# A National Estimate of Irrigation Canal Lining Water Conservation *

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**Abstract**

The impact of global climate change on water resources is already evident and expected to continue impacting the amount of water available for drinking, sanitation, and agriculture. Water conservation is often heralded as a means to mitigate the economic damages associated with water scarcity. In the agricultural sector, which is the largest user of freshwater resources, conservation efforts have primarily focused on farm-level irrigation efficiency. However, many water losses occur upstream of farm-level water use in the conveyance infrastructure that delivers water to farms. In this paper, we leverage unique irrigation water delivery organization level data from the Western U.S. to estimate how lining and piping conveyance infrastructure reduces the amount of water lost during transport to the farm, or conveyance losses. We find that increasing the proportion of an organization's conveyance infrastructure that is lined or piped by 10 percentage points decreases conveyance losses by 0.7 percentage points, which is a 4.3% reduction in expected conveyance losses. A simulated water-conservation supply curve based on these estimates suggests that a coordinated effort at canal lining could begin conserving water at the cost of less than $500 of upfront investment per acre-foot of annual water savings, though for most organizations the cost is $2,000 or higher.

**Keywords:** Irrigation Infrastructure, Water Resources, Conveyance Losses

**JEL Codes:** Q15, Q25, Q30

*The findings and conclusions in this manuscript are those of the authors and should not be construed to represent any official USDA or U.S. government determination or policy.

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# 1 Introduction

Water resources are vital in meeting the caloric and health needs of a growing world population (Molden, 2007). The expansion of irrigated agriculture in the past century has significantly increased the productivity of agriculture (Edwards and Smith, 2018; Njuki and Bravo-Ureta, 2019). However, global climate change is expected to increase water scarcity threatening global food security (Hanjra and Qureshi, 2010; Mancosu et al., 2015; Dinar et al., 2019). Researchers and policy-makers have heralded water conservation efforts as a means to mitigate the economic consequences of water scarcity (Gobarah et al., 2015). The literature has primarily focused on farm-level measures for meeting water conservation objectives such as increasing irrigation efficiency and improving on-farm irrigation water management (Pfeiffer and Lin, 2014; Koech and Langat, 2018). This paper builds on this literature by empirically examining how investments in off-farm water conveyance infrastructure, specifically the lining and piping of canals, can address water conservation goals.

Globally, many surface water-dependent agricultural production systems rely on conveyance infrastructure to deliver water from natural bodies of water to arable land. However, transporting water can result in conveyance losses as some water is lost to seepage or evaporation during transport.[1] In many cases water lost during conveyance imposes an economically significant cost on the irrigated agricultural sector. The economic cost of conveyance losses may grow as global climate change continues to increase water scarcity, particularly in snow-pack dependent production systems (Reidmiller et al., 2019; Evan and Eisenman, 2021). Despite the current and potential future costs of conveyance losses, a paucity of literature has rigorously examined the costs and benefits of conveyance loss mitigating investments. We leverage survey data representing the operation and infrastructure of irrigation water delivery organizations in the Western U.S. to empirically an-

[1] In a broadly defined hydrologic system conveyance losses are not an actual loss of water. Water seepage from main and lateral canals is stored in aquifers while evaporated water returns to the land in the form of precipitation. The water is lost in the sense that it is not immediately available for its intended use.

alyze the relationship between conveyance infrastructure characteristics and conveyance losses.

Investments in water conveyance infrastructure can diminish conveyance losses and help achieve water conservation objectives. Specifically, upgrading previously unlined (earthen) conveyance canals to lined canals or piped infrastructure can curtail conveyance losses by reducing seepage. However, lined and piped conveyance infrastructure constitutes a minority of total conveyance in the U.S. as upgrading canals is costly (Hrozencik et al., 2021). The U.S. Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) reports that lining one quarter mile of a relatively small unlined canal costs between 10 and 58 thousand dollars depending on canal size and lining material (USDA-NRCS, 2020). Costs may be significantly higher for larger irrigation canals. For example, lining sections of the All-American canal, which is among the largest canals in the U.S., cost more than $1.8 million per quarter mile (CNRA, 2009).

Meanwhile, the benefits of lining and piping water conveyance infrastructure remain uncertain. The engineering literature has leveraged analytical equations, simulation modeling, and flow measurements to estimate conveyance losses as a function of canal characteristics e.g., soil type, lining, size, flow rate, etc. (see Taylor (2016) for an extensive review of the conveyance loss/seepage engineering literature). However, much of this literature may lack external validity as study locations may not reflect average conditions for the universe of conveyance infrastructure. Given the high cost of lining canals, many of these studies occur in locations where conveyance losses were particularly large before infrastructure improvements (Baumgarten, 2019). As such, the results of these studies potentially overstate the water conservation impacts of canal lining by focusing on cases where infrastructure investments reap the largest conservation benefits.

In contrast, our empirical approach utilizes organization level variation in conveyance losses and the lining and piping of infrastructure to characterize the relationship between investing in conveyance infrastructure and water conservation. However, an or-

ganization's decision to line or pipe conveyance infrastructure may be endogenous to conveyance losses if organizations with high losses are more likely to line or pipe their conveyance infrastructure. We address this potential endogeneity using an instrumental variable approach that leverages a unique set of organization-level instruments correlated with the benefits and costs of infrastructure improvements but otherwise unrelated to conveyance losses. Our results reveal that increasing the proportion of conveyance lined or piped by 10 percentage points decreases conveyance losses by approximately 0.7 percentage points which translates into a 4.3% decrease in conveyance losses at the mean.

Irrigation water delivery organizations (e.g., irrigation districts, acequias, ditch companies, etc.) are important institutions in the Western U.S. where the majority of surface water-fed irrigated agriculture relies on off-farm water deliveries (USDA-NASS, 2019).[2] These organizations own and operate much of the infrastructure where conveyance losses occur. In 2019, more than 15% of all water brought into irrigation water delivery organization systems was lost during conveyance (USDA-NASS, 2020).[3] However, there is considerable conveyance loss heterogeneity across the nearly 600 irrigation water delivery organizations included in our analysis as some organizations have invested in lining and piping to reduce conveyance losses.

A relatively small economics literature has addressed irrigation infrastructure investments and conveyance losses. Much of this literature has employed theoretical modeling to understand how water lost during conveyance affects the optimal allocation of scarce water resources (Tolley and Hastings, 1960; Chakravorty and Roumasset, 1991; Chakravorty et al., 1995; Umetsu and Chakravorty, 1998). Umetsu and Chakravorty (1998) stand out in this literature by explicitly modeling irrigation system investment decisions. They

[2]The prevalence of off-farm surface water use in the Western U.S. is related to the unique legal institutions defining water rights within the region. Notably, the doctrine of prior appropriation divorces riparian land ownership from the process of water right allocations and instead assigns water rights based on beneficial use (Haar and Gordon, 1958). Allocating water based on beneficial use incentives water users to collectively invest in the infrastructure necessary to convey water from natural rivers and streams to arable land.

[3]Conveyance losses of 15% fall within the range of losses reported in the hydrological and agricultural engineering literature (Todd, 1970; Mohammadi et al., 2019; Karimi Avargani et al., 2020).

model investment as a function of canal seepage and return flows demonstrating how the benefits of diminished conveyance losses vary based on the availability of water losses for future use. Ward (2010) provides a comprehensive overview of the economic incentives and policy mechanisms determining irrigation infrastructure investments. Our paper builds on this nascent literature by providing, to our knowledge, the first representative estimates of the average expected water conservation benefits of canal lining and piping by irrigation organizations.

# 2 Background

Surface water sources supply irrigation water to more than 50% of irrigated land in the U.S. (USDA-NASS, 2019). In the Western U.S., the majority of surface water-fed irrigated agriculture relies on off-farm supplies (Hrozencik, 2021).[4] The legal institutions, notably prior appropriation, defining water rights in the much the Western U.S. have facilitated the prevalence of off-farm surface water-fed irrigated agriculture in the region.

The infrastructure required to deliver off-farm surface water to irrigated farms and ranches can be broadly classified into one of three categories: conveyance, storage, and turnout infrastructure (Hrozencik et al., 2021). Conveyance infrastructure includes canals and pipes used to deliver water to farms and ranches. System losses concentrate in conveyance infrastructure where in some cases seepage can significantly diminish water available for irrigation. Developing and maintaining the infrastructure necessary to deliver off-farm water constitutes a collective action problem addressed through a variety of institutional arrangements (Leonard and Libecap, 2019).

[4]On-farm surface water refers to "water from a surface source not controlled by a water supply organization. It includes sources such as streams, drainage ditches, lakes, ponds, reservoirs, and on-farm livestock lagoons on or adjacent to the operated land" (USDA-NASS, 2019). Off-farm surface water is "water from off-farm water suppliers, such as the U.S. Bureau of Reclamation; irrigation districts; mutual, private, cooperative, or neighborhood ditches; commercial companies; or community water systems. It includes reclaimed water from off-farm livestock facilities, municipal, industrial, and other reclaimed water sources" (USDA-NASS, 2019).

Irrigation water delivery institutions vary by state reflecting the historical and legal context of irrigated agriculture and water rights (Moses, 1959; Holleran, 2005; Libecap, 2011). Disparate institutional contexts have given rise to four broadly defined types of irrigation water delivery organizations: unincorporated mutuals, incorporated mutuals, irrigation districts, and Bureau of Indian Affairs irrigation projects and systems(**?**).[5] Unincorporated mutuals are informal partnerships between water conveyance infrastructure users, acequais[6] are a common example. Incorporated mutuals are legal entities owned by the users of the irrigation conveyance system, examples include ditch companies and mutual irrigation companies. Irrigation districts are entities given a statutory authority to assess taxes and fees for irrigation water delivery (Henley, 1968). Irrigation districts commonly receive a majority of their water supplies from State and Federal water projects (Leshy, 1982). The U.S. Department of the Interior's Bureau of Indian Affairs (BIA) owns, and in some cases operates, 16 irrigation projects and more than 100 irrigation systems throughout the Western U.S. (Office, 2007). BIA projects and systems deliver water to support irrigated agricultural production on tribal land, primarily in the Western U.S. (Carlson, 2018).

The water delivered by irrigation districts, mutuals, and BIA projects comes from a variety of sources. Survey data collected in 2019 indicate that more than 60% of the more than 70 million acre-feet[7] of water water entering irrigation organization conveyance systems was purchased or contracted from a Federal, State, of local/private irrigation project

[5]This categorization of irrigation water delivery organizations is by no means fully exhaustive. For example, in some regions there are commercial ditch companies that deliver irrigation water for a profit that were established under the auspices of the Carey Act of 1894 (43 U.S.C. 641 et seq.) (Lovin, 1987; Fereday, 1993).

[6]Acequias or community acequias are important irrigation institutions unique to the Southwestern United States, primarily New Mexico and Colorado. The history of acequias dates back to interactions between Spain and North African cultures, where community irrigation organizations were and still are common. The settlement and colonization of the Southwestern United States by Spain brought their irrigation institutions to North America, where they were melded with the irrigation practices of the American Indians to form modern-day acequias (Hutchins, 1928). Acequias differ somewhat from irrigation districts and ditch companies in that most water conveyance infrastructure is commonly owned by the community of acequia users who are expected to adhere to established community rules (Cox and Ross, 2011).

[7]1 acre-foot = 325,851 gallons.

(USDA-NASS, 2020). The majority of this purchased/contracted water comes from Federal irrigation projects such as those operated by the Department of the Interior's Bureau of Reclamation. The second largest water source for irrigation delivery organizations is direct diversions from natural bodies of water which constitute approximately 31% of the total water entering organizations' systems. Organizations also rely on pumped groundwater, irrigation drainage, and water delivered from municipal or industrial suppliers to a lesser extent. When aquifers are present irrigators may also supplement organization water deliveries with on-farm groundwater pumping. In some cases, irrigation water delivery organizations may assume a management role for the groundwater resources present in their service area. Finally, the urbanization of the Western U.S. has led many irrigation organizations to assume functions outside of irrigation water delivery, such as municipal water services.

The governance and oversight of irrigation water delivery organizations varies significantly based on organization type and State legal institutions. Many organizations are led by boards elected by water users granting constituents a voice in the management of their water supplier. These elected boards make short-run operation and management decisions for the organization as well as long-term planning and investment. In some cases, State regulators or organization by-laws require annual reports on water use. Elected boards also determine how revenues are collected and used to operate water storage and conveyance systems (e.g., hiring a ditch rider[8]). The methods of raising revenue vary across organization types. The most common means of raising revenues is charging fees to users based on water deliveries. Some organizations with statutory power to assess taxes, for example irrigation districts, generate revenue by taxing land. Other less formal organizations, like acequias, may not generate revenue and instead rely on the labor of water users to cooperatively maintain and operate irrigation infrastructure (Cox, 2014).

[8]A ditch rider is hired by an irrigation organization to maintain irrigation canals and open turnouts as appropriate to divert water for water deliveries through the water conveyance system (Waskom et al., 2007).

Organizations also use revenues to maintain and improve infrastructure. These maintenance and improvement activities can vary from routine infrastructure upkeep such as removing plants within and along canals to large scale investments in the organization's system such as building additional water storage capacity or lining previously unlined canals to reduce conveyance losses.

# 3 Theoretical Model

To motivate and inform the empirical model characterizing how water conveyance infrastructure influences conveyance losses, the theoretical framework uses a model in which a irrigation organization selects a level of canal lining as a production input within a cost-minimization problem.

The basic model posits an organization with a single output: water delivered to farms and ranches ($w_{ag}$). This approach is consistent with the fact that only 14% of organizations also deliver to non-agricultural users and only 3% of organizations also use water for electricity generation (Wallander et al., 2022). Organizations are assumed to face an exogenous price ($p_{ag}$) for water delivered. Under the cost-minimization approach, this fixes the organization's revenue, and so the initial model would be consistent with organizations that implement a per-acre delivery fee while holding delivered water constant.

The irrigation water delivery organization owns and operates conveyance infrastructure to deliver water to irrigated farms and ranches. The organization selects two inputs to determine the quantity of water delivered and the cost of delivering that water: total water brought into the delivery system ($w_{in}$) and percent of canals lined ($x_{lined}$). The marginal cost of water brought into the system ($p_w$) is a composite price that reflects the marginal cost of water acquisition (such as through a contract with a federal or state water project), the cost of moving water (primarily the energy costs of operating pumping), and other inputs costs such as labor inputs. Since lining of canals is a long-run capital

investment decision, the marginal costs of canal lining is expressed as an annualized cost ($ac_{lined}$).

The production function in this case is simply a loss function ($w_{ag} = (1-\alpha)*w_{in}$), where $\alpha$ is of the primary focus of this study, the conveyance loss function. The conveyance loss is the fraction of $w_{in}$ that is lost to seepage or evaporation while transporting. The conveyance loss function ($\alpha = f(x_{lined}, Z)$) is determined by the percent of the canals lined and a vector of other pre-determined characteristics ($Z$) such as soils and climate. Conveyance losses are bounded ($\alpha \in [0,1]$) and convex in investment ($\alpha'(x_{unlined}) < 0$ and $\alpha''(x_{unlined}) > 0$).

The organization faces a cost minimization problem:

$$\min L = p_w * w_{in} + ac_{lined} * x_{lined} + \lambda[w_{ag} - (1-\alpha) * w_{in}] \tag{1}$$

The first order conditions are:

$$\frac{\partial L}{\partial w_{in}} = p_w - \lambda(1-\alpha) = 0 \tag{2}$$

$$\frac{\partial L}{\partial x_{lined}} = ac_{lined} + \lambda(w_{in})\frac{\partial \alpha}{\partial x_{lined}} = 0 \tag{3}$$

To solve for the approximation of the optimal input decisions, we use a first-order Taylor series expansion around a baseline state of canal lining ($x_0$).

$$x^*_{lined} = x_0 + \left(1 - \frac{p_w}{\lambda}\right)\left(\alpha'\left(x^*_{lined}|Z\right) - \alpha'\left(x_0|Z\right)\right)^{-1} \tag{4}$$

Substituting for $\lambda$ from the second of the first order conditions gives:

$$x^*_{lined} = x_0 + \left(1 + \frac{p_w}{ac_{lined}}\right)\left((w_{in})\alpha'\left(x^*_{lined}|Z\right)\right)\left(\alpha'\left(x^*_{lined}|Z\right) - \alpha'\left(x_0|Z\right)\right)^{-1} \tag{5}$$

The implication of this model is that the optimal investment in canal lining depends up

on prices as well as the expected change in conveyance losses. The later is determined by the vector of pre-determined characteristics. This raises the possibility that in an econometric estimation of the conveyance loss function, the percentage of the canal system lined is potentially endogenous. The empirical model will test for such endogeneity.

# 4 Empirical Model

To understand how variation in water conveyance infrastructure influences conveyance loss we estimate the following econometric model.

$$Conveyance\ Losses_i = \beta_0 + \beta_1 * Conveyance\ Lined\ or\ Piped_i + \gamma * Z_i + \varepsilon_i \tag{6}$$

Where the dependent variable, 'Conveyance Losses$_i$', represents for the $i^{th}$ organization the percentage of total water diverted lost during conveyance. We model conveyance losses as a function of an organization's conveyance infrastructure, differentiating between lined and piped infrastructure. Specifically, 'Conveyance Lined or Piped$_i$' describes the percentage of the $i^{th}$ organization's total conveyance infrastructure that is either lined or piped. The associated parameter, $\beta_1$ , captures how changes in the lining or piping of an organization's conveyance infrastructure influence conveyance losses. The econometric model also includes an intercept term, $\beta_0$, and a matrix of other explanatory variables, $Z_i$ (e.g., state fixed effects, irrigable acres, the density of the organizations conveyance system, water scarcity indicators, water use reporting requirements, climate, etc.), with associated vector of estimated parameters, $\gamma$. Finally, $\varepsilon_i$ is an idiosyncratic error term.

Obtaining an unbiased estimate of the model's parameter of interest, $\beta_1$, is potentially complicated by endogeneity between conveyance losses and conveyance lining or piping decisions. Specifically, organizations with relatively large conveyance losses may have larger incentives to invest in the efficiency of conveyance infrastructure by lining main

and lateral canals or installing piped conveyance. Under this scenario, causation runs bilaterally between the conveyance infrastructure characteristics and conveyance losses resulting in a downward bias in the estimate of $\beta_1$.

We take an instrumental variable approach to address this potential endogeneity. Valid instruments must be adequate predictors of the endogenous explanatory variable, 'Conveyance Lined of Piped$_i$' and meet the exclusion restriction, that is only affect the dependent variable, 'Conveyance Losses$_i$', indirectly through the endogenous explanatory variable. We use a suite of organization-level characteristics as instruments for the potentially endogenous infrastructure characteristics. Our primary set of instruments leverages information on reasons for not lining canals as well as the importance of municipal water deliveries in organization operations. Specifically, we use four dummy variables indicating whether an organization lists the following as reasons for not lining their conveyance infrastructure: the expense of lining, groundwater recharge benefits, soil and geologic characteristics, and a final catch-all 'other' category. The final variable in this core set of instruments measures the percentage of total water distributed that is delivered to residential or municipal water users. The suite of variables indicating why infrastructure remains unlined directly influences observed organization infrastructure characteristics as they capture the organization's perception of the costs and benefits of lining or piping infrastructure. The municipal deliveries variable also affects lining and piping decisions as having additional water delivery customers increases the benefits of saving water through lining and piping investments. Finally, this suite of variables meets the exclusion restriction, affecting conveyance losses only indirectly through organization-level decisions to invest in lined or piped conveyance infrastructure.

To test the robustness of our results we expand this restricted set of instruments to a full suite of variables accounting for organization governance structure and function, local water market conditions, conveyance system constraints, water supplies, and the availability of substitutes for delivered water. For organization governance we include

variables indicating whether organization constituents vote on key decisions, whether the organization has any role in managing on-farm groundwater use, and whether an organization is registered as a non-profit corporation. Allowing voting gives constituents a voice in determining organization management and investment, such as investments in conveyance system improvements, but is otherwise unrelated to conveyance losses. The management of groundwater affects the organization's perception of the benefits of conveyance losses as that water may still be available for irrigation through pumping. An organization's non-profit status is an indicator of the organization's objectives which may affect investment decision but would otherwise not influence conveyance losses.

The full set of instruments also includes proxies for local water market conditions and conveyance system constraints. Specifically, we include an instrument that indicates whether the organization did not participate in water marketing due to low prices for sales and leases. This instrument potentially correlates with lining and piping decisions by capturing the benefits of water saved but is otherwise not related to organization level conveyance losses. We include three instruments associated with conveyance system constraints. These variables describe whether, under normal water supply conditions, an organization's conveyance system, particularly their turnouts and conveyance canals, constrain water deliveries broadly capturing the capacity of their conveyance system. These variables affect lining and piping decisions as organizations with delivery system capacity constraints benefit more from diminished conveyance losses.

The full set of instruments concludes with variables accounting for water supplies and the availability of substitutes for delivered water. Specifically, we included a variable that describes the percentage of an organization's total water supplies coming from a contracted source, such as a Federal, State, or local irrigation project. This variable captures the proportion of the organization's supply that is purchased rather than diverted as part of the organization's, or their constituents', portfolio of water rights. Purchasing a larger part of their water supply may influence lining and piping decisions by affecting the op-

portunity cost of water conservation. Finally, we include a variable indicating whether irrigators are able to supplement water deliveries by pumping groundwater. This variable affects lining and piping decisions by increasing the groundwater recharge benefits of unlined canals but is otherwise uncorrelated with conveyance losses.

# 5 Data

To estimate the econometric model outlined in equation 6 we leverage novel data collected in the 2019 Survey of Irrigation Organizations (SIO). The 2019 SIO was the first nationally representative data collection effort focused on water delivery organizations since the 1978 Census of Irrigation Organizations. SIO data were collected by the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA-NASS) during the Spring of 2020. SIO data were collected using a mailed paper questionnaire with web and telephone interviewing instruments also available for survey enumeration. The reported survey response rate was 44% (USDA-NASS, 2020). SIO data represent the operations of the organizations delivering water directly to farms or directly influencing some aspect of on-farm groundwater use in the 24 states where these types of irrigation organizations are most common.

We focus our analysis on a subset of the data collected in the 2019 SIO. Specifically, we use survey responses from 598 organizations that indicate delivering water to farms and ranches in 2019 and respond to the relevant sections of the survey instrument. Section A of the appendix outlines the data selection criteria used to winnow all survey responses to the 598 observations used to estimate our empirical models. Here we describe the data used to estimate our empirical models, beginning with an in depth discussion of the primary variables of interest, conveyance loss and conveyance infrastructure, and concluding with information about the remaining exogenous covariates and instrumental variables.

## 5.1 Conveyance Loss Data

Survey respondents were asked to report their conveyance losses at two points in the survey. First, the survey asked for all of the inflows and outflows from irrigation systems in terms of total acre-feet. Outflows included conveyance losses. Second, participants were asked to report the percentage conveyance loss in their systems.

Nationally-representative totals of reported inflows and outflows were summarized by USDA (USDA-NASS, 2020). In 2019, irrigation water delivery organizations brought 70.1 million acre-feet of water into their delivery systems and had 10.7 million acre-feet of conveyance losses. This indicated a national conveyance loss of 15.3 percent. Notably, total outflows, including the conveyance losses, were only 67.3 million acre-feet. So 4.0 percent of total inflows were either held back as storage within the irrigation systems, or outflows such as conveyance losses were under-reported.

Of the organizations that had positive deliveries to farms, over 500 records reported zero acre-feet of conveyance losses. About one-tenth of those reported positive percentage conveyance loss later in the survey. Due to the potential for under reporting of the acreage losses in volumetric terms, this study relies on the self-reported conveyance losses in percentage terms. As detailed in appendix A, missing values for percentage conveyance loss are imputed for those observations who did report volumetric conveyance loss. Observations with zero conveyance losses are excluded from this study. The small number of observations who report greater than 75 percent conveyance loss are also excluded.

Percent conveyances losses a skewed toward lower values (see Figure 1). Over half of observations report a conveyance loss below 20%. Table 1 presents conveyance loss summary statistics. The average conveyance loss is 16.7%. This is slightly larger than the volume-based national estimate cited above, but is consistent with the possibility that the national number includes under-reporting due to the ”zero” conveyance loss observations that are excluded from this study.

[Figure 1 about here.]

Table 1: **Summary Statistics for Outcomes**

| Statistic | Mean | St. Dev. |
|---|---|---|
| Conveyance Loss (%) | 16.7246 | 14.0360 |
| Conveyance Lined (%) | 11.0967 | 25.8775 |
| Conveyance Piped (%) | 21.9455 | 35.3606 |
| Conveyence Lined or Piped (%) | 33.0421 | 40.9757 |

## 5.2 Conveyance Infrastructure Data

Included as part of the data on the infrastructure operated by irrigation organizations, the survey asked respondents to report on the miles of canals and pipes used for delivering water to farms and ranches. Organizations reported the total number of miles of mains and laterals, and for each of those they separately reported on miles that are unlined, lined or piped. Those six categories were summed to calculate the total miles of conveyance infrastructure for each organizations. Based on that total, the shares for lined and piped miles were calculated.

As noted in more detail in appendix A, about one-forth of the survey respondents who reported delivering water did not provide any detail on conveyance infrastructure. Whether this was because the organizations did not keep records on miles of infrastructure or face unusual ownership arrangements in which they neither own nor operate the conveyance infrastructure is not clear from the survey questions.

Among the organizations used in this study who had adequate responses on all covariates, a large majority (74% of organizations) have zero miles of lined canals (Figure 2). A very small share (about 4% of organizations) have 100 percent of their canals lines. Among the organizations that are have a portion of their canals lined, there is a slight skew toward lower percentages. The average organization has lined 11% of its canals (Table 1).

Piping of canals is more common. The average organizations has piped 22% of its canals (Table 1). Compared to lining, a smaller majority (57% of organizations) have no piped conveyance infrastructure (Figure 2). About 12% or organizations have all of their canals piped. As with lining, among those organizations that have a portion of their canals piped, lower shares are slightly more common than larger shares.

About 16% of organizations have a mixed of lined and piped canals. Of those, only about one-forth (23 out of 93) have all of their canals either lined or piped.

[Figure 2 about here.]

## 5.3 Exogenous Covariates and Instrumental Variables

Table 2 presents summary statistics for the exogenous covariates and instrumental variables used to estimate equation 6. Note that these summary statistics represent a sample of the full set of organizations survey in the SIO, as described in appendix A. As such, reported statistics may differ from those reported by USDA-NASS (USDA-NASS, 2020).

The exogenous covariates included in our empirical model of conveyance losses consist of the following: 'Irrigable Acres', 'Conveyance Density', 'Sufficient Water in 2019', 'Required to Report Use', 'Phreatophyte Problems', and 'July Mean Daily Temperature.' 'Irrigable Acres' refers to the amount of land that could have received water from the organization in 2019, which could be larger than the amount of land irrigated using water delivered by the organization. Since organizations that serve larger areas move water over greater distances through larger systems, the expectation is that greater irrigable acres will be associated with higher conveyance losses. 'Conveyance Density' records the total conveyance infrastructure per irrigable acres and is measured in miles per acre. The expectation is that higher conveyance density will be associated with higher conveyances losses. 'Sufficient Water in 2019' is a dummy variable indicating whether an organization cited sufficient water supplies in 2019 as a reason for not engaging in water marketing. Since 2019 was an above average precipitation year in most areas of the Western U.S.,

Table 2: **Summary Statistics of Covariates**

| Statistic | Mean | St. Dev. |
|---|---|---|
| Exogenous Covariates | | |
| Irrigable Acres (000s) | 12.1941 | 33.6882 |
| Conveyance Density (mi/acre) | 0.0197 | 0.0563 |
| Sufficient Water in 2019 (0/1) | 0.2709 | 0.4448 |
| Required to Report Use (0/1) | 0.5468 | 0.4982 |
| Phreatophyte Problems (0/1) | 0.5836 | 0.4934 |
| July Mean Daily Temperature (°C) | 20.3289 | 3.1252 |
| Instruments | | |
| Unlined due to: | | |
| Expense (0/1) | 0.6288 | 0.4835 |
| GW Recharge (0/1) | 0.2291 | 0.4206 |
| Min. Seepage (0/1) | 0.1706 | 0.3764 |
| Other (0/1) | 0.1070 | 0.3094 |
| Municipal Deliveries (%) | 5.3061 | 14.2251 |
| Can Vote (0/1) | 0.9281 | 0.2585 |
| Manages GW (0/1) | 0.2324 | 0.4227 |
| Nonprofit (0/1) | 0.6990 | 0.4591 |
| Low Sale Price (0/1) | 0.0318 | 0.1755 |
| Peak Flow Risk (0/1) | 0.1940 | 0.3957 |
| Turnout Constrained (0/1) | 0.0502 | 0.2185 |
| Flow Constrained (0/1) | 0.1622 | 0.3689 |
| Contracted Supply (%) | 0.4687 | 0.4827 |
| Supplemental GW (0/1) | 0.1304 | 0.3371 |

the expectation is that a positive response will indicate that an organization had average or above average quantities of water moving through there system. If conveyance losses increase with 'percent utilization' of conveyance capacity, then a positive response would be expected to be associated with higher conveyance losses. 'Required to Report Use' is a dummy variable indicating whether the organization is required to report water use for irrigation to users/shareholders, water project managers of State or Federal suppliers, or any other regulatory authority. If reporting requirements lead to more efficient management, then the expectation is that this would be associated with lower conveyance losses. 'Phreatophye Problems' is a dummy variable expressing whether the organization reported having issues with vegetation (e.g., salt cedar, willow, etc.) along ditches and canals. Since such vegetation is directly responsible for conveyance losses, the ex-

pectation is that a positive response will be associated with higher conveyance losses. Finally, 'July Mean Daily Temperature' measures the average July daily temperature for the county where the irrigation organization is primary located using 30 year normal temperature data reported by PRISM (PRISM, 2021). The expectation is that higher average temperatures will be associated with higher conveyance losses.

The primary set of variables use to instrument for 'Conveyance Lined' and 'Conveyance Piped' include a set of four variables representing reasons organizations did not line their conveyance infrastructure as well as a variable capturing the proportion of water distributed to municipal and residential customers. Specifically, 'Unlined due to...' are a suite of dummy variables signaling whether the organization reported that the following were reasons for leaving conveyance unlined: lining is too expensive ('Expense'), unlined canals provide groundwater recharge ('GW Recharge'), water loss is minimal due to soils and geology ('Min. Seepage'), and 'Other' to account reasons not listed. 'Municipal Deliveries' is the percentage of total water distributed in 2019 that was delivered to municipal or residential customer.

The expanded set of instruments includes the following: 'Can Vote', 'Manages GW', 'Nonprofit', 'Low Sale Price', 'Peak Flow Risk', 'Turnout Constrained', 'Flow Constrained', 'Contracted Supply', and 'Supplemental GW'. 'Can Vote' indicates whether an organization's water users have input into management decisions through voting. 'Manages GW' signifies if the organization manages on-farm groundwater use within their service area. 'Nonprofit' is a dummy variable which equals one if the organization identified themselves as a registered non-profit organization. 'Low Sale Price' indicates whether an organization cited low sale prices as a reason for not engaging in water marketing in 2019. 'Peak Flow Risk' signals that, under normal water supply conditions, an organization is able to meet irrigator water needs during peak-flow demand less than 80% of the time. 'Turnout Constrained' and 'Flow Constrained' are dummy variables which equals one if an organization cited turnout technology or conveyance canal capacity, respectively, as

a 'significant' factor constraining their ability to meet peak-flow water demands. 'Contracted Supply' is the percentage of total water diverted into the organization's system coming from a Federal, State, or local irrigation project. Finally, 'Supplemental GW' indicates whether the organizations water users can increase groundwater withdrawals during times of drought when deliveries may be curtailed.

# 6 Results

Table 3 present results estimating the empirical model outlined in equation 6 using the data described in section 5. Column (1) presents OLS results from a simplified specification of our econometric model estimating conveyance losses as a function of only conveyance characteristics, differentiating between lined and piped conveyance, and state fixed effects. Column (2) also displays OLS estimation results but includes the full suite of other exogenous covariates described in section 5.3 and merges lining and piping variables into a single covariate. Columns (3) and (4) build on the OLS estimates by presenting results instrumenting for potential endogeneity in the conveyance infrastructure covariate. Column (3) results use the restricted set of instruments while column (4) results employ the full suite of instruments described in sections 4 and 5.3.

Column (1) displays OLS results from a simplified version of our econometric model estimating conveyance losses as a function of only conveyance characteristics and state fixed effects, separating the effects of lining versus piping conveyance infrastructure. These results, which do not instrument for potential endogeneity, demonstrate the expected negative relationship between improved conveyance infrastructure and conveyance losses. While the percentage of conveyance piped has a slightly larger negative impact on conveyance losses than the percentage of conveyance lined, the magnitudes are statistically indistinguishable. Based on this similarity, the remaining model results combine the shares of lining and piping jointly estimating that effect using a single explanatory

Table 3: **Conveyance Loss Empirical Model Results**

| | Dependent Variable: Conveyance Loss (%) | | | |
|---|---|---|---|---|
| | OLS | | IV | |
| | (1) | (2) | (3) | (4) |
| | 2 Endogenous | 1 Endogenous | Restricted IVs | Full IVs |
| Conveyance Lined | −0.0758* | | | |
| | (0.0298) | | | |
| Conveyance Piped | −0.0940*** | | | |
| | (0.0168) | | | |
| Conveyence Lined or Piped | | −0.0709*** | −0.0793** | −0.0753** |
| | | (0.0182) | (0.0277) | (0.0275) |
| Log Acres | | 1.4847*** | 1.4882*** | 1.4865*** |
| | | (0.3838) | (0.3840) | (0.3838) |
| Conveyance Density | | 12.0906 | 12.4641 | 12.2873 |
| | | (10.1797) | (10.1557) | (10.1993) |
| Sufficient Water in 2019 | | −1.6696 | −1.6663 | −1.6679 |
| | | (1.2583) | (1.2607) | (1.2597) |
| Required to Report Use | | −0.0346 | −0.0404 | −0.0377 |
| | | (1.2237) | (1.2239) | (1.2242) |
| Phreatophyte Problems | | 3.4898* | 3.2586* | 3.3681* |
| | | (1.4109) | (1.5413) | (1.5375) |
| July Mean Daily Temperature (°C) | | −0.0203 | −0.0180 | −0.0191 |
| | | (0.2386) | (0.2391) | (0.2392) |
| $R^2$ | 0.0837 | 0.1333 | 0.1328 | 0.1331 |
| Adj. $R^2$ | 0.0649 | 0.1079 | 0.1074 | 0.1077 |
| Num. obs. | 598 | 598 | 598 | 598 |
| RMSE | 18.7999 | 18.3628 | 18.3678 | 18.3642 |

$^{***}p < 0.001$;$^{**}p < 0.01$;$^{*}p < 0.05$.
All models include state fixed effects. Robust standard errors are shown in parenthesis.

variable, 'Conveyance Lined or Piped.'

All the model specifications that include the full suite of explanatory covariates (columns 2, 3, and 4) yield negative and statistically significant estimates of $\beta_1$, the parameter of interest from equation 6. These parameter estimates indicate that increasing the total percentage of conveyance infrastructure that is lined or piped by ten percentage points decreases conveyance losses by 0.7 to 0.8 percentage points depending on the specification. The magnitude of this effect is smallest in the OLS specification which follows intuition given the downward bias expected when not addressing the potential endogeneity of infrastructure characteristics. The magnitude of the effect increases slightly in both restricted and full instrumental variable (IV) specifications.

At the mean, this estimated 0.7 to 0.8 percentage point effect is a 4.3 percent decrease

in conveyance losses. As a robustness check for the nonlinearity of the percent variable near zero and full loss, we estimate a Probit model, which suggests that a 10 percentage point increase in conveyance lining or piping decreases conveyance losses by a corresponding 3.3 percent (Table C.1).

Table 4: **IV Tests**

| Test | Statistic | DF | Endog DF | p-value |
|---|---|---|---|---|
| Restricted IVs | | | | |
| Weak Instruments (Conveyence Lined or Piped) | 52.7759 | 5 | 576 | 0.0000 |
| Wu-Hausman | 0.1836 | 1 | 579 | 0.6684 |
| Full IVs | | | | |
| Weak Instruments (Conveyence Lined or Piped) | 20.6907 | 14 | 567 | 0.0000 |
| Wu-Hausman | 0.0536 | 1 | 579 | 0.8169 |

Table 4 reports relevant test statistics for the IV specifications. Specifically, we report 'Weak Instruments' and 'Wu-Hausman' test statistics. The Wu-Hausman statistic tests a null hypothesis of inconsistency in the OLS model (Hausman, 1978). For both the restricted and full IV specification test statistics, we fail to reject this null hypothesis. Based on this evidence that the OLS is the preferred specification among the current models. The Weak Instrument statistic tests a null hypothesis of a weak association between the suite of instruments and endogenously determined infrastructure characteristics (Stock et al., 2002; Stock and Yogo, 2005; Staiger and Stock, 1997). For both the restricted and full suite of instrumental variables we reject the null hypothesis of weak instruments. First stage regression results presented in Table B.1 in section B of the appendix further attest to instrument strength demonstrating a statistically significant correlation between instruments, particularly the restricted set, and endogenously determined infrastructure lining and piping.

Other explanatory variables included in the conveyance loss empirical model generally follow intuition. Log transformed irrigable acres, 'Log Acres', increases conveyance losses and is statistically significant across all model specifications. Organizations with expansive service areas have larger conveyance as water deliveries must generally travel

longer distances. This relationship holds even conditioning on the density of the organization's conveyance infrastructure, 'Conveyance Density,' which also increases losses but is not statistically significant. Organizations that did not engage in water marketing due to sufficient water ('Sufficient Water in 2019' == 1) are associated with lower conveyance losses but the relationship is not statistically significant. The sign of the coefficient is somewhat surprising if organizations without sufficient water are more likely to make water conservation investment e.g., lining or piping canals. Water use reporting requirements are also associated with lower conveyance losses implying that accountability to constituents or regulators may increase resource stewardship and conservation. Model results also indicate a positive and statistically significant relationship between conveyance losses and phreatophytes. This relationship follows intuition as phreatophytes may be responsible for a portion of conveyance losses as roots systems in and around conveyance infrastructure uptake water during transport. Finally, mean July daily temperature is negatively correlated with conveyance losses but the relationship is not statistically significant. This relationship potentially indicates how the water demands of irrigated agriculture, as represented by temperature, influence organization-level management of scarce water resources.

## 6.1 Simulation of Water Conservation Supply Curve

Based on the estimated conveyance loss function, we construct a simple supply curve for water conservation based on an assumed series of projects that would line 10 percent of the unlined canals for observations in our data. This exercise illustrates how a coordinated water conservation effort that begins with the least cost conservation options would initially capture a fair amount of low-cost conservation but will rapidly progress to more expensive options.

We estimate the change in water availability due to investments in conveyance infrastructure using the OLS model's estimate of $\beta_1$ ($\beta_1 = 0.071$), and assume that each orga-

nization increases their lined or piped infrastructure by 10%. Using organization level data on the total amount water inflow, we calculate the volume of the reduction in conveyance losses for each organization. We then use data on the total amount of conveyance infrastructure owned by each organization and canal lining cost estimates reported by USDA-NRCS to determine the total costs associated with lining 10% of each organization's conveyance (USDA-NRCS, 2020). The combination of estimated water savings and lining costs provide a marginal cost of conservation for each organization.

Figure 3 presents conveyance lining water conservation supply curve using three estimates of per mile lining costs based on the range of costs reported by USDA-NRCS (USDA-NRCS, 2020). The 'Low', 'Medium', and 'High' lining cost supply curves assume a lining costs of $40,000, $120,000, and $232,000 per mile. Figure 3 demonstrates the water conservation potential of focusing conveyance lining investments on the lowest cost per water conserved options. For example, increasing the proportion of conveyance lined by 10% just among organizations with costs per water conserved of less than $1,000 per acre foot would result in an annual increase in water availability ranging from 20,000 to 175,000 acre feet of water depending on the lining cost estimate. As increases in water availability due to canal lining occur annually, the price paid for this additional water is similar to an organization purchasing a water right. These costs are half of the average purchase price for an acre foot of water in Texas and Arizona, and a quarter of prices in California, suggesting that lining may be more cost effective than purchasing rights on the open market (Schwabe et al., 2020).

[Figure 3 about here.]

# 7 Conclusion

This paper analyzes the relationship between water conveyance infrastructure attributes and conveyance losses to characterize the benefits of investments in irrigation infrastruc-

ture. This research builds on past work in the engineering literature by utilizing novel survey data describing the operations and infrastructure of irrigation water delivery organizations in the Western U.S. to empirically understand the water conservation benefits of investments in conveyance infrastructure. Our results constitute a representative estimate of the impact of canal lining and piping on conveyance losses using a data set that provides externally validity for policy-relevant simulations. Results illustrate that canal lining and piping can provide cost-effective water conservation, initially at costs well below that of procuring new supplies.

There are several limitations of our analysis that merit mention. Firstly, our empirical modeling assumes linearity in the relationship between percentage of conveyance lined or piped and losses. However, this linear relationship is unlikely to hold toward the tails of the distribution of conveyance losses if there are diminishing returns to conveyance infrastructure investments. Additionally, future modeling of conveyance infrastructure investments should explicitly model the discrete nature of investment perhaps using sample selection models to jointly model the choice to line or pipe any infrastructure and how much infrastructure to improve.

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# Figures

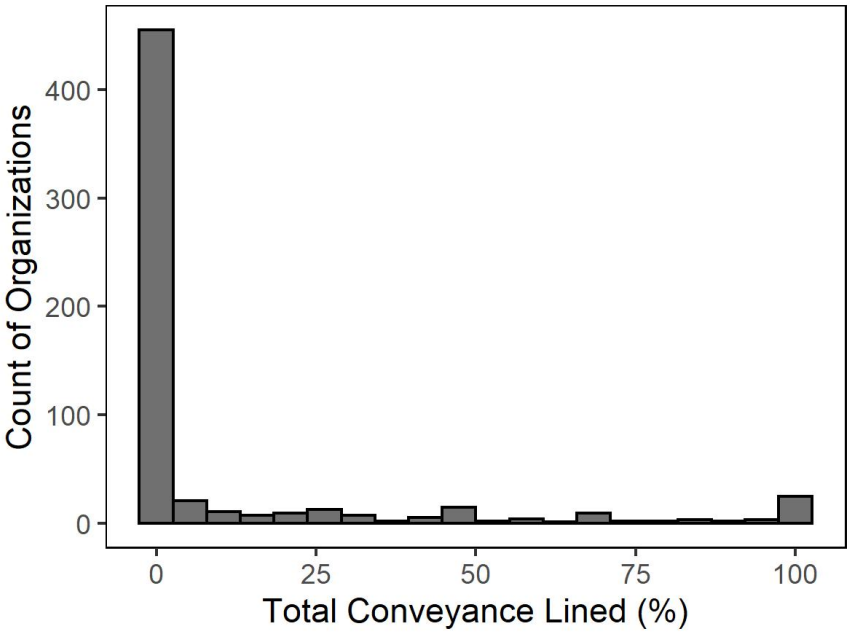



Figure 1: Distribution of Conveyance Losses (%)

Note: Survey responses with conveyance losses greater than 50% are grouped into the '50+' category to avoid data disclosure issues.

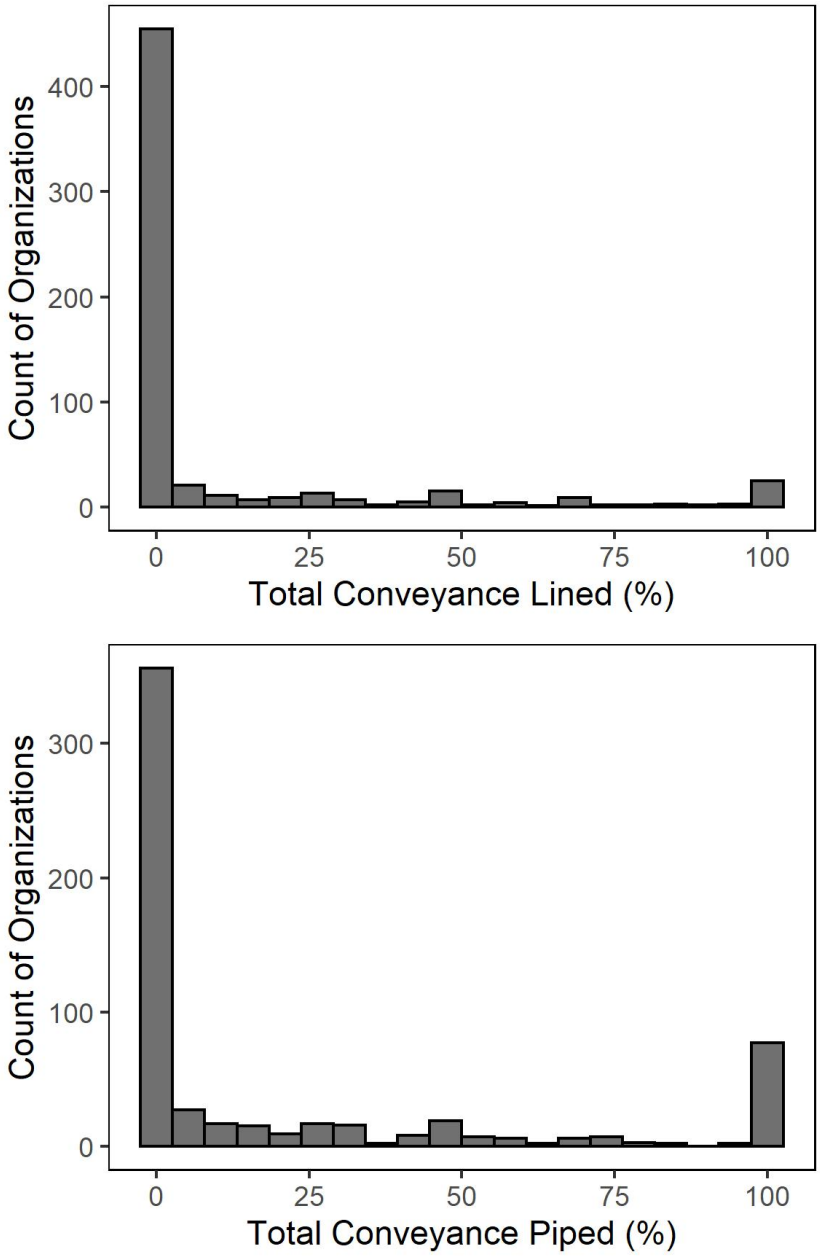



Figure 2: Distribution of Total Conveyance Lined and Piped

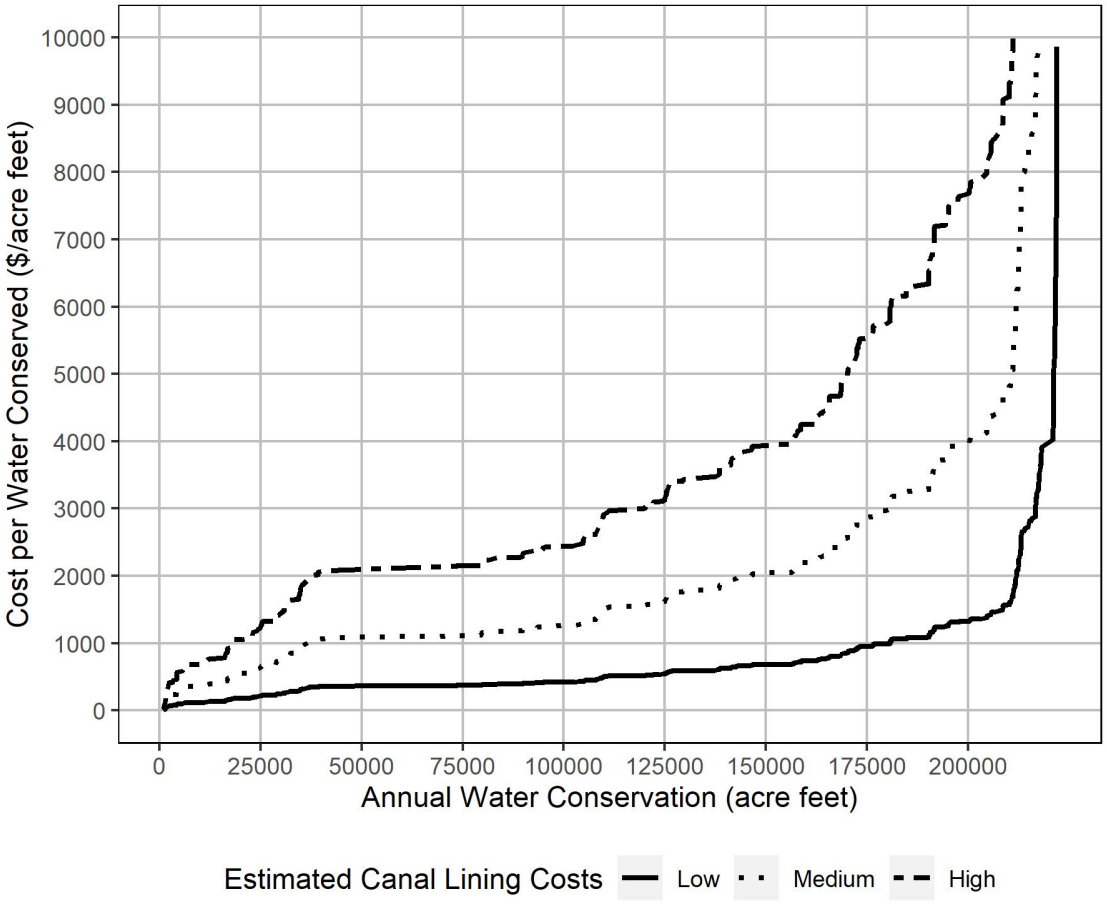



Figure 3: Supply Curve of Water Conservation through Conveyance Infrastructure Investments

# Appendices

## A Data Selection Criteria

The 2019 Survey of Irrigation Organizations (SIO) collected 1,360 survey responses from irrigation water delivery and groundwater management organizations. An observation weighting methodology was utilized to account for survey non-response, more information on this weighting methodology can be found in USDA-NASS SIO data publication (USDA-NASS, 2020). This section of the appendix describes in detail the data selection criteria used to filter the 1,360 survey responses in to the 598 observations used in the paper's empirical modeling.

Among the 1,360 survey responses, 98 responding organizations reported managing groundwater and not delivering water to farms and ranches. Most organizations that manage on-farm groundwater use and do not deliver water to farms do not own or operate water delivery infrastructure where conveyance losses may occur. As such, we exclude these 98 organizations' responses from our analysis leaving 1,262 usable survey responses. A total of 6 organizations that self-identify as irrigation water delivery organizations report not delivering water to farms and ranches during the 2019 growing season. Some of these organizations may have ceased operations or consolidated with another organization. In both scenarios these organizations no longer own or operate delivery infrastructure where conveyance losses may occur, thus we drop these 8 organizations' survey responses resulting in 1,254 survey responses.

The characteristics of an organization's conveyance infrastructure are used as dependent and explanatory variables in this paper's empirical modeling. The 2019 SIO collected detailed data on these characteristics, however several organizations that indicated delivering water to farms did not respond to survey questions related to their conveyance infrastructure. Given the importance of this information for our empirical modeling we exclude survey responses that did not answer at least one of the primary conveyance infrastructure system. Among the 1,254 organizations that report delivering water to farms and ranches in 2019, 397 organizations did not provide responses to any of the primary conveyance infrastructure questions. We exclude these organizations' survey responses from our analysis resulting in a 857 survey responses.

Conveyances losses is the primary dependent variable of interest in this paper's empirical modeling. The 2019 SIO survey instrument collected data on organization conveyance losses in two formats, as a percentage of total diversions and as a volume (in acre feet). Our empirical modeling primarily leverages data collected on conveyance losses

as a percentage of total diversions. Among the 857 organizations that report delivering water to farms and ranches in 2019 and respond to at least one of the primary conveyance infrastructure questions, 558 organizations provide a response to the conveyance losses as a percentage of total diversions question. 71 organizations that do not respond to the conveyance loss as a percentage of total diversions question do provide a response to the volumetric conveyance loss question. For these organizations, we impute conveyance losses as a percentage of total diversions using data collected on the total amount of water diverted in to the organization's conveyance system and the volumetric measurement of conveyance losses. This imputation process results in usable conveyance loss data for 629 organizations. Following insights gleaned from the engineering literature we additionally exclude organizations whose reported or imputed conveyance losses exceed 75% (Sultan et al., 2014; Kedir and Engineer, 2015; Syed et al., 2021). Dropping data based on this criteria, results in 624 survey responses.

Given the importance of the characteristics of an organization's conveyance infrastructure in our modeling, we limit the survey responses used in our analysis based on conveyance infrastructure per irrigable acre in the organizations service area. Several organizations report owning and operating extensive conveyance systems given the amount of irrigated land that could have received water from the organization in 2019 i.e. irrigable acreage. These outliers are likely related to respondents providing conveyance infrastructure information in incorrect units (e.g., yards instead of miles). To exclude these outliers we calculate total conveyance infrastructure (including canals, ditches, and pipes) per organization irrigable acreage (amount of irrigated land that could have received water from the organization in 2019). All organizations that have more than one mile of conveyance infrastructure per irrigable acreage are excluded, resulting in 617 usable survey responses.

Including state-level effects is important in our empirical analysis as the legal institutions defining water rights vary by state. Accurately estimating state-level effects is complicated by the relatively small number of observations located in some states. The number of responses primarily reflects the prevalence of irrigation water delivery organizations in a given state. Generally, states in Western U.S. have a relatively large number of organizations while states in the eastern U.S. have fewer. To avoid estimation issues and focus on the regions where irrigation water deliver organizations are most common we exclude observations where the state the organization is located has fewer than 5 total survey responses. This exclusion drops observations from 7 states located primarily in the Central and Eastern U.S. and results in 599 survey responses.

Finally, county-level average temperature is included as a covariate to control for

organization-level climate. We use the FIPS code associated with each organization to match to PRISM climate normals data. However, one survey response is coded with a faulty FIPS code that does not match any FIPS codes for the state where the organization is located. We drop this organization's response resulting in a usable sample of 598 survey responses.

# B Stage One Empirical Model Results

We estimate the first stage of our instrumental variables model using the restricted and full set of instruments. Table B.1 shows the results of these regressions. The restricted set of instruments includes binary responses to four reasons organizations could provide as reasons for not lining or piping all or part of their conveyance infrastructure: the expense of lining, the conveyance losses contributing to groundwater recharge, the soils having limited losses due to seepage when unlined, or an unspecified "other" category. The restricted set of instruments also includes the percent of municipal deliveries as a proxy for both the price of water sold and for the ability of the organization to finance canal lining. The full set of instruments adds other water delivery organization characteristics that may influence the extent of conveyance lining and piping but are not likely to directly affect conveyance losses. Some of the additional instruments capture key institutional characteristics: whether farmers can vote for organization leadership; whether the organization manages the groundwater resource; and whether the organization is a non-profit. Some of the additional instruments are proxies for whether the organizations faces constraints that would limit any use of saved water: low sales prices for water rights transfers, an indicator for whether the organization is frequently constrained in meeting farmer requests for water, and indicators for whether those constraints are related to turnouts or to conveyance capacity. The final additional instruments capture whether the organize purchases water through contracts (as opposed to withdrawing the water as-of-right from natural water bodies) and whether farmers served by the organization have the ability to supplement their water deliveries with groundwater pumping. In both models, exogenous covariates from the second stage are included.

Estimated coefficients are quite similar between the two models, with reasons for not lining having strong negative effects on the percentage of conveyance lined or piped, as is expected. Reasons for not lining are binary responses, so for example, the percent of conveyance lined by organizations that selected expense as a reason for not lining is 44.7 percentage points lower than the percent of conveyance lined by organizations that did not select expense as a reasons for not lining. Similarly, organizations that selected

groundwater recharge, minimal loss from seepage, or for other reasons for not lining have 19.9, 10.6, and 27.1 percentage points less conveyance lining or piping respectively. Organizations with 10 percentage points more municipal deliveries have 0.26 percent more conveyance lining on average.

Table B.1: **Stage 1 Results**

| | Conveyance Lined or Piped (%) | |
|---|---|---|
| | Restricted | Full |
| Unlined due to: | | |
| Expense | −45.5550*** | −44.6630*** |
| | (3.5220) | (3.5666) |
| GW Recharge | −19.5337*** | −19.9401*** |
| | (3.6714) | (3.6960) |
| Min. Seepage | −10.5982** | −10.6251** |
| | (4.0709) | (4.0459) |
| Other | −27.6633*** | −27.1488*** |
| | (5.1487) | (5.2370) |
| Municipal Deliveries | 0.2537** | 0.2597** |
| | (0.0865) | (0.0860) |
| Can Vote | | 6.9259 |
| | | (5.4170) |
| Manages GW | | 3.9764 |
| | | (3.0967) |
| Nonprofit | | −3.4510 |
| | | (3.1684) |
| Low Sale Price | | 2.1997 |
| | | (6.9842) |
| Peak Flow Risk | | −0.9500 |
| | | (3.2603) |
| Turnout Constrained | | 8.6259 |
| | | (5.3899) |
| Flow Constrained | | −1.6560 |
| | | (3.5868) |
| Contracted Supply | | 1.1791 |
| | | (2.8443) |
| Supplemental GW | | −5.3269 |
| | | (5.5269) |
| Log Acres | 2.8622*** | 2.7848** |
| | (0.8239) | (0.8807) |
| Conveyance Density | 49.2498** | 45.5376** |
| | (16.6107) | (16.7691) |
| Sufficient Water in 2019 | 1.5372 | 1.4463 |
| | (2.9827) | (3.0264) |
| Required to Report Use | 0.2793 | 0.3105 |
| | (2.5552) | (2.5645) |
| Phreatophyte Problems | −11.5282*** | −11.7517*** |
| | (3.0779) | (3.1205) |
| July Mean Daily Temperature (°C) | 0.0483 | 0.0507 |
| | (0.5668) | (0.5692) |
| $R^2$ | 0.5513 | 0.5580 |
| Adj. $R^2$ | 0.5349 | 0.5346 |
| Num. obs. | 598 | 598 |
| RMSE | 39.3728 | 39.3849 |

$^{***}p < 0.001;^{**}p < 0.01;^{*}p < 0.05$.
All models include state fixed effects. Robust standard errors are shown in parenthesis.

# C Probit Model

Linear probability estimates of the effect of conveyance lining and piping on water lost may be inaccurate, particularly at the extremes where changes in conveyance lining and piping may suggest conveyance losses in excess of 0 or 100 percent. A probit model allows for the physical reality that losses outside of these extremes is impossible.

Table C.1 shows the results of a probit model in which conveyance lining and piping is not endogenous as suggested by the Wu-Hausman test in Table 4. The estimated effect of a 10 percentage point increase in conveyance lining and piping is a 3.3 percent decrease in water lost due to conveyance. This estimate is smaller than the estimated 4.3 percent change derived from the linear probability model results of our main specification, but suggests that the linear probability estimate is in the right range.

Table C.1: **Probit Estimates**

| | Dependent Variable: Conveyance Loss (%) | |
|---|---|---|
| | 2 Endogenous | 1 Endogenous |
| Conveyance Lined | −0.0032* | |
| | (0.0015) | |
| Conveyance Piped | −0.0043*** | |
| | (0.0009) | |
| Conveyence Lined or Piped | | −0.0033*** |
| | | (0.0009) |
| Log Acres | | 0.0622 |
| | | (0.0167) |
| Conveyance Density | | 0.5019 |
| | | (0.6296) |
| Sufficient Water in 2019 | | −0.0681 |
| | | (0.0550) |
| Required to Report Use | | −0.0006 |
| | | (0.0525) |
| Phreatophyte Problems | | 0.1552 |
| | | (0.0619) |
| July Mean Daily Temperature (°C) | | −0.0010 |
| | | (0.0100) |
| AIC | 636.0868 | 638.2385 |
| BIC | 693.2035 | 717.3232 |
| Log Likelihood | −305.0434 | −301.1193 |
| Deviance | 150.1505 | 141.3984 |
| Num. obs. | 598 | 598 |

***$p < 0.001$;** $p < 0.01$;* $p < 0.05$.
All models include state fixed effects. Robust standard errors are shown in parenthesis.