Collective Action by Contract: Prior Appropriation Property Rights and the Development of Irrigation in the Western United States*

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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, abruptly replacing common-law riparian water rights. We build upon Ostrom and Gardner (1993) and model irrigation as a contracting problem to show how the features of prior appropriation were necessary to support welfare-increasing contracts for securing and sharing water and financing irrigation infrastructure among numerous, heterogeneous agents. We construct novel dataset of 7,800 rights in Colorado, established between 1852 and 2013 including location, date, size, infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, and precipitation to test the predictions of the model. Prior appropriation doubled infrastructure investment and raised the value of agricultural output beyond baseline riparian rights. The analysis reveals institutional innovation that informs both our understanding of the development of property rights, prior appropriation, and contemporary water policy.

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1 Introduction

Property rights are fundamental institutions for shaping economic behavior. When reasonably well defined, secure, and long-term 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 (Grief 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 because voluntary major shifts in property institutions are rare.[2] Indeed, once in place, property rights institutions endure influencing markets and long-term economic outcomes (Libecap, 2007). Accordingly, analysis of the endogenous emergence of property rights reveals the underlying factors leading to their adoption and how they, in turn, allow for welfare-enhancing economic activities, not possible otherwise. As we emphasize here, a critical role of property rights is facilitating valuable coordination to overcome collective action problems.

In this paper, we exploit the empirical setting of the westward settlement of the American frontier as a laboratory for institutional innovation and examination of the economic results. 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, 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 market actors and molding government 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 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. Prior appropriation displaced riparian rights

[1] Because of transaction costs, property rights are never fully complete. 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.

[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).

across an immense area of some 2,965,305 square miles (17 western states and 4 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]

Previous work has addressed why the riparian doctrine was not a feasible mechanism for allocating water in the West, but has failed to explain why prior appropriation emerged as the solution. [6] We address this gap in the literature and draw broader lessons for understanding of how property rights can be implemented to solve particular economic problems. In this case, prior appropriation provided for relative security of water access in a semi-arid region not possible under a riparian system. It then facilitated coordination among individuals in their investment decisions to overcome the collective action problems associated with irrigation emphasized by Coman (1911), Ostrom (2011), Libecap (2011), and Hanemann (2014). Our examination of the economic benefits of 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.

We present a simple model of contracting over irrigation investment to demonstrate how two key features of prior appropriation—quantification of water claims and priority-based allocation—made coordination more attractive and ultimately led to greater investment. To test the predictions of the model 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, crop choice, topography, stream flow, soil quality, precipitation, and drought in Colorado, the state where prior appropriation was most completely implemented initially. We examine individuals' decisions about where to establish a claim, whether to engage in cooperative behavior, and how much to invest in irrigation infrastructure and then estimate changes in revenue associated with these decisions.

We find that i) individuals preferred to establish claims near prior claimants, despite having potential reduced access to water, suggesting large expected benefits from cooperation; indeed,

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[4] Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, Wyoming, Alberta, British Columbia, Manitoba, and Saskatchewan (Scott, 2008, pp 101). Some of the less-arid jurisdictions have mixed systems of prior appropriation and riparian. Prior appropriation 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] The prohibition of moving water away from source streams inherent in riparian water rights that protect downstream flows is a standard argument for prior appropriation (See Getches, 2009). Indeed, the ability to move water from one place to another was a basis for the private irrigation systems we examine, 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). Nevertheless, as we describe, additional institutional innovation was required for irrigation investment to move water to remote sites.

under prior appropriation prior claimants advertised their diversion locations to encourage others to locate nearby, behavior that would not be advantageous under a riparian system, where new claimants would reduce diversion amounts to *all* prior claimants; ii) secure, recognized property rights facilitated coordination among large numbers of heterogeneous agents by reducing resource access 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. We show that the benefits of property rights were largest in areas that lacked cultural or other institutions for fixing water diversion amounts and then coordinating individual investment behavior; these attributes were less critical in areas where water users were in close-knit, small, older Hispanic communities and relied upon shared norms in farming and irrigation decisions. 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

Prior to Westward Expansion, surface water rights in the United States primarily were allocated under the riparian doctrine.[7] Riparian water rights are tied to the ownership of riparian lands; in order to use a surface water source, a potential claimant must own land adjacent to the stream they wish to access. At the same time, all owners of riparian land are granted “reasonable use” of surface waters adjacent to their property. Their use of water cannot excessively diminish surface flows to all other riparian owners. Riparian rights are not explicitly quantified and the only margin for formal exclusion of third parties is land ownership. Riparian rights cannot be transferred or traded and during drought all users are expected to reduce their use in a proportional manner, regardless of the timing or size of their initial use of the stream.

In contrast, the prior appropriation doctrine assigned rights via first possession, based on the timing of the initial claim. Construction of an irrigation ditch to divert a specific amount of water from a given location was sufficient to establish a claim which could later be legally recognized in court. Appropriative rights were explicitly quantified and tied to a specific use in a specific location, though no riparian land ownership was required to claim water. The first-come, first-served allocation of appropriative rights also resulted in a priority-based system of allocation during drought, whereby senior claims had to be fully satisfied before junior users could divert any water. Critically, the priority system protected prior diversion amounts from

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

being diminished by subsequent water claimants on a stream. This, of course, was not the case under riparian water rights.[8]

Figure1 depicts the dramatic shift in precipitation facing migrants across the North American frontier as provided by John Westley Powell to Congress in 1879. Figure 2 shows the corresponding distribution of major streams and types of water rights in the United States to illustrate the dramatic nature of the change in property rights regimes for water that occurred in jurisdictions west of the 100th meridian. The figure shows states/territories with either riparian rights or prior appropriation or hybrids of both. The dates indicate key constitutional, legislative, or judicial adoption of prior appropriation in each state.[9] As the figure indicates, 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. Prior appropriation emerged over a 40-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.

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. Colorado also exhibits many of the initial conditions facing migrants to the region prior to construction of large Bureau of Reclamation projects after 1902. Finally, Colorado played a disproportionate role in influencing early water rights development in other jurisdictions (Boyd, 1890, p. 136).[10]

[8] Early on, enforcement of diversion priority was a problem as late comers established claims upstream, diminishing flows available to more senior claims. For discussion of conflict and resolution see Boyd (1890) and Dunbar (1950).

[9] Mead (1901, p. 7-15) discusses 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. 170-171); 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).

[10] 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, 2916; Dunbar, 1950; Hobbs, 1997; Scott, 2008, p. 101).

Figure 3 depicts water and land resources as well as Water Divisions in Colorado. [11] Colorado covers an area of some 66,620,160 acres containing over 107,000 miles of streams with elevations ranging from 3,317 to 14,440 feet.[12] Colorado migrants came primarily from the northeast and north-central US where there was little need for irrigation and riparian rights had dominated (Colorado Water Institute, ND, 2; Dunbar, 1950, p. 42; Hobbs, 1997, p. 3; Romero, 2002, p. 527). The population of Colorado jumped sharply from 39,864 in 1870 to 539,700 people by 1900, fueled by migration into the farming regions east of the Rocky Mountains (US Census Bureau). Moreover, the heterogeneity of the migrants is demonstrated not only by the diverse regions in the US from which they came, but also by the large share of foreign-born individuals. For example, in 1880, 20.5% of the state's population came from abroad (Gibson and Jung, 2006, Table 14). These migrants confronted semi-arid conditions not found in the East or Western Europe and irrigation of crop lands and investment in conveyance capital to move water to distant sites were required. Large numbers, differences in background and origin, as well as limited information about appropriate farming techniques and irrigated agriculture raised the costs of organizing responses to these new conditions. Key to lowering organization costs was institutional innovation.

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. An 1872 statute continued the move toward prior appropriation by granting right-of-way to irrigation ditch 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 Engineer's 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 4 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.

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[12] The 1900 population of Colorado was 539,700, implying a population density of 1 person per 123 acres.

The western frontier was immense and varied in terrain, quality, and potential value, leading to high information and coordination costs for resource claimants. 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).[13] Emigrants 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 provide insufficient water during drought.[14] Early migrants also did not have the experience to relate mountain snowpack variation to differences in subsequent stream flow, and they did not know much about the sources or durability of soil quality or the types of crops that would be appropriate for different types of soils and the climate (Boyd, 1890, pp. 138-157).Learning about stream fluctuation, soil quality, and optimal farming techniques was time consuming and often led to failure. 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. While the need to separate water and land claims explains why the explicitly land-based riparian system was inadequate for the West, it does little to clarify the economic advantages of prior appropriation itself. Why was first possession the natural alternative to a riparian land share-based system? And why create a priority-based system for coping with drought rather than a proportional one? Contemporary policymakers repeatedly ask exactly these questions as they confront water allocation challenges associated with the appropriative doctrine which endure to this day—understanding why prior appropriation emerged in the first place is a critical first step in understanding the role of prior appropriation in adapting to the evolving challenges of water use in the West.

The economic problem of irrigation in the American West centered around the development of infrastructure, including dams, reservoirs, canals, and feeder ditches to capture, store, and deliver water (Libecap 2011, p. 72). Mead (1901, p. 8) estimated that private irrigation systems valued nearly at $200,000,000 (nearly $6 billion in 2015 dollars) were in place as of 1901 in the western United States, prior to the massive irrigation projects of the federal Reclamation Service. He also describes the complexity of raising capital and the coordination

[13] 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; Umbeck, 1977, 1981; Libecap, 1978, 2007; Reid, 1980; Zerbe and Anderson, 2001; McDowell, 2002; Clay and Wright, 2005; Stewart, 2009; Gaines, 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.

[14] 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, 2004a, b).

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.[15] Separating water claims from land rights was a necessary, but not a sufficient condition for bringing water to valuable arable lands in the face of the irrigation investment requirement (Hanemann, 2014; Crifasi, 2015). Haneman (2014) argues western irrigation was characterized by high fixed costs of investment in non-deployable capital with low marginal costs of water transport. Large canals and ditches had to be constructed to move water from the rugged riparian corridor to productive agricultural lands, but ditches—once constructed—were relatively cheap to use and maintain. The high fixed costs and capital intensity of ditch construction, combined with the delayed nature of income from agricultural investment, created a liquidity problem for farmers, often migrants who lacked significant assets. Credit markets were not readily available to overcome this liquidity problem for financing large-scale irrigation works to be used by many small farmers.

As Coman (1911), Ostrom (2011), and Hanemann (2014) point out, the ability to share diversion capacity in large main ditches, coupled with individual credit constraints, made irrigation a classic collective action problem. Construction of these large ditches required coordination between large numbers of heterogeneous individuals who arrived in the West across several decades—settlers individually lacked the assets to finance ditch construction but could potentially pool their resources to construct large ditches (Rettig, 2012, p. 3). The problem facing individuals was both how to secure a defined amount of water for diversion, not vulnerable to later riparian water claims and how to ensure cooperative behavior once the ditch was constructed.

While Hanemann (2014) argues that ditch construction and ditch management are quite different economic problems, the question of how designate and manage diversion capacity *ex post* bears directly on individuals' willingness to contribute to construction outlays *ex ante*. In particular, early potential contributors faced uncertainty both about the amount of long-term water available for diversion through a ditch and about the extent to which the ditch could be used by additional irrigators, who arrived later. This new entry problem was exacerbated by the fact that land claims were generally allocated in small, 160-acre increments under the Homestead and other Acts, creating the potential for a massive number of potential claimants along a stream and in the service area for a given ditch.

While Ostrom (2011) points to several examples of community-based provision of irrigation works through institutions such as the Mormon Church, the large number of heterogeneous migrants arriving over a broad time horizon precluded an Ostrom (1990)-style solution to these collective action problems across most of the West. Instead, contractual arrangements formed the primary basis for cooperation because they allowed individuals claim a defined diversion amount of water based on priority and then to pool their assets, assign responsibilities and penalties, and create legal entities which could pursue financing from creditors in the eastern United States (Hanemann, 2014).

[15] In the late 19th and early 20th centuries there were numerous investigations into irrigation in the western United States including Newell (1894), Mead (1901), and 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.

Figure 5 illustrates the insurmountable contracting problem facing potential irrigators and investors in costly irrigation infrastructure under a riparian system. The figure shows the potential 160-acre riparian homestead claims possible along the Cache La Poudre River in northern Colorado. The Cache La Poudre was a major source of irrigation water and early irrigation expansion. The figure also shows actual major canal and ditch investments. The riparian system protected all surface water users from unreasonable withdrawals by any riparian, hence prohibited any large-scale irrigation water diversion to remote sites. The only ways upstream infrastructure investors could have proceeded under a riparian system was to claim ownership of all other riparian lands, an action blocked by the federal land laws, or to contract with all subsequent riparian claimants to secure their water. This action would have entailed extremely high bargaining costs. As shown in the figure the numbers of potential riparian claims was large and parties arrived over time as new homesteaders staked claims. Hence, the set of bargaining parties was not fixed until the last homesteader staked a riparian claim. In the meantime, irrigation infrastructure investment that required access to sufficient water to be feasible would have to wait.

We argue that the distinguishing features of prior appropriation—quantification and priority-based allocation—were uniquely suited to overcome the collective action problems outlined above. Explicit quantification of individual claims under prior appropriation provided a basis for contracting that was lacking in unquantified, adjacent land share-based riparian rights. Moreover, the priority-based allocation of water under prior appropriation made incumbent users secure against future entry and related riparian water claims along the stream. This had two important implications. First, early users would have been more willing to engage in risky investment because their claims could not be dissipated by ensuring claimants. Second, assigning priority to earlier rights would have made senior users more willing to contract with new claimants within a ditch's potential service area, perhaps even leading them to invest in anticipation of subsequent waves of water users. In the next section we present a simple model of investment in irrigation infrastructure and derive testable predictions about how the structure of appropriative rights affects individuals' investment decisions.

3 Model

We generalize the simple model of irrigators in an asymmetric commons from Ostrom and Gardner (1993) to show how prior appropriation formed a basis for cooperation over a designated amount of water for diversion, made possible by prior appropriation, and not riparian water rights. In their model Ostrom and Gardner (1993) address the coordination problem between head-enders and tail-enders along a ditch and not on the hazard that a riparian system posted for infrastructure investment decisions when diversion amounts were always at risk from new riparian claimants. Given a fixed diversion amount for a ditch, we make three extensions to their model. First, we add a fixed cost so that irrigators cannot profitably invest in infrastructure without cooperating, consistent with the high fixed costs and credit constraints emphasized by Hanemann (2014). Second, we treat the model as a two-stage game with ditch investment in the first stage and ditch water delivery in the second stage, highlighting the coordination problem.

Third, we consider the full menu of possible contracts over investment and water deliveries and characterize the equilibria with and without property rights. Throughout we assume that all players have perfect information and look for the subgame perfect Nash equilibrium of the game.

Consider two irrigators, denoted player 1 and player 2, who must decide whether to jointly construct irrigation works. Investment decisions are made in the first period and water is delivered in the second period. Following Ostrom and Gardner's emphasis on asymmetry, we assume that player 1 (the "head-ender") can access the water before it reaches player 2 (the "tail-ender") during the second stage when water is delivered. The availability of water depends on the investments of both users in the first stage. With the addition of a fixed cost equal to 1, the production function for water then is $W = 2(x_1^{1/2} + x_2^{1/2}) - 1$ where x_1 and x_2 are the contributions of players 1 and 2, respectively. We normalize the price of water to 1.

The payoff for either individual acting alone is given by $U_i^0 = 2x_i^{1/2} - 1 - x_i$ which has as its solution $x_i^* = 1$ and $U_i^0(1) = 0$—when individuals act alone than cannot profitably build large enough irrigation works to be worth the investment. This reflects the high capital costs associated with irrigation infrastructure and underscores the need for joint action by irrigators. If they are able to coordinate their investment decisions, individuals can earn positive economic rents by jointly financing irrigation development. The more individuals involved in the cooperative venture, the larger the potential rents, as we will show below.

If individuals act jointly to produce W units of water, they must share that output. Suppose player 1's share is given by $\theta \in [0,1]$ so that player 1 gets θW units of water and player 2 gets $(1-\theta)W$ units of water in the second stage. Ostrom and Garnder (1993) consider the coordination problem that arises for different exogenously given values of θ, meant to reflect player 1's prior access to the water due to being closer to the head of the ditch. Our interest is in formally characterizing how the players might come to agree on a sharing rule θ that makes both of them better off than uncoordinated investment.

If individuals act together to maximize the joint surplus they solve:

$$\max_{x_1, x_2} \ 2\left(x_1^{1/2} + x_2^{1/2}\right) - 1 - x_1 - x_2$$

which has as its solution $x_1^* = x_2^* = 1$, which results in total available water of $W = 3$. This simple formulation captures the fact that individuals acting together to transport water via a ditch to their respective fields can make more water available by pooling their investments than by building two separate ditches, whereby both would have to overcome the capital investment problem separately. Since each individual supplies 1 unit of investment, there is a total surplus of 1 to be shared between the two individuals.

Our aim is to characterize the set of contracts $\{\theta, x_1, x_2\}$ that result in the efficient outcome and then determine under what conditions these contracts can be supported as an equilibrium between players 1 and 2. To see why the ditch contract must specify both investment levels and the sharing rule, consider the outcome when individuals agree on θ but choose their contributions individually. Player 1 solves:

$$\max_{x_1} \ \theta 2\left(x_1^{1/2} + x_2^{1/2}\right) - 1 - x_1$$

with player 2 solving a similar problem. Even if investment and deliveries occurred simultaneously, a contract would be necessary to ensure cooperative behavior resulting in a social surplus. To show this, we solve for x_1 and x_2 as functions of the sharing rule θ and get that $x_1(\theta) = \frac{1}{\theta^2}$ and $x_2(\theta) = \frac{1}{(1-\theta)^2}$, but this results in $W = 2(\theta + 1 - \theta) - 1 = 1$. In order for this to be an improvement over separate investment, each player must do at least as well as they did in the uncoordinated outcome:

$$\theta W - \frac{1}{\theta^2} \geq 0 \Leftrightarrow \theta \geq 1$$
$$(1-\theta)W - \frac{1}{(1-\theta)^2} \geq 0 \Leftrightarrow \theta \leq 0$$

Hence, agreeing on θ and then allowing each player to indepently choose their investment is not sufficient to realize the potential gains from trade because each bears the full cost of their investment but does not realize the entire gain. In order to achieve a surplus that can be divided between individuals, the contract must specify both the share (θ) and the investment inputs x_i.

Returning to the welfare-maximizing outcome, we know that $x_1^* = x_2^* = 1$ characterizes the efficient investment contributions. Contracts over θ must make both players better off than if they choose not to invest (or equivalently, to invest alone and earn 0), which allows us to bound the set of possible values for θ to achieve an efficient contract:

$$\theta W(x_1^*, x_2^*) - x_1^* > 0 \Leftrightarrow 3\theta > 1$$
$$(1-\theta)W(x_1^*, x_2^*) - x_2^* > 0 \Leftrightarrow 3(1-\theta) > 1.$$

In order for both players to weakly prefer the contract to sole investment, it must be that $\theta \in [\frac{1}{3}, \frac{2}{3}]$. So the set of welfare-maximizing contracts is characterized by $\left\{[\frac{1}{3}, \frac{2}{3}], 1, 1\right\}$. Both players are made better off through cooperating with any perfectly-enforced contract in this set because they earn strictly positive payoffs.

The problem arises when we consider the two-stage nature of the decision and player 1's prior access to the water. Suppose that the contract is not enforceable so that in the second stage player 1 is able to choose any $\theta \in [0,1]$, after investment decisions have been made. Clearly, the dominant strategy for player 1 is to set $\theta = 1$, resulting in a payoff of $3 - 1 = 2$ for player 1 and $0 - 1 = -1$ for player 2. Hence, in a two stage game where players invest first and receive water in stage 2, no contract with $\theta < 1$ can be supported as a subgame perfect Nash equilibrium because any contribution from player 2 earns a negative payoff due to player 1's deviation from the agreed upon θ once investment has taken place. This is opportunism when capital is not deployable (Williamson, 1993).

Hence, there is a problem of credible commitment. Even though player 1 would be better off with a cooperative contract than without, it is not possible to credibly convince player 2 that post-contractual opportunism will not take place once irrigation works are constructed. The fact that the cooperative payoff is higher than the equilibrium outcome means that player 1 would gladly constrain the set of possible strategies in period 2 in order to elicit player 2's investment contribution. That is, the players could achieve the first-best outcome if they had some mechanism to credibly constrain player 1's behavior in the second stage.

Ostrom and Gardner (1993), Ostrom (2011), and others emphasize the need for trust to overcome this problem and the role that group characteristics play in helping forming trust. With relatively small, stable groups of homogeneous users, trust and cooperation are possible so that joint investment may emerge as an equilibrium. This solution for "governing the commons" has been well-documented (Ostrom 1990, 2007, 2009, 2011; Ostrom and Gardner, 1993; Janssen and Anderies, 2011; Janssen and Rollins, 2012; York and Schoon, 2011). Unfortunately, these were not the conditions facing most migrants to the West, who were part of large-scale immigration.

We argue that prior appropriation was uniquely suited to solve the credible commitment problem in a setting where the informal basis for trust was absent. The particular problem is to constrain players in the second period to use the quantity of water dictated by the contract $\left\{[\frac{1}{3},\frac{2}{3}],1,1\right\}$ in the first period. The quantification of appropriative water rights—a critical institutional innovation among individuals who would have otherwise used unquantified riparian rights, both along a stream and along a ditch—did exactly that by assigning the right to annually divert a pre-specified amount of water from a particular location. Within that fixed diversion amount, a sharing rule could be devised. Once diversion rights were quantified, contracts of the form $\left\{[\frac{1}{3},\frac{2}{3}],1,1\right\}$ would be enforceable in court. Under perfect enforcement or sufficiently costly punishment, the dominant strategy for player 1 becomes adherence to the contract in the second period so that all contracts satisfying $\left\{[\frac{1}{3},\frac{2}{3}],1,1\right\}$ are supportable as a subgame perfect Nash equilibrium—cooperation can emerge. Under any other water right system that did not explicitly quantify diversion and subsequent ditch user water claims, $\left\{[\frac{1}{3},\frac{2}{3}],1,1\right\}$ would not be supportable as an equilibrium. Fixing rights to a specific amount based on initial appropriation solved the credible commitment problem and made coordinated investment the equilibrium outcome of an otherwise dismal coordination game.

Next, we use the model to demonstrate how potential competition for resources from future claimants affects the set of feasible contracts. Suppose the threat of additional claimants on the stream as would be the case under a riparian system reduces the probability that our players receive water to their ditch. Denote the probability of water delivery given the threat of entry as δ. Then the expected amount of water available if both players contribute 1 unit of investment is $\delta 3$ and the new incentive-compatibility constraints imply that $\theta \in [\frac{1}{3\delta}, 1 - \frac{1}{3}\frac{1}{\delta}]$. Hence, the set of feasible welfare-maximizing contracts is made smaller if claims made today are not secure against future entry. Moreover, the total surplus from investment is now $\delta 3 - 2$, which is strictly less than the surplus under no entry.

This is where the priority-based allocation of prior appropriation plays a significant role. By honoring water deliveries in the order in which rights were established, the appropriative doctrine guarantees that claims made in a given period are secure against future entry, essentially fixing $\delta = 1$. Doing so both increases the surplus from cooperating and expands the set of incentive-compatible, welfare-maximizing contracts, making agreement and cooperation a more likely outcome relative to the case where $\delta < 1$.

Finally, we consider the more general case of N players along a ditch to briefly analyze the effect of group size on incentives to cooperate. The model generalizes in a straightforward way to the case of N players. The welfare maximizing set of investments is given by $x_i^* = 1$, which results in total water $W = 2\left(\sum_{i=1}^{N} 1^{1/2}\right) - 1 = 2N - 1$. And the incentive-compatible set of shares for each individual, denoted θ_i, must satisfy:

$$\sum_{i=1}^{N} \theta_i = 1$$

$$\theta_i 2N - 1 \geq 0 \Leftrightarrow \theta_i \geq \frac{1}{2N} \qquad \forall i$$

if we again assume that some players have access to the water before others during the second period, we get the same result as in the 2-player version: without a rule to quantify and restrict water use, cooperation cannot be supported as an equilibrium.

In the case of N players it is possible to study how the payoffs to a given individual change as the group grows larger, for a given sharing rule θ_i. Suppose that users agree to share water equally so that $\theta_i = \frac{1}{N}$ $\forall i$ (note that this satisfies incentive compatibility constraints). Then, with a contracting specifying efficient contributions, the payoff to individual i as a function of N is $U_i(N) = \frac{1}{N}(2N-1) - 1$. Differentiating with respect to N we see that $\frac{\partial U_i(N)}{\partial = N} = \frac{1}{N^2} > 0$. The upshot is that if individual can agree to an equal sharing rule with full investment participation, individual profits are strictly increasing in group size (though at a decreasing rate).[16]

The extensions to our model underscore how priority allocation reshaped the economic problem facing irrigators in the West. Absent a secure quantified right with a priority guarantee, the arrival of additional claimants on a stream would reduce access for incumbent users—captured in our model by an increase in δ. Under a regime where δ increases and N grows, users are less likely to coordinate with one another and would undertake actions to deter additional entry on a given stream. With δ fixed at 1 under prior appropriation, incumbent claims are secure and the arrival of new claimants actually *increases* the opportunity for Pareto-improving contractual arrangements, a condition not found with a riparian system. Granting more secure property rights via quantification and priority created the potential for cooperation via contracts where before there existed only zero-sum competition and rent dissipation.

Our model yields several testable predictions about the behavior of individuals under prior appropriation which can be used to assess the validity of our argument that prior appropriation solved an important contracting problem. These predictions center on two important aspects of the decision to establish a water right: where to establish a claim and whether to formally coordinate investment decisions with other claimants.

The decision by junior claimants of where to establish a water right provides a test of whether cooperation with other claimants was actually a key feature of the economic problem of irrigation. In the baseline scenario with no cooperative interaction, Burness and Quirk (1980) show that under prior appropriation junior claimants are unambiguously worse off than senior claimants along a given stream because there is less water available for claiming and whatever claim they establish will have less security during drought. The ability to cooperate and pool capital with other users could overwhelm this effect, however. Indeed, our model predicts that

[16] Extending the game to N players does introduce the possibility of smaller groups of size $n < N$ forming and building competing structures. It is possible contracts designed by these smaller groups could dominate some contracts associated with a group of size N for some of the players. That is, a group of size N may not be coalition proof. We do not explore these issues here except to note that the sole investment, non-cooperative outcome would still be dominated by these coalitions and so the qualitative finding that prior appropriation facilitated group formation is robust to this possibility.

the benefits of cooperation are increasing in N under certain sharing rules, which would suggest benefits from locating diversion claims near other claimants.

The literature on first possession in patent contexts also indicates that first possession serves as a reward for early investment in settings where such investments generate a positive externality (e.g. research and innovation). In our setting, it is possible that innovation in how and where to divert water lowered claiming costs for subsequent claimants given general uncertainty about the environment.

The ability to cooperate around quantified water rights and the potential for private investments to generate positive social value are constitute the primary benefits associated with prior appropriation and with first possession more broadly. It is possible that prior appropriation emerged as dominant due to this benefits. On the other hand, prior appropriation may have been selected by early claimants in order to protect rents associated with being first-movers. The former explanation would predict that junior users would prefer to locate near existing claims in order to benefit from positive spillovers and to potentially engage in joint investment, whereas the latter would imply that early users captured rents so that subsequent claimants would locate elsewhere. Therefore, we examine the choice of where to establish a water right and predict, consistent with our theory, that new users will be more likely to establish claims near previous claimants.

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. The importance of collective action and potential social value associated with investment in irrigation works both derive from our characterization of the underlying challenges facing claimants in the West. Following Hanemann (2014), we emphasize the uncertainty associated with irrigation investment in a new climate and the high fixed costs associated with the rugged terrain and the distance between irrigable lands and available water. If uncertainty and resource scarcity were significant factors, we would 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 costlier for users to deduce such as flow variability over time and soil quality. Users are also more likely to be responsive to first-order resource characteristics such as drought.

Our second set of predictions relates directly to the outcomes of our model: cooperation and investment. Our model predicts that coordinated outcomes through contracting are more likely when prior claims are more secure against future entry because the menu of efficient, incentive-compatible contracts is larger.[17] While the model demonstrates that this makes agreement most likely under prior appropriation vis a vis other possible property rights regimes, such as a riparian system that did not assign priority, it also has direct implications for the probability of cooperation within the appropriative system itself. Burness and Quirk (1980) show that higher priority users have an unambiguously higher probability of receiving their water right in any given year because flows are stochastic and senior users must be satisfied before junior users. In the context of our model, this means that higher priority users have a higher value of δ, which means the set of feasible contracts is larger for high priority users. Accordingly, we predict that higher priority users are more likely to cooperate and jointly invest.

[17] Here we assume that a larger set of incentive-compatible contracts that maximize the social surplus make agreement more likely because there are more possible bargaining outcomes in this set. Various factors could influence what outcome is chosen in any given context, but a larger set should make agreement more likely.

We test our claim that cooperative contracts built around appropriative rights facilitate investment by comparing ditch investment by cooperative vs. non-cooperative claimants. As our model demonstrated, contracting outcomes which specify both investment and sharing rules *ex ante* lead to greater levels of investment than when individuals choose investment in an uncoordinated manner (assuming a fixed sharing rule, which is implied by prior appropriation). Moreover, cooperative claimants may be able to exploit economies of scale associated with overcoming the fixed costs and internalizing network externalities emphasized by (Hanemann, 2014). Thus, we predict that users who cooperate will tend to establish larger diversion infrastructure.

We summarize our hypotheses below before describing the data and our empirical tests:

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.
5. Cooperative claimants make larger investments than non-cooperative claimants.
6. Larger investments, indicated by ditch length, require more cooperating claimants.
7. Within cooperative ditches, there is a fixed, definite sharing rule.
8. Where there are norms to solve collective action problems regarding water access and use, formal prior appropriation will play less of a role in infrastructure investment.

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.[18] Colorado is divided into 7 Water Divisions that separately administer water rights, as depicted in Figure 6. 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

[18] 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.

diversion, iii) the name of the water source, iv) the size of the diversion, and v) the use or type of right. We restrict our analysis to agricultural rights.[19]

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 create measures of location quality by grid cell.[20] 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 6 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. Areas with productive, loamy soil are shaded in green.[21] 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 1 provides variable names, definitions, and summary statistics for the stream-level data and Appendix A 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.

4.2 Identification

We test our first prediction by estimating the effect of previous claims on a given stream on the probability and expected count of subsequent claims on that stream.[22] This gives our econometric model an inherently dynamic nature. We characterize the number of claims on

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[19] Most of the rights in our study area are agricultural; water rights associated with mining are primarily found in the western half of the state.

[20] 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.

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

[22] 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.

stream j in year t using a Poisson distribution.[23] The primary challenge to identification comes from the fact that there may location characteristics that are observed to claimants but unobserved to us as researchers, 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 prior claims—the history of claims on a given stream could proxy for unobserved stream quality and bias our estimates upwards. 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

$$E\left(y_{jt} | y_{jt-1}, \dots, y_{j0}, \boldsymbol{x_j}, u\_j\right) = u_j \exp(x_{jt}\beta + y_{jt-1}\rho)$$

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

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

then forming the likelihood function and integrating out the distribution of u_j conditional on y_{j0} and $\boldsymbol{x_j}$ 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 Poisson 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 heterogeneity and the conditional distribution of $\left(y_{jt} \middle| y_{jt-1}, \dots, y_{j0}\right)$ 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 1 and the unobserved effect in Equation 2. 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.[24] Second, we must assume that ν_j is independent of $\boldsymbol{x_j}$ and y_{j0}. This requires that the random component of the unobserved heterogeneity in site quality be random and not dependent on observed covariates.[25] 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

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[23] 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.

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

[25] But note that the unobserved component of Equation 1—u_j—is allowed to depend on $\boldsymbol{x_j}$ and y_{j0}.

summarized by the relationship between y_{jt} and y_{jt-1}.[26] We argue that conditioning on the cumulative diversions along a stream—an element of $\boldsymbol{x_j}$—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 Decisions

Table 2 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, evaluated at the means.[27] 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 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 with implication # 3 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). We predict with implication # 2 that limited information with high search costs implies that difficult-to-assess variables like Flow Variability and Soil Quality should not affect claiming behavior. We interact Lagged Claims with Summer Flow in all specifications to better understand the underlying tradeoff between water available and potential coordination benefits. The key test for the existence of benefits from coordination and positive externalities is whether the marginal effect of Lagged Claims is positive.

Nearly all of the variables in Table 2 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, water suppliest, and necessary farming techniques in the region, as was the case across the West.

[26] This is implicit in Equation 1.

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

Table 2 provides strong evidence for the existence of significant benefits from coordination and positive spillovers 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.

We are able to rule out the possibility that claimants' decisions to locate near prior 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 benefit, focusing on the benefits of cooperation with other water users.

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 build dams and reservoirs in order to divert water from the stream into a ditch 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).

The fact that claims were less prevalent during drought, combined with users' unresponsiveness to stream variability, points to the possibility of dissipation through over-claiming of the resource over time. 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.

The benefits of locating near prior claimants are on par with major changes in expected resource availability, but the accumulation of prior claims itself reduced resources available for future claimants. Column 2 of Table 2 indicates that an increase in the cumulative volume of claimed water on a stream reduces the probability of new claims on that stream by a 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 trade-off between resource availability and coordination benefits, we estimate the effect of Lagged Claims on the probability of New Claims for different size streams and plot the results in Figure 7.[28] 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 the probably of a new claim 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. 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.[29]

The development of water rights on South Boulder Creek near Boulder, Colorado, illustrates the economic behavior we identify in Table 2. 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 more remote lands that were often on bluffs above the creek.[30] 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).

Eventually, claiming on both streams ceased as all available farmland and water was fully appropriated. Figure 8 depicts the early development of claims on Boulder and South Boulder Creeks.[31] 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

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[28] 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 2.

[29] 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.

[30] 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).

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

Creek ceased in 1866, prior claims exceeded average summer flow by a factor of ten.[32] The trade-off between resource availability and positive benefits of coordinating with 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. Further supportive evidence for our statistical results is shown by the actions of migrants to the Cache La Poudre Valley in the 1870s. First, they relied upon scouting to ascertain the best ditch diversion and farmland locations. Second, they *advertised* for others with capital and settlement objectives to join them—something that would *not* have happened under a riparian system. At least 59 were included in the over 1,000 who responded to advertisements in the *New York Tribune*. Third, they formally pooled resources to develop irrigation infrastructure that cost $412,000 in 1873 or $7,234,720 in 2015 dollars to irrigate some 12,000 acres (Boyd, 1890, pp. 12, 31-38, 55, 59).

All told, 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%.[33] When deciding where to establish a claim, new users are more responsive to choices of earlier claimants than they are too 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 re-estimate 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.[34] Second, the distribution of unobserved heterogeneity may be incorrectly specified in Equation 2 if ν_j is not independent of $\boldsymbol{x_j}$. 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 2 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

[32] 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).

[33] 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 2, which should be interpreted as a lower bound on the magnitude of positive spillover effects from investment.

[34] 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 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.

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 B1. To alleviate concern over our identifying assumptions about the relationship between ν_j and $\boldsymbol{x_j}$, 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 B2 and B3.[35]

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, 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 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 contractual cooperation (Hutchins, 1929).[36] 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.[37] 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 3 provides summary statistics.

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 covariates because the quality of the land and

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

[36] The names of the ditches associated with each right can be used to consult the historical record as to whether they were formally incorporated. We have done this for a subset of the rights and find that our measure of cooperation is reasonable proxy for formal cooperation.

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

water resources near each right may 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 match these to 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.[38]

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 with focus on prior appropriation and ditch investment. 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, was one of the oldest settled regions in Colorado. Whereas Division 1 and the Colorado eastern plains were settled by more recent waves of eastern and European migrants, who formed formal mutual ditch companies to access capital and develop and maintain irrigation systems, Division 3 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; Crawford, 1988; Smith, 2016). Community-owned large ditches, or *acequia*

[38] 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.

madres, were managed by ditch bosses (*mayordomos*) who oversaw construction and annual maintenance contributions by local users, rotated water access, and arbitrated disputes.[39] 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). As we pointed out above, Division 1 was comprised of larger numbers of heterogeneous migrants from elsewhere in the US (Hicks and Pena, 2003). 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.[40] The conditions in Division 3 were consistent with settings in which social norms serve as a sufficient basis for limiting new entry on a stream and for building trust that "head-enders" on a ditch will not behave opportunistically when choosing how much water to appropriate in the second stage of the irrigation game from our model. Indeed, the conditions outlined above are similar to the examples of successful informal cooperation outlined by Ostrom and Gardner (1993). In this setting, the added benefit of priority appropriation as a mechanism for enforcing contracts is small to non-existent. This is in direct contrast to Division 1, where there was no other feasible enforcement mechanism. Our implication # 8 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 implication # 4 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.

The biggest threat to identification of the effect of priority on investment is that rights with higher priority also tend to be established earlier in time, when less water has been claimed and less development has taken place. It could be that cooperation is more advantageous under these conditions, in which case we would potentially conflate the effect of priority with the effect of timing. Our measure of priority is relative to the total number of claims within a given stream; the top 10% (for example) of claims involves a different number of users for each stream, so priority may not be highly correlated with the extent to which a given stream is already developed. To further address potential identification issues, we will estimate the effect of

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

[40] See Appendix Table B7 for a comparison of the two groups.

priority on investment within watershed, conditional on the total amount of land development along the stream, as we describe below.

We use a fixed-effect logit regression to obtain semi-parametric estimates of the marginal effect of priority on coordination among rights holders in infrastructure investment, relying primarily on within-watershed variation for identification.[41] 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 4 presents the estimated marginal effects of each priority decile on the probability of cooperation, relative to the 5th decile.[42] 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.

As hypothesized, we find a higher probability of coordinating for investment in infrastructure for rights above the 5th Decile and a lower probability of coordinating for rights below the 5th Decile. Figure 9 depicts the marginal effects of each priority decile on cooperation associated with the model in Column 2 of Table 4. 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 rights holders. This general pattern holds within Division 1 and Division 3 separately, particularly with respect to the lowest-priority right-holders. As Figure 9 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.

Those rights holders with the most variable water supply were the least likely to jointly invest in irrigation capital. By contrast, rights holders in the top half of the priority distribution face relatively smaller differences in their exposure to water supply variability and have a high likelihood of securing water and not stranding ditch capital and hence have a similar probability of coordinating among their members. 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 rights holders as described in implication # 6, cooperation among water claimants leads to greater irrigation infrastructure investmentOur 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

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[41] 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.

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

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.

Coordination between water rights holders 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. 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.

Table 5 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 decade fixed effects and a variety of controls for access to water and land resources.[43] We estimate the model across Divisions 1 and 3, allowing us to directly test whether ditches tended to be longer in either division and whether cooperation had a differential effect in Division 1.[44] Average ditch length is not statistically different between the two divisions, suggesting that underlying factors influencing the profitability of ditch investment were similar across divisions. The effect of cooperation on ditch investment differs markedly, however. We find that cooperative claimants' ditches are 13,609 to 15,436 meters (8.5 to 9.6 miles) longer than those of non-cooperative claimants' in Division 1 but that coordination does not affect ditch investment in Division 3.

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 4) makes it unlikely that legal status varied sharply between groups, pointing toward another explanation for differences in investment incentives. Another possibility is that difference in wealth led to different investment outcomes. 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.

One potential concern with our results on ditch investment is that investment and cooperation are jointly determined, making CoOp endogenous in Table 5. 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 (6.5 miles) long. The upshot is that the cooperative status of a water claim is exogenous to ditch length because the former necessarily

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

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

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 B5.

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). Mutual ditch companies were the most common form of water supply organization in Division 1 and within them shareholders held a pro rata ownership in the water rights of the company and were subject to assessments for maintenance and development costs (Rettig, 2012, p. 3).

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 10 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 11 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.[45] 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.[46] 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%.[47]

Focusing on income per acre 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. These results are summarized in Table 6. 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%.

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.[48] 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 6 makes it clear that the riparian system would have constrained rights holders 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

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[45] 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.

[46] 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.

[47] 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.

[48] 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 $).

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 4 and 5 suggest that first possession provided this incentive structure by granting a more secure property right and Table 6 confirms that non-riparian 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 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 3 summarizes the possible channels through which building a cooperative ditch could increase per-acre income.

$$\frac{dIPA}{dCoOp} = \frac{\partial IPA}{\partial Acres}\left[\frac{\partial Acres}{\partial Ditches} \times \frac{\partial Ditches}{\partial CoOp} + \frac{\partial Acres}{\partial CoOp}\right] + \frac{\partial IPA}{\partial Ditches} \times \frac{\partial Ditches}{\partial CoOp} + \frac{\partial IPA}{\partial CoOp}$$

We estimate a series of linear regressions using the GMM technique mentioned above to obtain each of the partial derivatives in Equation 3 and to construct the total effect of coordination on income per acre. Table 7 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 B6. The first row of Table 7 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 3, 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.

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 non-riparian vs. riparian farms reported in Table 6 by a factor of five. While reaching non-riparian 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 5) 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 8 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.[49] Finally, using an 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.[50] This represents the estimated share of state income due to agricultural production that could not have taken place under the riparian doctrine.

Table 8 indicates that irrigation of non-riparian lands contributed 2% to 14% of state income in 1910 and 3% to 21% in 1930. Moreover, we estimate that more than half of the value generated by irrigated agriculture came from non-riparian lands. This estimate may be 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. On the other hand, Adelman and Robinson's (1986) estimation of general equilibrium multipliers from increases in the value of agricultural production suggest that the contribution of irrigated agriculture to state incomes reported here due to access to more productive non-riparian lands may be considerably understated. Still, our back-of-the-envelope calculation gives a sense of the importance of infrastructure investment for the development of irrigated agriculture in the West. Western states relied on irrigation for a substantial portion of their income by 1930, and our analysis has shown that the structure of water rights under prior appropriation was uniquely suited to overcome the investment and coordination issues facing claimants on the unknown Western Frontier.

6 Conclusion

Prior appropriation created an institutional framework for cooperation to generate socially-valuable investments that lowered information costs regarding the most favorable

[49] 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.

[50] 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.

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, or 6.2 miles) 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, cooperation, 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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Table 1: Stream-Level Summary Statistics

Variable	N	Mean	S.D.	Min	Max	Definition
New Claims	311,364	0.0253	0.529	0	61	Number of new claims on stream j in year t.
NewClaim	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.
InitialClaim	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 ow from 1890 to 2000.
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 ow estimates used to calculate ow variability could be constructed only for a subset of data due to the availability of other variables used in the hydrologic model.

Table 2: Empirical Determinants of Prior Appropriation Claims

$\frac{\partial \Pr(NewClaims > 0)}{\partial x}$	(1)	(2)	(3)
	Poisson Estimates, $Y = New\ Claims_{jt}$		
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)
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		□-4.84e-08**	0.000000104**
(cfs)		(2.33e-08)	(5.20e-08)
Total Homesteaded			-0.000000546**
Acres			(0.000000230)
N	248,745	248,745	248,745

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

Table 3: 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 ow from 1890 to 2000.
Roughness	6,479	142.7	107.7	0.0720	934.2	Avg. Slope times 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.
Homesteaded Acres	7,999	346.3	1,297	0	35,463	Acres homesteaded during year 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.
1^{st} Priority Decile	7,999	0.248	0.432	0	1	Dummy var. =1 claims with priority in top 10% on a stream.
2^{nd} Priority Decile	7,999	0.0815	0.274	0	1	Dummy var. =1 claims with priority in 11-20% on a stream.
3^{rd} Priority Decile	7,999	0.0911	0.288	0	1	Dummy var. =1 claims with priority in 21-30% on a stream.
4^{th} Priority Decile	7,999	0.0913	0.288	0	1	Dummy var. =1 claims with priority in 31-40% on a stream.
5^{th} Priority Decile	7,999	0.0729	0.260	0	1	Dummy var. =1 claims with priority in 41-50% on a stream.
6^{th} Priority Decile	7,999	0.111	0.314	0	1	Dummy var. =1 claims with priority in 51-60% on a stream.
7^{th} Priority Decile	7,999	0.0973	0.296	0	1	Dummy var. =1 claims with priority in 61-70% on a stream.
8^{th} Priority Decile	7,999	0.0783	0.269	0	1	Dummy var. =1 claims with priority in 71-80% on a stream.
9^{th} Priority Decile	7,999	0.0780	0.268	0	1	Dummy var. =1 claims with priority in 81-90% on a stream.
99^{th} Priority Decile	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 ow data available.

Table 4: Marginal Effects of Priority on Cooperation

$Y = CoOp$	Divisions 1-3		Division1	Division3
1st Priority Decile	0.123***	0.119***	0.0207	0.194**
	(0.0359)	(0.0390)	(0.0779)	(0.0797)
2nd Priority Decile	0.0541	0.0725	0.0154	0.123
	(0.0456)	(0.0472)	(0.0929)	(0.0999)
3rd Priority Decile	0.0882*	0.119**	-0.00675	0.202*
	(0.0468)	(0.0488)	(0.0861)	(0.115)
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)	(0.0995)
7th Priority Decile	0.0366	0.0359	-0.0761	0.146
	(0.0401)	(0.0421)	(0.0674)	(0.104)
8th Priority Decile	-0.0591	-0.0910*	-0.181**	-0.0301
	(0.0447)	(0.0485)	(0.0753)	(0.0900)
9th Priority Decile	-0.160***	-0.211***	-0.238**	-0.292*
	(0.0465)	(0.0522)	(0.0939)	(0.168)
99th Priority Percentile	-0.236***	-0.330***	-0.488***	-5.193***
	(0.0643)	(0.0774)	(0.189)	(0.984)
Homesteads	Yes**	Yes*	Yes	Yes
Summer Flow	Yes***	Yes***	Yes*	Yes**
Flow Variability	Yes	Yes	Yes	Yes*
Roughness	Yes	Yes	Yes	Yes
Acres Loamy Soil	Yes	Yes	Yes	Yes
Acres Along Stream	Yes	Yes	Yes*	Yes
Watershed Fixed Effects	No	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
N	4756	4354	1206	937

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

Table 5: Effects of Cooperation and Priority on Investment

	(1)	(2)	(3)	(4)
	$Y = DitchMeters$			
Division 1	2889.3	5689.2	2503.0	6590.3
	(2368.4)	(4827.0)	(2994.1)	(6089.9)
CoOp	-674.1	-724.7	-1022.6	-1149.8
	(1573.0)	(2195.5)	(1837.2)	(2117.7)
Division 1 × CoOp	15436.7^{***}	14123.6^{***}	14776.7^{***}	13609.2^{***}
	(5192.3)	(4423.1)	(5683.4)	(4861.2)
Claim Size	238.1^{***}	247.1^{***}	237.0^{***}	241.8^{***}
	(66.04)	(73.80)	(61.75)	(72.01)
Summer Flow	2.408^{*}	0.869	2.240	0.827
	(1.378)	(1.014)	(1.455)	(1.047)
Flow Variability	99.50	261.2	115.7	234.2
	(122.6)	(193.0)	(122.6)	(195.1)
Roughness	-5.214	-63.56	0.773	-65.88
	(9.949)	(61.02)	(20.17)	(61.09)
Acres Loamy Soil	0.348	0.854	0.283	0.904
	(0.251)	(2.173)	(0.279)	(2.305)
Homesteaded Acres	-2.825^{**}	-2.045	-2.371^{*}	-1.916
	(1.321)	(1.517)	(1.430)	(1.647)
Watershed Fixed Effects	No	Yes	No	Yes
Decade Fixed Effects	No	No	Yes	Yes
Observations	550	550	550	550
R^2	0.323	0.449	0.326	0.451

Spatial HAC standard errors in parentheses

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

Table 6: 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

Table 7: 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	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
* $p < .1$, ** $p < .05$, *** $p < .01$

Table 8: Contribution of Agriculture to State/Territory Income

	1910			1930		
	Irrigated Crop Value	% of State Income	No-Rip % of State Income	Irrigated Crop Value	% of State Income	No-Rip % of State Income
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 46.

Figure 1: New Precipitation Conditions in the Semi-Arid West

Source: Powell, 1879, frontispiece, reprinted in Worster (2001, 349).

Figure 2: Property Rights Innovation via Prior Appropriation

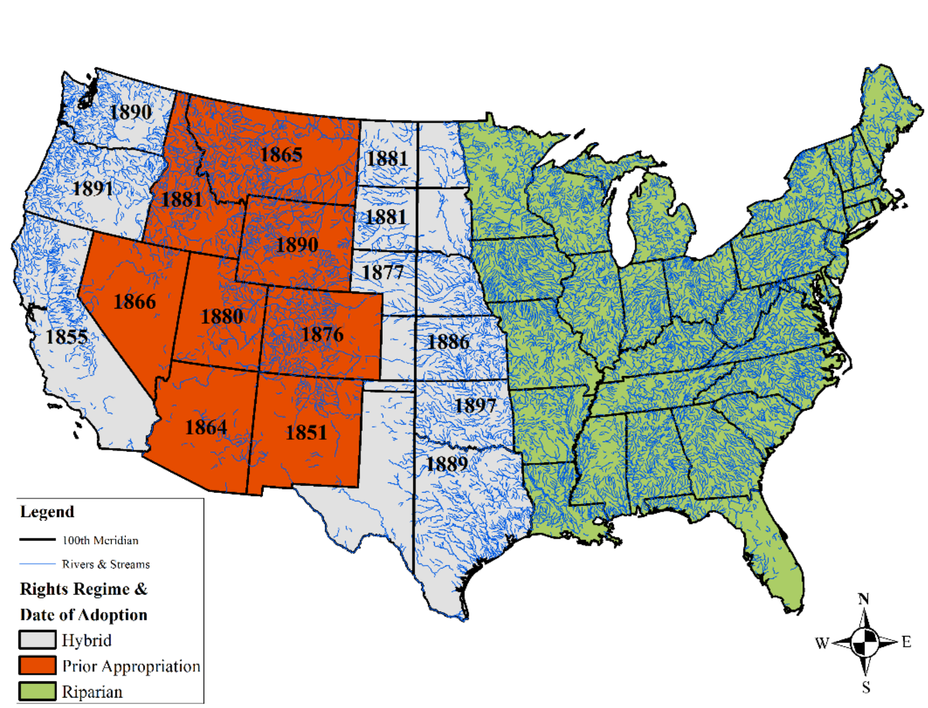


Figure 3: Water Resources and Terrain in Colorado

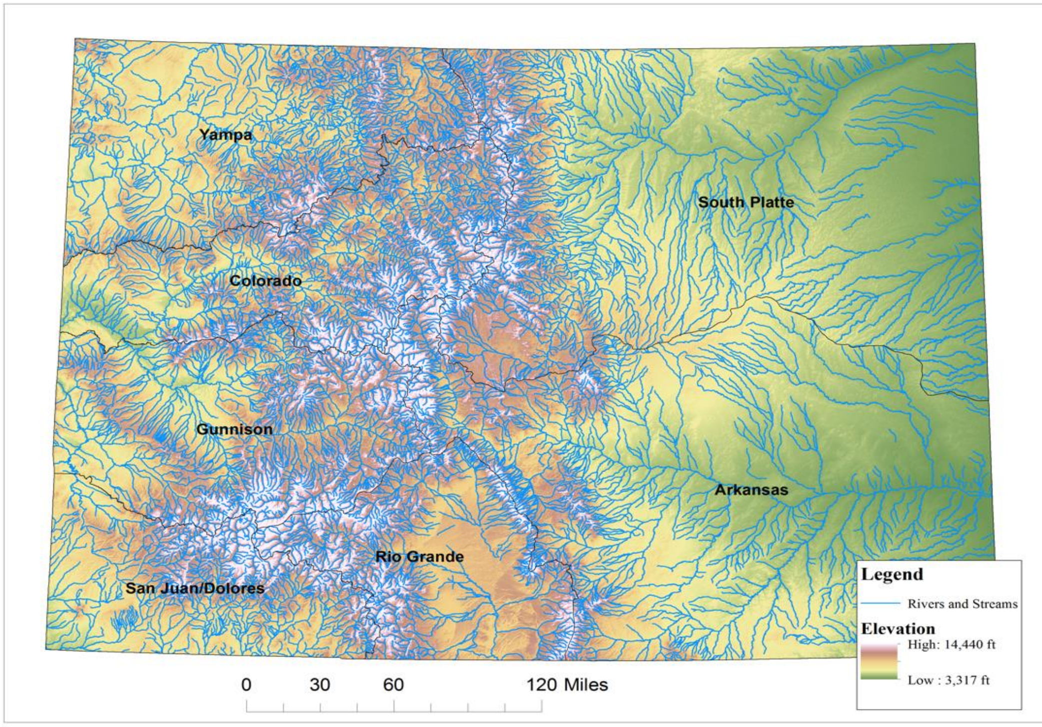


Figure 4: The Timing and Volume of Water Claims in Colorado

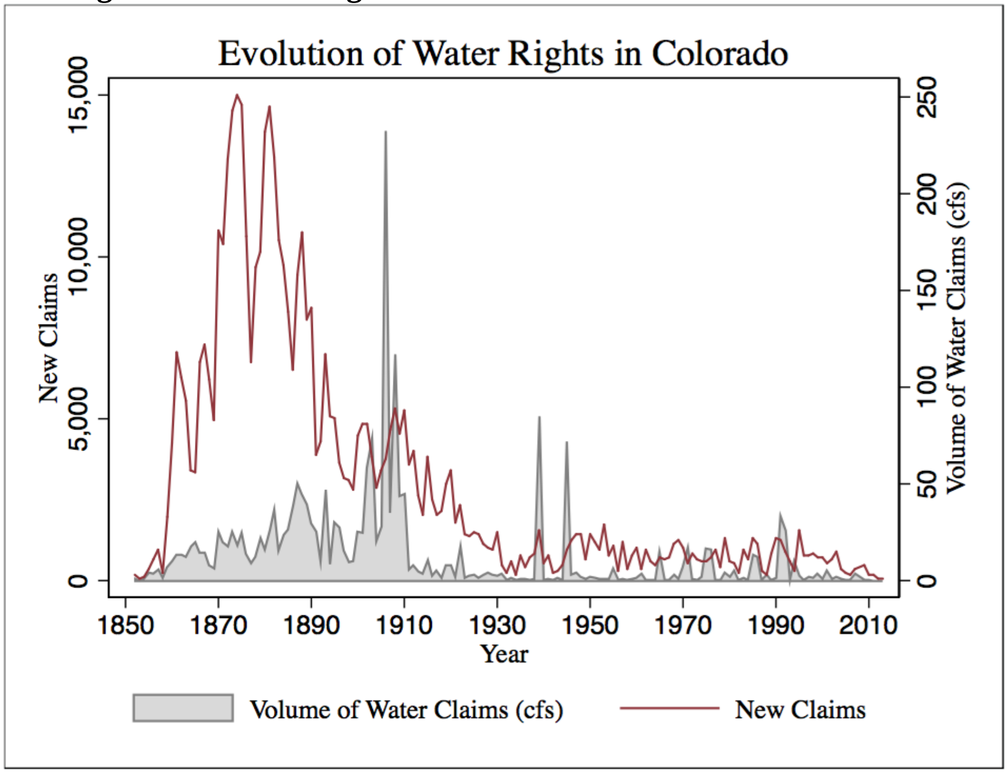


Figure 5: Potential Riparian Homestead Claims and Actual Irrigation Infrastructure Investment
Cache La Poudre River Colorado, 1890

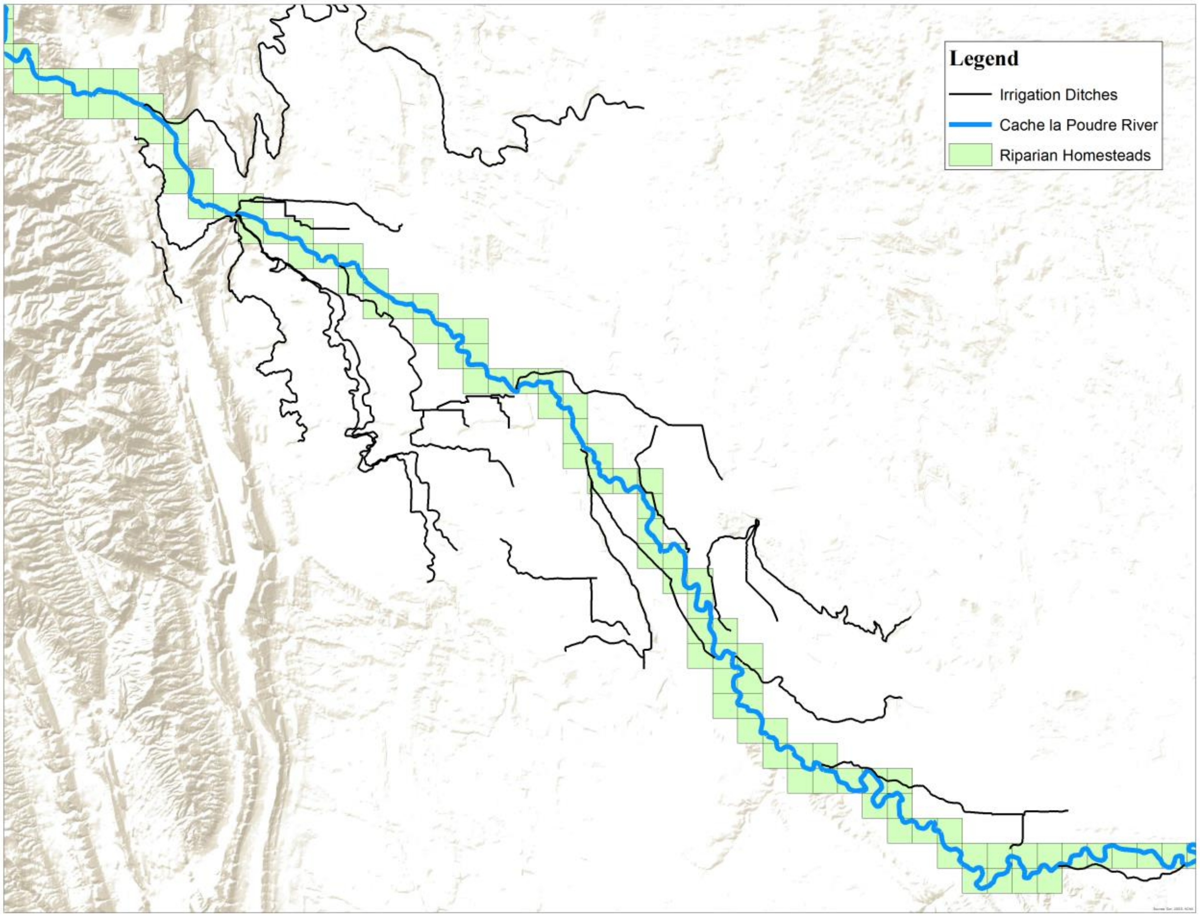


Figure 6: Possible and Actual Claim Sites

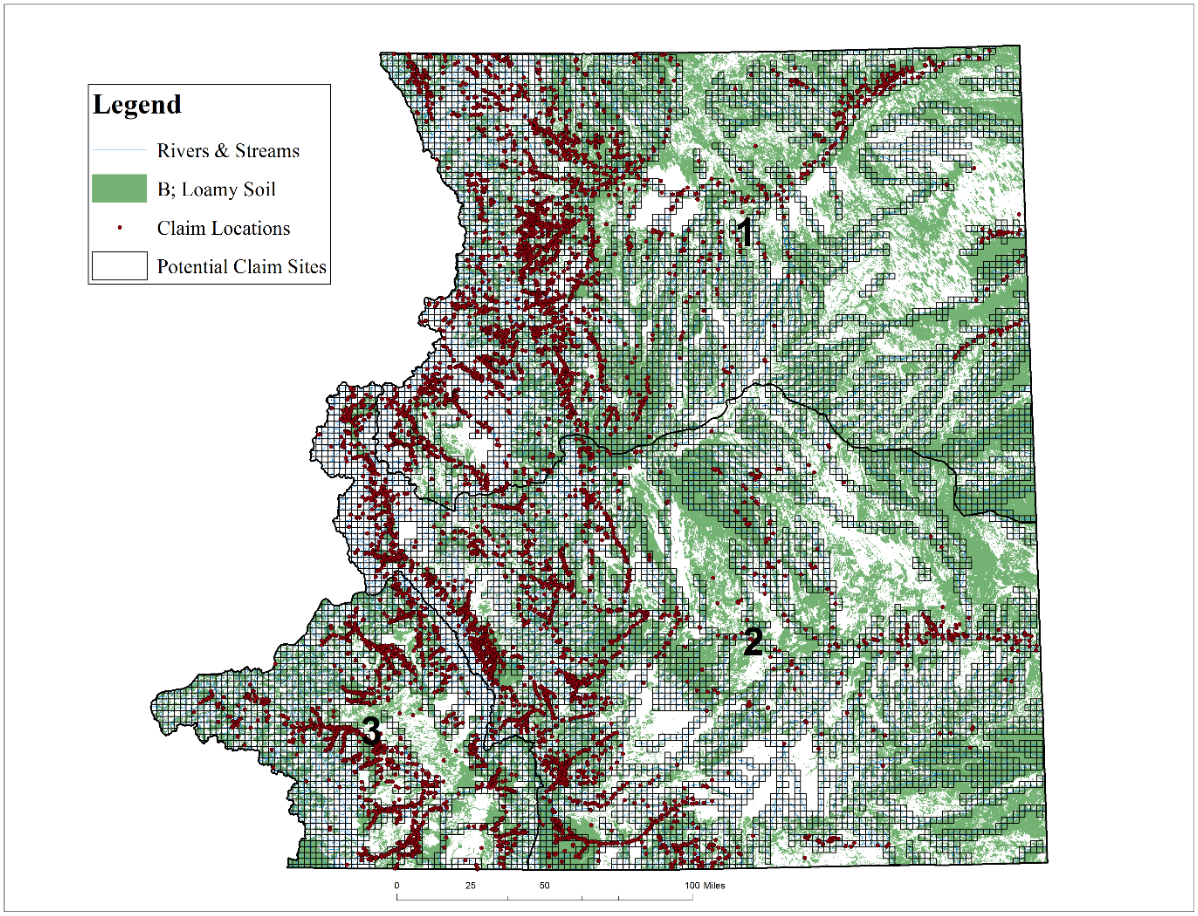


Figure 7: The Information-Resource Trade-Off

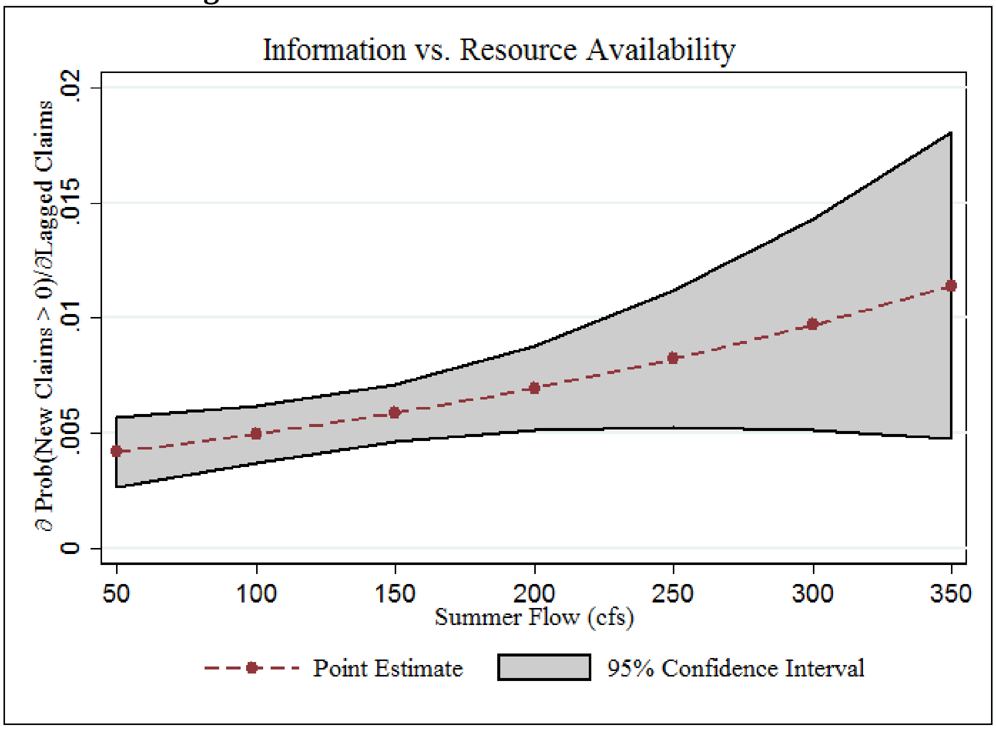


Figure 8: Evolution of Claims Near Boulder, Colorado

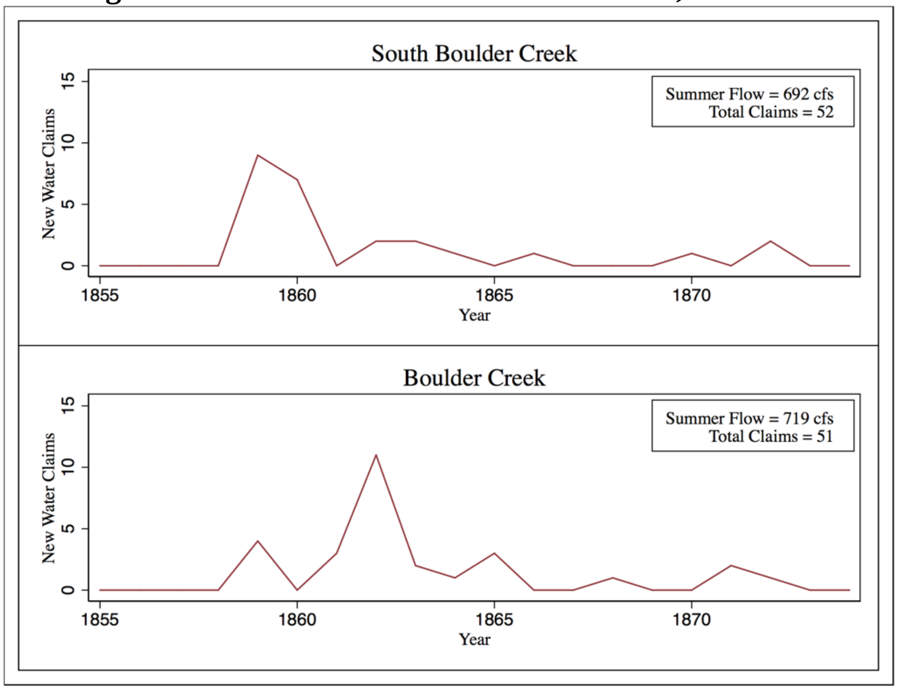


Figure 9: Marginal Effects of Priority on Cooperation

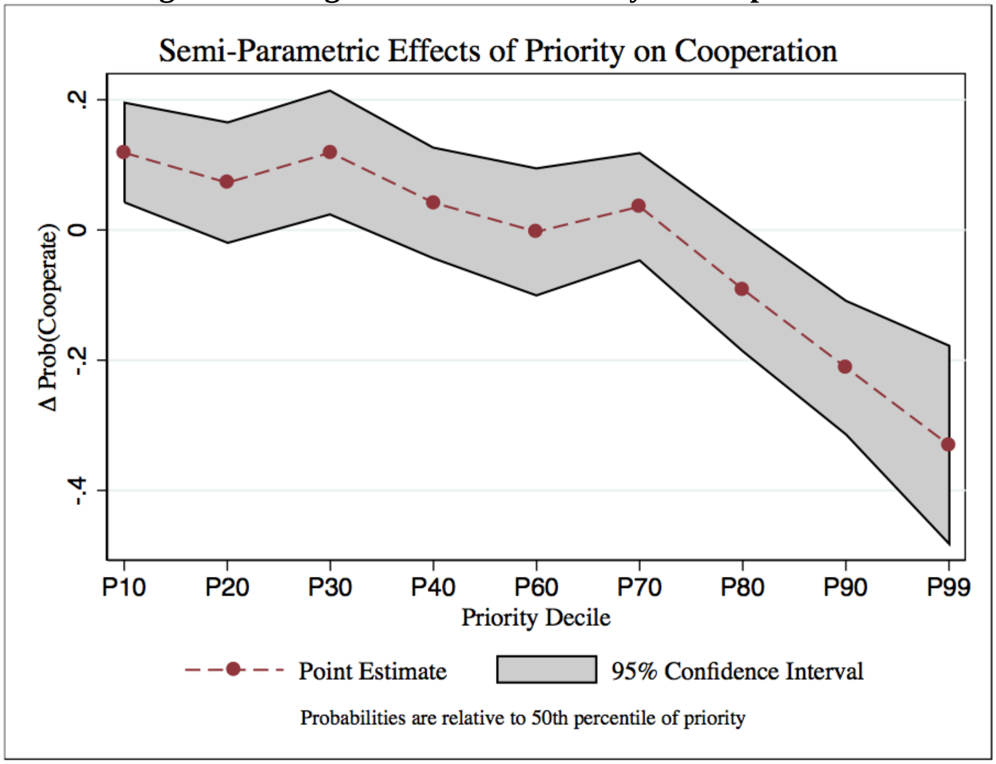


Figure 10: Riparian and Arable Lands in Eastern Colorado

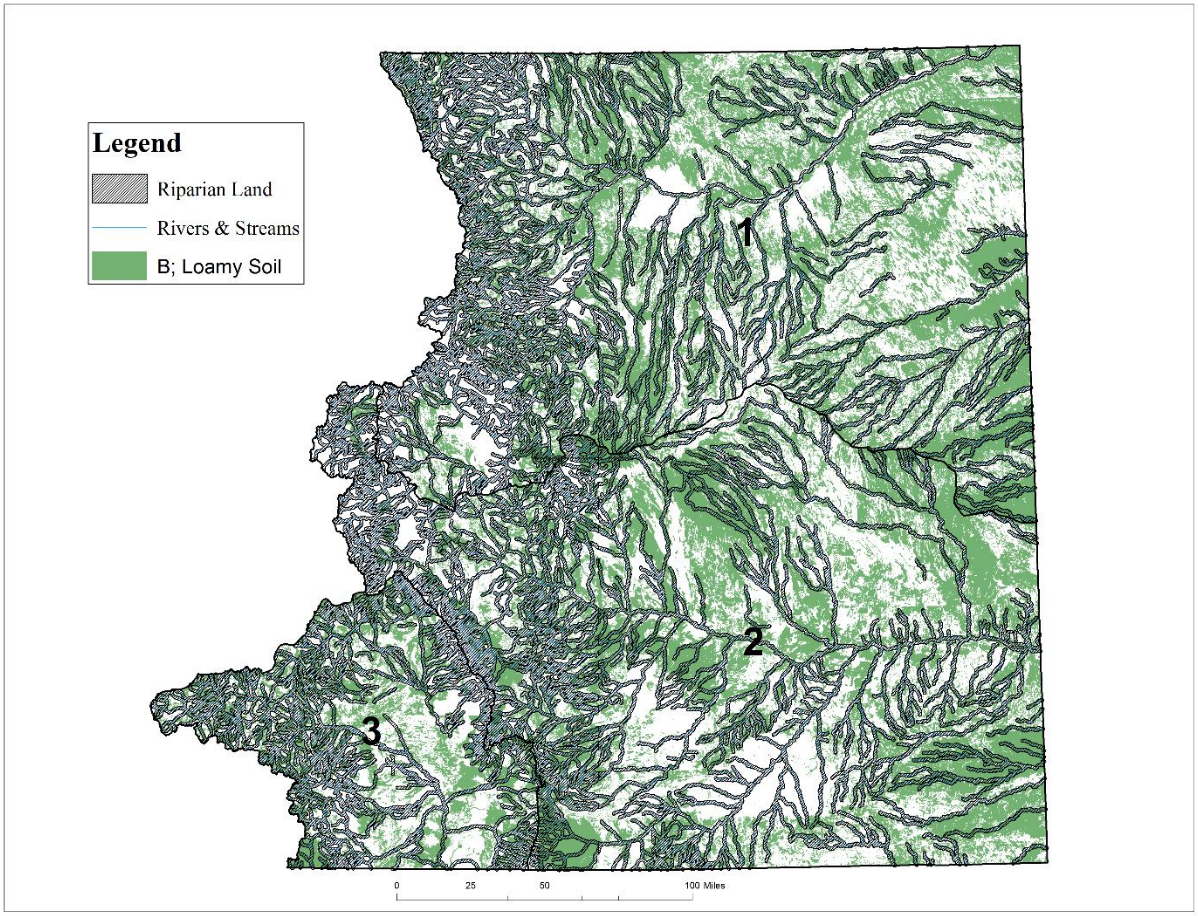
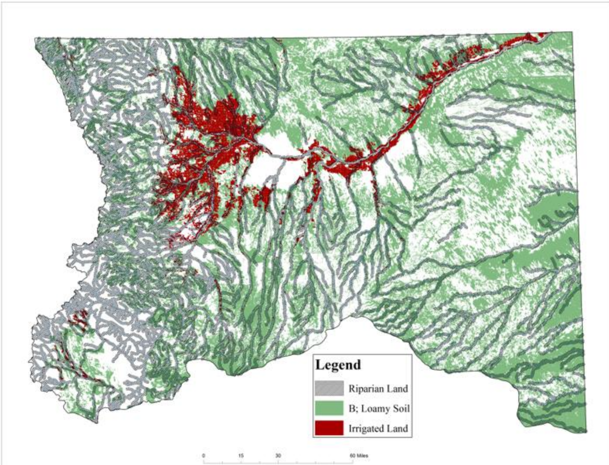
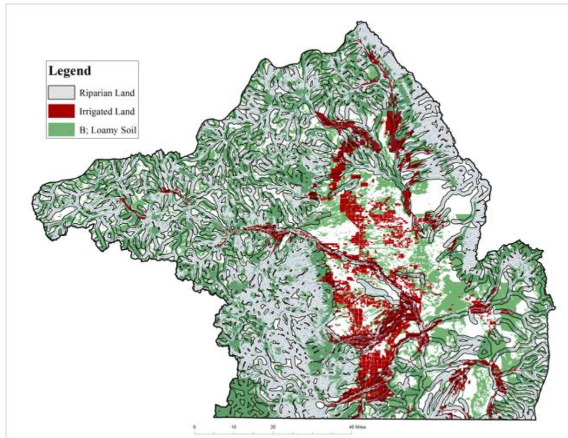


Figure 11: Riparian and Irrigated Land





Appendix A: GIS 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.[1] 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.[2] 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 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).[3] 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.[4] 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.[5] 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.

[1] 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.

[2] 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.

[3] 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.

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

[5] 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 Table B1: Estimated Average Partial Effects on Prob (New Claims)

$\frac{\partial \Pr(NewClaims > 0)}{\partial x}$	(1)	(2)	(3)
	Probit Estimates, $Y = 1(New\ Claims_{jt} > 0)$		
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)
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$_{t-1}$	0.000120***	0.000124***	0.000121***
	(0.0000202)	(0.0000209)	(0.0000289)
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

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

Table B2: Coefficient Estimates from Fixed Effects Poisson

	(1)	(2)	(3)	(4)
	Fixed Effect Poisson Estimates, $Y = New\ Claims_{jt}$			
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)
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		-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 × Drought			0.0584	
			(0.0783)	
Total Homesteaded Acres				- 0.0000350***
				(0.00000789)
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 B3: Coefficient Estimates from Fixed Effects Logit

	(1)	(2)	(3)	(4)
		$Y = 1(New\ Claims_{jt} > 0)$		
1(Lagged Claims>0)	1.935***	1.930***	1.963***	1.720***
	(0.0820)	(0.0711)	(0.0851)	(0.0855)
1(Lagged Claims>0)× Flow	-0.0000602	-0.0000184	-0.0000157	-0.0000939
	(0.0000605)	(0.0000105)	(0.000131)	(0.000128)
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		- 0.00000246	- 0.00000235	0.00000797***
		(0.00000417)	(0.00000368)	(0.00000337)
1(Lagged Claims>0)× Total Water Claimed		- 0.00000184	- 0.00000175	- 0.00000238
		(0.00000526)	(0.00000566)	(0.00000793)
1(Lagged Claims>0)× 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 B4: Marginal Effects of Priority on Cooperation

$Y = CoOp$	Divisions 1-3		Division1	Division3
1st Priority Decile	0.123***	0.119***	0.0207	0.194**
	(0.0359)	(0.0390)	(0.0779)	(0.0797)
2nd Priority Decile	0.0541	0.0725	0.0154	0.123
	(0.0456)	(0.0472)	(0.0929)	(0.0999)
3rd Priority Decile	0.0882*	0.119**	-0.00675	0.202*
	(0.0468)	(0.0488)	(0.0861)	(0.115)
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)	(0.0995)
7th Priority Decile	0.0366	0.0359	-0.0761	0.146
	(0.0401)	(0.0421)	(0.0674)	(0.104)
8th Priority Decile	-0.0591	-0.0910*	-0.181**	-0.0301
	(0.0447)	(0.0485)	(0.0753)	(0.0900)
9th Priority Decile	-0.160***	-0.211***	-0.238**	-0.292*
	(0.0465)	(0.0522)	(0.0939)	(0.168)
99th Priority Percentile	-0.236***	-0.330***	-0.488***	-5.193***
	(0.0643)	(0.0774)	(0.189)	(0.984)
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 Loamy Soil	0.00000849	0.0000125	0.0000630	- 0.0000436
	(0.0000132)	(0.0000205)	(0.0000433)	(0.0000285)
Acreage Along Stream	- 0.00000346	- 0.00000743	- 0.0000245*	0.0000101
	(0.00000461)	(0.00000823)	(0.0000146)	(0.0000107)
Watershed Fixed Effects	No	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
N	4756	4354	1206	937

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

Table B5: Effects of Cooperation and Priority on Investment

	(1)	(2)	(3)	(4)
	Ditch Meters	Ditch Meters	Ditch Meters	Ditch Meters
1^{st} Priority Decile	1560.5	3063.8	1288.2	2600.9
	(5018.2)	(6857.4)	(5070.6)	(6508.7)
2^{nd} Priority Decile	-5635.2	-3113.9	-6370.7	-3686.7
	(6836.7)	(8339.7)	(6715.4)	(7758.8)
3^{rd} Priority Decile	-4689.7	698.6	-4445.3	1035.0
	(6444.2)	(7287.0)	(6974.5)	(7179.2)
4^{th} Priority Decile	-4477.8	-5562.5	-4585.0	-5683.7
	(5501.9)	(7365.9)	(6154.6)	(7237.2)
6^{th} Priority Decile	-4183.5	-1258.7	-3765.1	-1658.5
	(5448.3)	(7872.3)	(6320.8)	(7764.0)
7^{th} Priority Decile	-4493.0	-2773.5	-4261.4	-3900.8
	(5675.9)	(6668.2)	(6044.6)	(6674.1)
8^{th} Priority Decile	-7635.1	-4838.8	-7367.6	-6488.4
	(6226.0)	(6884.3)	(6668.6)	(6951.6)
9^{th} Priority Decile	-6592.2	-4933.4	-6372.3	-6414.7
	(5848.6)	(7273.6)	(6258.4)	(7529.4)
99^{th} Priority Percentile	-693.5	696.9	-835.8	-1149.4
	(9964.7)	(9276.2)	(10628.2)	(10158.1)
Division 1	3410.6	5281.6	2576.4	1419.4
	(2541.5)	(8858.2)	(2784.5)	(8557.2)
CoOp	-522.1	-805.8	-1048.1	-1352.0
	(1615.8)	(2483.0)	(1882.7)	(2384.2)
Division 1 × CoOp	12853.9^{**}	11773.1^{***}	13025.2^{**}	11602.0^{**}
	(5177.8)	(4264.6)	(5537.5)	(4486.8)
Summer Flow	2.275	0.666	2.200	0.696
	(1.423)	(0.960)	(1.490)	(1.007)
Flow Variability	108.2	315.7^{*}	117.4	289.1
	(138.4)	(188.2)	(134.3)	(188.2)
Roughness	6.020	-68.41	4.999	-66.25
	(23.08)	(58.90)	(20.81)	(59.21)
Acres Loamy Soil	0.530^{*}	0.819	0.455	0.892
	(0.308)	(2.196)	(0.340)	(2.291)
Homesteaded Acres	-2.322^{*}	-1.638	-2.134	-1.732
	(1.309)	(1.477)	(1.456)	(1.579)
Watershed Fixed Effects	No	Yes	No	Yes
Decade Fixed Effects	No	No	Yes	Yes
Observations	550	550	550	550
R^2	0.331	0.455	0.334	0.458

Spatial HAC standard errors in parentheses
* $p < .1$, ** $p < .05$, *** $p < .01$

Table B6: Income Per Acre Pre-1960

	Division 1			Division 3		
	(1) Reduced Form	(2) Irrigated Acres	(3) Income Per Acre	(4) Reduced Form	(5) Irrigated Acres	(6) 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	-0.638	-3.239	-0.244	155.0	-234.3	155.0
Soil	(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	-0.0883**	-0.433**	-0.0873**	-0.0108	0.0797	-0.0119
Acres	(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	106.5	15.38	96.04	76.97	-541.8	69.67
Percentile	(99.42)	(334.4)	(94.73)	(83.40)	(601.3)	(81.17)
Watershed Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	104		104	104	161	160
R^2	0.949		0.777	0.952	0.795	0.687

Spatial HAC standard errors are reported in parentheses. Soil quality in Division 3 is collinear with watershed _xed e_ects. * $p < .1$, ** $p < .05$, *** $p < .01$

Table B7: 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)
Income Per Acre	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
Near Stream	(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 Per	84.68	11.1
Township	(146.38)	(41.37)
Number of Streams	625	439