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3 The Cost-Effectiveness of Irrigation Canal Lining and Piping in the Western United States

R. Aaron Hrozencik, Nicholas A. Potter,
and Steven Wallander

3.1 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, Tieu, and Huynh 2019; Siirila-Woodburn et al. 2021). Researchers and policy makers have heralded water conservation efforts as a means to mitigate the economic consequences of water scarcity (Gobarah et al. 2015). A growing economics literature has analyzed the efficacy of differing water conservation efforts in addressing water scarcity issues (Pfeiffer and Lin 2014; Gobarah et al. 2015; Koech and Langat 2018). This study contributes to this literature by examining the conservation potential of investments in irrigation infrastructure, specifically the lining and piping of water conveyance infrastructure to reduce water lost during transport. Water conveyance lining and piping have received relatively limited attention in the water conservation literature. However, these investments are receiving renewed

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attention from policy makers interested in promoting climate resilience in the agricultural sector (Fischer and Willis, 2020).

Farmers and policy makers have a suite of options at their disposal to address the growing scarcity of water resources. These options range from on-farm water management strategies such as irrigation scheduling (Wang et al. 2021), conservation tillage practices (Huang et al. 2021), cover cropping (Novara et al. 2021), and altered crop rotations (Williams, Wuest, and Long 2014); to the adoption of efficiency enhancing irrigation technologies such as drip irrigation systems (Van der Kooij et al. 2013) and low pressure center pivot irrigation systems (Pfeiffer and Lin 2014). There also exist opportunities to conserve water before it reaches irrigated farms and ranches, including managing forests to increase snowpack and streamflow (Gleason et al. 2021), covering water storage reservoirs to reduce evaporative losses (Lehmann, Aminzadeh, and Or 2019), and improving water delivery infrastructure to diminish the amount of water lost during conveyance (Plusquellec 2019). This paper focuses on the water conservation potential of investments in off-farm water conveyance infrastructure, specifically the lining and piping of canals.

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 snowpack dependent production systems (Reidmiller et al. 2019; Evan and Eisenman 2021; Siirila-Woodburn et al. 2021). Despite the current and potential future costs of conveyance losses, literature rigorously examining the costs and benefits of conveyance loss mitigating investments remains limited (Plusquellec 2019). A recent survey of 230 studies on water conservation investments only included 10 studies that estimated the conservation potential of canal lining or piping (Pérez-Blanco, Hrast-Essenfelder, and Perry 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 decision 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

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.

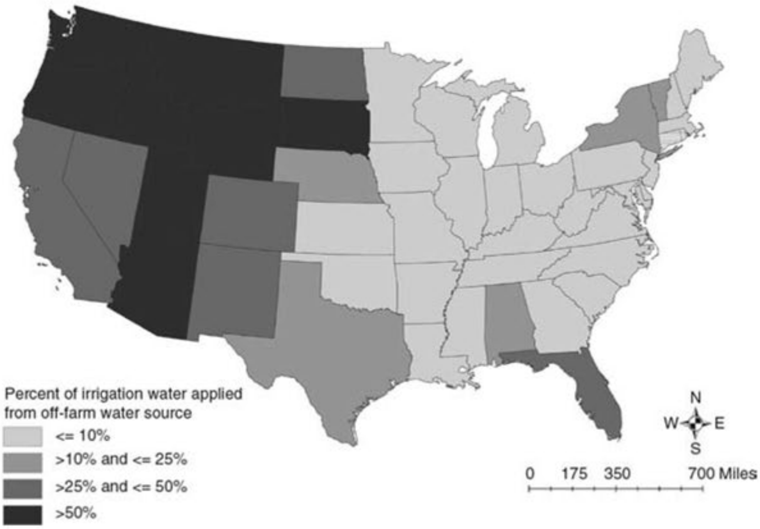

Fig. 3.1 Prevalence of Off-Farm Water Use by Irrigated Agricultural Sector

Note: Data for Connecticut and Rhode Island are suppressed due to disclosure concerns. Off-farm surface water is surface water from off-farm water suppliers, such as the US 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

supplies water to the local delivery organization.[2] 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. This study focuses on the decisions of irrigation delivery organizations using data from USDA's 2019 Survey of Irrigation Organizations, the first nationally representative data set of irrigation organizations collected in over forty years (Wallander, Hrozencik, and Aillery 2022). Irrigation water delivery organizations (e.g., irrigation districts, acequias, ditch companies, etc.) are important institutions in the western US, where the majority (see figure 3.1) of surface water-fed irrigated agriculture relies on off-farm water deliveries (USDA-NASS

2. Off-farm surface water refers to "water from off-farm water suppliers, such as the US 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). Meanwhile, 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).

2019; Hrozencik 2021).[3] These organizations own and operate much of the infrastructure where conveyance losses occur. In 2019, more than 15 percent of all water brought into irrigation water delivery organization systems was lost during conveyance (USDA-NASS 2020).[4]

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 reduce seepage losses and, in the case of piping, can also reduce evaporation losses. However, most of the irrigation canals managed by irrigation organizations in the western US are unlined, and organizations cite the cost of upgrading canals as the primary barrier to investing in lining or piping (Hrozencik, Wallander, and Aillery 2021). The US Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) reports that lining one mile of a relatively small canal costs between $30 thousand and $228 thousand, 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 US, 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 million and $3.2 million per mile. However, piped irrigation infrastructure requires less maintenance and lasts longer than most lined canals (Newton and Perle 2006).

When considering the potential for canal lining and piping, uncertainty about the benefits, i.e., the expected reductions in conveyance losses, is as important as costs. Despite the potential importance of the benefits of improved conveyance infrastructure, there are no standard estimates to inform public or private investment decisions. A number of studies from the engineering literature leverage 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, attempting to extrapolate from these studies to the full population of irrigation delivery organizations raises concerns of external validity. There are several reasons that by focusing on places in time and space where infrastructure investments reap the largest conservation

3. The prevalence of off-farm surface water use in the western US 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.

4. Conveyance losses of 15 percent fall within the range of losses reported in the hydrological and agricultural engineering literature (Todd 1970; Mohammadi, Rizi, and Abbasi 2019; Karimi Avargani et al. 2020).

benefits, these studies potentially overstate the water conservation impacts of canal lining for the average irrigation organization. First, the locations selected for engineering simulations may not reflect average conditions for the universe of conveyance infrastructure. In addition, 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, these infrastructure improvement projects yield larger reductions in conveyance losses than might be expected from lining or piping an average unimproved canal. Finally, some of these studies do not account for the potentially rapid degradation of canal performance over time, which can be particularly acute for canals lined with rigid materials like concrete (Plusquellec 2019).

To the extent that the economics literature has treated the relationship between water conveyance infrastructure and losses, the research has primarily used theoretical modeling to understand how water lost during conveyance could influence the optimal allocation of scarce water resources (Tolley and Hastings 1960; Chakravorty and Roumasset 1991; Chakravorty, Hochman, and Zilberman 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. This study extends this literature by providing the first econometric estimates of the average expected water conservation benefits of canal lining and piping by irrigation organizations in the western US. Our empirical approach estimates the impact of canal lining or piping on conveyance losses while conditioning on other factors—such as climate, region, and vegetation along canals (i.e., phreatophytes)—that are also drivers of conveyance losses. The theoretical model for this paper illustrates how an organization's decision to line or pipe conveyance infrastructure is likely to be driven by expected losses with and without irrigation, which suggests that in an econometric estimation the share of miles lined or piped could be endogenous with respect to observed conveyance losses. To test for bias due to such potential endogeneity, this study implements an instrumental variable control function approach. Our results suggest that on average, increasing the share of conveyance that is piped by 1 percentage point decreases conveyance losses by between 0.1 and 0.17 percentage points. We also find that lining canals reduces conveyance losses, however the magnitude of this effect is relatively smaller, ranging from 0.07 to 0.06 percentage points. We leverage these empirical estimates to develop water conservation supply curves for lining and piping canals. Results indicate that strategic investments in the piping and lining of canals can increase aggregate water availability by between 0.3 percent and 1.75 percent for a cost less than $20,000 per acre-foot conserved.

3.2 Theoretical Model

This research is focused on estimating the expected change in conveyance losses as a function of canal lining and piping. Conveyances losses are calculated as the percentage of water brought into a delivery system (w_{in}) that is not either directly delivered to agricultural users (w_{ag}) or otherwise discharged from the system (w_{other}). We are interested in estimating conveyance losses as a function of the percentage of an organization's conveyance infrastructure that is lined (γ_{lined}) or piped (γ_{piped}) and a vector of other variables, such as climate and organization characteristics (X_{CL}).

$$(1) \qquad CL \equiv 100 * \left[\frac{w_{in} - w_{ag} - w_{other}}{w_{in}}\right] = f(\gamma_{lined}, \gamma_{piped}, X_{CL}).$$

Conveyance losses are bounded ($CL \in [0,1]$) and hypothesized to be convex in lining and piping investment ($CL'(\gamma_{lined}) < 0$; $CL''(\gamma_{lined}) > 0$; $CL'(\gamma_{piped}) < 0$; $CL''(\gamma_{piped}) > 0$).

To illustrate how estimation of this equation might be impacted by endogeneity, we develop a simple theoretical model exploring organization decision making around canal lining and piping. The model posits an organization with a single output—water delivered to farms and ranches (w_{ag})—and assumes that this value is fixed due to limited water supply, conveyance size, rights to water, or other restrictions. The idea that irrigation water at the farm gate is a fixed quantity is found in other models of on-farm crop choice and irrigation investment decisions (Moore, Gollehon, and Carey 1994). We also assume that other water outflows (e.g., deliveries to residential customers, releases for downstream users, or environmental flow requirements) are also fixed by contract or water right obligations to constituents. These assumptions restrict a delivery organization's choice to the amount of water brought into the organization's system (w_{in}^*) and investment in lining and piping, captured as the percent of canals lined (γ_{lined}^*), and the percent of canals piped (γ_{piped}^*).

The organization chooses water inflows and conveyance lining and piping to minimize costs, reflecting the fact that most irrigation delivery organizations are either irrigation districts, which function more like regulated utilities, or ditch companies ("mutuals" or acequias), which function as cooperatives and do not operate as profit maximizing firms. Organizations face a marginal cost of water brought into the system (p_w) that is a composite price reflecting 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 that vary with w_{in}. Since lining and piping canals is a long-run capital investment decision, the marginal costs of canal improvement is expressed as an annualized cost (ac_{lined} and ac_{piped}). These variables enter into the following cost minimization problem.

$$\min_{p_w, \gamma_{lined}, \gamma_{piped}} Cost_{w_{ag}} = p_w * w_{in} + ac_{lined} * \gamma_{lined} + ac_{piped} * \gamma_{piped}$$

$$s.t.$$

$$(1 - f(\gamma_{lined}, \gamma_{piped}, X_{CL})) * w_{in} = w_{ag} + w_{other} \tag{2}$$

$$\gamma^*_{lined} \geq 0$$

$$\gamma^*_{lined} \leq 100$$

$$\gamma^*_{piped} \geq 0$$

$$\gamma^*_{piped} \leq 100$$

The first constraint captures the water budget in which the net water inflows, subject to conveyance losses, must equal to the fixed water outflows. The last four constraints capture the possibility that organizations may face corner solutions in their lining and piping investment decisions. The Lagrangian form of this optimization problem incorporates shadow prices for all of these constraints.

$$\begin{aligned} \min_{p_w, \gamma_{lined}, \gamma_{piped}} \mathcal{L} = {} & (p_w * w_{in} + ac_{lined} * \gamma_{lined} + ac_{piped} * \gamma_{piped}) \\ & + \lambda_1((1 - f(\gamma_{lined}, \gamma_{piped}, X_{CL})) * w_{in} = w_{ag} + w_{other}) \\ & + \lambda_2(\gamma^*_{lined} \geq 0) + \lambda_3(\gamma^*_{lined} \leq 100) + \lambda_4(\gamma^*_{piped} \geq 0) \\ & + \lambda_5(\gamma^*_{piped} \leq 100). \end{aligned} \tag{3}$$

The first-order conditions for an interior solution, where λ_2 to λ_5 all equal zero, are:

$$\frac{\partial \mathcal{L}}{\partial w_{in}} = p_w - \lambda_1(1 - f(\gamma_{lined}, \gamma_{piped}, X_{CL})) = 0$$

$$\frac{\partial \mathcal{L}}{\partial \gamma_{lined}} = ac_{lined} + \lambda_1(w^*_{in}) \frac{\partial f(\gamma_{lined}, \gamma_{piped}, X_{CL})}{\partial \gamma_{lined}} = 0$$

$$\frac{\partial \mathcal{L}}{\partial \gamma_{piped}} = ac_{piped} + \lambda_1(w^*_{in}) \frac{\partial f(\gamma_{lined}, \gamma_{piped}, X_{CL})}{\partial \gamma_{piped}} = 0$$

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 (γ^0_{lined} and γ^0_{piped}), which implies a baseline state of conveyance loss (CL^0).

$$\text{(4)} \qquad \gamma^*_{lined} = \gamma^0_{lined} + \left(1 - \frac{p_w}{\lambda_1}\right)(f'(\gamma^*_{lined} \mid X_{CL}) - f'(\gamma_0 \mid X_{CL}))^{-1}.$$

Substituting for λ_1 from the second of the first-order conditions gives:

$$\text{(5)} \qquad \gamma^*_{lined} = \gamma^0_{lined} + \left(1 + \frac{p_w}{ac_{lined}}\right)((w_{in})f'(\gamma^*_{lined} \mid \gamma^0_{piped}, X_{CL}))$$
$$(f'(\gamma^*_{lined} \mid \gamma^0_{piped}, X_{CL}) - f'(\gamma^0_{lined} \mid \gamma^0_{piped}, X_{CL}))^{-1}.$$

The implication of this model for the research question in this paper is that the optimal investment in canal lining or piping depends upon the price of bringing water into these systems and the cost of lining or piping as well as the expected change in conveyance losses. 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.

3.3 Empirical Model

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

$$\text{(6)} \qquad \textit{Conveyance Losses}_i = G(\beta_0 + \beta_1 * \textit{Conveyance Lined}_i + \beta_2 * \textit{Conveyance Piped}_i + \gamma X_i) + \varepsilon_i,$$

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 nonlinear 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 (Unimproved$_i$) 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

$$\text{(7)} \quad Conveyance\{Unimproved_i, Lined_i, Piped_i\} = G(\lambda Z_i + \gamma X_i) + \varepsilon_i .$$

This approach instruments for endogenously determined conveyance characteristics while recognizing the interdependence of lining, piping, and unlined/piped conveyance infrastructure.

Recognizing the bounded nature of conveyance losses expressed as a fraction of total diversions, we use a control function estimation to address the potential endogeneity of Conveyance Lined$_i$ and Conveyance Piped$_i$ in our second stage model. The control function approach is preferred over other methods (e.g., two stage least squares) when the second stage is nonlinear 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

$$\text{(8)} \quad \begin{aligned} Conveyance\ Losses_i = G(&\beta_0 + \beta_1 * Conveyance\ Lined_i \\ &+ \beta_2 * Conveyance\ Piped_i + \gamma * W_i \\ &+ \phi_1 \nu_{Lined} + \phi_2 \nu_{Piped}) + \varepsilon_i , \end{aligned}$$

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 5.

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 lining and piping variables. Our instruments leverage information on reasons for not lining canals, the importance of municipal water deliveries in organization operations, and the role that constituents have in organization decision making. Specifically, we instrument for potentially endogenous conveyance infrastructure characteristics with the following variables: (1) a dummy variable indicating whether an organization cited expense as a reason for not lining their conveyance infrastructure; (2) a variable capturing the share of water delivered to the municipal sector; and (3) a dummy variable indicating whether constituents have input in organization management decisions through direct voting or representatives on an elected or appointed board. Not improving conveyance infrastructure due to expense represents exogenous local material and construction costs. These costs have no impact on conveyance losses outside of their effect on infrastructure improvement decisions provided that local construction and material markets are not dominated by organization infrastructure projects. The share of water delivered to the municipal sector reflects the benefits of conserved water as organizations can sell additional water supplies to municipal customers. These benefits presumably do not influence conveyance losses except through lining and piping as they primarily indicate the extent of residential development within the organization's service area, which is likely orthogonal to geographical and geological characteristics impacting conveyance losses. Finally, constituent input likely increases the likelihood that organization decision making aligns with constituent priorities related to water supply reliability and conveyance losses. As such, this input affects infrastructure investment but is otherwise unrelated to conveyance losses provided that organizations do not adjust their governance structures in response to losses.

3.4 Data

To estimate the econometric model outlined in equation 4 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 US 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 percent (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 survey responses 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.[5] 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.

3.4.1 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, specifying conveyance losses as part of outflows. Second, participants were asked to report conveyance loss as a percent of diversions.[6]

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, suggesting that about 4 percent of total inflows were either held back as storage within the irrigation systems, or outflows such as conveyance losses were underreported.

Due to the potential for underreporting conveyance losses in volumetric terms, this study relies primarily on self-reported conveyance loss in percentage terms. Missing or 0 percent conveyance losses are imputed from volumetric conveyance losses for those observations that reported volumetric

5. 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). We use the following criteria to select the observation used in our empirical analysis. In parentheses after each inclusion criteria are the number of remaining observations that meet that criteria as well as all other preceding criteria. (1) Water delivery organization (1,262); (2) Delivered water to farms in 2019 (1,254); (3) Provided information on conveyance infrastructure (857); (4) Report less than one mile of conveyance infrastructure per irrigable acreage (845); (5) Report non-zero conveyance losses or have 100 percent of total conveyance piped and report zero conveyance losses (692); (6) Are located within a state with at least 5 observations (674); and (7) Report correct FIPS number for state where organization is located (673).

6. 484 respondents provided information on conveyance losses in terms of volume of water lost and the share of water lost. For these organizations, comparing the reported share of water lost to the reported volume of water lost (converted to a share of total water diverted) results in a correlation coefficient of 0.734. Approximately 71 percent of organizations that disclose conveyance losses in percentage and volumetric terms report values within 10 percentage points, when converting the volumetric conveyance loss data to a share using total water diverted.

Table 3.1 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

conveyance loss. Of the 673 respondents in our sample, 598 report positive conveyance losses as a percent of diversions or in acre-feet. Of these, 530 report positive conveyance losses in percentage terms. Observations that report zero conveyance loss in both measures are only included if they report that 100 percent of their conveyance infrastructure is piped.[7] About 15 percent of the "zero" conveyance loss organizations report that 100 percent of their infrastructure is piped.

Percent conveyances losses are skewed toward lower values. Over 70 percent of organizations report a conveyance loss below 20 percent. Table 3.1 presents conveyance loss summary statistics. The average conveyance loss is 14.9 percent. This is slightly smaller than the volume-based national estimate cited above, but is consistent with the possibility that the national number includes underreporting due to some of the "zero" conveyance loss organizations that are excluded from our sample.

3.4.2 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 main and lateral canals, and for each of those they separately reported on miles that are unlined (i.e., unimproved), 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.

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.

Figure 3.2 demonstrates the heterogeneity of organization-level conveyance infrastructure characteristics by plotting the percent of organizations and acreage served by an organization falling within differing, mutually exclusive categories of conveyance characteristics. Approximately 43 per-

7. Piping can conceivably reduce conveyance losses to zero (Newton and Perle 2006).

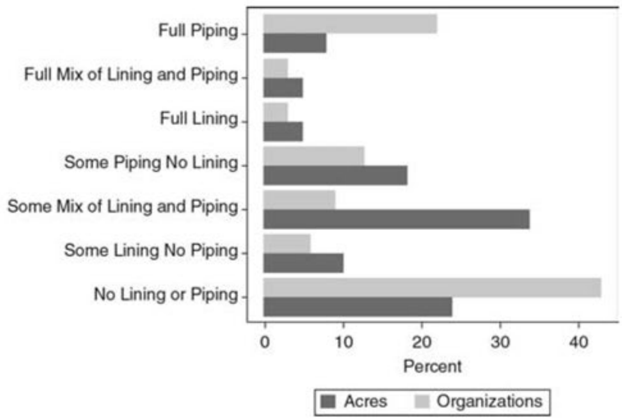

Fig. 3.2 Categories of lining and piping shares by percentage of organizations and acreage
Source: USDA-NASS, 2019 Survey of Irrigation Organizations.

cent of organizations have no lined or piped conveyance infrastructure. These organizations account for 23 percent of acreage served, indicating that organizations with no lined or piped canals are generally small in terms of acreage and service area. Meanwhile, 9 percent of organizations delivering water to 34 percent of acreage have some mix of lined and piped infrastructure, suggesting that larger organizations are more likely to invest in both lined and piped conveyance. Finally, 22 percent of organizations serving 8 percent of acreage have a fully piped conveyance system. Organizations with a fully lined or a full mix of lined and piped conveyance are relatively less common, each accounting for about 3 percent of organizations and 2 percent and 5 percent of acreage, respectively.

3.4.3 Exogenous Covariates and Instrumental Variables

Table 3.2 presents summary statistics for the exogenous covariates and instrumental variables used to estimate equation 4. Note that these summary statistics represent a sample of the full set of organizations surveyed in the SIO. 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," "July Mean Daily Temperature," "Water Stress," and "Drought Risk." "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

Table 3.2 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
Water Stress	0.8602	1.3503
Drought Risk	2.7153	0.2147
Unlined due to:		
GW Recharge (0/1)	0.2036	0.4029
Min. Seepage (0/1)	0.1516	0.3589
Other (0/1)	0.0951	0.2936
Instruments		
Unlined due to Expense (0/1)	0.5587	0.4969
Municipal Deliveries (share)	0.0574	0.1511
Can Vote (0/1)	0.9287	0.2576

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 US, 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. "Unlined Due to:(x)"are a suite of dummy variables signaling whether the organization reported that the following were reasons for leaving conveyance unlined: 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.

"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 as greater volumes of water are lost to evaporation (Wang et al. 2013). "Water Stress" is an index variable based HUC-8 level output from the Water Supply Stress Index Model (WaSSI) (Sun et al. 2015). HUC-8 level historical water stress output from WaSSI is mapped to county cropland geospatial data to derive a county-level measure of historical water stress, which is then matched to the organizations within that county. In cases where multiple HUC-8s occur within a county, the county-level measure is an area weighted average. "Drought Risk" is the standard deviation of July Palmer Modified Drought Index (PDMI) data calculated using weather station data spanning the past century (Mo and Chelliah 2006; Wallander et al. 2013). Weather station point data are spatially interpolated to the county level, which is then matched to organizations within the county. Including climatic and water stress related variables aims to control for the role that expectations related to water scarcity and drought have in determining conveyance losses.

We instrument for potentially endogenous "Conveyance Lined" and "Conveyance Piped" with a set of three variables representing information on reasons for not lining canals, the importance of municipal water deliveries in organization operations, and the role that constituents have in organization decision making. Specifically, "Unlined Due to Expense" is a dummy variable indicating whether an organization cited expense as a reason for not improving conveyance infrastructure. "Municipal Deliveries" is the share of total organization water outflows delivered to municipal customers. "Can Vote" is a dummy variable representing whether constituents have input in organization management decisions through direct voting or representatives on an elected or appointed board.

3.5 Results

Table 3.3 presents results estimating the empirical model outlined in equation 4 using the data described in section 3.4. 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 4 but does not instrument for potentially endogenous conveyance lining or piping decisions. Column 3 also presents fractional response logistic model results but instruments for potential endogeneity in the conveyance infrastructure covariates using a control function approach.

Table 3.3 **Conveyance loss empirical model results**

	Linear Uninstrumented	Logistic Uninstrumented	Logistic Control Function
Conveyance Lined (share)	−0.0684**	−0.0623*	0.0620
	(0.0243)	(0.0250)	(0.0569)
Conveyance Piped (share)	−0.1004***	−0.1328***	−0.1750***
	(0.0156)	(0.0192)	(0.0310)
Unlined due to:			
GW Recharge	0.0275	0.0247*	0.0239
	(0.0150)	(0.0119)	(0.0123)
Min. Seepage	−0.0212	−0.0170	−0.0228
	(0.0155)	(0.0138)	(0.0135)
Other	0.0130	0.0107	0.0108
	(0.0182)	(0.0139)	(0.0141)
Log Acres	0.0149***	0.0151***	0.0131***
	(0.0038)	(0.0034)	(0.0035)
Conveyance Density	0.1349	0.1211	0.1236
	(0.0905)	(0.0697)	(0.0700)
Sufficient Water in 2019	−0.0105	−0.0134	−0.0103
	(0.0112)	(0.0112)	(0.0112)
Required to Report Use	−0.0049	−0.0038	0.0014
	(0.0110)	(0.0107)	(0.0111)
Phreatophyte Problems	0.0420***	0.0443***	0.0328*
	(0.0126)	(0.0122)	(0.0140)
July Mean Daily Temperature (°C)	−0.0028	−0.0031	−0.0024
	(0.0022)	(0.0022)	(0.0023)
Water Stress	0.0051	0.0050	0.0044
	(0.0040)	(0.0037)	(0.0038)
Drought Risk	0.0738**	0.0820**	0.0822**
	(0.0257)	(0.0277)	(0.0276)
R^2	0.2575	0.2690	0.2698
Adj. R^2	0.2312	0.2419	0.2404
Num. obs.	673		
n		673	673
DF		649	647
Sigma		0.1255	0.1255

Note: 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 percent of conveyance piped and no conveyance loss.
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

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, Ramalho, and Murteira (2011).

Nearly all model specifications yield negative and statistically significant estimates of β_1 and β_2, the parameters of interest from equation 4. 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 approximately 0.06 percentage points. However, this result is only statistically significant and negative for the specifications which do not instrument for potential endogeniety between conveyance lining/piping and losses. The control function IV specification yields a parameter estimate suggesting a positive relationship between lining and conveyance losses, however this result is not statistically significant. 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 0.1 and 0.175 percentage points.

The difference in the average marginal effect of piping versus lining conveyance infrastructure may be related to the relevant lifespan of each canal improvement option. Namely, piped canals generally have a longer lifespan than lined canals (Newton and Perle 2006). Lined conveyance infrastructure can degrade quickly without costly routine maintenance to address cracked lining materials, which can significantly increase conveyance losses (Plusquellec 2019). Given that the data used to estimate the effect of lining and piping on conveyance losses do not include information on the age of the improved infrastructure, our estimated effects relate to the efficiency of lined and piped canals of an average age within our data. These estimated effects may underestimate the conveyance loss mitigation potential of newly improved canals, particularly lined canals.

Parameter estimates for the suite of explanatory variables citing why organizations leave canals unimproved (Unlined Due to:[x]) follow intuition. Citing groundwater recharge (GW Recharge) as a reason for not improving conveyance is associated with higher conveyance losses as these losses contribute toward potential groundwater recharge objectives. Reporting minimal seepage (Min. Seepage) as a reason for not improving canals is negatively linked to conveyance losses as cited soil and geologic attributes diminish losses. Finally, the catch-all Other category for reasons for not lining canals is positively correlated with conveyance losses.

Other explanatory variable parameter estimates also 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 losses 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 negatively associated conveyance losses but the relationship is not statistically significant.

Logistic model estimates indicate that water use reporting requirements are also generally associated with lower conveyance losses. However, these estimates are not statistically significant and the sign of the parameter estimate changes for the control function logistic model specification. 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, the suite of parameters associated with variables capturing the effects of climate and water scarcity on conveyance losses yields somewhat surprising results. Increasing water stress and drought risk are both associated with increased conveyance losses, however this relationship is only statistically significant for drought risk. Higher conveyance losses in locations with higher incidence of drought potentially suggest that other climatic conditions that covary with drought (e.g., air temperature, solar radiation), which increase evaporative losses, may be driving the estimated relationship. Parameter estimates for July mean temperature run contrary to this reasoning as all three model specifications find a negative relationship between July temperatures and conveyance losses. However, this relationship is not statistically significant.

3.5.1 Statistical Tests and First-Stage Model Results

In table 3.4 we report relevant test statistics for the IV control function specification. We conduct a Wu-Hausman test of the null hypothesis that both the uninstrumented model (column 2 in table 3.3) and the instrumented model (column 3 in table 3.3) are consistent (Hausman 1978). We also conduct tests examining instrument strength for the IV control function specification. The standard F-Test for weak instruments (Stock, Wright, and Yogo 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.

The Wu-Hausman test statistic fails to reject the null hypothesis that both models are consistent, suggesting that endogeneity is not a significant issue for the uninstrumented model. As such, our preferred specification, based on efficiency criteria, is the uninstrumented logistic specification (column 2

Table 3.4 **IV tests**

Test	Statistic	DF	Endog DF	p-value
Wald (Conveyance Lined)	96.9672	3		0.0000
Wald (Conveyance Piped)	260.0475	3		0.0000
Wu-Hausman	0.4221	1	649	0.5159

Table 3.5 **First-stage model results**

	Dependent Variables: Share of Conveyance	
	Lined	Piped
	(1)	(2)
	Instruments	
Unlined due to Expense	−2.8705***	−3.6111***
	(0.3107)	(0.2287)
Municipal Deliveries (share)	2.1602**	1.1836
	(0.7413)	(0.6202)
Can Vote	−0.2438	0.7623*
	(0.3889)	(0.3514)
	Exogenous Covariates	
Unlined due to:		
GW Recharge	−1.4177**	−2.1157***
	(0.4793)	(0.4142)
Min. Seepage	−0.7078	−2.0006***
	(0.3712)	(0.3653)
Other	−2.6238***	−3.0544***
	(0.4867)	(0.3247)
Log Acres	0.3368***	0.1345*
	(0.0709)	(0.0582)
Conveyance Density	5.3123*	5.3715***
	(2.3253)	(1.4192)
Sufficient Water in 2019	−0.1561	0.2684
	(0.2670)	(0.2006)
Required to Report Use	−0.0608	0.4145*
	(0.2734)	(0.1987)
Phreatophyte Problems	−0.0074	−1.0203***
	(0.2702)	(0.2039)
July Mean Daily Temperature (°C)	−0.0020	0.0810^*
	(0.0499)	(0.0361)
Water Stress	−0.0589	−0.1467
	(0.1135)	(0.0965)
Drought Risk	0.0811	0.2710
	(0.5588)	(0.3868)

in table 3.3). Finally, Wald test statistics suggest that instrumental variables explain a significant degree of variation in the share of conveyance lined and conveyance piped, suggesting that weak instruments are not a concern.

While the Wu-Hausman test statistic reveals a preference for the uninstrumented model specification, results from the first stage of the IV control function specification are useful in understanding factors that influence organization conveyance infrastructure characteristics. Table 3.5 presents these first-stage model results related to the IV control function specification. We begin with a discussion of the estimated relationship between instrumental variables and canal lining and piping and then briefly discuss how other exogenous covariates influence conveyance infrastructure.

The expense of improving conveyance infrastructure is negatively associated in a statistically significant manner with the share of organization conveyance that is lined and piped, indicating the importance of exogenous costs in determining conveyance improvement investments. Meanwhile, the share of water delivered to municipal customers is positively correlated with the share of conveyance that is lined and piped, however this relationship is only statistically significant for canal lining. This result demonstrates the importance of the opportunity cost of water lost in conveyance in determining organization conveyance investment decisions. Having a means to sell water conserved increases the share of lined and piped conveyance infrastructure. Finally, constituent ability to influence organization decision making yields mixed results with respect to lining and piping. Constituent voting decreases canal lining but increases canal piping, however this relationship is only statistically significant for the share of piped conveyance. This result potentially indicates a preference among constituents for canal piping compared to lining.

The remaining exogenous covariates also reveal informative relationships concerning the share of lined and piped conveyance. The suite of variables concerning reasons organizations do not improve conveyance canals all yield the expected negative relationship. Additionally, organizations with larger and more dense conveyance systems have larger shares of lined and piped canals. This relationship suggests the importance of capital constraints in determining conveyance characteristics as larger, potentially less capital-constrained organizations have a larger share of their canals lined and/or piped.

3.5.2 Conditional Marginal Effect of Lining and Piping Conveyance

The average marginal effects of canal lining and piping presented in table 3.3 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 percent 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 3.3, which separately plots the conditional marginal effects for differing shares of lining and piping. Specifically, figure 3.3 calculates the marginal effect for the full range of observed shares of conveyance that is lined or piped using regression results from column (2) of table 3.3 and conditioning on the mean or mode of all covariates.[8] The left panel of figure 3.3 plots the conditional

8. 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.

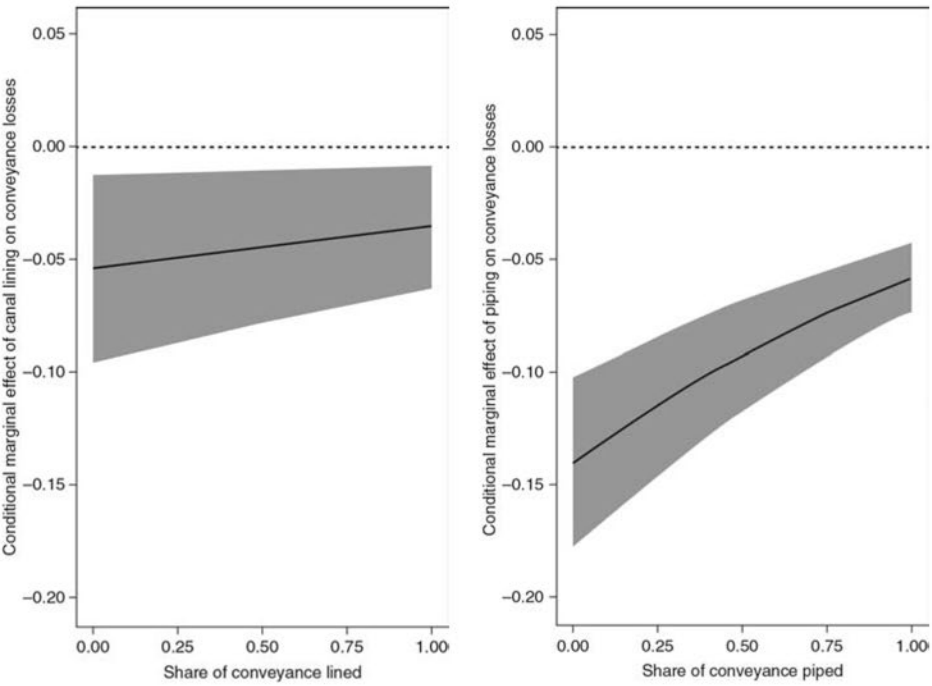

Fig. 3.3 Marginal effect of canal lining and piping on conveyance losses
Note: Marginal effects are calculated using methods outlined in Ramalho, Ramalho, and Murteira (2011). The shaded area represents the 95 percent confidence interval for the marginal effect estimated at a given level of the share 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.

marginal effect of lining and demonstrates that the effect of lining becomes marginally smaller across the [0,1] range. The right panel of figure 3.3 plots the conditional marginal effect of piping and indicates that the impact of piping also wanes across the [0,1] range. For example, increasing the share of conveyance piped for an organization with no piped infrastructure by 1 percentage point leads to an approximate 0.15 percentage point reduction in conveyance losses. Meanwhile, the same increase in piped conveyance for an organization with 75 percent of its conveyance piped yields approximately a 0.07 percentage point reduction in conveyance losses.

3.5.3 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 or pipe 100 percent of an organization's unimproved canals (either unlined or unpiped). This exercise illustrates how a coordinated water conservation effort that begins with least cost conservation options would initially capture a fair amount of low-cost conservation but will rapidly progress to more expensive options. This exercise also provides a useful means to compare the relative cost-effectiveness of investments in lining versus piping canals.

We estimate the change in water availability due to investments in the lining and piping of conveyance infrastructure using results from the logistic model specification (see column 2 of table 3.3) to calculate, for each organization, the predicted change in conveyance losses if all unimproved infrastructure was lined or piped. To estimate this change in organization level conveyance losses we use a linear approximation of the conditional marginal effect functions (see figure 3.3), conditioning based on the organization-level observed covariate values. We integrate this function between each organization's current level of lining or piping and 100 percent lined or piped to find the total change in conveyance losses associated with fully lining or piping remaining unimproved infrastructure. For example, consider an organization that currently has 10 percent of its conveyance lined, 10 percent of its conveyance piped, and 80 percent of its conveyance is unimproved. To simulate how fully lining or piping the remaining unimproved canals affects conveyance losses, we estimate how losses change when lining or piping the remaining 80 percent of the organization's conveyance, taking into account how the marginal effect changes as a larger share of infrastructure is lined or piped. Reductions in conveyance losses are then aggregated across all organizations and converted into percentages of total water inflows to facilitate comparison with aggregate conveyance losses. Finally, we leverage estimated canal lining and piping costs to calculate, for each organization, the cost of fully lining/piping all unimproved canals. Specifically, we integrate cost estimates provided by the USDA's Natural Resources Conservation Service (NRCS) and organization-level data on the length of unimproved canals to calculate the cost associated with fully lining or piping (USDA-NRCS 2020a; USDA-NRCS 2020b). Many construction options exist when lining and piping canals. For example, canals may be lined with concrete or less expensive geomembranes. As such, we calculate lining and piping costs using three cost estimates ("Low," "Medium," and "High").[9]

The combination of estimated changes in conveyance losses and lining/piping costs provides a marginal cost of conservation for each organization. Ordering these organization-level marginal costs yields supply curves for water conservation resulting from lining and piping, which are introduced

9. Low, Medium, and High canal lining costs are \$30,000, \$60,000, and \$228,000, respectively, per mile of lined canals. These costs are drawn from an NRCS publication and correspond to minimum, mean, and maximum cost estimates. 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 involving the piping of irrigation infrastructure (USDA-NRCS 2020b).

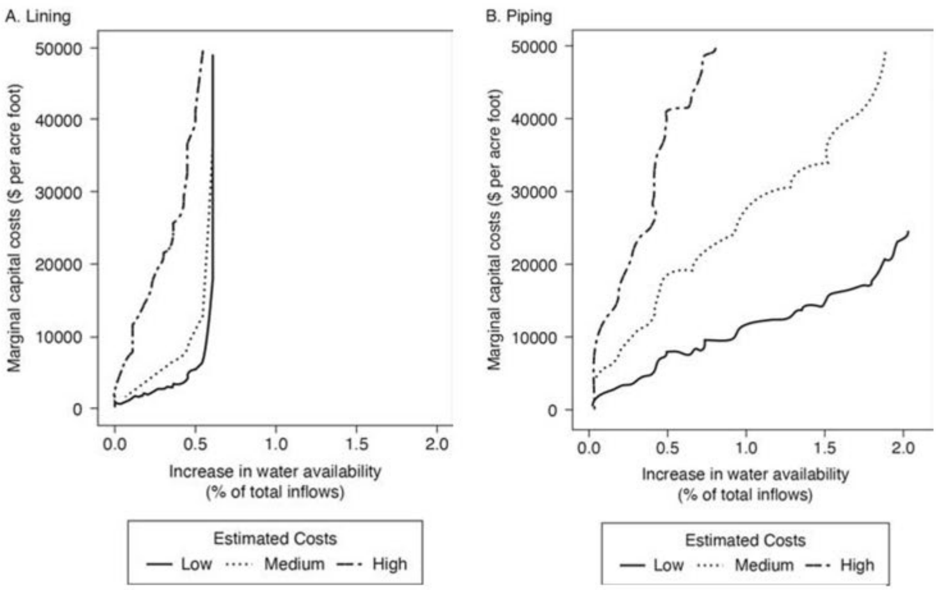

Fig. 3.4 Supply curve of water conservation through lining and piping conveyance infrastructure investments

Note: Panels A and B represent the water conservation supply curves for lining and piping, respectively. The Low, Medium, and High costs for lining canals refer to $30,000, $60,000, and $228,000 per mile of lined canals, respectively (USDA-NRCS 2020a). The Low, Medium, and High costs for piping canals refer to $629,000, $1,512,000, and $3,239,000 per mile of piped canal, respectively. Marginal capital costs represent private costs for lining and piping infrastructure which in some cases may differ from the total social costs of improving water conveyance infrastructure. For example, conveyance losses may be recharging an aquifer that supplies water for a wetland habitat. Lining or piping conveyance could potentially impose additional social costs if diminishing losses reduce water flows to the wetland and damage the habitat. The effects of lining and piping on water availability presented here relate to the average age of infrastructure in the data used to estimate our empirical model (see table 3.3). Newly lined and piped canals may yield larger increases in water availability than those estimated here.

in figure 3.4. Figure 3.4a demonstrates the water conservation potential of investments in canal lining. Our simulation exercise indicates that strategic investments in canal lining can increase total water availability by 0.3 percent to 0.6 percent, depending on the cost scenario. In the low cost scenario these increases are achieved for less than $20,000 per acre-foot conserved and correspond to between a 2 percent and 4 percent reduction in aggregate conveyance losses. Figure 3.4b presents the water conservation capacity of piping investments. Depending on the cost scenario, strategic investments in piping irrigation conveyance can yield between 0.3 percent to 1.75 percent increases in total water availability. In the lost cost scenario these increases are obtained for less than $20,000 per acre-foot conserved. These changes in water availability correspond to between a 2 percent and 12 percent decrease in total conveyance losses. As increases in water availability due to canal lining and 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 US, suggesting that lining or piping may be more cost effective than purchasing rights on the open market (Schwabe et al. 2020).

Comparing figure 3.4a and figure 3.4b demonstrates the differences in the relative cost efficiency of canal piping and lining. Namely, canal lining is relatively more cost effective than piping when aiming to achieve small (between 0.1 percent and 0.5 percent depending on the cost scenario) aggregate increases in water availability. For larger increases in water availability piping canals is more effective as the low price of lining projects is outweighed by their relatively smaller reduction in conveyance losses. Together these results suggest that a combination of investments in lining and piping may be optimal to achieve water conservation objectives. Finally, given that our empirical estimates of the impact of conveyance improvements correspond to effects for the average age of lined and piped infrastructure within our sample, it may be the case that newly lined or piped canals yield larger increases in available water, making initial investments in conveyance improvements more cost effective than calculated here.

3.6 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 US to empirically characterize 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 0.17 percentage points. We also find that lining canals generates reductions in conveyance losses, however these effects are smaller in magnitude ranging from 0.06 to 0.07 percentage points.

A simple simulation exercise focused on the costs and benefits of conveyance lining and piping demonstrates how investments in improved water conveyance infrastructure can provide cost-effective water conservation, initially at costs near that of procuring new supplies via market transaction (Schwabe et al. 2020). These simulations demonstrate that conveyance investments can increase total water availability by between 0.3 percent and 1.75 percent, which corresponds to between a 2 percent and 12 percent decrease in aggregate conveyance losses. For smaller increases in water availability lining canals is more cost effective than piping. However, for larger increases in water availability piping is more cost effective, indicating that a mix of both lining and piping investments is likely optimal to meet water conservation objectives.

Together our empirical and simulation modeling results provide important evidence informing the use of conveyance infrastructure improvements to conserve water. Growing water scarcity concerns throughout the western US and globally underscore the importance of understanding the costs and benefits of the range of policy mechanisms and investments available to enhance water availability (Hanjra and Qureshi 2010: Mancosu et al. 2015: Dinar, Tieu, and Huynh 2019; Siirila-Woodburn et al. 2021). Ample research explores the water conservation potential of farm-level practices and technology adoption (Van der Kooij et al. 2013; Pfeiffer and Lin 2014; Williams, Wuest, and Long 2014; Wang et al. 2021; Huang et al. 2021; Novara et al. 2021). Our research builds on this extensive literature by providing novel evidence regarding how investments in off-farm infrastructure can increase water availability, affording policy makers another tool to address water scarcity and support the irrigated agricultural sector.

The estimated water conservation potential of investments in conveyance infrastructure invite additional research questions which merit attention within the literature. For example, our empirical modeling does not specifically address the longevity of lined and piped canals which may be particularly important for lined canals which degrade relatively quickly (Plusquellec 2019). Additional research is needed characterizing how the dynamics of conveyance infrastructure longevity affect investment decisions. Finally, our simulation model focuses solely on the water conservation returns of the initial capital costs for installing improved conveyance infrastructure. However, there are potentially maintenance and operation costs which may influence organization investment decisions and water conservation outcomes. Additional research is needed to understand these dynamics and their impact on optimal public and private investment in conveyance infrastructure improvements.

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