that occurred west of the 100th meridian. The figure shows states/territories with either riparian rights or prior appropriation or hybrids of both—those along the 100th meridian and those on the west coast. The dates are those of key constitutional, legislative, or judicial adoption of

[8] Hanemann (2014) points out that the key issue among migrants was raising capital for very capital-intensive agriculture.

[9] Rose (1990) discusses the early evolution of riparian water rights in the eastern United States.

prior appropriation.[10] It is evident that populations in states with abundant water resources held to the riparian doctrine; those in states with both dry and wet regions maintained mixed systems; and those in the most arid states with lower stream density rapidly adopted prior appropriation. We explore the economic contributions of prior appropriation that led to this adoption.

Figure 1: Property Rights Innovation

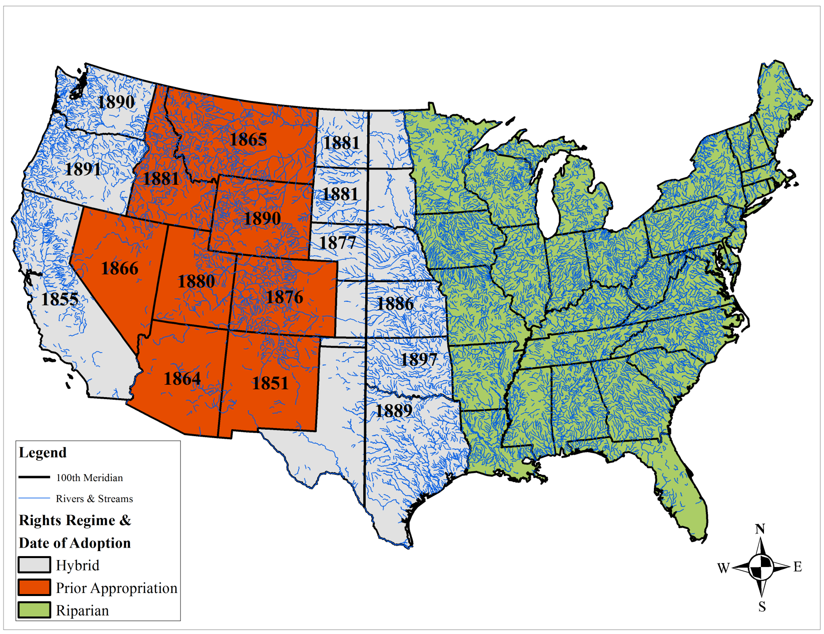


Table 1 presents the results of a simple linear probability model for whether a state/territory adopted prior appropriation, replacing common-law riparian rights in the contiguous United

[10]Mead (1901, p. 7-15) discussions the imperative to shifting from riparian to prior appropriation to promote irrigation in semi-arid regions. Dates of prior appropriation adoption: Arizona: Territory Arizona, Howell Territorial Code, Ch. LV, Hutchins (1977, p. 170); Colorado: Constitution art. XVI 5 and 6; *Coffin v. Left Hand Ditch Co* (6 Colo 443); Idaho: An Act to Regulate the Right to the Use of Water for Mining, Agriculture, Manufacturing, and Other Purposes (1881), Hutchins (1977, p. 170); Montana: *Mettler v. Ames Realty Co.*, 61 Mont. 152, 170-171, 201 Pac. 702, MacIntyre (1994, p. 307-8); New Mexico: Territorial Constitution Art XVI 2; Hutchins (1977, p. 228); Nevada: *Lobdell v. Simpson*, 2 Nev. 274, 277, 278; Hutchins (1977, p. 170-71); Utah: Utah Laws 1880, ch. XX; Wyoming: Constitution Art VIII 1-5; Hutchins (1977, p. 300); California: *Irwin v. Phillips*, 5 Cal. 40 (1855); Hutchins (1977, p. 181, 233-34); Kansas: 1886 Kans. Sess. Laws 154, ch. 115; Hutchins (1977, p. 170); Nebraska: Neb. Laws p. 168(1877); Hutchins (1977, p. 212); North Dakota: Terr. Dak. Laws 1881, ch. 142; Hutchins (1977, p. 213); Oklahoma: Terr. Okla. Laws 1897, ch. 19; Hutchins (1977, p. 171, 215); Oregon: Oregon Laws 1909, Ch. 216. Oregon Revised Stat. ch. 539; Hutchins (1977, p. 170); South Dakota: Terr. Dak. Laws 1881, ch. 142; Hutchins (1977, p. 170, 220); Texas: Tex. Gen. Laws 1889, ch. 88; Hutchins (1977, p. 170); Washington: Wash. Sess. Laws 1889-1890, p. 706; Sess. Laws 1891, ch. CXLII, Hutchins (1977, p. 170).

States.[11] The dependent variable is equal to one for states/territories (or their sub-regions) that adopted prior appropriation and zero for areas that maintained the riparian doctrine.[12] This simple exercise underscores the impression in Figure 1 that inhabitants of states with lower stream density, less rainfall, and more rugged terrain were more likely to implement prior appropriation. These are states where agriculture would require diversion of water from streams that were sparsely and unevenly distributed across the rugged terrain.

Table 1: Adoption of Prior Appropriation

	Y = $\mathbb{1}$(Prior Appropriation)		
Stream Density	-0.285^{***}	-0.0875	-0.576^{**}
	(0.0887)	(0.0592)	(0.225)
Roughness	0.000910^{***}	0.000691^{***}	0.000750^{***}
	(0.000111)	(0.000118)	(0.000105)
Precipitation		-0.000507^{***}	-0.000329^{**}
		(0.000118)	(0.000136)
(Stream Density)^2			0.218^{**}
			(0.0875)
Constant	0.152^{*}	0.577^{***}	0.539^{***}
	(0.0888)	(0.148)	(0.141)
N	57	57	57
R^2	0.610	0.706	0.729

Robust standard errors in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

To better understand the economic factors that led to the rise of prior appropriation, we focus on Colorado—the place where settlers in the westward movement of the agricultural frontier first encountered semi-arid terrain in a territory not dominated by preexisting riparian water rights holders.[13] Colorado covers an area of some 66,620,160 acres containing over

[11]Stream density is aggregated perennial flow lengths divided by area; high-resolution data are from the National Hydrography Dataset (NHD). Precipitation is 30-year average annual rainfall data from PRISM Climate Group. Terrain Ruggedness Index (TRI) uses the Riley method and classification syntax are averaged over the area (see ArcGIS methods for TRI calculation below). Digital elevation model (DEM) used for TRI calculations from USGS, downloaded from GeoCommunity.

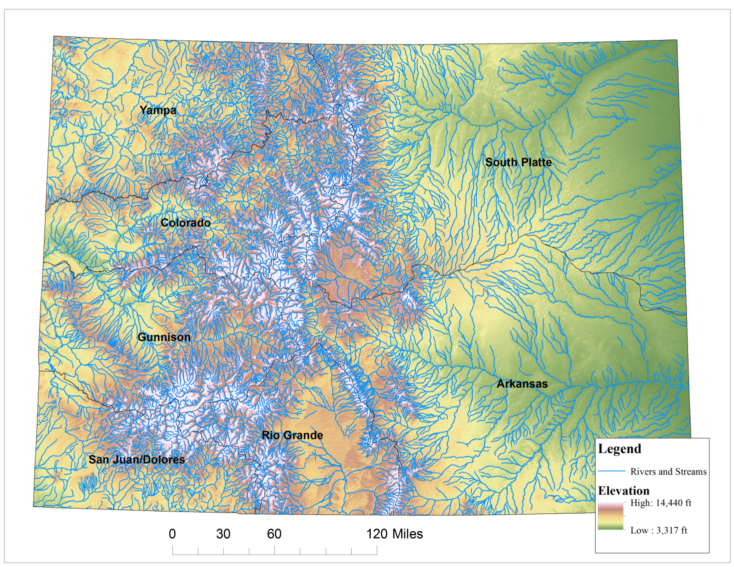
[12]We divide the states with hybrid water rights regimes into sub-regions according to their climate. North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas are divided along the 100th meridian, Washington and Oregon are divided along the Cascade Mountain Range, and California is divided into northern and southern regions at the latitude of Lake Tahoe, defining much wetter and drier regions of these states.

[13]Prior appropriation first emerged in Colorado as a full tangible property right to water and became known as the Colorado Doctrine. It was a general template for other western territories and states and, generally, western Canadian provinces (Schorr, 2005). Only in the wetter states of California, Oregon, and Washington did remnants of riparian water rights remain (Hess, 1916; Dunbar, 1950; Hobbs, 1997).

107,000 miles of streams with elevations ranging from 3,317 to 14,440 feet.[14] Settlers in the 19th century had to confront this vast resource and determine the best location in which to establish rights to land and water.

Prior appropriation emerged over a 20-year period, whereby more formal rights and supporting institutions were adopted as competition for water increased (Demsetz, 1967). Because the native population had been displaced and the federal government was remote, early migrants had a relatively open slate to define property institutions to frontier resources. Colorado migrants came primarily from the northeast and north-central US where there was little need for irrigation and riparian rights dominated (Colorado Water Institute, ND, 2; Dunbar, 1950, p. 42; Hobbs, 1997, p. 3; Romero, 2002, p. 527) In Colorado, however, irrigation of crop lands and investment in conveyance capital to move water to distant sites were required. As we show prior appropriation made these feasible. Figure 2 depicts water and land resources as well as Water Divisions in Colorado and demonstrates the scale of the information and decision problem facing potential claimants.

Figure 2: Water Resources and Terrain in Colorado

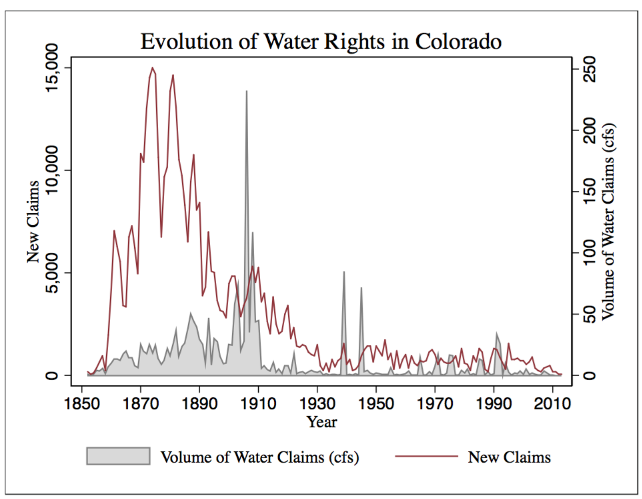


The first Colorado Territorial Legislature in 1861 enacted legislation as a precursor to prior appropriation, allowing water to be diverted from streams to remote locations, abrogating common-law riparian principles that kept water on adjacent lands. A 1872 statute continued the move toward prior appropriation by granting right of way to irrigation ditch

[14]The 1900 population of Colorado was 539,500, implying a population density of 1 person per 123 acres.

companies. In 1876 the Colorado Constitution formally proclaimed prior appropriation as the basis for water rights in the state. Statutes in 1879 and 1881 added administrative structures for measurement, monitoring, and dispute resolution. The state was divided into water divisions and subdivided into watershed districts with local water supervisors and courts. A state Hydrologic Engineers Office was created and county clerks were to record appropriative claims that previously had been announced informally at diversion sites. Finally, in 1882 the Colorado Supreme Court in *Coffin v Left Hand Ditch Co* (6 Colo 443) rejected remnants of riparianism in favor of prior appropriation (Colorado Water Institute ND, pp. 3-8; Dunbar, 1950, pp. 245-60; Hobbs, 1997, pp. 6-9, 32; Romero, 2002, pp. 536-9). This legal infrastructure provided for the official definition and transfer of prior appropriation water rights and investment in irrigation capital. It has been described as the Colorado System, and it was adopted generally by most other western state legislatures, courts, or constitutions (Colorado Water Institute, ND, p. 1; Hess, 1916, pp. 652-6; Hemphill, 1922, pp. 15-8; Dunbar, 1983, 1985). Priority access to water was defined by stream, so that being the first claimant on a given watercourse granted the highest priority to water in any given year. Figure 3 shows the evolution of water claims in Colorado over time and indicates that claimants arrived in waves, primarily in the latter half of the 19th century.

Figure 3: The Timing and Volume of Water Claims in Colorado



3 Economic Model of Riparian vs. Appropriative Rights

We build upon the model of prior appropriation developed by Burness and Quirk (1979) to provide new insights into the conditions under which prior appropriation is more efficient than riparian water rights and derive testable implications. We begin by characterizing the diverter's problem under prior appropriation and the aggregate rents generated by water claims under this system. Then, we present the diverter's problem under a share-based system that approximates a riparian regime in which shares are based on adjacent land ownership, and we compare the aggregate rents generated by each for a given number of users. Finally, we show that for a sufficiently large positive information externality from investment in establishing claims, prior appropriation is the efficient rights allocation mechanism.[15]

The model takes the timing and arrival of claimants as given, focusing on sequential claims established by homogeneous users. Users establish a water right by constructing diversion infrastructure of size x on the basis of their expected deliveries of water and earn revenues from diversion according to the function $R(x)$ satisfying $R'(x) > 0, \quad R''(x) < 0$. The costs of constructing diversion capacity of size x are given by the function $C(x)$ satisfying $C'(x) > 0, \quad C''(x) > 0$. Define $p_i = \sum_{j=1}^{i-1} x_j$ to be the total volume of water claimed prior to user i.

Let the random variable S be the total water available in the stream in a given year, with cumulative distribution function $F(s) = Pr(S \leq s)$ and probability density function $f(s)$. We assume that users cannot divert more water than their diversion infrastructure allows. Hence, in choosing diversion capacity (and claim size) users face a trade-off between the known costs of investment and variable flows that may or may not exceed constructed capacity. For simplicity we assume that capacity investment is a once-and-for-all decision.

3.1 Investment and Aggregate Rents in the Baseline Case

Under prior appropriation, users maximize their expected profits by choosing what size claim to establish, subject to the availability of water. Each user i solves

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = \left[1 - F(p_i + x_i)\right] R(x_i) + \int_{p_i}^{p_i + x_i} R(t - p_i) f(t) dt - C(x_i). \tag{1}$$

[15] Positive return-flow externalities also existed, whereby the diversion and subsequent runoff by upstream claimants smoothed out the natural flow of rivers and made more water available downstream than had previously been the case (Crifasi, 2015). We note that these and other benefits existed but do not model them explicitly.

Expected profits can be broken into three parts. First, there is the revenue from receiving a full allocation x times the probability that stream flows are sufficiently large for all senior claims to be satisfied and user i to receive her full allocation. Second, there is the expected revenue from diverting a less than full allocation for levels of stream flow that allow a partial diversion. This occurs when $p_i < s < p_i + x_i$; all claims senior to user i are satisfied, but user i exhausts the remaining water before receiving her full diversion. Finally, the user bears the cost of constructing diversion facilities regardless of how much water she receives. The first-order condition is

$$\begin{aligned}\frac{\partial \mathbb{E}\left[\pi(x_i)\right]}{\partial x_i} &= -f(p_i + x_i)R(x_i) + \left[1 - F(p_i + x_i)\right] R'(x_i) + f(p_i + x_i)R(x_i) - C'(x_i) = 0 \\ &= \left[1 - F(p_i + x_i)\right] R'(x_i) - C'(x_i) = 0. \end{aligned} \tag{2}$$

Users maximize expected profit by setting the expected marginal revenue of a claim equal to the marginal cost of establishing that claim. If the second-order condition for a maximum is satisfied then, Equation 2 has a unique solution that defines an implicit function $x_i = x_i^{*PA}(p_i)$ and the profit function for user i under prior appropriation is[16]

$$\begin{aligned} V_i^{PA} = \mathbb{E}\left[\pi(x^{*PA}(p_i))\right] &= \left[1 - F(p_i + x^{*PA}(p_i))\right] R(x^{*PA}(p_i)) + ... \\ ... + \int_{p_i}^{p_i + x^{*PA}(p_i)} & R(t - p_i) f(t) dt - C(x^{*PA}(p_i)). \end{aligned} \tag{3}$$

Define $\mathbf{V^{PA}} = \sum_{i=1}^{N} V_i^{PA}$ as the aggregate rents on a given stream from claims established under the prior appropriation doctrine. Then we have

Proposition 1: *Under prior appropriation, aggregate profits V^{PA} are increasing and concave in the number of appropriators for $N < \bar{N}^{PA}$ and have a unique maximum at $\bar{N}^{PA}$.*

Proof: see Appendix A. The intuition is that claiming will continue as long as the marginal claimant's expected profits are positive and that the final entrant will earn zero expected profits. Hence, aggregate profits are increasing in N for $N < N^{PA}$ and decreasing in N for $N > N^{PA}$.

Under a riparian or other share-based system, users are able to divert shares of annual flow

[16] The second order condition is $\frac{\partial^2 \mathbb{E}[\pi(x_i)]}{\partial x_i^2} = -f(p_i + x_i)R'(x_i) + \left[1 - F(p_i + x_i)\right] R''(x_i) - C''(x_i) \leq 0$. This holds without further assumption because $f(\cdot)$ is a proper pdf and hence must be non-negative.

based on the size of their adjacent land holdings. For simplicity we assume equal shares.[17] The arrival of a new claimant reduces the water available for all incumbent claimants by reducing the size of each user's share. In a true riparian setting, the geography of the river determines N, the total number of claimants, by constraining how many users can hold riverfront property. To simplify the analysis we treat N as a parameter.[18] In a given year with water flow S, each user is able to divert S/N units of water. Hence, the diverter's problem under a share system is

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = [1 - F(Nx_i)]R(x_i) + \int_0^{Nx_i} \left[R\left(\frac{t}{N}\right) f(t)dt \right] - C(x_i). \tag{4}$$

The first two terms in Equation 4 are expected revenues for a user with diversion capacity x_i in a share system with $N-1$ other users. The probability that user i receives enough water for a full diversion size x_i is the probability that their share of the flow is greater than the capacity they have constructed, or $Pr(S/N > x_i) = Pr(S > Nx_i) = [1 - F(Nx_i)]$. The second term is the expected revenue from diverting some amount less than x_i for levels of stream flow less than Nx_i. The costs of constructing diversion capacity are the same as under prior appropriation. The first-order necessary condition for a maximum is

$$[1 - F(Nx_i)]R'(x_i) - C'(x_i) = 0. \tag{5}$$

Again, users set the expected marginal revenue of diversions equal to the marginal cost of establishing a given amount of diversion capacity. The difference between this condition and the analogous condition under prior appropriation is that expected diversions in the share system depend on the number of other users in the system. If we assume that the second-order condition is satisfied, the first order condition defines an implicit function $x_i =$

[17] In practice, riparian systems require that other parties on the stream be allowed "reasonable use."

[18] N, the number of claimants, may be endogenous in a more generalized water share system where riparian lands are not a prerequisite for holding a water right. Under such a system the diverter's problem is to maximize expected profits by choosing how much diversion infrastructure to build, given the expected flow of the river and expected number of other users on the stream. Of course, the Nash Equilibrium of this strategic game is for users to enter until expected profits for all users are zero, resulting in full rent dissipation.

$x_i^{*S}(p_i, N)$ that can be used to generate the profit function for user i:[19]

$$V_i^S = [1 - F\left(N x_i^{*S}(p_i, N)\right)] R\left(x_i^{*S}(p_i, N)\right) + \int_0^{N x_i^{*S}(p_i, N)} \left[R\left(\frac{t}{N}\right) f(t) dt\right] - C\left(x_i^{*S}(p_i, N)\right). \tag{6}$$

Define $\mathbf{V^S} = \sum_{i=1}^{N} V_i^S = N V^S$ as the aggregate rents on a given stream from claims established under the riparian doctrine. Then we have

Proposition 2: $V^{PA} \lesseqgtr V^S$. *Either property rights regime can dominate for a given N.*

Proof: See Appendix A. The intuition for is that for any particular N, the distribution of diversion capacity will be different under each rights regime. A given N in the prior appropriation system implies a hierarchy of both diversion capacity and rents, with the highest-priority user establishing the largest investments and earning the greatest rents (see Proposition 1). In the riparian system, users all establish equal diversion capacity and earn equal rents. Aggregate diversion capacity is lower under the riparian system, but that capacity is used more efficiently than under the appropriative system under which some users earn higher marginal returns than do others. The result is that aggregate rents may be higher for shares, even though less water is used.[20]

The relative efficiency of either system is closely related to the concavity of the profit function. For constant marginal revenue and marginal cost, the two systems result in equal aggregate investment and profit. As the revenue function becomes more concave or the cost function more convex, the relative efficiency of the share system (for a given level of investment) increases because there are larger gains from reallocating marginal units of water equally across users. In contrast, assigning rights as shares reduces incentives to invest and lowers available diversion capacity. Prior appropriation is more likely to dominate when the number of potential entrants grows large because it secures the investments of senior users, making them indifferent to the arrival of new claimants (see Appendix A). The fact that new arrivals cannot dissipate rents captured by earlier claimants not only creates incentives for early investment but prevents classic open-access dissipation of the resource due to over-

[19]The second-order condition is $\frac{\partial^2 \mathbb{E}[\pi_i(x_i)]}{\partial x_i^2} = -N f(x_i) R'(x_i) + [1 - F(N x_i)] R'' - C''(x_i) \leq 0$.

[20]Burness and Quirk (1979) show these two effects separately. They establish that aggregate rents are higher with a share-based system for a given level of investment but that aggregate investment is higher under appropriation for a given N. They do not compare aggregate rents across the two systems for a given N.

entry. For this reason, prior appropriation becomes more profitable relative to shares when the number of potential users grows large relative to stream flow.

3.2 Positive Information Externalities from Prior Claims

General uncertainty about resource conditions and high information and transportation costs characterized the western frontier and created the need for coordination among potential claimants. Prior claims would lower costs for additional claimants by i) providing valuable information about where and how it is profitable to divert and use water, ii) providing infrastructure that can be shared or added to at lower cost, or iii) creating general agglomeration effects from clustered claiming and settlement (Crifasi, 2015). We allow for the existence of an additive positive externality from prior claims γp_i that lowers the fixed costs of establishing subsequent claims. The claimant's problem under prior appropriation in the presence of this positive externality is

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = \left[1 - F(p_i + x_i)\right] R(x_i) + \int_{p_i}^{p_i+x_i} R(t - p_i) f(t) dt - C(x_i) + \gamma p_i. \tag{7}$$

It is immediately apparent that the existence of an additive externality will not affect the magnitude of claims $x^{*PA}(p_i)$ under prior appropriation but will increase profits for junior users by reducing their fixed costs. Define $\mathbf{V^E} = \sum_{i=1}^{N} V_i^E$ as the aggregate rents on a given stream from claims established under the prior appropriation doctrine in the presence of a positive externality. This gives

Proposition 3: *In the presence of a positive externality from prior claims ($\gamma > 0$), V^{PA} has a convex region for small N and for sufficiently large γ, $V^E > V^S$.*

Proof: see Appendix A. The intuition is that aggregate rents under prior appropriation may increase at an increasing rate if the positive externality for junior claimants is large enough to offset their decrease in profit from facing lower expected available flows and constructing smaller capacity. Under these conditions, aggregate rents under the prior appropriation doctrine exceed those under the riparian system.

We assume that the positive externality exists only under prior appropriation for several reasons. First, prior appropriation protects senior users' investments from the arrival of junior users and thus makes them willing to engage in activities that generate positive externalities, such as information and infrastructure sharing. In contrast, each new arrival in a riparian system reduces the expected rents of incumbent users who thus have an incentive to avoid generating positive externalities by concealing information and refusing to coordinate or share infrastructure capacity. Second, users who own a share of annual diversions rather than a fixed amount face greater uncertainty in their expected diversion, making them less willing to bear the fixed costs of collective organization and capital construction.

3.3 Behavior of Claimants under Prior Appropriation

Next, we characterize individuals' choice of where to establish a first-possession claim under the baseline case relative to when there are large positive externalities generated by prior claims. We derive testable hypotheses about the behavior of claimants under the prior appropriation doctrine when γ is high. This will allow us to test the implications of our model despite the fact that we tend to observe either prior appropriation or riparian rights in a given area, with relatively little variation in which regime dominates—broadly, the eastern United States uses the riparian doctrine, and the arid western states use the prior appropriation doctrine (Figure 1).

We assume that unknown streams are of equal expected productivity so that the choice of where to establish a claim can be analyzed by comparing the value of being the ith claimant on a stream with the value of establishing the first claim on another stream of equal expected quality. For a new user to choose to follow prior claimants when other sites are available, the expected profits must be higher for junior claimants for at least some number of total users N. This gives

Proposition 4: *In the convex region of V^E, profits are increasing for junior claimants relative to senior claimants, $V_i^E > V_{i-1}^E$, and users follow rather than search for a new stream.*

Proof: see Appendix A. Proposition 4 follows directly from Proposition 3 because, for aggregate rents to be convex in N, junior claimants must earn higher profits than the prior claimant so that aggregate profits are increasing at an increasing rate, due to the positive externality. This is true only for relative small N, however, because the resource scarcity effect eventually dominates the positive externality.

Proposition 4 has direct behavioral implications for where claimants choose to locate under prior appropriation depending on the magnitude of γ. Proposition 1 makes clear that profits decline with priority if there is no positive externality. Users would in general be better off searching for new streams, and hence have higher priority, rather than following prior claimants. This would imply that users would on average be less likely to locate on a particular stream in a particular year if there were more claims on that stream in the previous year.

3.4 Information Costs, Excess Claiming, and Testable Predictions

Claiming effort by senior claimants is more likely to generate positive externalities for junior claimants when there is uncertainty about the quality of water and land resources and when information and infrastructure investment is costly. In addition to directly testing for whether new claimants follow prior claimants, we derive predictions about the effect of different resource characteristics on the decision of where to establish a water right.

If information costs are an important determinant of behavior in allocating rights, we expect claiming behavior to be more responsive to resource characteristics that are easier to observe. Factors that affect the value of diverted water and can be observed directly—topography, current flow, and elevation—are predicted to have a larger effect on claims than resource characteristics that are more costly for users to deduce such as flow variability and soil quality. Flow variability is particularly important because users may establish excess claims on a given stream if they do not account for the inter-annual variability of flows. The prior appropriation system includes an inherent check against overuse of water on a stream within any given year because new claimants can establish rights to residual water only after senior diversions have been satisfied.

If users lack full knowledge about the probability of receiving similar flows in the future, there is a potential systemic bias in the structure of appropriative water rights that can lead to excess claiming. If users are especially prone to claim water in years of high flow, then legal claims will come to exceed expected annual flows, and "paper" water rights will exceed "wet" water rights. We can analyze claiming behavior during drought to test for this systematic bias—if claims are less likely during drought, then users must respond to first-order resource availability, but not to underlying variability in flows.

Finally, our model relies on the assumption that users are more willing to coordinate with other water claimants if their investments are more secure. The comparison in our model is between users who own a fixed diversion and users who own a share of annual diversions. We cannot directly test for differences in behavior between these two groups, but we can assess the effect of property rights security on investment and coordination within the prior appropriation system. The assumptions of our model imply that senior right-holders should be more willing to coordinate and invest in infrastructure than junior rightsholders because their expected water deliveries are more certain.

Summary of Predictions

1. An increase in the number of claims on a stream will increase the number of subsequent claims on that stream.

2. Easily observed resource characteristics such as topography and average flow will be stronger determinants of claiming locations than are less apparent characteristics such as flow variability and soil quality

3. Fewer claims will be established during drought.

4. Users with higher priority are more likely to cooperate in investing in diversion infrastructure.

4 Empirical Determinants of Prior Appropriation Claims

4.1 Location Data

We assemble a unique data set of all known original appropriative surface water claims in Colorado. We combine geographic information on the point of diversion associated with each right with data on hydrology, soil quality, elevation, homestead claims, and irrigation to test our hypothesis about the determinants of first-possession claims.[21] Colorado is divided into 7 Water Divisions that separately administer water rights, as depicted in Figure 2. We focus on Divisions 1 to 3 (the South Platte (1), Arkansas (2), and Rio Grande (3)), which compose the eastern half of Colorado, are home to the majority of the state's agriculture, and have more complete diversion data available than other divisions. For each claim we know i) the date and geographic location of original appropriation, ii) the name of the structure or ditch associated with the diversion, iii) the name of the water source, and iv) the size of the diversion.

Our goal is to characterize individuals' choices of where to establish first-possession claims to water over time, so we divide Divisions 1 to 3 into a grid of 1-square-mile sections and

[21]GIS data on water rights were obtained directly from the Colorado Department of Water Resources. To our knowledge this is the first time such a comprehensive dataset has been compiled for water rights in any western state.

create measures of location quality by grid cell.[22] Analyzing only the location where rights were actually claimed ignores a substantial amount of individuals' choice sets, so including information on other claimable locations is critical for avoiding selection bias.

Figure 4 shows a map of Divisions 1 to 3 with the original location of all claims in our data set, the major streams, and the grid squares used for the analysis.[23] Areas with productive soil are shaded in green.[24] The figure makes clear the massive spatial scale of the water resources in Colorado and the extent to which ignoring unclaimed locations discards valuable information about individuals' opportunity sets. We aggregate grid-level characteristics up to the stream level and construct a panel of 1,922 streams from 1852 (the date of the first claim in our data) to 2013 (the date of the most recent claim), resulting in 311,364 total observations of which we are able to constructing overlapping covariates for 248,745.

Table 2 provides variable names, definitions, and summary statistics for the stream-level data and Appendix B provides detailed descriptions of how the geographic covariates were constructed. Variables relating to the stock and flow of rights along a river change over time, whereas measures of resource quality are fixed. We aggregate from grid squares to streams for four reasons. First, priority varies by stream, so the fundamental trade-off between high-priority access and low information costs occurs at the stream level. Second, we observe variation in flow at the stream level, so subdividing beyond streams does not provide additional information about the water resource. Third, the count of claims in a given square mile in a given year is extremely small, by construction. Using such a fine spatial resolution reduces the variation in the dependent variable and results in an arbitrarily large number of zeros in the data. Fourth, the potential for measurement error in how we have delineated grid squares is reduced by aggregating to a larger spatial unit that is defined on the basis of underlying hydrologic variation rather than a more arbitrary partitioning of space.

[22]This grid approximates the Public Land Survey (PLSS) grid but fills in gaps where GIS data on PLSS sections are not available. Actual homesteads and other land claims were defined as subsets of PLSS sections, so grid-level variation is similar to actual variation in land ownership and land use.

[23]We discard sections that do not intersect any water features in our analysis because water claims can be established only where there is water.

[24]We use soil group B, which is composed primarily of loamy soil and is the most productive for agriculture.

Figure 4: Possible and Actual Claim Sites

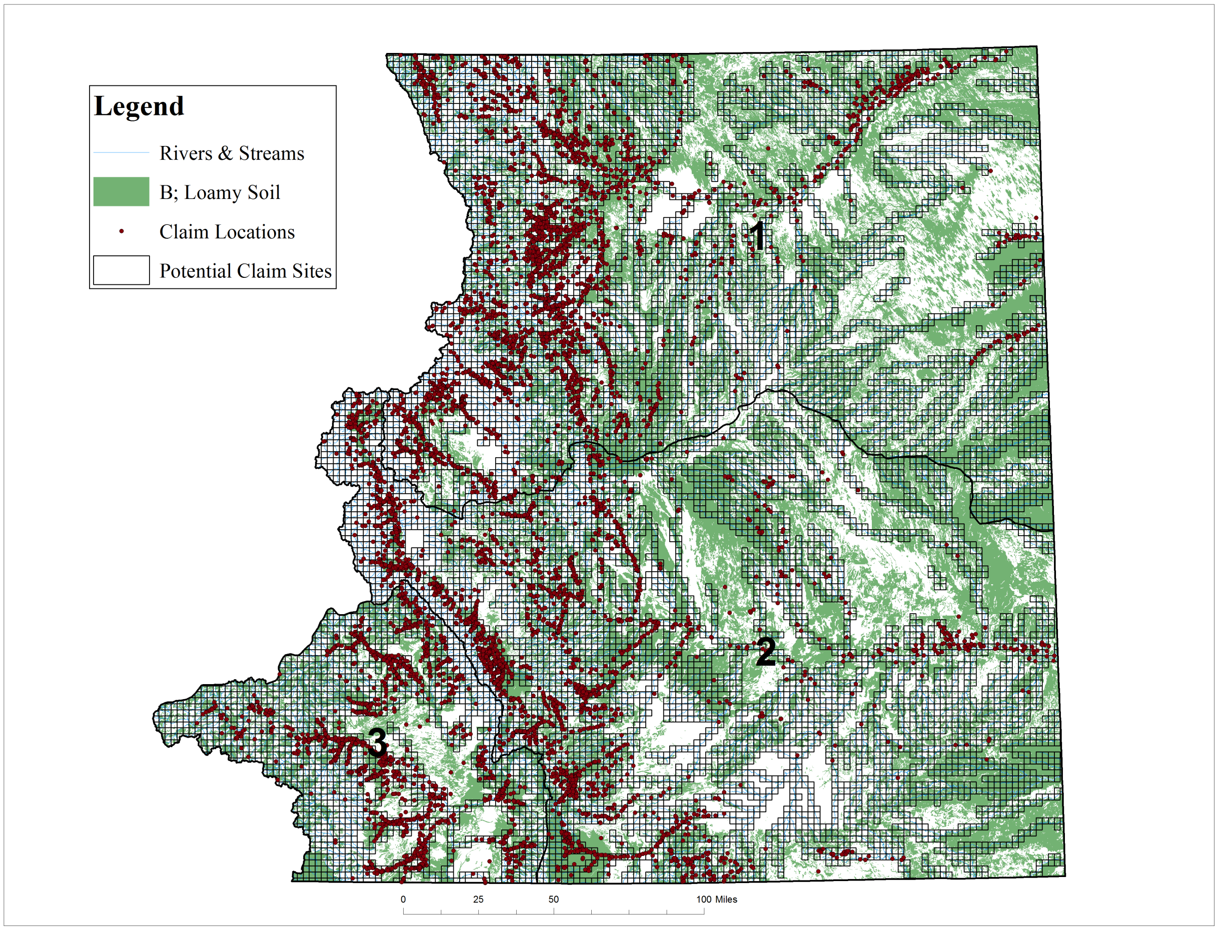


Table 2: Stream-Level Summary Statistics

Variables	N	Mean	S.D.	Min	Max	Definition
New Claims	311,364	0.0253	0.529	0	62	Number of new claims on stream j in year t.
$\mathbb{1}$(New Claims)	311,364	0.0110	0.1045	0	1	Dummy variable equal to 1 if New Claims >0 in year t.
Initial Claims	311,364	0.00156	0.0510	0	2	Number of new claims on stream j in year 0.
$\mathbb{1}$(Initial Claims)	311,364	0.00104	0.0322	0	1	Dummy variable equal to 1 if Initial Claims >0.
Summer Flow	250,452	68.19	227.6	0	4,638	Flow (cfs) on stream j from May to August, averaged over 1890-2000.
Roughness	311,202	290.1	282.5	0.174	3,299	S. D. of slope multiplied by average slope along stream j.
Flow Variability	250,452	5.761	56.22	0.00687	1,353	S. D. of summer flow from 1890 to 2000.
$\mathbb{1}$(Drought)	311,364	0.160	0.367	0	1	Dummy variable = 1 during major drought years.
Homestead Acres_{t-1}	309,281	77.66	677.5	0	72,628	Number of acres homesteaded in township crossed by stream j in year $t-1$.
Homestead Claims_{t-1}	309,281	0.399	2.837	0	242	Number of homestead claims in township crossed by stream j in year $t-1$.
Total Homesteaded Acres	311,364	7,905	20,085	0	326,297	Cumulative acres homesteaded in township crossed by stream j as of year t
Percent Claimed	307,476	2.13	5.54	0	35.99	Cumulative prior water claimed/Summer Flow on stream j in year t
Watershed Acres	311,364	5,460.68	187,325.2	18.43	8,215,323	Total size of watershed containing stream j
Acres Loamy Soil	311,364	367.29	3,973.91	0	173,086.5	Acres within 10 miles of stream j with loamy soil

Notes: 1) Data on homesteads were provided by Dippel et al. (2015) and are based on Bureau of Land Management digitization of all land patents from the settlement of the western United States. 2) Drought variables are based on major drought years described in Henz et al. (2004). 3) Annual historical flow estimates used to calculate flow variability could be constructed only for a subset of data due to the availability of other variables used in the hydrologic model.

4.2 Identification of Positive Spillovers in Establishing Water Rights

The presence of an additional senior user on a stream reduces the availability of water and makes any junior claimants worse off and should make the arrival of subsequent claimants less likely unless a positive externality exists. Hence, we look for evidence of positive spillovers by estimating the effect of previous claims on a given stream on the probability and expected count of subsequent claims on that stream.[25] This gives our econometric model an inherently dynamic nature. We characterize the number of claims on stream j in year t, which has the properties of a count variable, using a Poisson distribution.[26] The primary challenge to identification comes from the fact that there are unobserved location characteristics that we cannot measure so that the presence of prior claims could act as a proxy for unobserved site quality and cause us instead to attribute the effect of these site attributes to positive spillovers. We can condition on soil quality, roughness, population pressure, stream flow, and stream variability, but any other variation in location quality observed by claimants but unobserved by us will bias our estimates if unaddressed.

Wooldridge (2005) provides a method for using initial values of y_{jt} to estimate Average Partial Effects (APE) of y_{jt-1} on y_{jt} that are averaged across the distribution of unobserved heterogeneity. We assume that y_{jt} has a Poisson distribution with conditional mean

$$\mathbb{E}(y_{jt}|y_{jt-1}, ..., y_{j0}, \mathbf{x_j}, u_j) = u_j \exp(x_{jt}\beta + y_{jt-1}\rho), \tag{8}$$

where u_j is a site-specific unobserved effect. Wooldridge shows that ρ can be identified by specifying a distribution for $u_{jt}|y_{j0}, \mathbf{x_j}$. In particular, if we assume

$$u_j = \nu_j \exp(\delta y_{j0} + \gamma \mathbf{x_j}), \qquad \nu_j \sim \text{gamma}(\eta, \eta), \tag{9}$$

then forming the likelihood and integrating out the distribution of u_j conditional on y_{j0} and $\mathbf{x_j}$ results in an estimator that is equivalent to the random effects Poisson estimator in Hausman et al. (1984). We implement this solution and estimate a random effects model controlling for y_{j0} to recover the partial effects of the variables of interest, averaged over the distribution of u_j. Placing parametric restrictions on the distribution of unobserved

[25]This is more appropriate than a multinomial approach because our hypotheses concern how changes in the characteristics of the possible choices themselves affect behavior, whereas multinomial choice models are designed to estimate how individual characteristics affect the choices that those individuals make. We lack data on individual characteristics but are able to construct rich panel data on locations, so we rely on dynamic panel methods for our estimations.

[26]In a given year most of the 1,922 streams receive zero new claims, there cannot be a negative number of claims, and the maximum number of claims on any stream in a given year is 62.

heterogeneity and the conditional distribution of $(y_{jt}|y_{jt-1}...y_{j0})$ is what allows us to use the initial values y_{j0} to trace the evolution of y_{jt} separately from the unobserved effect. We prefer this method to a fixed effects approach, which would necessarily discard all streams that never receive a claim, resulting in potential selection bias.

Identification requires several assumptions. First, we must assume that we have correctly specified the densities for the outcome of interest in Equation 8 and the unobserved effect in Equation 9. We maintain this assumption, emphasizing the count nature of our dependent variable and the standard use of a gamma distribution for modeling random effects in similar contexts.[27] Second, we must assume that ν_j is independent of $\mathbf{x_j}$ and y_{j0}. This requires that the random component of the unobserved heterogeneity in site quality be random and not dependent on observed covariates.[28] Our covariates are either fixed geographic characteristics or lagged values of other variables, making this assumption plausible.

Third, we must assume that the dynamics of y_{jt} follow a first-order Markov process—that the dependence of y_{jt} on the complete history of claims in the same location can be summarized by the relationship between y_{jt} and y_{jt-1}.[29] We argue that conditioning on the cumulative diversions along a stream—an element of $\mathbf{x_j}$—alleviates concern that the cumulative stock of claims prior to period $t-1$ could directly affect y_{jt}. In any given period, users direct their location choice on the basis of what users in the previous period did and the total amount of the resource that is still available for claiming, but the total number of claims is not directly relevant except through its effect on y_{jt-1}. Claims from the previous period provide a signal to potential followers about whether claiming on stream j is profitable, given the declining rents of claiming on a given stream as claims accumulate. Beyond this signal, the effect of prior claims will be captured in our measurement of cumulative prior diversions.

4.3 Empirical Estimates of Claiming Externalities

Table 3 reports the results of the random effects Poisson estimator. We calculate and report the estimated average marginal effects of each of the covariates on the probability of a stream receiving at least one new claim in a given year.[30] All specifications control for stream size and variability (Summer Flow and Flow Variability), drought, land quantity and quality (Roughness, Acres Loamy Soil, Watershed Acres), population pressure (Lagged

[27]We perform a variety of simulations and confirm that the estimator is robust to alternative data generating processes for u_j.

[28]But note that the unobserved component of Equation 8—u_j—is allowed to depend on $\mathbf{x_j}$ and y_{j0}.

[29]This is implicit in Equation 8.

[30]Averaged across the distribution of unobserved heterogeneity u_j.

Homestead Claims), and Initial Claims (required for identification). Column 2 controls for the total amount of water already claimed on a stream, and Column 3 also controls for the total number of acres already homesteaded in the same township as the stream. We predict that claims will be more likely when water is abundant (higher Summer Flow, less water claimed, and Drought = 0) and when there is population pressure (more lagged Homestead Claims). Limited information with high search costs implies that difficult-to-assess variables like Flow Variability and Soil Quality should not affect claiming behavior. The key test for the existence of positive externalities is whether the coefficient on Lagged Claims is positive.

Nearly all of the variables in Table 3 have the expected signs. Across all three specifications, the probability of new water claims is greater when there are more Lagged Water Claims or Lagged Homestead Claims, Watershed Acres are greater, and the stream—measured by Summer Flow—is larger. New Claims are less likely during Drought and when more of the land around the stream has already been homesteaded. In Column 2, more Total Water Claimed reduces the probability of new claims, but the coefficient becomes positive in Column 3 once we control for Total Homesteaded Acres, implying that the scarcity of the water and land endowments was linked.

Consistent with our intuition, several of the variables have no effect of the probability of new water claims on a stream. Long-term Flow Variability and Acres of Loamy Soil are insignificant, with precisely estimated zero coefficients in all three specifications. This is consistent with our hypothesis that claimants in the 19th century faced significant information problems. Migrants were unable to assess the inter-annual variability of stream flow or the viability of soil because they lacked knowledge of the long-term climate and necessary farming techniques in the region, as was the case across the West.

Table 3 provides strong evidence for the existence of significant positive externalities in the definition of prior appropriation water rights. The estimated coefficient on Lagged Claims is statistically significant across specifications and indicates that the probability of at least one new claim on a stream in any particular year increases by about a half of a percentage point for each claim established on that stream the previous year. This is an effect size of roughly 20%, as the mean probability of new claims is just 2.5%, meaning that the presence of just five new claims on a stream doubles the probability of new claims on the same stream in the following year. Combined with the finding that critical resource characteristics did not influence location choice, this result suggests that early claimants generated important information for subsequent claimants.

We are able to rule out the possibility that claimants' decisions to locate near prior

Table 3: Empirical Determinants of Prior Appropriation Claims

$\frac{\partial Pr(NewClaims > 0)}{\partial x}$	(1)	(2)	(3)
	Poisson Estimates, Y = New Water Claims$_{jt}$		
Lagged Claims	0.00556***	0.00570***	0.00490***
	(0.000658)	(0.000621)	(0.000622)
Summer Flow	0.0000590*	0.0000594*	0.0000641*
	(0.0000330)	(0.0000333)	(0.0000345)
Flow Variability	−0.0000167	−0.0000172	−0.0000198
	(0.0000122)	(0.0000125)	(0.0000127)
$\mathbb{1}$(Drought)	−0.0105***	−0.0101***	−0.00832***
	(0.00158)	(0.00169)	(0.00132)
Roughness	−0.0000169	−0.0000170	−0.0000233
	(0.0000168)	(0.0000169)	(0.0000191)
Acres Loamy Soil	−0.00000191	−0.00000159	0.00000182
	(0.00000313)	(0.00000302)	(0.00000299)
Watershed Acres	0.00000500*	0.00000501*	0.00000520*
	(0.00000282)	(0.00000289)	(0.00000293)
Homestead Claims$_{t-1}$	0.000220***	0.000254***	0.000297**
	(0.0000451)	(0.0000550)	(0.000133)
Initial Claims	0.00941**	0.00934**	0.00329
	(0.00394)	(0.00386)	(0.00505)
Total Water Claimed (cfs)		−4.84e-08**	0.000000104**
		(2.33e-08)	(5.20e-08)
Total Homesteaded Acres			−0.000000546**
			(0.000000230)
N	248,745	248,745	248,745
χ^2 for $H_0 : R.E. = 0$	7,979.36	7,571.86	8,322.72

Notes: Standard errors are clustered by stream and are reported in parentheses. N= 248,745 is the number of stream-year cells for which we have overlapping data on all covariates. * $p < .1$, ** $p < .05$, *** $p < .01$

claimants are driven by other benefits not related to water claims by examining the role of population growth in the evolution of water rights. Although the existence of new homestead claims in the same township as a stream makes new claims on that stream more likely by about 0.02 percentage points in the following year, a single water claim has the same effect on the probability of new claims as roughly 22 homestead claims. This indicates that water claimants' decision to follow prior claimants was driven by benefits specific to the definition of water rights rather than by a general positive benefit of locating near other settlers on the frontier. In Section 5 we analyze the mechanisms for this resource-specific externality.

The estimated effect of Lagged Claims is also large relative to other covariates. Claims are more likely to be established on larger streams, but the effect of a single lagged claim is equivalent to a 95 cfs increase in Summer Flow, about 1/3 greater than the average stream's Summer Flow of 68 cfs. Similarly, although claims are about 40% less likely during a major drought, the presence of just two prior claims on a stream could offset this major resource shock. These relative magnitudes demonstrate the economic significance of the externalities generated by early claimants—the information and potential coordination benefits of locating near prior claimants are on par with major shifts in the availability of water resources.

Information benefits provided by early claimants included demonstration of where and how irrigation ditches could be established. As we detail below, the best locations to divert water from the stream were not obvious initially and had to be discovered by experimenting. Techniques for irrigating flat, plateaued lands above stream channels were particularly valuable but not initially apparent. The development of these methods attracted waves of subsequent settlers to jointly claim water and land in areas previously considered unproductive (Boyd, 1890).

Though information generated by early claimants generated a positive externality by lowering information costs for subsequent claimants, it also created the possibility for rent dissipation. The fact that claims were less prevalent during drought, combined with users' unresponsiveness to stream variability, points to the possibility of dissipation through overclaiming of the resource identified in our theory (although we note that a share-based allocation would have exacerbated rent dissipation due to over-entry). Claims are more likely when water is more abundant, indicating a first-order responsiveness to resource abundance that does not account for the underlying variability in the resource. It so happens that much of the settlement of the Great Plains and the western United States occurred during a period of unusually high rainfall (Libecap and Hansen, 2002; Hansen and Libecap, 2004). This bias in the timing of water claims, rather than some inherent institutional weakness in the initial allocation of property rights, can explain the mismatch between legal water rights and available supplies observed today.

Early claims generated real value for subsequent claimants equivalent to major changes in expected resource availability, but the accumulation of prior claims itself reduced resources available for future claimants. Column 2 of Table 3 indicates that an increase in the cumulative volume of claimed water on a stream reduces the probability of new claims on that stream by an statistically-significant but economically-small margin—an increase in the volume of claimed water of over 100,000 cfs would be required to offset the positive effect of a lagged claim. In contrast, an increase in the cumulative total of homesteaded acres along a stream reduced the probability of new claims by about 1% for every 1,800 acres claimed (roughly ten homesteads).

Reductions in available resources had a real effect on claimants' behavior, although the effect of water availability is quite small. This minuscule effect may be driven by claimants' lack of full knowledge of the legal volume of prior claims—the sum of "paper" water rights may not have been of primary concern to settlers as they observed flows and chose claim sites. If claimants imperfectly understood or partially disregarded the actual measurement of water, then the average Summer Flow of a stream is likely to be a better measure of what they perceived the resource constraint to be.

To assess the the trade-off between resource availability and information externalities, we estimate the effect of Lagged Claims on the probability of New Claims for different size streams and plot the results in Figure 5.[31] The vertical axis is the estimated marginal effect of Lagged Claims on the probability of at least one new claim on a stream, and the horizontal axis is average stream size. The figure shows how the effect of Lagged Claims on Pr(New Claims) varies with stream size and depicts a clear trade-off between the benefits of following earlier users and the reduced expected benefits from decreased water availability. The positive effect of lagged claims is monotonically increasing in stream size.[32] Claimants were more likely to follow prior users on larger streams than on smaller ones, indicating a direct positive effect of following that depends on there being enough water for subsequent claimants.[33]

The development of water rights on South Boulder Creek near Boulder, Colorado, illustrates the economic behavior we identify in Table 3. The earliest claims on South Boulder Creek are associated with the Jones and Donnelly Ditch, which was established in 1859 to irrigate fertile land near the creek (Crifasi, 2015, p. 105). Seven other water rights were established on South Boulder Creek in that same year. This prompted an additional eight claimants to follow suit and establish water rights the following year, 1860. Finding the fertile lowlands already homesteaded, these new claimants developed methods for irrigating

[31]We do this by including an interaction term between Lagged Claims and Summer Flow, which is present in all of the models whose marginal effects are presented in Table 3.

[32]Figure 5 is a visual depiction of the cross-partial derivative $\frac{\partial^2 Pr(NewClaims)}{\partial LaggedClaims \partial SummerFlow}$.

[33]It may also be that the range of learning opportunities was narrowed on smaller streams, where the number of possible diversion sites and techniques was smaller than on large streams.

Figure 5: The Information-Resource Trade-Off

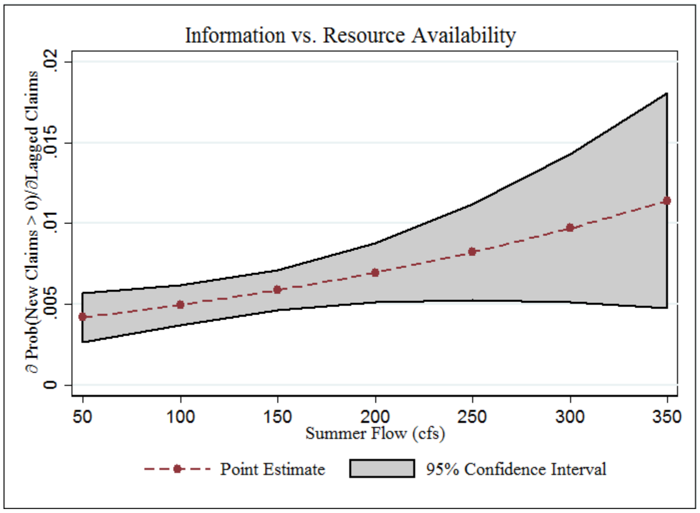
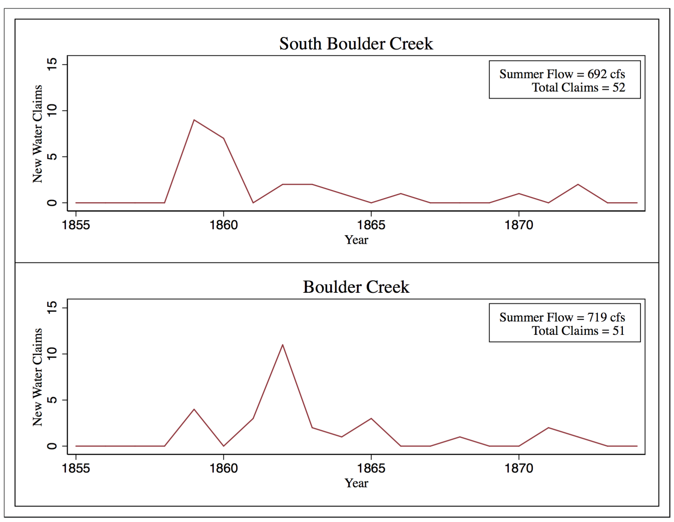


Figure 6: Evolution of Claims Near Boulder, Colorado



more remote lands that were often on bluffs above the creek.[34] This discovery prompted a subsequent wave of similar "high line" ditches on Boulder and South Boulder Creeks, including the north Boulder Farmer's Ditch, which would eventually supply much of the water for the city of Boulder (Crifasi, 2015, p. 187).

[34]Lemuel McIntonish, who filed his claim in 1862, built one of the first "high line" ditches in Colorado, demonstrating for the first time that highlands could be irrigated by diverting water further upstream and guiding it to one's land at a shallow grade (Crifasi, 2015, p. 187).

Eventually, claiming on both streams ceased as all available farmland and water was fully appropriated. Figure 6 depicts the early development of claims on Boulder and South Boulder Creeks.[35] Claiming fell in 1861 on South Boulder Creek after two years of heavy claiming—between 1859 and 1861 the volume of claimed water went from zero to over twice our estimate of the mean summer stream flow. Similarly, when the multi-year wave of new claims on Boulder Creek ceased in 1866, prior claims exceeded average summer flow by a factor of ten.[36] The trade-off between resource availability and positive externalities from prior claims is borne out in analysis of claiming behavior on particular streams—new claimants are initially quick to follow prior claimants, but they are equally quick to find new streams once the resource constraint binds.

We find strong evidence of high information costs, resource constraints, and positive spillovers in the search and investment required to establish prior appropriation water rights. Conditional on resource availability, homestead pressure, and unobserved site quality, an increase in the number of new water claims along a particular stream increases the probability of new claims along that same stream in the next year by 20%.[37] When deciding where to establish a claim, new users are more responsive to choices of earlier claimants than they are to many important, but difficult-to-observe, resource characteristics. The fact that claims are more likely when water is abundant indicates a systematic bias in the timing of claims that explains the overcapacity of irrigation infrastructure described by Coman (1911), Teele (1904), Hutchins (1929), and Libecap (2011).

4.4 Robustness

We reestimate our model using a set of alternative estimators to evaluate the robustness of our identification strategy given the unique character of our data set. Three primary concerns could threaten identification. First, our data set contains a large number of 0s because in any year most streams receive 0 claims.[38] Second, the distribution of unobserved

[35] Most water rights established after 1875 in the Boulder Valley were for "tailings" or return flows of preexisting claims (Crifasi, 2015).

[36] The excess of claimed water above estimated flow can be explained by the ability of parties to re-appropriate return flows from prior users and our inability to measure actual flows prior to 1890. Early measurements of water rights were notoriously rough, making exact comparisons between water rights and flow difficult (Crifasi, 2015).

[37] In a series of robustness checks, discussed in Appendix B, we find evidence of attenuation bias due to excess zeros and find that alternative estimators produce larger estimated marginal effects than our main results reported in Table 3, which should be interpreted as a lower bound on the magnitude of positive spillover effects from investment.

[38] In any given year, most of the 1,922 streams in our sample do not receive new claims. Moreover, the identifying assumption for the random effects probit is slightly less restrictive for our setting in that it

heterogeneity may be incorrectly specified in Equation 9 if ν_j is not independent of $\mathbf{x_j}$. Third, estimates of ρ are biased if the errors in our model are serially correlated. More broadly, we rely on a distributional assumption for identification and wish to show that our estimates are robust to alternative assumptions.

We address the first problem by reproducing the estimated marginal effects from Table 3 using a random effects Probit—also discussed in Wooldridge (2005)—where the dependent variable is a dummy that is equal to 1 if there was a new claim along stream j in year t. The Probit is more robust to the presence of excess zeros because it is designed for only 0 and 1 outcomes, whereas the Poisson distribution is more sensitive. The results are reported in Appendix Table C1. To alleviate concern over our identifying assumptions about the relationship between ν_j and $\mathbf{x_j}$, we estimate fixed effects Poisson and fixed effects Logit models and find results similar to the random effects Poisson and Probit. These results are reported in Appendix Tables C2 and C3.[39]

We address the problem of potential serial correlation in the error in two ways. First, we restrict the data set to claims prior to 1950 and estimate the model by using a linear GLS technique from Hsiang (2010) that allows for an AR(1) structure in addition to spatial autocorrelation in the error term. Second, we perform a series of Monte Carlo simulations to understand the behavior of the random effects Poisson estimator in the presence of serially correlated errors and/or excess 0s in the dependent variable. Our results suggest attenuation bias in the presence of either complication, suggesting that our estimates are lower bounds on actual effect sizes.

5 Economic Implications of Prior Appropriation

5.1 Claim-Level Data

Next, we analyze the economic outcomes associated with prior appropriation claims to understand the specific mechanisms for the externality identified in Section 4, focusing on coordination and investment. We use a single water right as the unit of analysis in this section and develop separate, rights-level measures of the geographic covariates from the previous section by matching rights to the characteristics of the grid sections within 10 miles of each right, providing measures of the quality of nearby lands that would have been

requires that the probability of a new claim in year t depends only on whether there was a claim in the previous year and not whether there were claims in other, earlier years.

[39]We not not estimate marginal effects in these models. Instead, we report the raw coefficient estimates.

available for development. We also construct the variable CoOp, which is equal to 1 for claims established on the same stream on the same day as other rights. We argue that these rights are associated with ditch companies and other forms of formal cooperation (Hutchins, 1929). We obtained GIS data on irrigation canals and ditches for Divisions 1 (South Platte) and 3 (Rio Grande) in addition to GIS data on crop choice and irrigated acreage by crop for certain historical years from the Colorado Department of Water Resources.[40] Each right has a unique identifier number that we use to match to ditches and irrigated lands, resulting in 550 rights for which we have complete data. Table 4 provides summary statistics for the claim-level data.

Stream flow, flow variability, and homesteads are defined by stream as in Section 4. We measure the quality of the land endowment or potential land endowment associated with each right slightly differently in this section than in Section 4. For each right we calculate the number of acres of loamy soil within 10 miles of the point of diversion in addition to the roughness of the terrain within a 10-mile radius of the point of diversion. We also calculate the total acreage of all 1-mile grid squares that are adjacent to the stream. These variables capture the quality of the land endowment available for claiming in proximity to each right. For the subset of our data that we are able to match to actual irrigated areas, we calculate the characteristics of irrigated lands associated with each right. We control for these important geographic covariates because the quality of the land and water resources near each right may have a direct effect on agricultural output that would bias our estimates of the effect of property rights on returns to irrigation if unaddressed.

To measure farm size, we calculate the total number of acres irrigated associated with each right for which we have matching data, captured in the variable Irrigated Acres. Our irrigation data also tell us how many acres of which crops were irrigated with the water from each right. We use estimates of average yield per acre and prices for Colorado for each crop in our data set from the Census of Agriculture from 1936 and 1956 to estimate the total value of irrigated agricultural output for each water right. The variable Total Income reports the crop income associated with a right in a given year, in 2015 dollars. These data form our primary basis for estimating the returns to irrigated agriculture in Colorado.[41]

[40]We use data for 1956 for Division 1 and 1936 for Division 3. No data are available for Division 2.

[41]Because there are potentially other irrigated parcels for which the Department of Water Resources does not have data, our estimates of the value of agricultural production due to the expansion of irrigated acreage made possible by the prior appropriation doctrine may be biased downward.

Table 4: Claim-Level Summary Statistics

Variable	N	Mean	S.D.	Min	Max	Definition
Claim Size	7,999	15.63	123.4	0	8,631	Volume of water (cfs).
Claim Date	7,999	-23,211	11,900	-39,346	19,395	Days since 1/1/1960.
Total Income	778	605,953	2,833,755	0	4.56e+07	Income from acres irrigated using right i in year t.
Irrigated Acres	778	1,592.6	5,811.7	1.516	91,987	Total acres irrigated using right i in year t.
Income Per Acre	778	544.44	390.91	68.23	1,933	Income per acre from acres irrigated using right i in year t.
Ditch Meters	778	10,658	28,420	45.06	352,729	Meters of ditch associated with right i.
Percent Loamy Soil	778	1.022	4.803	0	1	Share of Irrigated Acres possessing loamy soil.
Acres Loamy Soil (Parcel)	778	37.43	102.3	0	640	Acres of loamy soil on acres irrigated by right i.
Acres Loamy Soil (Proximity)	6,482	3,804	4,078	0	16,291	Acres of loamy soil within 10 miles of right i.
Stream Length	7,889	5.258	4.291	0.0550	36.23	Length of stream (km) that right i lies on.
CoOp	7,999	0.259	0.438	0	1	Dummy var. = 1 for rights associated with cooperation or mutual ditches.
Summer Flow	7,889	501.8	1,266	0	8,470	Flow (cfs) on stream j from May to August, averaged over 1890-2000.
Flow Variability	6,337	23.82	145.6	0	1,224	S. D. of summer flow from 1890 to 2000.
Roughness	6,479	142.7	107.7	0.0720	934.2	Avg. Slope*S. D. of Slope (within 10 miles of right).
Acres	6,482	11,022	11,902	0	53,696	Total acres near stream j associated with right i.
Claim Year	7,999	1896	32.54	1852	2013	Year in which right i was established.
Homestead Acres	7,999	346.3	1,297	0	35,463	Acres homesteaded during in which right i was established.
Homesteads	7,999	2.179	7.024	0	131	Number of new homesteads during year in which right i was established.
1st Priority Decile	7,999	0.248	0.432	0	1	Dummy var. =1 claims with priority in top 10% on a stream.
2nd Priority Decile	7,999	0.0815	0.274	0	1	Dummy var. =1 claims with priority in 11-20% on a stream.
3rd Priority Decile	7,999	0.0911	0.288	0	1	Dummy var. =1 claims with priority in 21-30% on a stream.
4th Priority Decile	7,999	0.0913	0.288	0	1	Dummy var. =1 claims with priority in 31-40% on a stream.
5th Priority Decile	7,999	0.0729	0.260	0	1	Dummy var. =1 claims with priority in 41-50% on a stream.
6th Priority Decile	7,999	0.111	0.314	0	1	Dummy var. =1 claims with priority in 51-60% on a stream.
7th Priority Decile	7,999	0.0973	0.296	0	1	Dummy var. =1 claims with priority in 61-70% on a stream.
8th Priority Decile	7,999	0.0783	0.269	0	1	Dummy var. =1 claims with priority in 71-80% on a stream.
9th Priority Decile	7,999	0.0780	0.268	0	1	Dummy var. =1 claims with priority in 81-90% on a stream.
99th Priority Percentile	7,999	0.0499	0.218	0	1	Dummy var. =1 claims with priority in 91-99% on a stream.

Note: We have data on 7,999 claims in eastern Colorado, but only 778 claims have matching ditch data. Of these, only 550 have complete elevation and flow data available.

In this section we document the role of formal property rights as a coordinating institution for resolving collective action problems associated with the development of natural resources. To do this, we estimate the effect of priority-differentiated water rights on coordination and investment in irrigation infrastructure in Colorado. First, we examine the determinants of cooperation across all of eastern Colorado, focusing on the hypothesis that users with more secure (higher-priority) water rights are more likely to coordinate. Then, we use a subset of our data to estimate the effect of coordination on investment and how this effect varies across different institutional settings. We do this using data on ditch investment and income per acre for Divisions 1 (South Platte) and 3 (Rio Grande), which comprised markedly different institutional settings for the development of prior appropriation.

5.2 Formal vs. Informal Institutions: Division 1 vs. 3

Differences in resource and user characteristics between Water Divisions 1 and 3 in Colorado provide a novel setting for analyzing the comparative advantages of formal property regimes relative to informal institutions for collective action. Broadly, conditions in Division 3 were consistent with the necessary conditions for successful common-pool resource management laid out by Ostrom (1990), whereas conditions in Division 1 were not. Differences in geography between Divisions 1 and 3 meant that there was much greater potential for entry of subsequent claimants in Division 1; the average number of potential riparian homesteads across all streams was 50 in Division 1 but just 28 in Division 3. Similarly, Division 1 was much more heavily settled than Division 3, increasing potential bargaining costs of water users. The average township in Division 1 had 84 homestead claims, compared to 11 homesteads per township in Division 3.

Division 3, composed mainly of the San Luis River Valley, had a predominantly Hispanic population living in small, close-knit communities with relatively long use of communal norms to govern ditch management and irrigation water allocation (Mead, 1901; Hutchins, 1928; Smith, 2016). Community-owned large ditches or *acequia madres*, were managed by ditch bosses or *mayordomos* who oversaw construction and annual maintenance contributions by local users, rotated water access, and arbitrated disputes.[42] This setting required little outside capital investment and the collective action problem was solved by custom (Hutchins, 1928; Meyer, 1984, pp. 64-73, 81; Smith, 2016). In contrast, Division 1 was comprised of larger numbers of heterogeneous migrants from elsewhere in the US (Hicks and Peña, 2003).

[42]In fact, observation of these and other *acequias* in northern New Mexico prompted the first settlers to attempt irrigation in eastern Colorado (Crifasi, 2015).

In this setting, the legal doctrine of prior appropriation was the common denominator among parties seeking to form and finance an irrigation network (Hobbs, 1997, p. 4; Crisfasi, 2015). This key difference between the two jurisdictions allows us to assess the role of formal property rights as a coordinating mechanism with and without the presence of informal institutions.[43] Our prediction is that appropriative rights will generate larger benefits across a variety of outcomes in Division 1 than in Division 3.

5.3 Property Rights Security and Coordination

First, we examine the determinants of cooperation, focusing on the hypothesis that users with more secure (higher-priority) water rights are more likely to coordinate. Priority is an ordinal ranking of rights along a stream. Including this simple priority measure in a regression would force the effect of priority to be linear, implying that the difference between being the 1st and 2nd claimant is the same as the difference between being, say, the 14th and 15th claimant. To allow for a non-linear, semi-parametric effect of priority on cooperation in ditch construction, we rank rights by priority and create bins for each decile of the distribution of priority by stream, yielding 10 dummy variables—one for each decile. For example, if the 1st Decile Dummy is equal to 1, the associated water right was among the first 10% of claims along its stream and had high-priority access to water during drought. This approach allows changes in priority to affect the probability of coordination differently at different points in the distribution of priority.

We use a fixed-effect logit regression to obtain semi-parametric estimates of the marginal effect of priority on coordination among rightsholders in infrastructure investment, relying primarily on within-watershed variation for identification.[44] The dependent variable is a dummy that is equal to 1 for rights that are established on the same stream on the same day. We control for stream characteristics, land quality within ten miles, population pressure, and watershed and year fixed effects. Table 5 presents the estimated marginal effects of each priority decile on the probability of cooperation, relative to the 5th decile.[45] Columns 1 and 2 are estimated jointly for all three divisions, whereas columns 3 and 4 report the results for Divisions 1 and 3 separately.

We find a higher probability of coordinating for investment in infrastructure for rights

[43] See Appendix Table C7 for a comparison of the two groups.

[44] We use watershed fixed effects rather than stream fixed effects because coordination and spatial competition over irrigation works was often not limited to a single stream. Rather, development occurred based on what lands where arable, which varies by watershed.

[45] Marginal effects are estimated at the median values of the controls, and standard errors are clustered by watershed.

Table 5: Marginal Effects of Priority on Cooperation

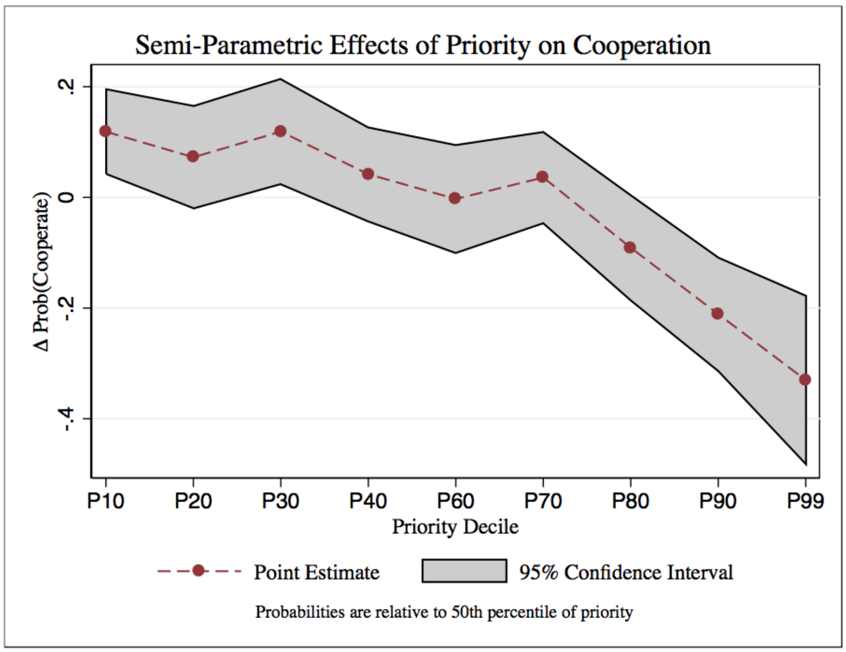
$Y = CoOp$	Divisions 1-3		Division 1	Division 3
1st Priority Decile	0.123***	0.119***	0.0207	0.194**
	(0.0359)	(0.0390)	(0.0779)	(0.0861)
2nd Priority Decile	0.0541	0.0725	0.0154	0.123
	(0.0456)	(0.0472)	(0.0929)	(0.102)
3rd Priority Decile	0.0882*	0.119**	−0.00675	0.202*
	(0.0468)	(0.0488)	(0.0861)	(0.119)
4th Priority Decile	0.0318	0.0419	0.0624	0.00619
	(0.0432)	(0.0431)	(0.0855)	(0.0905)
6th Priority Decile	−0.0154	−0.00285	−0.0558	0.0391
	(0.0518)	(0.0495)	(0.0698)	(0.0997)
7th Priority Decile	0.0366	0.0359	−0.0761	0.146
	(0.0401)	(0.0421)	(0.0674)	(0.107)
8th Priority Decile	−0.0591	−0.0910*	−0.181**	−0.0301
	(0.0447)	(0.0485)	(0.0753)	(0.0902)
9th Priority Decile	−0.160***	−0.211***	−0.238**	−0.292*
	(0.0465)	(0.0522)	(0.0939)	(0.175)
99th Priority Percentile	−0.236***	−0.330***	−0.488***	−5.193***
	(0.0643)	(0.0774)	(0.189)	(1.314)
Homesteads	Yes**	Yes*	Yes	Yes
Summer Flow	Yes***	Yes***	Yes*	Yes**
Flow Variability	Yes	Yes	Yes	Yes*
Roughness	Yes	Yes	Yes	Yes
Acres of Loamy Soil	Yes	Yes	Yes	Yes
Acres	Yes	Yes	Yes*	Yes
Watershed Fixed Effects	No	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
N	4,756	4,354	1,206	937

Standard errors are clustered by watershed and reported in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

above the 5th Decile and a lower probability of coordinating for rights below the 5th Decile. Figure 7 depicts the marginal effects of each priority decile on cooperation associated with the model in Column 2 of Table 5. Users with prior appropriation water rights in the top 10% of priority on a given stream are about 12 percentage points more likely to jointly establish claims and ditches than are users in the middle decile, while very junior right-holders in the 10th decile are 20-30 percentage points less likely to coordinate. Taken together, these estimates imply that water right-holders with the highest priority on a stream were 40 percentage points more likely to coordinate with one another than were the most junior rightsholders. This general pattern holds within Division 1 and Division 3 separately, particularly with respect to the lowest-priority right-holders. As Figure 7 indicates, much of this effect is concentrated in the bottom half of the distribution of priority—the effect of priority on investment is larger for users with low priority.

Figure 7: Marginal Effects of Priority on Cooperation



Those righsholders with the most variable water supply were the least likely to jointly invest in irrigation capital. By contrast, rightsholders in the top half of the priority distribution face relatively small differences in their exposure to stream variability and have a high likelihood of securing water and not stranding ditch capital and hence have a similar probability of coordinating. However, each drop in priority in the lower half of the distribution represents a larger shift in real access to water, generating larger effects on the probability of coordination. The more heterogeneous users become in their exposure to risk, the less likely they are to cooperate. This finding is consistent with that of Wiggins and Libecap (1985), who find that cooperation among oil field operators in oil field coordination and investment becomes less likely as they become more heterogeneous.

5.4 Formal Coordination as a Basis for Investment

Next, we assess the extent to which ditch investment differed according to whether or not claimants coordinated with other water rightsholders. Our measure of investment is the length of the ditch (in meters) associated with a given water right. Longer ditches were costlier to construct but allowed users access to more valuable farmland, particularly in Colorado, where land adjacent to streams was often rugged and unsuitable for farming (Hayden, 1869). The costs of ditch investment had to be borne up front, before there was reliable information about the availability of water over time. Mead (1901, p. 8) estimated that private irrigation systems valued nearly at $200,000,000 (nearly $6 billion in 2015 $) were in place as of 1901 in the western United States. He also describes the complexity of raising capital and the coordination and consolidation among irrigation companies in the Cache La Poudre valley, one of the first areas in Colorado to be placed under large-scale irrigation.[46]

Coordination between water rightsholders could increase ditch investment because i) it allowed users to share these up front costs, ii) it allowed for the possibility of pooling water claims during times of limited flow to maximize the value of irrigated agriculture, iii) it created a framework for governance and assignment of maintenance responsibilities, and iv) it helped prevent post-contractual opportunism from informal promises of water deliveries (Hanemann, 2014; Crifasi, 2015, p. 158). Users who cooperated still developed individual ditches known as laterals to bring water to their own particular fields (see Figure 9 below). This gives us unique ditch lengths for each water right in this portion of our sample, even if those users were part of a cooperative effort.

Prior appropriation facilitated the cooperation necessary for development by making users in any given period secure against the arrivals of future claimants. A share system must confront the problem of how to incorporate demands of future claimants, whereas prior appropriation right-holders are ensured that their rights are paramount relative to future arrivals. In fact, claimants eventually began constructing large ditches for the sole purpose of selling access to future settlers in need of water (Crifasi, 2015). This development required security of ownership so that ditch builders could reap the rewards of their investment. Prior appropriation also provided a way to clearly delineate group membership by creating a secure property right that could serve as a legal basis for incorporation—new arrivals would

[46]In the late 19th and early 20th centuries there were numerous investigations into irrigation in the western United States including Newell (1894), Mead (1901), Adams et al. (1910). Newell (1894) reports irrigation system values of $94,412,000 in 1890 in 11 western states. He also reports data on differences in ditch construction costs according to ditch width.

have to buy their way into existing arrangements. This reduced uncertainty about group size and heterogeneity, which lowered the costs of collective action (Ostrom, 1990; Libecap, 2011). Finally, having quantified, secure property rights made incumbent water users willing to accommodate and even transact with new arrivals because their senior claims were not threatened by new, junior claims. As previously noted, the additional benefits of these formal property rights are predicted to be lower in areas where informal institutions had already supplied a remedy for collective action problems, as in Division 3.

Table 6 reports our estimates of the effect of cooperation and priority on Ditch Meters using a GMM approach developed by Hsiang (2010) that adjusts for possible spatial and time-series autocorrelation in the error term. We include watershed and year fixed effects and a variety of controls for access to water and land resources, with complete results on the controls reported in Appendix Table C5.[47] Columns 1, 2, and 3 are estimated jointly across Divisions 1 and 3, while Columns 4 and 5 are estimated separately for each division.[48] In our preferred specifications we find that cooperative claimants' ditches are 10,198 meters longer than those of non-cooperative claimants' in Division 1 but that coordination does not affect ditch investment in Division 3.[49]

Two possible alternative explanations for the null effect of coordination on investment in Division 3 are that the predominantly Hispanic population either i) lacked full access to the legal system for enforcing prior appropriation claims or ii) had less wealth and access to credit than settlers in Division 1, thereby reducing investment. The fact that high-priority claimants are more likely to cooperate in Division 3, just as in Division 1 (Table 5), makes it unlikely that legal status varied sharply between groups, pointing toward another

[47]The pattern of spatial dependence follows Conley (2008).

[48]Ditch data are not available for Division 2.

[49]One potential concern with our results on ditch investment is that investment and cooperation are jointly determined, making CoOp endogenous in Table 6. If this is true, then the finding that CoOp ditches are longer may be due to simultaneity bias. We argue that the empirical time line associated with establishing and then developing a water claim resolves this issue. While intended ditch length may be simultaneously determined with whether or not a right is claimed cooperatively, actual ditch construction is a costly and time-consuming process—the average ditch in our sample is 10.5 kilometers long. The upshot is that the cooperative status of a water claim is exogenous to ditch length because the former necessarily predates the latter. A similar concern could be stated and similarly dismissed with respect to the endogeneity of priority. To check the robustness of our results we reproduce them first by omitting priority and then by using the number of claims in the same month and same watershed as a given right as an instrument for CoOp and obtain similar estimates of key parameters. The number of claims in the same month and same watershed as a given right affects the probability of cooperation because rights established nearby other rights (in space and time) have more other claims with which to potentially cooperate. At the same time, the number of new claims in a given month should not directly affect the investment of any particular claim, except through its effect on the cooperative status of that claim. In general we find that after controlling for coordination, priority has no direct effect on ditch investment. For the sake of brevity we do not report the coefficients for each decile, but they are available in Appendix Table C3.

Table 6: Effects of Coordination and Priority on Investment

$Y = DitchMeters$	Divisions 1 & 3			Division 1	Division 3
CoOp	5,963.9**	4,461.5**	4,472.0**	10,197.9**	−2,202.6
	(2,736.0)	(2,199.0)	(2,195.7)	(4,004.1)	(2,139.6)
Claim Size	244.7***	255.7***	256.3***	352.2***	130.0***
	(61.56)	(69.15)	(69.33)	(102.0)	(29.70)
Priority Controls	Yes	Yes	Yes	Yes	Yes
Summer Flow	Yes	Yes	Yes	Yes	Yes
Flow Variability	Yes	Yes*	Yes*	Yes	Yes**
Roughness	Yes	Yes	Yes	Yes	Yes
Acres of Loamy Soil	Yes***	Yes	Yes	Yes**	Yes
Claim Year	Yes	Yes	Yes	Yes	Yes
Homesteads		Yes			
Homestead Acres			Yes	Yes	Yes
Watershed Fixed Effects	No	Yes	Yes	Yes	Yes
N	550	550	550	292	258
R^2	0.293	0.354	0.353	0.464	0.169

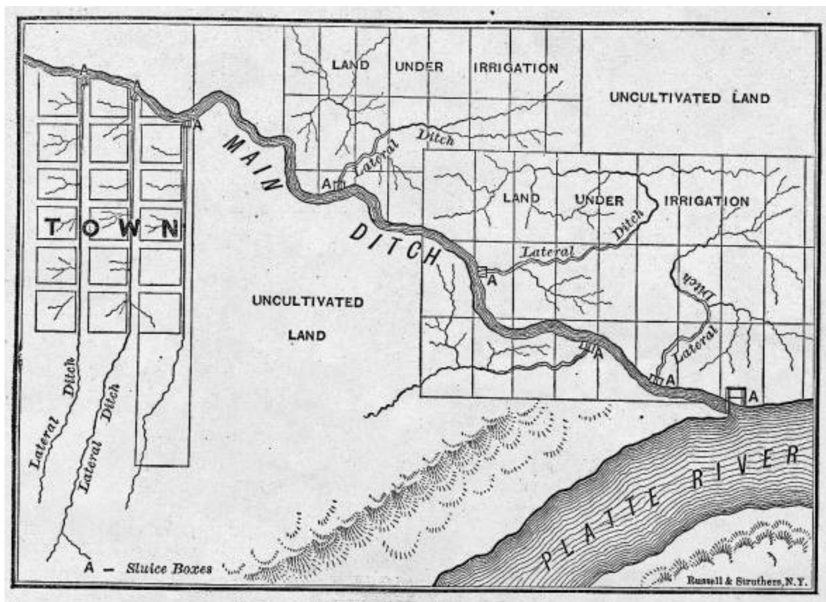
Spatial HAC standard errors reported in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

explanation for differences in investment incentives. However, differences in wealth would result in less ditch building overall but should not reduce the role of formal coordination for projects that were undertaken. Instead, we argue that the differential role of formal coordination in Divisions 1 and 3 can be explained by the dominant communal norms in Division 3, which rendered formal property institutions less crucial in that area. In contrast, Division 1 required formal legal rights as a basis for coordination among many heterogeneous claimants.

To illustrate the role of priority on investment in Division 1, consider the McGinn Ditch on South Boulder Creek and north Boulder Farmer's Ditch on Boulder Creek. Both ditches were large, cooperative investments. The McGinn Ditch was constructed in 1860 and had the number 2 priority on South Boulder Creek. Farmer's Ditch was the longest ditch in the Boulder Valley when it was constructed in 1862, costing \$6,500 (\$165,000 in 2015 dollars) and irrigated over 3,000 acres of land (Crifasi, 2015, p. 187). Even larger ditches followed. The Larimer and Weld Canal from the Cache La Poudre River, was constructed sequentially between 1864 and 1878 with the huge capacity of 720 cfs (5,400 gallons) and was 53 miles long to irrigate 50,000 acres (Hemphill 1922, p. 15; Dunbar 1950, p. 244). Construction costs for such ditches were financed either through forming non-profit mutual ditch companies among irrigators or through organizing commercial ditch companies with a broader group of investors, such as the Colorado Mortgage and Investment Company of London, England (Dunbar 1950, pp. 253-58, Libecap 2011, p. 73).

Figure 8: Coordinated Investment



THE COLORADO SYSTEM OF IRRIGATION.

Source: *Harper's Weekly*, 6/20/1874, p 514.

Figure 8, from the June 20th, 1874, issue of *Harper's Weekly*, depicts an arrangement typical for eastern Colorado and highlights the increase in arable land associated with coordinated development of irrigation canals.

5.5 Irrigation and Income Per Acre

Ultimately the purpose of establishing a water right in Colorado was to provide water as an input to irrigated agriculture. Prior appropriation added value to agricultural endeavors by encouraging search and investment and by separating water rights from riparian land holdings, allowing for much greater and more productive areas to be irrigated than would have been possible under the riparian system. To estimate the magnitude these benefits, we begin by depicting the extent of land resources that could have been irrigated under the riparian doctrine, given that settlers on the Western frontier were generally constrained to homestead sites totaling 160 to 320 acres. We conservatively assume that land within a half mile of a stream or river could have been claimed and considered to be adjacent to the water for the purposes of assigning riparian water rights.

Figure 9 depicts riparian lands in eastern Colorado—indicated by cross hatch shading—and the location of loamy soils (hydrologic soil call B) best suited to farming—indicated with green shading—and reveals that the riparian doctrine would have both constrained the total area of land available for farming and have precluded the ability to irrigate some of the most productive soils in the region that were remote from streams. We match our data on water rights with GIS data on actual irrigated acreage prior to the advent of groundwater pumping in Divisions 1 and 3 to calculate the actual contribution of the prior appropriation doctrine to agriculture in the region.

Figure 9: Riparian and Arable Land in Eastern Colorado

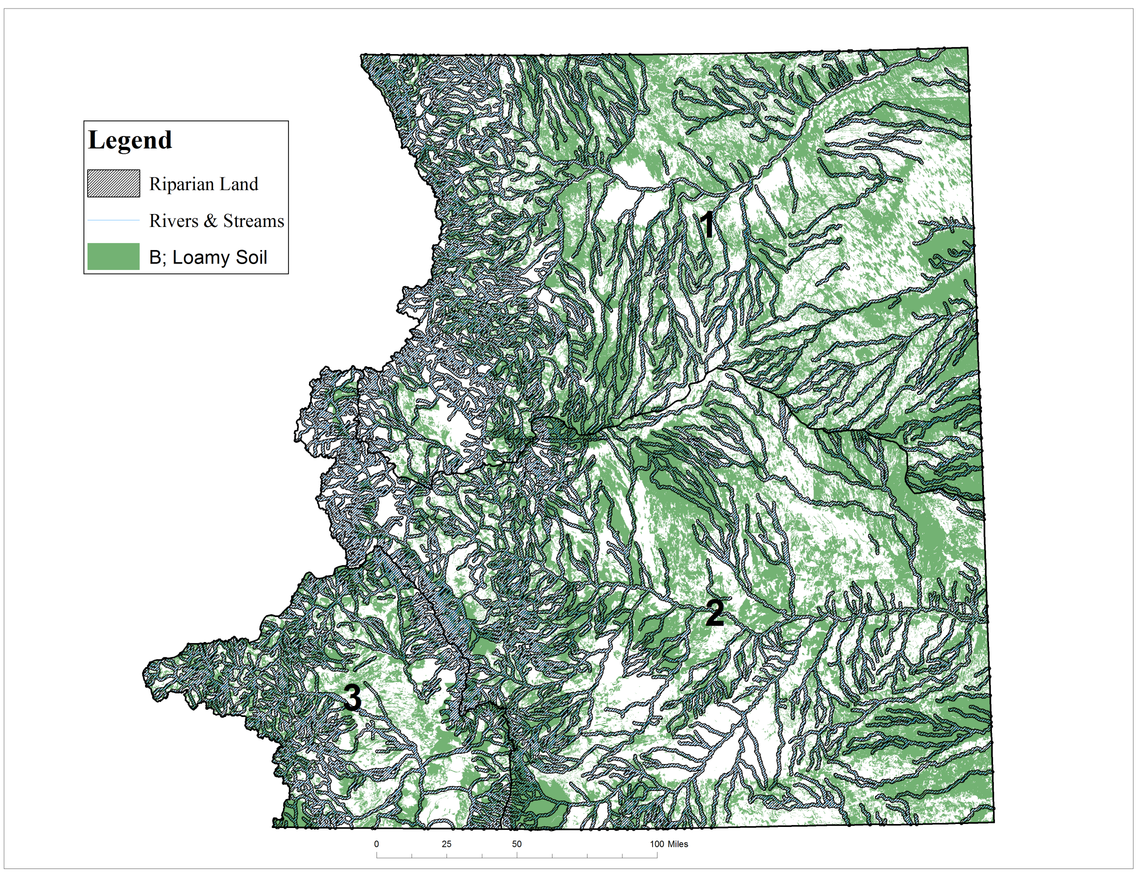
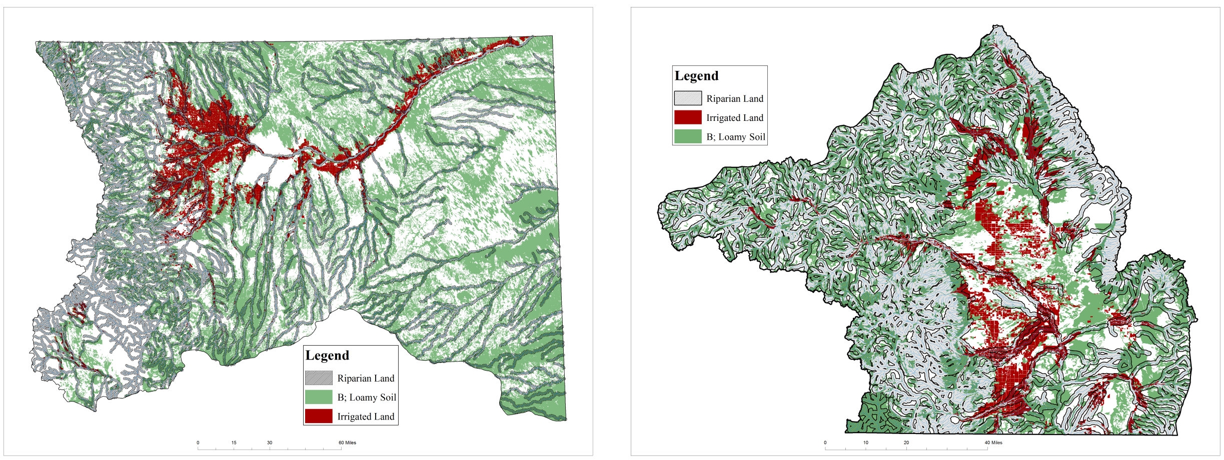


Figure 10 depicts riparian land and actual irrigated acreage in 1956 for Division 1 and

1936 for Division 3, the earliest years for which GIS data are available in each division.[50] We focus on these early years so that we can isolate the effect of access to surface water as from the effect of access to groundwater.[51] Roughly 45% of the irrigated land in Division 1 and 34% in Division 3 were riparian. The ability to claim water from streams and put it to use on non-adjacent land allowed for substantial growth in irrigated acreage in both divisions, resulting in an additional 546,552 acres of usable farmland—an increase of 133%.[52]

Figure 10: Riparian and Irrigated Land



(a) Division 1 (b) Division 3

Focusing on per-acre returns allows us to better understand the contribution of prior appropriation to farm productivity. We combine our rights-level data on irrigated acres and crop choice with historical state-level data from the Census of Agricultural on prices and yields for each crop to estimate the value of production on riparian and non-riparian lands.

[50]Data for a contemporaneous cross-sectional or panel comparison are not available. To alleviate concern about the comparison over time, we collect county-level data on the number of farms, average farm size, and average farm value for both areas in 1935 and 1954 (the closest years to our sample years for which data are available) from the Census of Agriculture. We calculate the percentage change in each outcome between 1935 and 1954 and find no statistically significant difference in changes over time across divisions. The total number of farms fell in both divisions, while both average farm size and value increased. We also collect data on average yields for irrigated wheat in both periods in both divisions and find no statistically significant difference in the change in yield from 1936 to 1956 across divisions. These tests imply that economic conditions in agriculture in the two divisions moved in similar ways over the 20-year period.

[51]Estimates from later in the 20th century are contaminated by the ability of farmers to supplement their surface water rights by pumping groundwater. The technology for groundwater pumping became widely available after World War II.

[52]These land-based estimates form an upper bound on the expansion of irrigated agriculture made possible by prior appropriation. The counterfactual scenario involving adherence to the riparian doctrine may have resulted in more riparian land being irrigated, given that non-riparian lands would have been unavailable.

These results are summarized in Table 7. The value of non-riparian irrigated agricultural production was $228,480,781 in Division 1 and $58,583,937 in Division 3. The ability to move water away from streams increased combined agricultural output in Colorado in our sample years by 134%.

Table 7: Irrigated vs. Riparian Land (2015 $)

	Division 1		Division 3	
	Riparian	Non-Riparian	Riparian	Non-Riparian
Irrigated Acres	337,917	408,275	72,350	138,277
Total Farm Income	$183,310,710	$228,480,781	$30,948,204	$58,583,937
Median Farm Size	147	760	99	262
Average Income Per Acre	$527.50	$548.32	$601.67	$600.10
	(3.28)	(3.05)	(14.64)	(12.36)

Standard error of the mean reported in parentheses for Income Per Acre.

The variation in income per acre across land type and division is striking. In Division 1, the average non-riparian farm earned roughly $20 more per acre than the average riparian farm, while farms in Division 3 exhibit no difference.[53] This suggests that non-riparian lands were more productive than riparian lands. This is consistent with the fact that users incurred substantial infrastructure costs to reach non-riparian lands and left much of the riparian corridor untouched.

Table 7 makes it clear that the riparian system would have constrained rightsholders to the more rugged terrain adjacent to streams and limited total farm size, assuming only riparian homesteads had access to water. This, in turn, would have precluded important 20th-century innovations in farming technology centered around the development of large, flat farms in the West (Gardner, 2009; Olmstead and Rhode, 2001). Previous studies of prior appropriation have emphasized the ability to separate water from streams as a necessary condition for irrigation in the arid West, but this does not explain fully why a first-possession mechanism was adopted. Another necessary ingredient for successful irrigation was an incentive structure to facilitate costly investment. Tables 5 and 6 suggest that first possession provided this incentive structure by granting a more secure property right and Table 7 confirms that nonriparian lands were in fact more productive and allowed for larger farms.

Taken together, these results suggest that formal coordination under the prior appropriation doctrine was an important determinant of per-acre income for farmers. Coordination

[53] This difference is statistically significant at the 99% level. Newell (1894, p. 6) provides estimates for the value of irrigated agricultural production/acre at $361/acre for all of Colorado (in 2015 $).

facilitated ditch investment, which in turn provided access to more productive land and may have allowed for more efficient, larger farms and cooperation along other productive margins. Equation 10 summarizes the possible channels through which building a cooperative ditch could increase per-acre returns.

$$\frac{\mathrm{d}IPA}{\mathrm{d}CoOp} = \frac{\partial IPA}{\partial Acres}\left[\frac{\partial Acres}{\partial Ditches}\cdot\frac{\partial Ditches}{\partial CoOp} + \frac{\partial Acres}{\partial CoOp}\right] + \frac{\partial IPA}{\partial Ditches}\cdot\frac{\partial Ditches}{\partial CoOp} + \frac{\partial IPA}{\partial CoOp}. \quad (10)$$

We estimate a series of linear regressions using the GMM technique mentioned above to obtain each of the partial derivatives in Equation 10 and to construct the total effect of coordination on income per acre. Table 8 presents our estimates of the effect of cooperation on income per acre by division. The results used to construct these estimates are available in Appendix Table C6. The first row of Table 8 reports the reduced-form estimate of cooperation on income per acre, not controlling for ditch length or farm size. The second row contains our estimate corresponding to the various channels in Equation 10, estimated using GMM with spatial HAC standard errors that are uncorrelated across equations, and the third row presents a robustness check using seemingly unrelated regression (SUR) to account for possible correlation in the errors across equations.

Table 8: The Effect of Coordination on Income Per Acre

	Division 1	Division 3
Reduced Form[a]	105.7***	−7.934
	(28.60)	(51.50)
Back of the Envelope[b]	132.20***	−10.53
	(15.06)	(29.04)
SUR[c]	109.12***	−12.32
	(38.16)	(49.74)

[a] Spatial HAC GMM standard errors reported in parentheses
[b] Spatial HAC GMM standard errors estimated equation-by-equation. Standard error of the prediction obtained using the delta method and assuming errors are uncorrelated across equations
[c] Correlated standard errors reported in parentheses
* $p < .1$, ** $p < .05$, *** $p < .01$

Income per acre was \$105 to \$132 higher (relative to a mean of \$544 per acre) for users in Division 1 who coordinated their water rights claims and investment. This exceeds the average difference in productivity for nonriparian vs. riparian farms reported in Table 7 by a factor of five. While reaching nonriparian lands did lead to greater income per acre, users who cooperated generated even greater benefits. This suggests that ditch investment was critical for productivity and that the ability to build longer ditches via formal cooperative arrangements (documented in Table 6) increased productivity substantially by granting access to the most productive lands.

In contrast, we find no effect of cooperation on income per acre in Division 3. This difference is driven largely by the fact that coordination promoted ditch investment in Division 1 but not in Division 3. Both divisions faced a classic collective action problem in the development of irrigation works. In Division 3 this problem was largely solved in a classic Ostrom (1990) manner with cultural norms and informal mechanisms, which worked well given the small number of homogeneous users. In this settings formal property rights added little value. Division 1 was rapidly settled by a large number of heterogeneous claimants, making a norm-based solutions untenable. Here, the collective action problem was solved by contracting based on formal, legal property rights.

5.6 Irrigated Agriculture and the Development of the West

By the late 19th century the role of irrigated agriculture in expanding economies was increasingly recognized (Newell, 1894). We perform a back-of-the-envelope calculation of the contribution of irrigated agriculture and prior appropriation to economic development in the Western United States in the early 20th century. Table 9 presents our estimates of the value of irrigated crop production for western states in 1910 and 1930. We use data from Easterlin (1960) and from the Bureau of Economic Analysis on personal income by state and the 1910 and 1930 US Censuses of Agriculture to estimate the value of irrigated crops and report those estimates as a percentage of state or territory income.[54] Finally, using an

[54] Department of Commerce, BEA Survey of Current Business, May 2002 and unpublished data, "Personal Income and Personal Income by State, 1929-2001," provided to the authors by Robert A. Margo. State income values were calculated on a state basis by multiplying population by per capita income. Population data for 1910 and 1930 from US Agricultural Data, 1840-2010, distributed by the Inter-University Consortium for Political and Social Research (ICPSR). For 1910, per capita income was calculated by taking the mean of per capita income from 1900 and 1920. Per capita income from 1900 was taken from Easterlin 1960, Table A-3. Per capita income for 1920 and 1930 were taken from unpublished data from Easterlin and the BEA. The 1910 values of irrigated crops were calculated by summing individual crop values by state. Data from irrigated crop values were taken from the 1910 Census of Agriculture, Volumes 6 and 7. The 1910 Census of Agriculture notes that data for irrigated crops were taken from supplemental schedules, and the information is considered to be incomplete. Therefore, all available irrigated crop value data were summed. The 1930 values of irrigated crops were calculated by summing the eight most valuable crops according to state. The number of crops included in the calculation was chosen to be eight, as the 9th crop value added less than 5% to the total irrigated crop value. Data for irrigated crop values were taken from US Agricultural Data, 1930, distributed by ICPSR.

average of the share of non-riparian income in total agricultural income from Divisions 1 and 3 in Colorado, we estimate the value of non-riparian irrigated agriculture as a percentage of state income.[55] This represents the estimated share of state income due to agricultural production that could not have taken place under the riparian doctrine.

Table 9: Contribution of Agriculture to State/Territory Income

	1910			1930		
	Irrigated Crop Value	% of State Income	Non-Rip. %	Irrigated Crop Value	% of State Income	Non-Rip. %
Arizona	$109,088,226	7.8%	4.4 %	$218,429,933	6.8%	3.9%
California	$1,198,335,054	5.4%	3.1%	$4,730,240,019	6.6%	3.8%
Colorado	$955,887,896	15.4%	8.8%	$1,216,338,604	14.4%	8.2%
Idaho	$411,487,005	26.0%	14.8%	$1,176,322,174	38.2%	21.8%
Montana	$357,644,113	12.9%	7.3%	$543,002,901	14.2%	8.1%
Nevada	$129,481,278	19.7%	11.3%	$199,548,712	18.5%	10.6%
New Mexico	$132,129,974	9.2%	5.2%	$282,107,719	14.2%	8.1%
Oregon	$182,079,466	3.9%	2.2%	$425,281,996	5.2%	3.0%
Utah	$355,860,090	15.1%	8.6%	$526,011,917	14.8%	8.4%
Washington	$182,766,338	2.9%	1.7%	$896,351,083	6.2%	3.5%
Wyoming	$182,849,867	13.7%	7.8%	$355,530,834	19.1%	10.9%

Notes: 1) All dollar amounts are reported in 2015 dollars. 2) Territory income is used for states prior to statehood. 3) Calculations are detailed in footnote 53.

Table 9 indicates that irrigation of non-riparian lands contributed 2% to 14% of state income in 1910 and 3% to 21% in 1930. These estimates understate the total impact on state income due to multipliers across the economy. Adelman and Robinson (1986), for example, estimate multipliers of 1.8 to 2.1 for every dollar of income from agriculture. Overall, irrigated agriculture played a critical role in the development of the West, accounting for more than 10% of total income in many states by 1930. Moreover, we estimate that more than half of the value generated by irrigated agriculture came from non-riparian lands.[56]

[55] We calculate a weighted average of the share of non-riparian income of total irrigated income from Divisions 1 and 3, weighted by total irrigated acreage in each division. We estimate that roughly 57% of irrigated land is non-riparian and could not have been irrigated under a strict riparian system.

[56] This estimate is an upper bound on the value-added by prior appropriation because strict adherence to the riparian doctrine would likely have led to the irrigation of more riparian lands, relative to what we observe today.

6 Conclusion

Prior appropriation encouraged socially-valuable search that lowered information costs regarding the most favorable diversion locations. Prior claims raised the probability of subsequent claims by 20%, an effect equivalent to a near doubling of stream size in attracting settlers. Denser settlement, in turn, brought agglomeration economies in the joint investment in large irrigation infrastructure. The ability to coordinate and combine formal, tradable prior appropriation rights along with greater certainty of water deliveries for high-priority rights holders facilitated joint development of canal systems. The top 10% of senior claimants were 40 percentage points more likely to form ditch companies than were those below the median priority. This cooperation in turn led to a doubling of average ditch length (about 10 km) that greatly expanded irrigable, high-quality land, especially in Division 1. Longer ditches brought more productive non-riparian land under irrigation, with the longest, cooperative ditches adding over $100 per acre to productivity. Prior appropriation water rights not only encouraged investment, but were exchanged routinely to consolidate and redirect water (Hemphill, 1922). There was no detectable effect, however, in Division 3 where formal rights appear not to have been required to coordinate effort. Overall, under prior appropriation between 3.5% and 20% of western state incomes by 1930 were directly attributable to irrigated agriculture, much of which would not have been feasible under the default riparian rights system. These estimates do not incorporate multiplier effects from higher agricultural incomes that might have doubled the economic impact in each state.

The value of any particular form of property right to a natural resource is its ability to align individual incentives to reconcile competing demands and to encourage innovation, investment, and reallocation. The western frontier provides a unique laboratory for analyzing the development or modification of property institutions. Prior appropriation emerged in response to new conditions in a setting where institutional change could occur at relatively low cost with high expected net returns. The migration of thousands of frontier claimants was fueled by anticipation of capturing resource rents that required a new property rights regime. Although migrants were numerous and dissimilar in many ways, they carried with them common notions of individual ownership of land and other natural resources and an ability to modify institutions as local conditions suggested. In case of prior appropriation of water, claimants applied existing first-possession allocation of agricultural and mineral land to water, rather than adhering to an eastern riparian system that offered lower returns under semi-arid conditions.

Once in place, prior appropriation molded expectations for the creation and distribution of net rents and the associated range of uses, exchange, time frames, and investment in water. These conditions remain today among property rights holders. In the face of new demands for water for environmental, urban, and industrial use along with more variable and possibly declining supplies, water rights will be exchanged and water reallocated (Brewer et al., 2008; Murphy et al., 2009; Culp et al., 2014). Such transfers can take place within the prevailing rights system. Doing so not only recognizes the long-term benefits associated with prior appropriation but reflects the economic, social, and political path dependencies associated with it. Recent policy discussions calling for a restructuring of water rights to shares of total annual allowable uses or to mandate instream environmental flows do not sufficiently consider the value of and stakes in the contemporary priority rights system. Unlike the earlier frontier setting, major uncompensated movement to any new institutional arrangement would not be at low cost.

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Appendix A: Theory

Proposition 1: *Under prior appropriation, aggregate profits V^{PA} are increasing and concave in the number of appropriators for $N < \bar{N}^{PA}$ and have a unique maximum at $\bar{N}^{PA}$.*

Proof: First, note that $\frac{\partial V^{PA}}{\partial N} = \frac{\partial \sum_{i=1}^{N} V_i^{PA}}{\partial N} = V_N^{PA}$; the arrival of new claimants under prior appropriation does not alter senior claimants' behavior, so the change in aggregate profit is just the profit of the new arrival. Burness and Quirk (1979) show that under the appropriative system profits are strictly lower for junior claimants: $V_i^{PA} > V_j^{PA} \quad \forall \quad i < j$. This implies that aggregate profits are increasing but at a decreasing rate: $\frac{\partial^2 V^{PA}}{\partial N^2} = V_N^{PA} - V_{N-1}^{PA} < 0$. Denote the marginal entrant who earns zero profit to be $\bar{N}^{PA}$. For $N < \bar{N}^{PA}$, each user earns strictly positive profit so $V_i^{PA} > 0 \quad \forall \quad i < \bar{N}^{PA}$. Similarly, any additional claimants would earn negative profit after $\bar{N}^{PA}$: $V_j^{PA} < 0 \quad \forall \quad j > \bar{N}^{PA}$. By definition, $V_{\bar{N}^{PA}}^{PA}$=0. Hence, V^{PA} is increasing an concave in N with a unique maximum at $\bar{N}^{PA}$. QED.

Proposition 2: $V^{PA} \lesseqgtr V^S$. *Either property rights regime can dominate.*

Proof: We prove Proposition 2 by providing an example of either regime dominating.

Case 1: $V^{PA} > V^S$. We begin by noting that $\bar{N}^{PA}$ is the maximum number of users that establish rights under prior appropriation, even if the number of potential users N exceeds $\bar{N}^{PA}$ (see Proposition 1). Next, consider the first-order necessary condition for the shareholder's problem:

$$[1 - F(Nx_i)]R'(x_i) = C'(x_i).$$

Since $F(\cdot)$ is a proper cumulative density function, $\lim_{n\to\infty}[1 - F(Nx_i)] = 0$ and the first order condition reduces to

$$0 = C'(x_i).$$

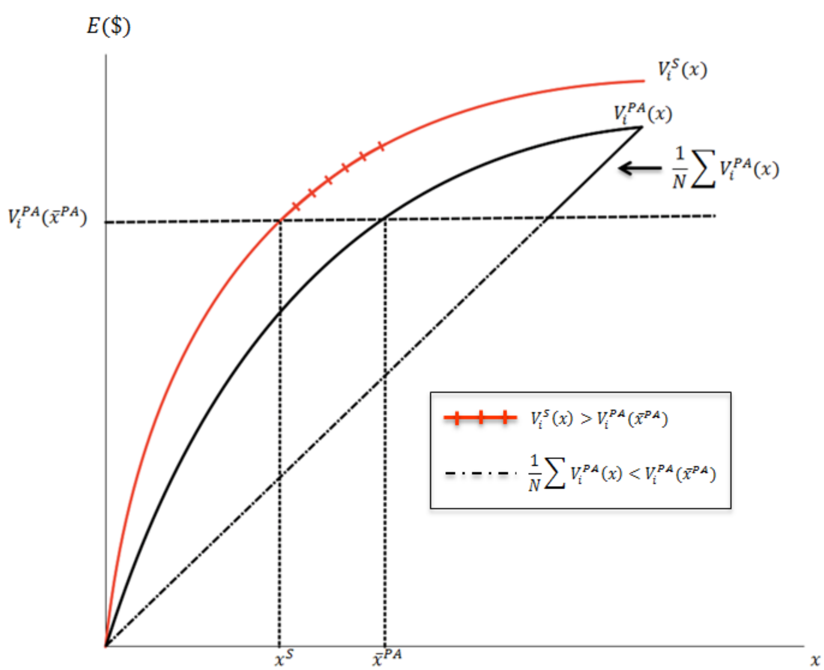
It follows that $x_i^* = 0$, $V^S(0) = 0 < V^{PA}$. For sufficiently large N, the expected share size approaches zero and expected revenues do not exceed expected costs, resulting in zero investment. In this same scenario, the prior appropriation system allows the first $\bar{N}^{PA}$ users to enter and make secure investments, resulting in positive (and thus higher) aggregate expected profit.

Case 2: $V^S > V^{PA}$. Burness and Quirk (1979) establish that expected profits under the share system are higher than under prior appropriation *for a given* x, but that investment is higher under prior appropriation *for a given* N. We want to show that it is possible for $NV_i^S(x_i^s(N)) > \sum_{i=1}^N V_i^{PA}$ given $Nx_i^S < \sum_{i=1}^N x_i^{PA}$ for some N. Which is equivalent to $V_i^S(x_i^s(N)) > \frac{1}{N}\sum_{i=1}^N V_i^{PA}$ given $x_i^S(N) < \frac{1}{N}\sum_{i=1}^N x_i^{PA}$. That is, we need to show that it is possible for a the profits of a share size smaller than the average prior appropriation claim to exceed the average profits from prior appropriation.

Define $\bar{x}^{PA} = \frac{1}{N}\sum_{i=1}^N x_i^{PA}$ to be the size of the average prior appropriation claim for a given N. From Jensen's Inequality we have that $V^{PA}(\bar{x}^{PA}) \geq \frac{1}{N}\sum_{i=1}^N V_i^{PA} \quad \forall \quad N$ since V^{PA} is concave. Since $V_i^S(x) > V_i^{PA}(x)$ for any given x, it must be that $V_i^S(\bar{x}^{PA}) > V_i^{PA}(\bar{x}^{PA})$. Finally, we note that $\frac{\partial V_i^S}{\partial x} > 0$ (greater investment results in greater expected profit, for a given N). Taken together, these inequalities imply that $\exists \quad x_i^S(N) < \bar{x}^{PA}$ satisfying $V_i^S(x_i^S(N) > \frac{1}{N}\sum_{i=1}^N V_i^{PA}$ (see graph) as long as $V_i^S(x)$ is continuous in x.

Hence, we can have either $V^{PA} > V^S$ or $V^{PA} < V^S$. QED.

Figure 11: Proposition 2



Proposition 3: *In the presence of a positive externality from prior claims ($\gamma > 0$), V^E has a convex region for small N and for sufficiently large γ, $V^E > V^S$.*

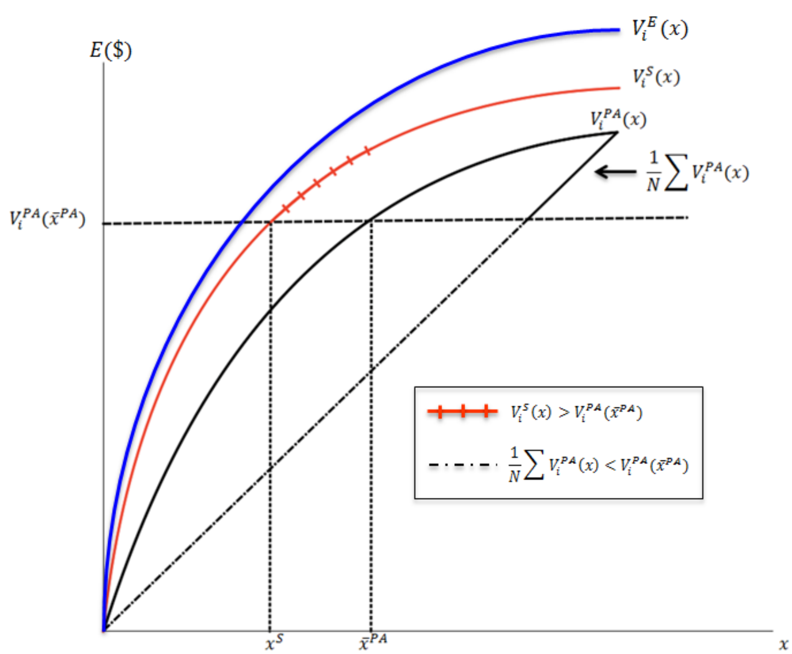
Proof: First, we establish that V^E has a convex region (in N) for sufficiently large γ.

$$\begin{aligned}\frac{\partial^2 V^E}{\partial N^2} &= V_N^E - V_{N-1}^E \\ &= V_N^{PA} + \gamma p_N - V_{N-1}^{PA} - \gamma p_{N-1} \\ &= V_N^{PA} - V_{N-1}^{PA} + \gamma(p_N - p_{N-1}) > 0 \iff \gamma > \frac{V_{N-1}^{PA} - V_N^{PA}}{p_N - p_{N-1}} = \frac{-\frac{\partial^2 V^E}{\partial N^2}}{x_N^{PA}}.\end{aligned}$$

If the positive externality is the larger than the ratio of the change in profits to the investment of the marginal user, then V^E is convex.

Next, we establish that $V^E > V^S$ for sufficiently large γ. Note that $V_i^E = V_i^{PA} + \gamma p_i$. This implies $V^E = \sum_{i=1}^N V_i^{PA} + \gamma x_1^{PA} + \gamma(x_1^{PA} + x_2^{PA}) + ... + \gamma(x_1^{PA} + ... + x_{N-1}^{PA}) = V^{PA}(N) + \gamma \sum_{i=1}^N (N-i) x_i^{PA}$. Recall that the case where shares dominate prior appropriation relied on the fact that Jensen's Inequality implies $V_i^S(x) > V_i^{PA}(x)$, but since $V_i^E(x) > V_i^{PA}(x)$, the conclusion that $\exists \quad x_i^S(N) < \bar{x}^{PA}$ satisfying $V_i^S(x_i^S(N) > \frac{1}{N}\sum_{i=1}^N V_i^{PA}$ no longer follows (see graph). QED.

Figure 12: Proposition 3



Proposition 4: *In the convex region of V^E, profits are increasing for junior claimants relative to senior claimants: $V_i^E > V_{i-1}^E$ and users follow rather than search for a new stream.*

Proof:

Assume V^E is convex in N

$\Rightarrow \frac{\partial^2 V^E}{\partial N^2} = V_i^E - V_{i-1}^E > 0$

$\Rightarrow V_i^E > V_{i-1}^E$.

For the second part of the proof note that in the convex region of V^E, $V_i^E > V_1^E$ for $i > 1$. Hence, junior claimants on streams earn higher expected profits than the earliest claimants in the presence of a sufficiently large positive externality. If expected flows are equal across streams, being a junior claimant strictly dominates claiming a new stream, and users follow. QED.

Appendix B: G.I.S. Data Construction

GIS Hydrologic data on basins, stream names, and network characteristics come from the National Hydrography Data Set (NHD). The NHD has been programmed as a linear network geodatabase that allows for tracing elements' relative positions along the network, a feature which we exploit. Estimates of stream flow across this network were obtained from NHDPLUS V2.[57] Elevation data are measured at 30-meter intervals and come from the National Elevation Dataset. These data are used to compute the slope and standard deviation of slope in the neighborhood of each right. Our soil data are from the USDA Soil Survey Geographic Database (SSURGO).

We calculate measures of resource quality relating to both land and streams for each grid square. We calculate the average and standard deviation of slope in each grid square and construct the variable roughness, which is the average slope multiplied by the standard deviation of slope.[58] We use the SSURGO data to calculate the number of acres of soil in each hydrologic soil group defined by the USDA. This measure of soil quality is based on the structure of the soil itself rather than its current water content. This allows us to use a current GIS measure of soil quality to estimate historical soil quality over the period of our

[57]NHDPLUS, provided by the Horizon Systems Corporation, is an augmented version of the National Hydrography dataset that has been combined with the National Elevation Data Set and the PRISM climate dataset to produce a variety of flow-related statistics across the entire stream network.

[58]This construction captures the fact that both steeper terrain and more variable terrain contribute to rugged topography and make various forms of development more difficult.

study. We focus on Soil group B, which is comprised primarily of loamy soil and is the most productive for agriculture. We also calculate the total area (in acres) of the watershed that a square resides in using the HUC8 classification of watersheds from the NHD.

We perform a network trace to locate each square along the stream network defined by the NHD and use this location to create a variety of variables relating to the water resource itself. We calculate the distance from each grid square to the head of the stream it lies on (as delineated by the NHD).[59] The NHDPlus V2 dataset created by Horizon Systems Corporation provides monthly and annual stream flow estimates for each stream on the NHD network. We use this information to create a measure of the total flow across May through August.[60] We combine these contemporary estimates of stream flow with contemporary and historical estimate of precipitation from the PRISM dataset and elevation data from the NED to estimate a model for predicting historical flows along the entire stream network. We use these estimates to calculate the average summer flow and standard deviation of flow from 1890 to 2000.[61] The variable Summer Flow is the century-long average of total summer flow, based on flows in May through August of each year. The variable Flow Variability is the standard deviation of stream flow for a given reach over this period. Details on the hydrologic and econometric models underlying these calculations are available upon request.

[59]For most streams the entire length of the stream is used. Major rivers are divided into reaches within the NHD, and we maintain this division because we believe it reflects the fact that relative positive along major rivers is less critical than relative position along smaller streams.

[60]These are the months during which irrigation is critical to support crop growth.

[61]PRISM data on historical precipitation are only available back to 1890. Rather than clip our dataset and having yearly estimates of flow, we use century long averages to capture average stream characteristics.

Appendix C: Robustness Checks and Additional Results

Table C1: Estimated Average Partial Effects on Prob(New Claims)

$\frac{\partial Pr(NewClaims > 0)}{\partial x}$	(1)	(2)	(3)
	Probit Estimates, Y = $\mathbb{1}$(New Claims$_{jt}$ >0)		
$\mathbb{1}$(Lagged Claims>0)	0.0456***	0.0459***	0.0365***
	(0.00490)	(0.00492)	(0.00420)
Summer Flow	0.00000590***	0.00000720***	0.00000656***
	(0.00000186)	(0.00000209)	(0.00000201)
Flow Variability	−0.00000228	−0.00000271	−0.00000364
	(0.00000459)	(0.00000482)	(0.00000479)
$\mathbb{1}$(Drought)	−0.00247***	−0.00246***	−0.00186***
	(0.000341)	(0.000353)	(0.000325)
Roughness	−0.00000254***	−0.00000284***	−0.00000386***
	(0.000000911)	(0.000000928)	(0.000000986)
Acres Loamy Soil	0.000000115	0.000000126	0.00000133**
	(0.000000468)	(0.000000475)	(0.000000535)
Watershed Acres	0.000000968***	0.00000107***	0.00000100***
	(0.000000202)	(0.000000204)	(0.000000211)
Homestead Claims$_{jt-1}$	0.000120***	0.000124***	0.000121***
	(0.0000202)	(0.0000209)	(0.0000289)
$\mathbb{1}$(Initial Claims>0)	0.0112***	0.0113***	0.00894***
	(0.00139)	(0.00132)	(0.00104)
Total Water Claimed (cfs)		−2.04e-08***	2.13e-08***
		(6.23e-09)	(6.17e-09)
Total Homesteaded Acres			−0.000000122***
			(2.19e-08)
N	248,745	248,745	248,745
χ^2	2,081.90	2,148.38	2,326.26

Notes: Standard errors are clustered by stream and reported in parentheses. N= 248,745 is the number of stream-year cells for which we have overlapping data on all covariates. * $p < .1$, ** $p < .05$, *** $p < .01$

Table C2: Coefficient Estimates - FE Poisson

	(1)	(2)	(3)	(4)
	Y = New Water Claims$_{jt}$			
Lagged Claims	0.352***	0.364***	0.362***	0.310***
	(0.0271)	(0.0254)	(0.0255)	(0.0230)
Lagged Claims*Flow	−0.0000412**	−0.0000653**	−0.0000646**	−0.0000668***
	(0.0000196)	(0.0000269)	(0.0000269)	(0.0000208)
$\mathbb{1}$(Drought)	−0.646***	−0.621***	−0.638***	−0.502***
	(0.0715)	(0.0732)	(0.0802)	(0.0730)
Homestead Claims$_{t-1}$	0.0137***	0.0159***	0.0158***	0.0181**
	(0.00240)	(0.00272)	(0.00274)	(0.00787)
Total Water Claimed (cfs)		−0.00000303**	−0.00000302**	0.00000675***
		(0.00000145)	(0.00000144)	(0.00000149)
Lagged Claims* Total Water Claimed		0.000000247	0.000000225	−0.000000351
		(0.000000311)	(0.000000306)	(0.000000258)
Lagged Claims*$\mathbb{1}$(Drought)			0.0584	
			(0.0783)	
Total Homesteaded Acres				−0.0000350***
				(0.00000789)
N	112,217	112,217	112,217	112,217
χ^2	292.8	427.0	423.4	422.2

Notes: Robust standard errors are reported in parentheses. N= 112,217 is the number of stream-year cells for which we have overlapping data on all covariates. Streams that never receive a claim are dropped from the fixed effects specification. * $p < .1$, ** $p < .05$, *** $p < .01$

Table C3: Coefficient Estimates - Fixed Effects Logit

	(1)	(2)	(3)	(4)
		Y = $\mathbb{1}$(New Claims$_{jt}$ >0)		
$\mathbb{1}$(Lagged Claims>0)	1.935***	1.930***	1.963***	1.720***
	(0.0820)	(0.0711)	(0.0851)	(0.0855)
$\mathbb{1}$(Lagged Claims>0)*Flow	−0.0000602	−0.0000184	−0.0000157	−0.0000939
	(0.0000605)	(0.0000105)	(0.000131)	(0.000128)
$\mathbb{1}$(Drought)	−0.544***	−0.524***	−0.458***	−0.414***
	(0.0622)	(0.0605)	(0.0632)	(0.0560)
Homestead Claims$_{t-1}$	0.0176***	0.0177***	0.0179***	0.0225***
	(0.00282)	(0.00341)	(0.00310)	(0.00760)
Total Water Claimed (cfs)		−0.00000246	−0.00000235	0.00000797**
		(0.00000417)	(0.00000368)	(0.00000337)
$\mathbb{1}$(Lagged Claims>0)* Total Water Claimed		−0.00000184	−0.00000175	−0.00000238
		(0.00000526)	(0.00000566)	(0.00000793)
$\mathbb{1}$(Lagged Claims>0)*$\mathbb{1}$(Drought)			−0.437*	
			(0.225)	
Total Homesteaded Acres				−0.0000317***
				(0.00000710)
N	112,217	112,217	112,217	112,217

Notes: Robust standard errors are reported in parentheses. N= 112,217 is the number of stream-year cells for which we have overlapping data on all covariates. Streams that never receive a claim are dropped from the fixed effects specification. * $p < .1$, ** $p < .05$, *** $p < .01$

Table C4: Marginal Effects of Priority on Cooperation

	(1)	(2)	(3)	(4)
	Divisions 1-3		Division 1	Division 3
1st Priority Decile	0.123***	0.119***	0.0207	0.194**
	(0.0359)	(0.0390)	(0.0779)	(0.0861)
2nd Priority Decile	0.0541	0.0725	0.0154	0.123
	(0.0456)	(0.0472)	(0.0929)	(0.102)
3rd Priority Decile	0.0882*	0.119**	−0.00675	0.202*
	(0.0468)	(0.0488)	(0.0861)	(0.119)
4th Priority Decile	0.0318	0.0419	0.0624	0.00619
	(0.0432)	(0.0431)	(0.0855)	(0.0905)
6th Priority Decile	−0.0154	−0.00285	−0.0558	0.0391
	(0.0518)	(0.0495)	(0.0698)	(0.0997)
7th Priority Decile	0.0366	0.0359	−0.0761	0.146
	(0.0401)	(0.0421)	(0.0674)	(0.107)
8th Priority Decile	−0.0591	−0.0910*	−0.181**	−0.0301
	(0.0447)	(0.0485)	(0.0753)	(0.0902)
9th Priority Decile	−0.160***	−0.211***	−0.238**	−0.292*
	(0.0465)	(0.0522)	(0.0939)	(0.175)
99th Priority Percentile	−0.236***	−0.330***	−0.488***	−5.193***
	(0.0643)	(0.0774)	(0.189)	(1.314)
Homesteads	−0.00399**	−0.00320*	−0.00345	−0.00159
	(0.00166)	(0.00190)	(0.00295)	(0.00350)
Summer Flow	0.0000155***	0.0000211***	0.0000354*	0.0000383**
	(0.00000591)	(0.00000636)	(0.0000186)	(0.0000159)
Flow Variability	−0.000282	−0.000609	0.00189	−0.00300*
	(0.000252)	(0.00144)	(0.00293)	(0.00169)
Roughness	−0.000134	−0.000111	0.000368	−0.000840
	(0.000120)	(0.000141)	(0.000373)	(0.000746)
Acres of Loamy	0.00000849	0.0000125	0.0000630	−0.0000436
Soil	(0.0000132)	(0.0000205)	(0.0000433)	(0.0000285)
Acreage Along	−0.00000346	−0.00000743	−0.0000245*	0.0000101
Stream	(0.00000461)	(0.00000823)	(0.0000146)	(0.0000107)
Watershed Effects	No	Yes	Yes	Yes
Year Effects	Yes	Yes	Yes	Yes
N	4,756	4,354	1,206	937

Standard errors are clustered by watershed and resorted in parentheses
* $p < .1$, ** $p < .05$, *** $p < .01$

Table C5: Effects of Cooperation and Priority on Investment

	(1)	(2)	(3)	(4)	(5)
	Divisions 1 & 3			Division 1	Division 3
1st Priority Decile	3,891.1	3,179.9	3,230.5	15,898.6***	−13,274.3
	(7,957.6)	(6,944.3)	(6,908.2)	(5,321.7)	(11049.2)
2nd Priority Decile	−4,638.4	−3,609.0	−3,463.8	9,612.0	-16908.4
	(9,036.7)	(8,451.1)	(8,399.5)	(6,847.9)	(12398.0)
3rd Priority Decile	−5,055.8	−348.8	−267.3	18,908.4***	−14,920.8
	(8,657.2)	(7,454.8)	(7,410.0)	(5,773.6)	(11363.1)
4th Priority Decile	−3,142.4	−6,221.5	−6,157.4	1,630.6	-12,027.0
	(7,991.9)	(7,506.7)	(7,466.0)	(6,647.8)	(10,047.3)
6th Priority Decile	−4,690.8	−1,487.7	−1,568.5	10,418.2	-14,269.1
	(8,450.9)	(7,975.6)	(7,975.1)	(7,351.9)	(12,226.6)
7th Priority Decile	−5,845.4	−4,365.9	−4,384.2	−972.1	−8,698.5
	(8,353.6)	(6,887.6)	(6,837.7)	(5,670.3)	(12,088.3)
8th Priority Decile	−8,103.3	−5,729.3	−5,778.6	−2,603.8	−7,205.5
	(8,450.3)	(7,065.3)	(7,026.3)	(5,652.6)	(12,387.4)
9th Priority Decile	−8,720.3	−6,641.4	−6,747.5	5,386.8	-12,553.9
	(8,491.4)	(7,512.1)	(7,480.5)	(7,462.0)	(10,847.0)
99th Priority Percentile	−550.4	−751.9	−986.2	9,380.4	−14,208.5
	(12,560.4)	(9,532.2)	(9,616.6)	(9,735.9)	(13,410.6)
CoOp	5,963.9**	4,461.5**	4,472.0**	10,197.9**	−2,202.6
	(2,736.0)	(2,199.0)	(2,195.7)	(4,004.1)	(2,139.6)
Claim Size	244.7***	255.7***	256.3***	352.2***	130.0***
	(60.72)	(68.96)	(69.14)	(100.5)	(34.75)
Summer Flow	1.706	0.723	0.669	0.445	−0.604
	(1.144)	(0.968)	(0.967)	(1.963)	(1.023)
Flow Variability	56.94	349.2*	350.0*	173.2	287.1*
	(139.2)	(190.7)	(190.8)	(278.3)	(168.6)
Roughness	−19.79	−61.18	−61.21	22.55	−60.57
	(23.60)	(59.05)	(59.04)	(71.02)	(67.32)
Acres of Loamy Soil	0.904***	0.773	0.760	−2.842**	4.660
	(0.293)	(2.195)	(2.197)	(1.353)	(4.045)
Claim Year	1.268	2.425	2.426	−5.042	85.42
	(4.376)	(4.755)	(4.736)	(6.011)	(131.9)
Homestead Claims		−284.3			
		(227.0)			
Homesteaded Acres			−1.664	0.709	−1.954
			(1.481)	(1.782)	(1.702)
Watershed Fixed Effects	No	Yes	Yes	Yes	Yes
N	550	550	550	292	258
R^2	0.317	0.454	0.454	0.569	0.317

Spatial HAC standard errors are reported in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

Table C6: Income Per Acre Pre-1960

	(1)	(2)	(3)	(4)	(5)	(6)
	Division 1			Division 3		
	Reduced Form	Irrigated Acres	Income Per Acre	Reduced Form	Irrigated Acres	Income Per Acre
CoOp	105.7***	-251.7	81.04***	−7.934	−162.5	−10.51
	(28.60)	(165.4)	(28.94)	(51.50)	(230.5)	(51.30)
Claim Size	1.139**	−3.963	1.162**	0.664*	−5.044	0.525
	(0.468)	(3.819)	(0.444)	(0.354)	(4.783)	(0.547)
Summer Flow	0.0249*	0.0448	0.0133	0.0348	−0.0726	0.0349
	(0.0128)	(0.0995)	(0.0128)	(0.0230)	(0.117)	(0.0237)
Flow Variability	−16.74***	−41.80	−15.87***	−2.871	−22.34	−3.046
	(4.991)	(29.78)	(5.036)	(4.676)	(21.96)	(4.738)
Roughness	−0.157	4.510	−0.212	−0.587	−0.893	−0.546
	(1.679)	(10.43)	(1.659)	(0.645)	(4.196)	(0.649)
Percent Loamy Soil	−0.638	−3.239	−0.244	155.0	-234.3	155.0
	(2.953)	(7.928)	(2.981)	(147.5)	(502.5)	(154.4)
Ditch Meters		0.0723***	0.00208*		0.206***	0.00239
		(0.0101)	(0.00117)		(0.0449)	(0.00424)
Irrigated Acres			0.0109			−0.00433
			(0.0107)			(0.00911)
Homesteaded Acres	−0.0883**	−0.433**	−0.0873**	−0.0108	0.0797	−0.0119
	(0.0356)	(0.172)	(0.0337)	(0.0173)	(0.0599)	(0.0178)
1st Priority Decile	43.19	−60.89	19.98	158.0**	356.4	156.0**
	(37.52)	(190.1)	(38.39)	(63.24)	(452.8)	(64.16)
2nd Priority Decile	11.28	−450.8	19.50	136.5*	213.5	137.7*
	(60.62)	(589.5)	(55.27)	(75.81)	(304.0)	(75.19)
3rd Priority Decile	142.3***	626.8	116.1**	82.67	106.5	84.03
	(45.50)	(434.9)	(50.68)	(64.20)	(316.5)	(62.52)
4th Priority Decile	35.01	−27.43	27.69	132.0	−103.8	130.1
	(49.52)	(218.3)	(46.03)	(96.47)	(355.8)	(96.95)
6th Priority Decile	75.06	65.17	86.39*	126.2*	22.23	126.2*
	(50.32)	(265.8)	(47.11)	(69.30)	(340.2)	(67.82)
7th Priority Decile	153.8	−107.9	143.5	121.1	758.3	133.3*
	(97.15)	(312.2)	(101.3)	(74.07)	(527.0)	(75.88)
8th Priority Decile	146.6*	119.6	149.9*	113.7	−245.0	97.70
	(77.84)	(255.1)	(75.92)	(87.59)	(687.2)	(97.28)
9th Priority Decile	218.7***	−29.53	201.8***	190.0*	−358.2	189.7*
	(50.71)	(256.7)	(51.83)	(97.70)	(350.1)	(97.79)
99th Priority Percentile	106.5	15.38	96.04	76.97	−541.8	69.67
	(99.42)	(334.4)	(94.73)	(83.40)	(601.3)	(81.17)
Watershed Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
N	169	169	169	178	178	178
R^2	0.873	0.830	0.879	0.692	0.735	0.698

Spatial HAC standard errors are reported in parentheses. Soil quality in Division 3 is collinear with watershed fixed effects.

* $p < .1$, ** $p < .05$, *** $p < .01$

Table C7: Division 1 vs. 3

	Division 1	Division 3
Total Income	785,035.7	323,869.8
	(139,492.2)	(111,086.7)
Irrigated Acres	1,397.6	671.0
	(240.1)	(175.3)
IPA	561.9	523.4
	(17.8)	(26.9)
Claim Size	22.2	19.4
	(2.6)	(1.9)
Claim Date	−29,936.76	−29,163.77
	(316.8)	(354.3)
Acres Loamy Soil	60.2	11.1
	(8.1)	(1.7)
Ditch Meters	13,522.2	7,724.0
	(1532.2)	(965.1)
Potential Riparian Claims	50.42	28.43
Per Stream	(72.93)	(47.46)
Actual Appropriative Claims	3.11	2.48
Per Stream	(9.77)	(9.58)
Actual Homestead Claims	84.68	11.1
Per Township	(146.38)	(41.37)
Number of Streams	625	439