A National Estimate of Irrigation Canal Lining and Piping Water Conservation [*]

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April 25, 2022

Abstract

Global climate change is already impacting water resources and, in many areas, reducing the amount of water available for drinking, sanitation, and agriculture. Water conservation can be a means to mitigate the economic damages associated with water scarcity, including scarcity arising from climate change. In the agricultural sector, most water conservation efforts have focused on farm-level irrigation efficiency. However, since over one-third of water applied for agricultural irrigation in the U.S. comes from off-farm supplies, improvements in delivery and conveyance efficiency also have the potential to significantly reduce water losses. This study utilizes survey data from irrigation water delivery organizations in the Western U.S. to estimate the impact of lining and piping conveyance infrastructure on conveyance losses. The average irrigation delivery organization reports a conveyance loss of 15 percent of the total water brought into their system in 2019. Using a control function estimation, this study finds that at the margin an increase of one percentage point in the share of conveyance infrastructure piped leads to an expected 0.16 percentage point reduction in conveyance losses. A simulated water-conservation supply curve based on these estimates shows that about 2.3 percent of total water brought into these systems could be recaptured at a private capital cost below $10,000 per acre foot.

Keywords: Irrigation Infrastructure, Water Resources, Conveyance Losses

JEL Codes: Q15, Q25, Q30

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[*] 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, the literature that has rigorously examined the costs and benefits of conveyance loss mitigating investments is limited. A recent survey of 230 studies on water conservation investments only included 10 studies that estimated the conservation potential of canal

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[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.

lining or piping (Pérez-Blanco et al., 2020).

The sector structure and the related data sources are one reason for the limited focus on canal lining and piping. Typically irrigation with off-farm surface water involves three levels of decisions making: 1) the farmer who is irrigating; 2) a local water delivery organization that manages conveyance infrastructure such as ditches, canals, and turnouts; and 3) a large water capture and storage project (often managed by a federal or state agency) that supplies water to the local delivery organization. A significant amount of research and data collection has been focused on either the farm-level decision making or the large state and federal water projects. Very limited research and data collection has been focused on irrigation delivery organizations. The data used for this study represent the first nationally-representative dataset of irrigation organizations collected in over forty years (Wallander et al., 2022).

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 700 irrigation water delivery organizations included in our analysis as some organizations have invested in lining and piping to reduce conveyance losses.

Investments in water conveyance infrastructure can diminish conveyance losses and help achieve water conservation objectives. Specifically, upgrading previously unlined

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[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 incentivizes 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).

(earthen) conveyance canals to lined canals or piped infrastructure can curtail conveyance losses by reducing seepage and/or evaporation. 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, 2020a). 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). Piping irrigation infrastructure is even more costly. Recent irrigation infrastructure piping projects funded by USDA-NRCS report per mile piping costs between $0.6 and 3 million per mile. However, piped irrigation infrastructure requires less maintenance and lasts longer than most lined canals (Newton and Perle, 2006).

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 potentially lacks 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 organization'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 control function 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, on average, increasing the share of conveyance that is piped by 1 percentage point decreases conveyance losses by between 0.1 and 0.19 percentage points. We also find that lining canals reduces conveyance losses, however the magnitude of this effect is smaller.

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 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 much of Western U.S. have facilitated the prevalence of off-farm surface water-fed irrigated agriculture in the region. Figure 1 maps the prevalence of the irrigated agricultural sector's use of off-farm water using state-level data reported in the 2018 Irrigation and Water Management Survey (USDA-NASS, 2019).

[Figure 1 about here.]

From point of capture to on-farm use, the full irrigation infrastructure is subject to multiple opportunities for water to be lost from the system through seepage or evaporation. These losses can be represented as technical inefficiencies and are often grouped into three categories: 1) distribution efficiency, 2) conveyance efficiency, and 3) (on-farm) application efficiency (Cai et al., 2003; Nair et al., 2013). The conveyance stage of the process is generally the purview of local delivery organizations that manage conveyance infrastructure to deliver water to multiple farms and ranches.

The infrastructure used for the conveyance stage of off-farm water delivery 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

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[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).

water constitutes a collective action problem addressed through a variety of institutional arrangements (Leonard and Libecap, 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(Libecap, 2011).[5] Unincorporated mutuals are informal partnerships between water conveyance infrastructure users, acequias[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

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[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).

more than 70 million acre-feet[7] of water entering irrigation organization conveyance systems was purchased or contracted from a Federal, State, or local/private irrigation project (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

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

[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, like acequias, may not generate revenue and instead rely on the labor of water users to cooperatively maintain and operate irrigation infrastructure (Cox, 2014). 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 an irrigation organization selects a level of canal improvement (lining or piping) as a production input within a cost-minimization problem. A cost-minimization framework is appropriate for two reasons. First, most irrigation delivery organizations are either irrigation districts or incorporated mutuals, which function more like regulated utilities or cooperatives rather than profit maximizing firms. Second, water rights may constrain irrigation delivery organizations decisions in ways analogous to quantity restriction in the cost minimization framework.

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 improved ($x_{improved}$). 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 input costs such as labor inputs. Since improving canals is a long-run capital investment decision, the marginal costs of canal improvement is expressed as an annualized cost ($ac_{improved}$).

The production function in this case is simply a loss function ($w_{ag} = (1-\alpha) * w_{in}$), where α is 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 ($\alpha = f(x_{improved}, Z)$) is determined by the percent of the canals improved 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 ($\alpha'(x_{unimproved}) < 0$ and $\alpha''(x_{unimproved}) > 0$).

The organization faces a cost minimization problem:

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

The first order conditions are:

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

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

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).

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

Substituting for λ from the second of the first order conditions gives:

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

The implication of this model is that the optimal investment in canal lining or piping depends upon prices as well as the expected change in conveyance losses. The latter 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 or piped is potentially endogenous. The empirical model tests for such endogeneity.

4 Empirical Model

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

$$Conveyance\ Losses_i = G(\beta_0 + \beta_1 * Conveyance\ Lined_i + \beta_2 * Conveyance\ Piped_i + \gamma X_i) + \varepsilon_i \quad (1)$$

where the dependent variable, 'Conveyance Losses$_i$', represents for the i^{th} organization the fraction of total water diverted lost during conveyance and $G(\cdot)$ is the logistic function (Papke and Wooldridge, 1996). 'Conveyance Lined$_i$' and 'Conveyance Piped$_i$' describe the fraction of the i^{th} organization's total conveyance infrastructure that is lined and piped, respectively. The fraction of conveyance lined and conveyance piped are potentially interdependent and endogenous factors affecting conveyance loss. The associated parameters, β_1 and β_2, capture how changes in the lining and piping of an organization's conveyance infrastructure influence conveyance losses. The econometric model also includes an intercept term, β_0, and a matrix of other explanatory variables, X_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, γ. Finally, ε_i is an idiosyncratic error term.

We model conveyance losses as a non-linear function of an organization's conveyance infrastructure, differentiating between lined and piped infrastructure. Obtaining unbiased estimates of the model's parameters of interest, β_1 and β_2, is potentially complicated by endogeneity between conveyance losses and conveyance lining and piping decisions. 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 estimates of β_1 and β_2. We take an instrumental variable (IV) approach to address this potential endogeneity. Because of nonlinearity in both the first and second stage, we employ a control function model to estimate effects.

However, the choices of how much conveyance to line and to pipe are interdependent since lined conveyance cannot be piped and vice-versa. The fraction of conveyance lined ('Conveyance Lined$_i$'), the fraction of conveyance piped ('Conveyance Piped$_i$'), and the fraction of conveyance that is neither lined nor piped must sum to one. We address the fractional and interdependent nature of the endogenous covariates in the first stage of our model with the use of a fractional multinomial model following the methods outlined in Papke and Wooldridge (1996), with unlined being the reference case, specifically

$$Conveyance\{Unlined_i, Lined_i, Piped_i\} = G(\lambda Z_i + \gamma X_i) + \varepsilon_i. \tag{2}$$

This approach instruments for endogenously determined conveyance characteristics while recognizing the interdependence of lining, piping, and unlined/piped conveyance infrastructure. See appendix B for stage one model results.

Recognizing the bounded nature of conveyance losses expressed as a fraction of total diversions, we use a control function estimation to control for the potential endogeneity of 'Conveyance Lined$_i$' and 'Conveyance Piped$_i$' in our second stage model. The control function approach is preferred over methods (e.g., two stage least squares) when the second stage is non-linear as control function methods allow for more straightforward hypothesis testing for model selection and covariate exogeneity (Wooldridge, 2015). We estimate a fractional response model that takes the form

$$\begin{aligned} Conveyance\ Losses_i = & G(\beta_0 + \beta_1 * Conveyance\ Lined_i + \beta_2 * Conveyance\ Piped_i + \\ & \gamma * W_i + \phi_1 \nu_{Lined} + \phi_2 \nu_{Piped}) + \varepsilon_i \end{aligned} \tag{3}$$

where ν_{Lined} and ν_{Piped} are the residuals for 'Conveyance Lined' and 'Conveyance Piped' from the estimation of the first stage model represented by equation 2.

Valid instruments must be adequate predictors of the endogenous explanatory variables, 'Conveyance Lined$_i$' and 'Conveyance 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 variables. 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 opportunity 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 1 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 673 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 673 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 except those observations that report having 100% of their conveyance infrastructure piped which can in many scenarios reduce losses to 0 (Newton and Perle, 2006). About 15% of the ”zero” conveyance loss organizations report that 100% of their infrastructure is piped. Appendix C presents modeling results using differing rules related to the inclusion of observations reporting zero conveyance losses. The small number of observations who report greater than 75 percent conveyance loss are also excluded.

Percent conveyances losses are skewed toward lower values (see Figure 2). Over 70% of organizations report a conveyance loss below 20%. Table 1 presents conveyance loss summary statistics. The average conveyance loss is 14.9%. 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 some of the ”zero” conveyance loss organizations that are excluded from this study.

Table 1: **Summary Statistics for Outcomes**

Statistic	Mean	St. Dev.
Conveyance Loss (share)	0.1486	0.1424
Conveyance Lined (share)	0.0986	0.2464
Conveyance Piped (share)	0.3064	0.4141

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 organization. Based on that total, the shares for lined and piped miles were calculated.

As noted in more detail in appendix A, about one-fourth 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. The observations are excluded from the study.

Among the organizations used in this study who had adequate responses on all covariates, a large majority (77% of organizations) have zero miles of lined canals (Figure 2). A very small share (about 3% of organizations) have 100 percent of their canals lined. 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 10% of its canals (Table 1).

Piping of canals is more common. The average organizations has piped 31% of its canals (Table 1). Compared to lining, a smaller majority (51% of organizations) have no piped conveyance infrastructure (Figure 2). About 22% of 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 14% of organizations have a mixed of lined and piped canals. Of those, only about one-fourth (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 1. Note that these summary statistics represent a sample of the full set of organizations surveyed in the SIO, as described in appendix A. As such, reported statistics may differ from those reported by USDA-NASS (USDA-NASS, 2020).

Table 2: **Summary Statistics of Covariates**

Statistic	Mean	St. Dev.
Exogenous Covariates		
Irrigable Acres (000s)	11.1041	31.9556
Conveyance Density (mi/acre)	0.0214	0.0592
Sufficient Water in 2019 (0/1)	0.2734	0.4460
Required to Report Use (0/1)	0.5468	0.4982
Phreatophyte Problems (0/1)	0.5290	0.4995
July Mean Daily Temperature (°C)	20.3693	3.1288
Instruments		
Unlined due to:		
Expense (0/1)	0.5587	0.4969
GW Recharge (0/1)	0.2036	0.4029
Min. Seepage (0/1)	0.1516	0.3589
Other (0/1)	0.0951	0.2936
Municipal Deliveries (share)	0.0574	0.1511
Can Vote (0/1)	0.9287	0.2576
Manages GW (0/1)	0.2348	0.4242
Nonprofit (0/1)	0.7043	0.4567
Low Sale Price (0/1)	0.0297	0.1699
Peak Flow Risk (0/1)	0.1842	0.3880
Turnout Constrained (0/1)	0.0565	0.2310
Flow Constrained (0/1)	0.1530	0.3603
Contracted Supply (share)	0.0048	0.0048
Supplemental GW (0/1)	0.1248	0.3308

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 conveyance 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., the expectation is that a positive response will indicate that an organization had average or above average quantities of water moving through their 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. ‘Phreatophyte 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 expectation 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 primarily 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 used 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 presents results estimating the empirical model outlined in equation 1 using the data described in section 5. Column (1) presents results from a linear version of our primary econometric model. Column (2) displays estimation results from the nonlinear, fractional response logistic model presented in equation 1 but does not instrument for potentially endogenous conveyance lining or piping decisions. Columns (3) and (4) also present fractional response logistic model results but instrument for potential endogeneity in the conveyance infrastructure covariates with a control function approach. 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. To facilitate result interpretation and comparison between the linear and nonlinear model results all nonlinear model results are presented as average marginal effects following methods outlined in Ramalho et al. (2011).

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

	Dependent Variable: Conveyance Loss (share)			
	(1)	(2)	(3)	(4)
	Linear	Logistic	Logistic Control Function	
	Uninstrumented	Uninstrumented	Restricted IVs	Full IVs
Conveyance Lined (share)	−0.0747***	−0.0686**	0.0771	−0.0306
	(0.0213)	(0.0248)	(0.0628)	(0.0519)
Conveyance Piped (share)	−0.1066***	−0.1385***	−0.1906***	−0.1580***
	(0.0147)	(0.0189)	(0.0314)	(0.0292)
Log Acres	0.0167***	0.0168***	0.0145***	0.0161***
	(0.0033)	(0.0034)	(0.0035)	(0.0035)
Conveyance Density	0.1680	0.1650*	0.1706*	0.1674*
	(0.0903)	(0.0772)	(0.0771)	(0.0777)
Sufficient Water in 2019	−0.0115	−0.0139	−0.0108	−0.0127
	(0.0112)	(0.0111)	(0.0110)	(0.0112)
Required to Report Use	−0.0007	0.0006	0.0061	0.0023
	(0.0107)	(0.0106)	(0.0108)	(0.0107)
Phreatophyte Problems	0.0416***	0.0435***	0.0291*	0.0378**
	(0.0116)	(0.0125)	(0.0144)	(0.0141)
July Mean Daily Temperature (°C)	−0.0008	−0.0007	−0.0000	−0.0005
	(0.0020)	(0.0020)	(0.0021)	(0.0020)
R^2	0.2394	0.2489	0.2495	0.2481
Num. obs.	673	673	673	673

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.
All models include state fixed effects. Robust standard errors are shown in parenthesis. All models have 673 observations that include all irrigation organizations with some conveyance loss as well as those with 100% of conveyance piped and no conveyance loss.

Nearly all model specifications yield negative and statistically significant estimates of β_1 and β_2, the parameters of interest from equation 1. Parameter estimates of β_1 indicate that, for the average organization, increasing the amount of conveyance that is lined by 1 percentage point decreases conveyance losses by between 0.03 and 0.075 percentage points. However, this result is only statistically significant for the specifications which do not instrument for potential endogeniety between conveyance lining/piping and losses. Generally, the IV specifications suggest that lining canals has a smaller impact on conveyance losses compared to piping infrastructure. The restricted IV model indicates a positive relationship between canal lining and conveyances losses, however this result is not statistically significant. Evidence on the impact of piping on conveyance losses is more compelling. All parameter estimates of β_2 are negative and statistically significant suggesting that, for the average organization, increasing the share of conveyance that is piped by 1 percentage point decreases conveyance losses by between 0.11 and 0.19 percentage points. The relative efficacy of piping versus lining conveyance infrastructure follows intuition as piping is less susceptible to evaporative losses compared to lined canals (Newton and Perle, 2006).

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 and is statistically significant in all fractional response logistic model specification. 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. Logistic model estimates indicate that water use reporting requirements are also associated with higher conveyance losses which is also counter intuitive as intuition would suggest that accountability to constituents or regulators would increase resource stewardship and conservation. However, these estimates are not statistically significant implying that reporting requirements do not effect conveyance losses.

Model results also indicate a positive and statistically significant relationship between conveyance losses and organization level issues with phreatophytes. This relationship follows intuition as phreatophytes may be responsible for a portion of conveyance losses as root 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.

[Figure 3 about here.]

The average marginal effects of canal lining and piping presented in table 3 belie important effect heterogeneity based on the current share of an organization's conveyance that is lined or piped. Namely, the marginal impact of increasing the share of conveyance that is piped by 1 percentage point may differ for an organization that has 50% of its conveyance piped compared to an organization that has none of its conveyance piped. We explore effect heterogeneity as a function of current conveyance in figure 3 which separately plots the conditional marginal effect of lining and piping for differing shares of lining and piping. Specifically, figure 3 calculates the marginal effect for the full range of observed shares of conveyance that is lined or piped using regression results from column (4) of table 3 and conditioning on the mean or model of all covariates.[9] The left panel of figure 3 plots the conditional marginal effect of lining and demonstrates that the effect of lining become marginally smaller across the $[0,1]$ range but remains statistically indistinguishable from zero. The right panel of figure 3 plots the conditional marginal effect of piping and indicates that the impact of piping wanes across the $[0,1]$ range. For example, increasing the share of conveyance piped for an organization with no piped infrastructure by one percentage point leads to a 0.15 percentage point reduction in

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[9] To calculate conditional marginal effects we set all continuous covariates at their mean and all binary covariates at their mode. State level effects are not included.

conveyance losses. Meanwhile, the same increase in piped conveyance for an organization with 75% of its conveyance piped yields approximately a 0.07 percentage point reduction in conveyance losses.

In Table 4 we report relevant test statistics for the restricted and full IV control function specifications. The standard F-Test for weak instruments (Stock et al., 2002; Stock and Yogo, 2005; Staiger and Stock, 1997) does not apply in the nonlinear case, so we instead report the Wald statistic for the joint null hypothesis that in the first stage the coefficients of all instruments are not different from zero. We also conduct a Wu-Hausman test of the null hypothesis that both the uninstrumented model (column 2 in Table 3) and the instrumented models are consistent (Hausman, 1978).

In the restricted IV case, we reject the null hypothesis that both models are consistent, suggesting that endogeneity is an issue for the uninstrumented model. When the full set of IVs is included, we fail to reject the null. The Wald tests suggest that in all models, the instruments explain a significant degree of variation in the share of conveyance lined and conveyance piped, suggesting that weak instruments are not a concern. 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.

Table 4: **IV Tests**

Test	Statistic	DF	Endog DF	p-value
	Restricted IVs			
Wald (Conveyance Lined)	112.1274	5		0.0000
Wald (Conveyance Piped)	272.1622	5		0.0000
Wu-Hausman	6.0347	1	654	0.0140
	Full IVs			
Wald (Conveyance Lined)	121.8396	14		0.0000
Wald (Conveyance Piped)	289.8135	14		0.0000
Wu-Hausman	2.4631	1	654	0.1165

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 pipe 100 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. See appendix D for a similar simulation related to the costs and benefits of canal lining.

We estimate the change in water availability due to investments in the piping of conveyance infrastructure using results from the logistic control function model full IV specification (see column (4) of table 3) to calculate, for each organization, the change in conveyance losses predicted if all unlined and unpiped infrastructure was piped. To estimate this change in organization level conveyance losses we use a linear approximation of the conditional marginal effect of piping curve (see figure 3), conditioning based on the organization level observed covariate values. We integrate this function between each organization's current level of piping and 100% piping to find the total change in conveyance losses associated with fully piping remaining unlined and unpiped infrastructure. 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 piping cost estimates reported by USDA-NRCS to determine the total costs associated with piping all of each organization's unlined and unpiped conveyance (USDA-NRCS, 2020a). The combination of estimated water savings and piping costs provide a marginal cost of conservation for each organization. Finally, we scale the change in water availability by total water inflows for the 673 organizations in our sample to calculate how differing levels of water costs associate with increases in aggregate water availability.

Figure 4 presents conveyance piping water conservation supply curve using three estimates of per mile piping costs based on the range of costs reported by irrigation piping projects recently funded by USDA-NRCS (USDA-NRCS, 2020a,b). The 'Low', 'Medium', and 'High' piping cost supply curves assume costs of $629,000, $1,512,000, and $3,239,000 per mile which correspond to the minimum, mean, and maximum per mile costs reported in recently funded PL-566 projects. Figure 4 demonstrates the water conservation potential of focusing conveyance piping investments on the lowest cost per water conserved options. For example, fully piping infrastructure among organizations with costs per water conserved of less than $10,000 per acre foot would result in an annual increase in water availability ranging from 0.7 to 2.3% of total water inflows. As increases in water availability due to canal piping occur annually, the price paid for this additional water is similar to an organization purchasing a water right. These costs are relatively similar to observed water market transactions in the Western U.S. suggesting that piping may be more cost effective than purchasing rights on the open market (Schwabe et al., 2020).

[Figure 4 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 infrastructure. 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 external validity for policy-relevant simulations. We find that, for the average organization, increasing the share of their conveyance that is piped decreases conveyance losses by between 0.1 and 0.19 percentage points. We also find that lining canals generates reductions in conveyance losses, however these effects are smaller in magnitude and not statistically different from zero. A simple simulation exercise focused on the costs and benefits of conveyance piping demonstrates how investments in improved water conveyance infrastructure can provide cost-effective water conservation, initially at costs near that of procuring new supplies.

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Figures

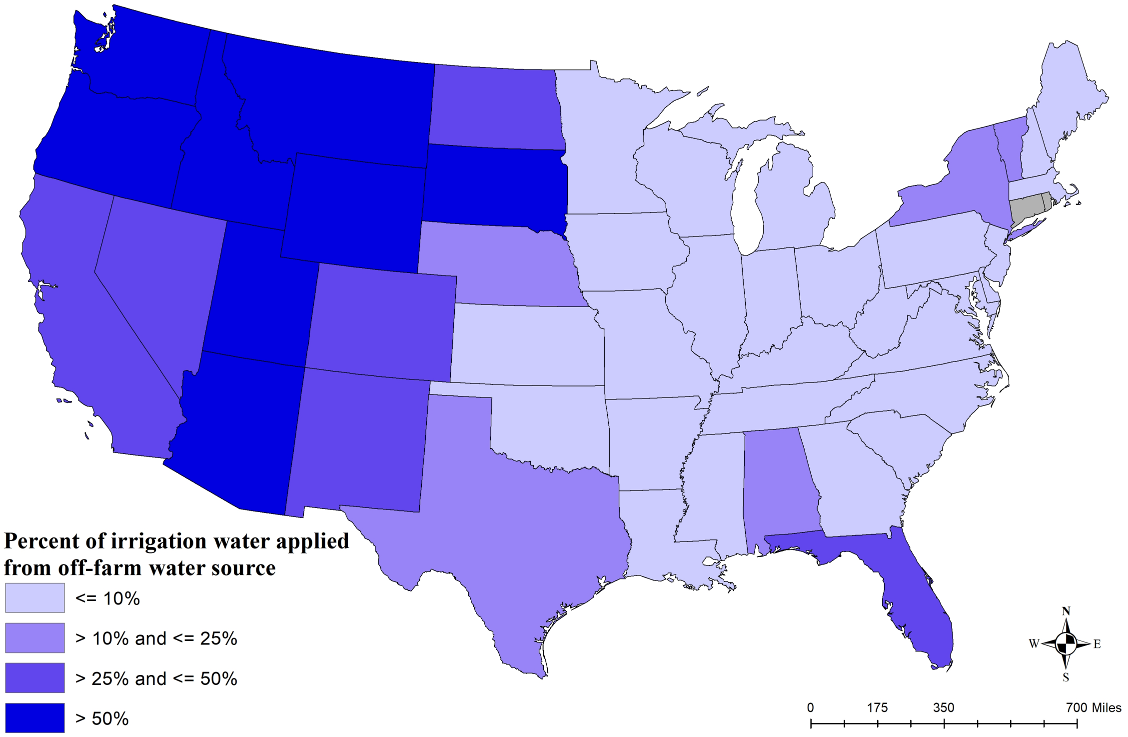

Figure 1: Prevalence of Off-Farm Water Use by Irrigated Agricultural Sector

Note: Data for Connecticut and Rhode Island are suppressed due to disclosure concerns. 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).
Source: USDA-NASS, 2018 Irrigation and Water Management Survey

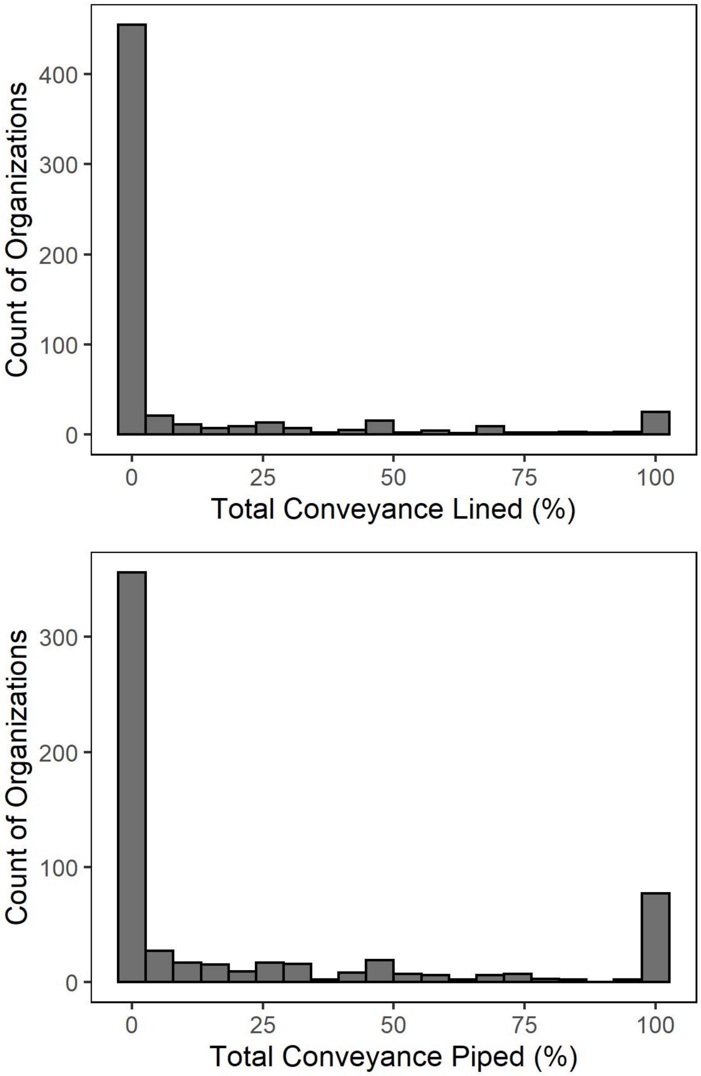

Figure 2: Distribution of Total Conveyance Lined and Piped

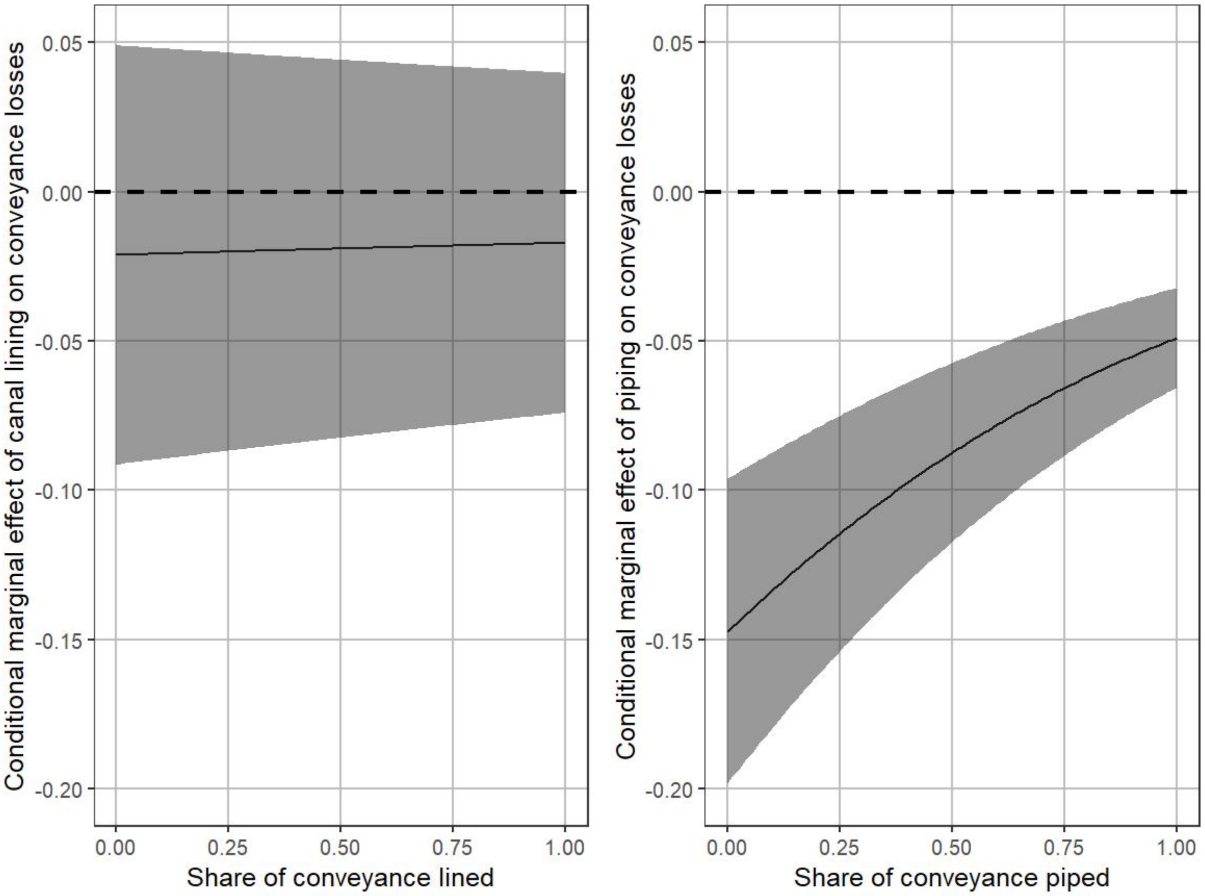

Figure 3: Marginal Effect of Canal Lining and Piping on Conveyance Losses

Note: Marginal effects are calculated using methods outlined in (Ramalho et al., 2011). The shaded area represents the 95% confidence interval for the marginal effect estimated at a given level of the share of conveyance lined or piped. The marginal effects of lining and piping are calculated setting all continuous variables as their mean and all dummy variables as their mode except for state-level effects which are set to zero.

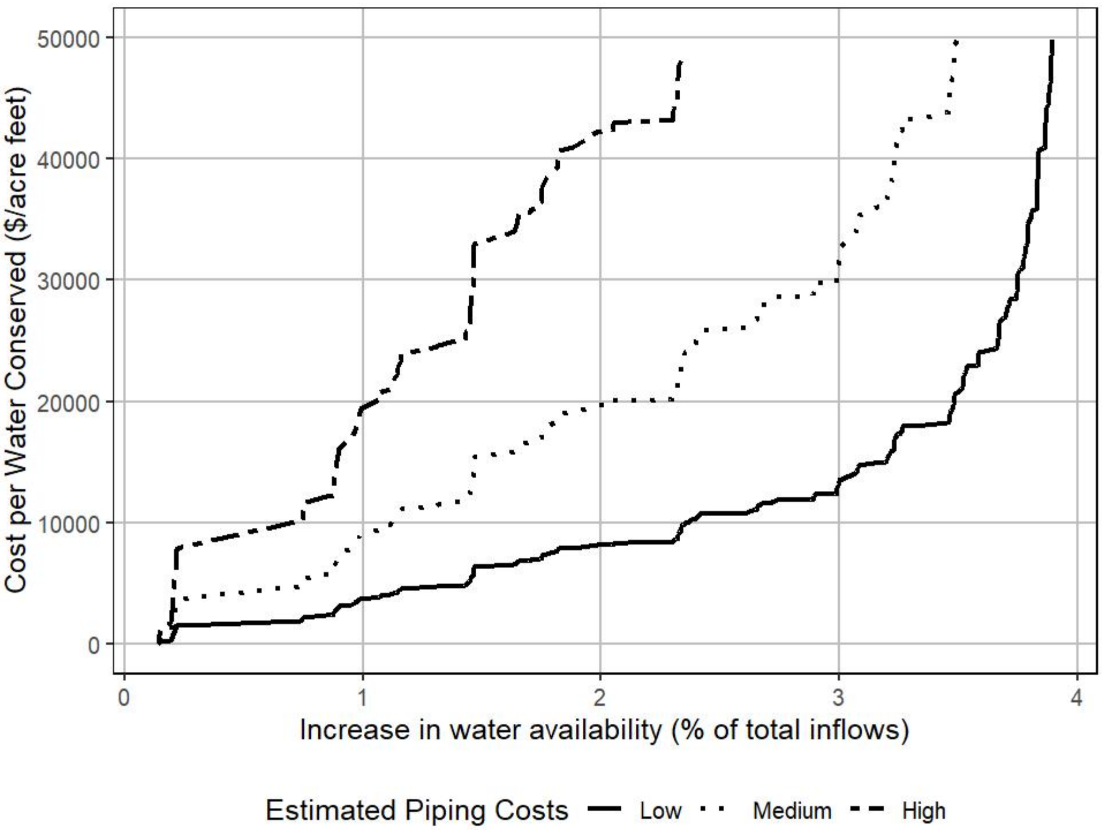

Figure 4: Supply Curve of Water Conservation through Piping Conveyance Infrastructure Investments

Costs represent private capital costs for piping infrastructure which in some cases may differ from the total social costs of piping water conveyance infrastructure. For example, conveyance losses may be recharging an aquifer which supplies water for a wetland habitat. Piping conveyance could potentially impose additional social costs if diminishing losses reduces water flows to the wetland and damages the habitat.

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 673 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.

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 845 usable 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 845 organizations that report delivering water to farms and ranches in 2019 and respond to at least one of the primary conveyance infrastructure questions, 552 organizations provide a response to the conveyance losses as a percentage of total diversions question.

70 organizations that do not respond to the conveyance loss as a percentage of total diversions question do provide a non-zero 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 into the organization's conveyance system and the volumetric measurement of conveyance losses. This imputation process results in usable conveyance loss data for 622 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 617 survey responses.

There is reason to believe that some organizations that some organizations that zero conveyance losses, particularly if a large proportion of their conveyance infrastructure is piped (Newton and Perle, 2006). Among the 223 organizations that report zero conveyance losses in acre feet and do not provide information on conveyance losses in percentage terms, 75 of these organizations report that 100% of their conveyance infrastructure is piped. We include these organizations in our sample leading to a sample size of 692. We test the robustness of our results to section C where we relax and restrict the rule determining which, if any, zero conveyance loss observations are included in the sample (see tables C.1 and C.2).

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 674 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 673 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.

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

	Dependent Variables: Share of Conveyance			
	Restricted IVs		Full IVs	
	(1) Lined	(2) Piped	(3) Lined	(4) Piped
Unlined due to:				
Expense	-2.8800^{***}	-3.5752^{***}	-2.8365^{***}	-3.5844^{***}
	(0.3084)	(0.2254)	(0.3273)	(0.2357)
GW Recharge	-1.4504^{**}	-2.1542^{***}	-1.4821^{**}	-2.0907^{***}
	(0.4852)	(0.4158)	(0.4945)	(0.4153)
Min. Seepage	-0.6944	-1.9643^{***}	-0.6561	-2.0227^{***}
	(0.3718)	(0.3607)	(0.3751)	(0.3641)
Other	-2.5723^{***}	-3.0464^{***}	-2.5647^{***}	-2.9991^{***}
	(0.4857)	(0.3278)	(0.4839)	(0.3251)
Municipal Deliveries	2.1123^{**}	1.2043^{*}	2.2423^{**}	1.3342^{*}
	(0.7429)	(0.6080)	(0.7171)	(0.6071)
Can Vote			-0.0279	0.8859^{*}
			(0.4292)	(0.3662)
Manages GW			0.4106	-0.1012
			(0.2851)	(0.2334)
Nonprofit			-0.2950	-0.2449
			(0.2671)	(0.2036)
Low Sale Price			0.9817	0.2927
			(0.7145)	(0.6315)
Peak Flow Risk			-0.2285	0.2180
			(0.2978)	(0.2440)
Turnout Constrained			-0.4837	0.9775^{*}
			(0.6903)	(0.4618)
Flow Constrained			-0.2128	-0.2645
			(0.3464)	(0.2525)
Contracted Supply			9.5804	8.0683
			(24.7783)	(18.6115)
Supplemental GW			-0.5591	-0.1108
			(0.3751)	(0.3005)
Log Acres	0.3272^{***}	0.1553^{**}	0.3321^{***}	0.1299^{*}
	(0.0772)	(0.0593)	(0.0717)	(0.0589)
Conveyance Density	5.1528^{*}	5.5946^{***}	5.1944^{*}	5.1008^{***}
	(2.4360)	(1.4361)	(2.3222)	(1.3528)
Sufficient Water in 2019	-0.1837	0.2361	-0.2492	0.2640
	(0.2715)	(0.2021)	(0.2742)	(0.2031)
Required to Report Use	-0.0779	0.4447^{*}	-0.0552	0.3972
	(0.2684)	(0.2009)	(0.2764)	(0.2051)
Phreatophyte Problems	0.0272	-1.0370^{***}	0.0128	-1.0527^{***}
	(0.2705)	(0.2030)	(0.2713)	(0.2040)
July Mean Daily Temperature (°C)	-0.0107	0.0702^{*}	-0.0088	0.0759^{*}
	(0.0454)	(0.0343)	(0.0467)	(0.0345)

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$.

All models include state fixed effects. Robust standard errors are shown in parenthesis.

C Sample Specifications and Zero Conveyance Loss

In this section we test the robustness of our main econometric results to the data inclusion rules surrounding the inclusion of observations that report zero conveyance losses. Section A of the appendix outlines the sample selection rules used to determine the sample of 673 organizations used to estimate our primary econometric model. The primary sample includes organizations that report zero conveyance losses only when those organizations also report having 100% of their conveyance infrastructure piped. All other observations reporting zero conveyance losses are dropped from the sample. Here we test how both restricting and relaxing this assumption influences our primary restricted (table C.1) and full (table C.2 IV regression results. Specifically, we estimate restricted and full IV models using differing rules to determine the sample of data. The first sample ('Loss > 0') is restricted to include only those observations with conveyance losses greater than 0 . The second sample ('Loss ≥ 0 & C1') matches that used for the main text's modeling which includes organizations that report zero conveyance losses that also have 100% of their conveyance infrastructure piped. The third sample ('Loss ≥ 0 & C2') further relaxes the data inclusion rule and includes organizations that report zero conveyance losses that also have at least 50% of their conveyance infrastructure piped. Finally, the fourth sample ('Loss ≥ 0 & C3') presents the most relaxed data inclusion rule including organizations that report zero conveyance losses that also have at least 50% of their conveyance infrastructure piped or lined. For both the restricted and full IV models, altering the data inclusion rules results in qualitatively similar results for the key explanatory variables of interest, 'Conveyance Lined' and 'Conveyance Piped,' providing some evidence that our results are not an artifact of assumptions made in determining the sample.

Table C.1: **Restricted IV Estimates for Varying Samples**

	Dependent Variable: Conveyance Loss (share)			
	Loss > 0	Loss ≥ 0 & C1	Loss ≥ 0 & C2	Loss ≥ 0 & C3
Conveyance Lined (share)	0.0345	0.0771	0.0457	0.0661
	(0.0719)	(0.0628)	(0.0645)	(0.0672)
Conveyance Piped (share)	−0.1416**	−0.1906***	−0.1779***	−0.2073***
	(0.0442)	(0.0314)	(0.0321)	(0.0337)
Log Acres	0.0160***	0.0145***	0.0146***	0.0133***
	(0.0038)	(0.0035)	(0.0035)	(0.0034)
Conveyance Density	0.1744	0.1706*	0.1688*	0.1786*
	(0.0922)	(0.0771)	(0.0758)	(0.0741)
Sufficient Water in 2019	−0.0116	−0.0108	−0.0114	−0.0090
	(0.0123)	(0.0110)	(0.0109)	(0.0107)
Required to Report Use	0.0043	0.0061	0.0043	0.0054
	(0.0120)	(0.0108)	(0.0107)	(0.0103)
Phreatophyte Problems	0.0304*	0.0291*	0.0325*	0.0202
	(0.0151)	(0.0144)	(0.0143)	(0.0139)
July Mean Daily Temperature (°C)	−0.0000	−0.0000	−0.0004	0.0003
	(0.0023)	(0.0021)	(0.0020)	(0.0020)
R^2	0.1542	0.2495	0.2506	0.2561
Num. obs.	598	673	686	701

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

Table C.2: **Full IV Estimates for Varying Samples**

	Dependent Variable: Conveyance Loss (share)			
	Loss > 0	Loss ≥ 0 & C1	Loss ≥ 0 & C2	Loss ≥ 0 & C3
Conveyance Lined (share)	−0.0854	−0.0306	−0.0492	−0.0260
	(0.0662)	(0.0519)	(0.0553)	(0.0609)
Conveyance Piped (share)	−0.0839*	−0.1580***	−0.1498***	−0.1666***
	(0.0416)	(0.0292)	(0.0302)	(0.0323)
Log Acres	0.0176***	0.0161***	0.0159***	0.0149***
	(0.0038)	(0.0035)	(0.0034)	(0.0034)
Conveyance Density	0.1677	0.1674*	0.1660*	0.1734*
	(0.0934)	(0.0777)	(0.0761)	(0.0758)
Sufficient Water in 2019	−0.0137	−0.0127	−0.0129	−0.0109
	(0.0124)	(0.0112)	(0.0110)	(0.0109)
Required to Report Use	−0.0013	0.0023	0.0011	0.0020
	(0.0120)	(0.0107)	(0.0105)	(0.0103)
Phreatophyte Problems	0.0396**	0.0378**	0.0400**	0.0318*
	(0.0148)	(0.0141)	(0.0141)	(0.0138)
July Mean Daily Temperature (°C)	−0.0007	−0.0005	−0.0008	−0.0005
	(0.0022)	(0.0020)	(0.0020)	(0.0020)
R^2	0.1530	0.2481	0.2508	0.2547
Num. obs.	598	673	686	701

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

D Water Conservation Supply Curve, Canal Lining

This section presents a similar water conservation supply curve to that presented in section 6.1 but for canal lining rather than canal piping. Figure D.1 shows the relationship between the costs of water conservation and increases in water availability due to lining for three estimated canal lining costs where ‘low’, ‘medium’, and ‘high’ corresponds to $40,000, $120,000, and $230,000 per mile lined, respectively. Note that compared to figure 4, figure D.1’s effect are smaller in magnitude as the estimated impact of lining on conveyance losses is smaller. For example, fully lining all organizations with cost per acre foot conserved less than $10,000 would yield less than a 0.1% increase in total water availability.

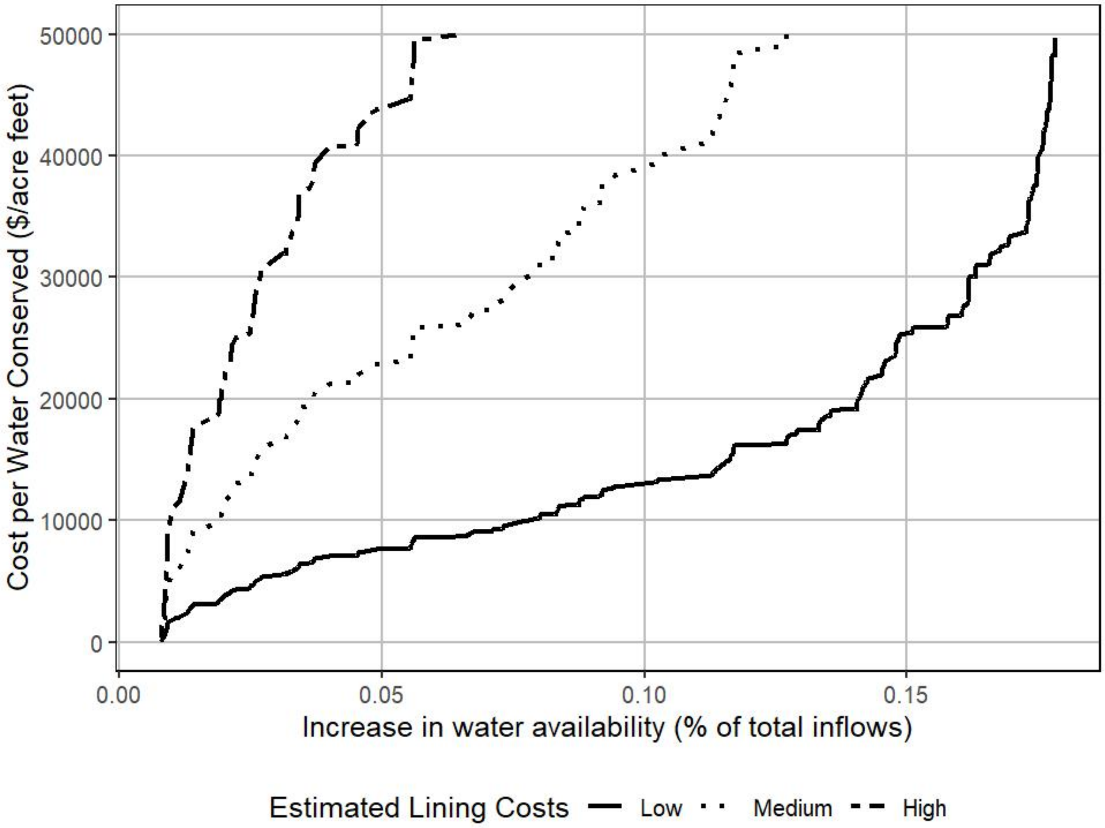

Figure D.1: Supply Curve of Water Conservation through Piping Conveyance Infrastructure Investments

Costs represent private capital costs for piping infrastructure which in some cases may differ from the total social costs of lining water conveyance infrastructure.