United States Department of Agriculture

A National Estimate of Irrigation Canal Lining and Piping Water Conservation

NBER Workshop: Economic Perspectives on Water Resources, Climate Change, and Agricultural Sustainability

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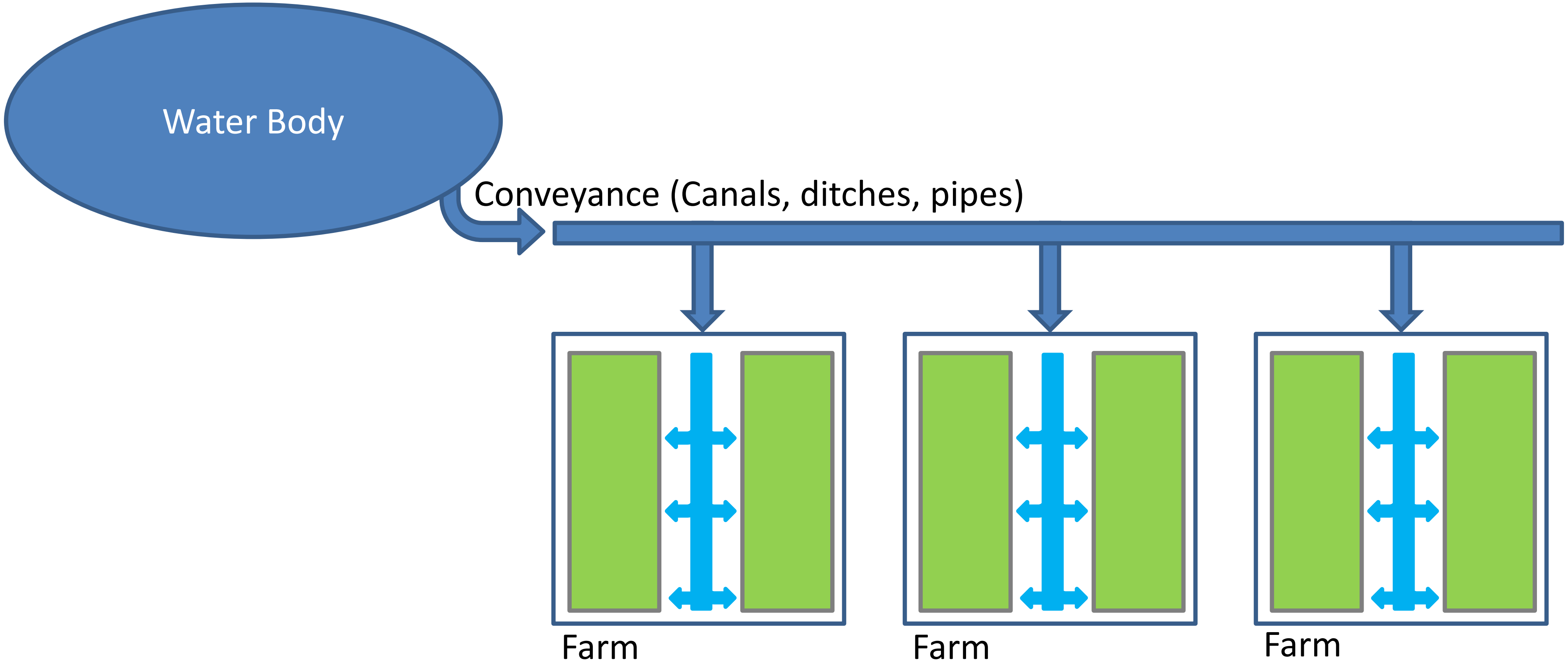
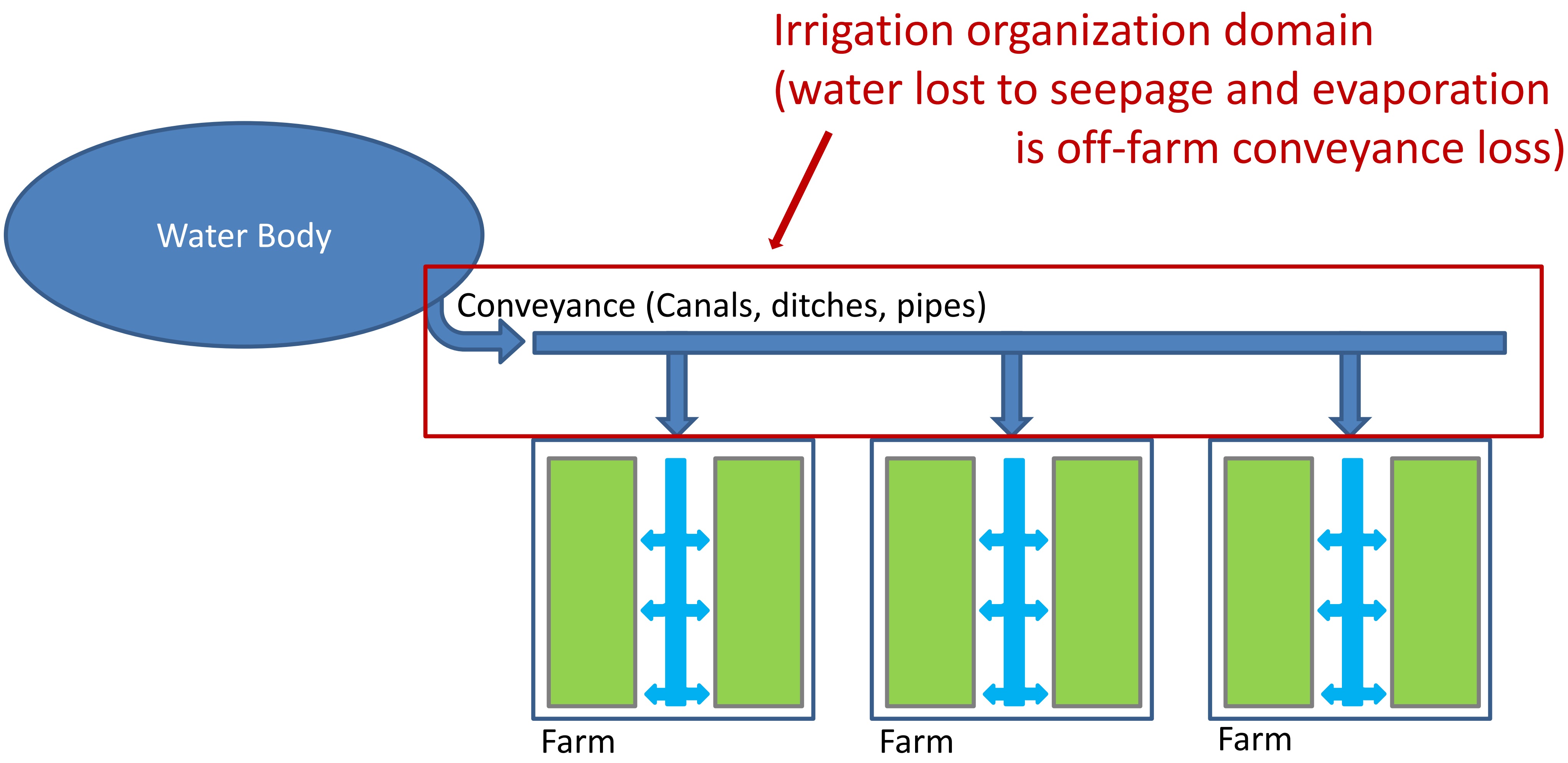
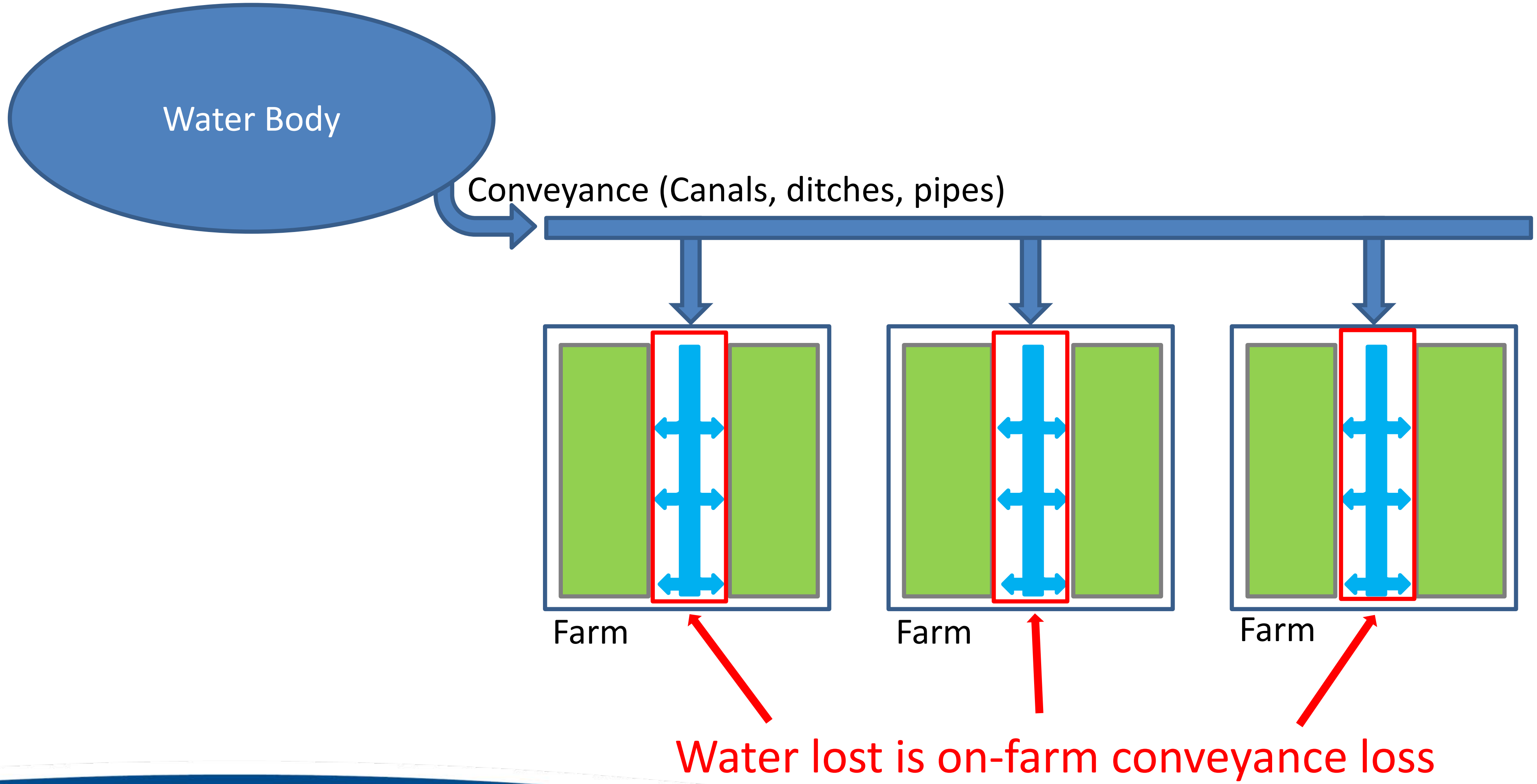
Research questions

- How large are conveyance losses within irrigation delivery systems (ditch companies and irrigation districts)?
- How much does lining and piping of canals and laterals reduce conveyance losses?
  - Is there evidence of endogeneity in the correlation between lining and conveyance losses?
- What is the water conservation potential of investments in conveyance infrastructure?


Water Body
Conveyance (Canals, ditches, pipes)
Farm
Farm
Farm


Irrigation organization domain
(water lost to seepage and evaporation
is off-farm conveyance loss)
Water Body
Conveyance (Canals, ditches, pipes)
Farm
Farm
Farm

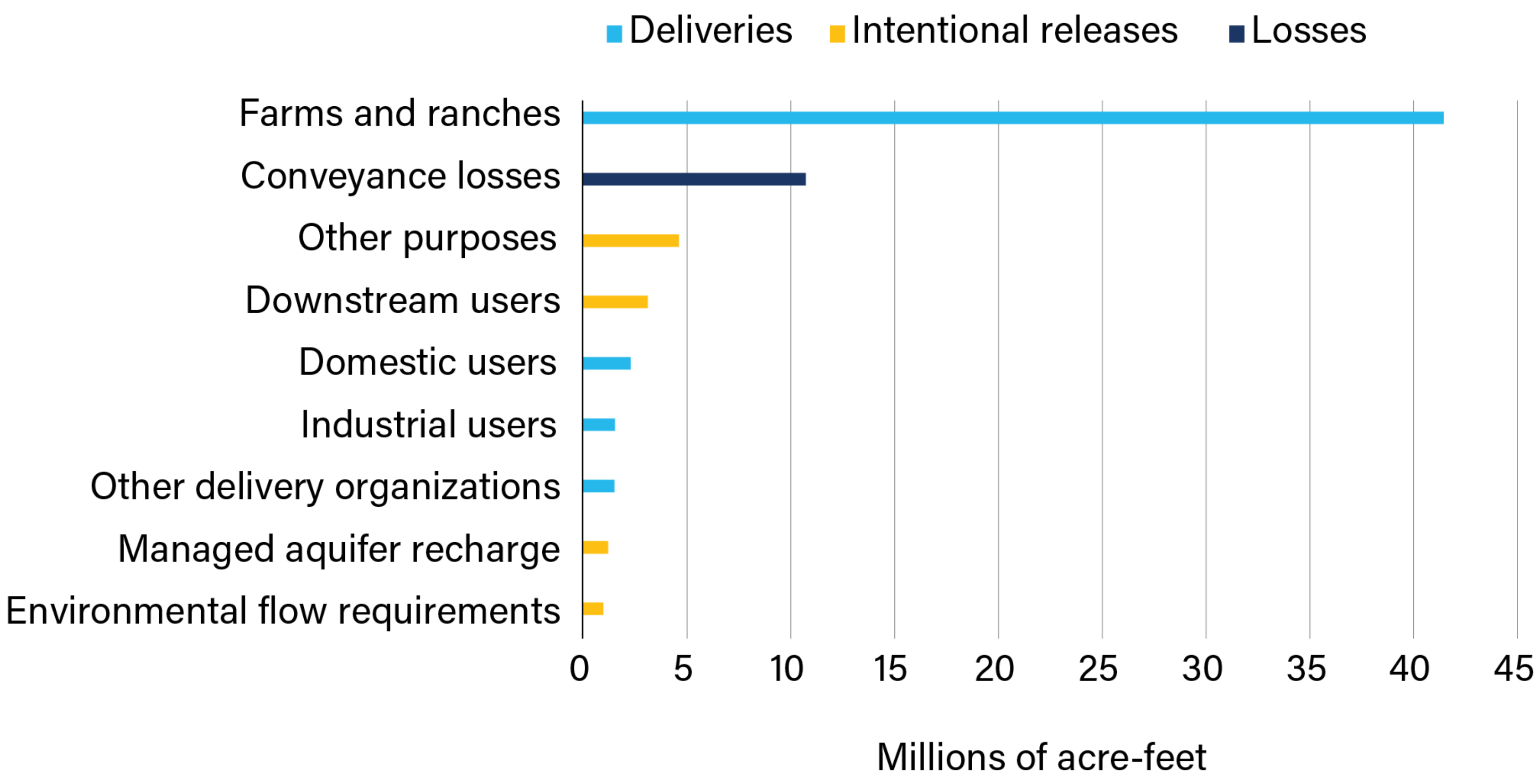

Water Body
Conveyance (Canals, ditches, pipes)
Farm
Farm
Farm
Water lost is on-farm conveyance loss

Conveyance of off-farm water

- Off-farm water requires significant infrastructure: diversions, canals, ditches, turnouts, piping, etc…
- About 15% of all water is lost during conveyance (USDA-NASS 2020)
- Opportunity cost of conveyance losses are likely to grow as water scarcity increases (Reidmiller et al., 2019; Evan and Eisenman, 2021)

Water outflows for irrigation water delivery organizations, 2019

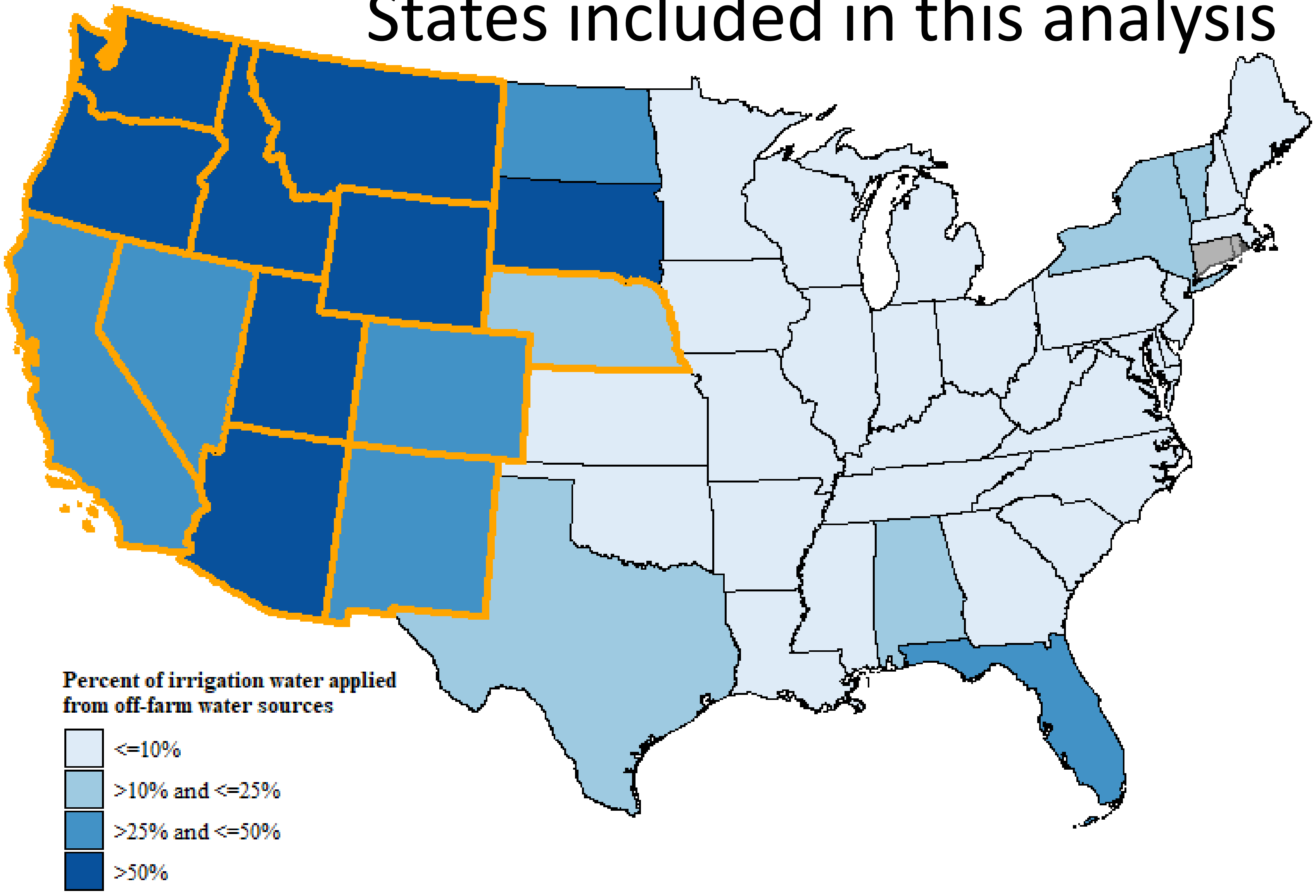
USDA Economic Research Service
U.S. DEPARTMENT OF AGRICULTURE



Note: Acre-feet is the amount of water needed to cover one acre of land under a foot of water. Conveyance losses represent water lost during transport or storage because of groundwater seepage or evaporation. Conveyance loss data only accounts for self-reported losses that occurred within organizations' storage and conveyance infrastructure and do not account for losses that might occur before water entered the organizations' systems or after water is delivered to the farm.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2019 Survey of Irrigation Organizations. Data as of December 17, 2020.

States included in this analysis



Source: USDA-NASS, 2018 Irrigation and Water Management Survey.

Why not line and pipe all conveyance?

- Less than half of conveyance is lined (Hrozencik et al. 2021)
- Lining/piping is costly. Piping can range from $629,000 to 3,239,000 per mile (USDA-NRCS, 2020).
- In some cases, purchasing additional water rights may be less expensive than lining/piping
    - $85,000 per acre-foot on the Colorado front range (2020)
    - $2,500 per acre-foot in Arizona Mohave desert (2018)

Research has focused on the farmer who is applying water for irrigation

Farmers may respond to water scarcity by

- Improving on-farm irrigation water management such as automation and precision-applications (Koech and Langat, 2018)

- Improving on-farm irrigation infrastructure increases efficiency but may also increase use on the extensive margin (Pfeiffer and Lin, 2014)

Relatively little empirical work on the water delivery organization side

- Constrained by a lack of data (Wallander et al., 2022)
- Engineering estimates of effect of lining/piping conveyance on conveyance loss (Sultan et al., 2014; Taylor 2016)
  - May lack external validity (i.e. site selection is not random)
- Umetsu and Chakravorty (1998) model investment decisions as a function of seepage and return flows
- Ward (2010) provides a comprehensive overview of the economic incentives and policy mechanisms determining irrigation infrastructure investments.

Empirical Approach

Endogeneity of conveyance loss and conveyance lining/piping

$$Conveyance\ Loss_i = G(Conveyance\ Lined_i, Conveyance\ Piped_i, X_i) \qquad (1)$$

$$Conveyance\ \{Unlined_i, Lined_i, Piped_i\} = F(E[Conveyance\ Loss_i], Z_i, X_i) \qquad (2)$$

Where:

- $Conveyance\ Loss_i$ is water lost in conveyance as a share of total water conveyed
- $Conveyance\ Lined_i$ and $Conveyance\ Piped_i$ are the share of total conveyance
- Z_i is a set of explanatory variables that are orthogonal to $Conveyance\ Loss_i$
- X_i is a set of exogenous explanatory variables

First stage

The first stage is a **fractional multinomial model** (Papke and Wooldridge 1996)

- decisions to line/pipe/leave unlined are mutually exclusive

$$Conveyance\ \{Unlined_i, Lined_i, Piped_i\} = F(\phi Z_i + \rho X_i) + \mu_i$$

Where:

- $Conveyance\ \{Unlined_i, Lined_i, Piped_i\}$ must sum to one.
- Z_i are a set of instruments (e.g. cost of lining/piping, need for groundwater recharge)
- X_i is a set of exogenous explanatory variables (e.g. temperature, irrigable acres, phreatophytes)

Second stage

The second stage is a **fractional response model** estimated with a **control function** approach (Wooldridge 2015)

- Nonlinearity in responses in both stages

$$Conveyance\ Losses_i = G\left(\beta_0 + \beta_1 \times Conveyance\ Lined_i + \beta_2 \times Conveyance\ Piped_i + \gamma X_i + \psi_1 \nu_{lined} + \psi_2 \nu_{piped}\right) + \varepsilon\_i$$

where ν_{lined} and ν_{piped} are the residuals for $Conveyance\ Lined_i$ and $Conveyance\ Piped_i$ from the first stage.

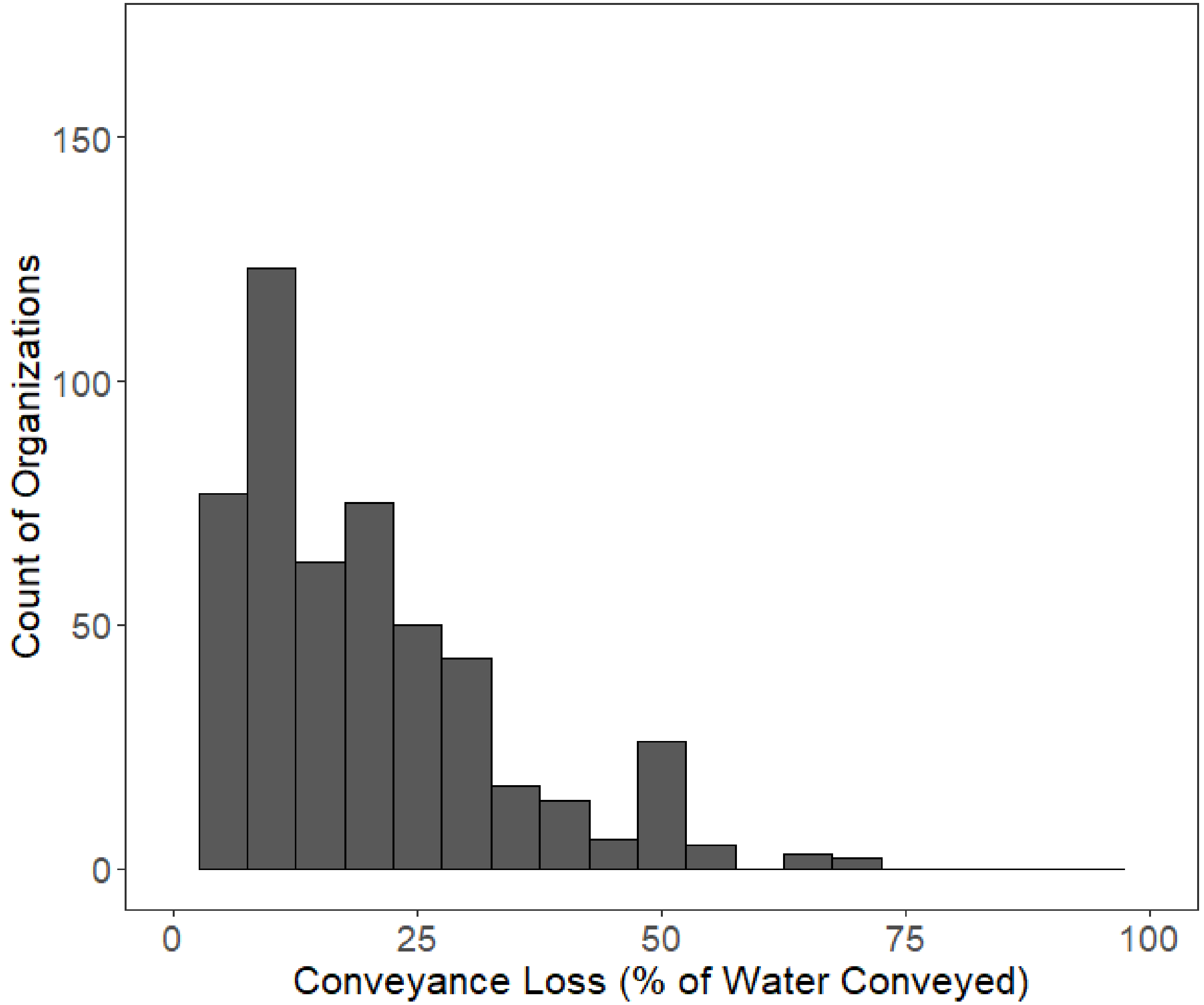
Data

2019 Survey of Irrigation Organizations

- Collected data representing 2,677 organizations involved in managing local water supplies
  - 2,543 water delivery organizations
  - 735 groundwater organizations
    - 582 are both delivery and groundwater

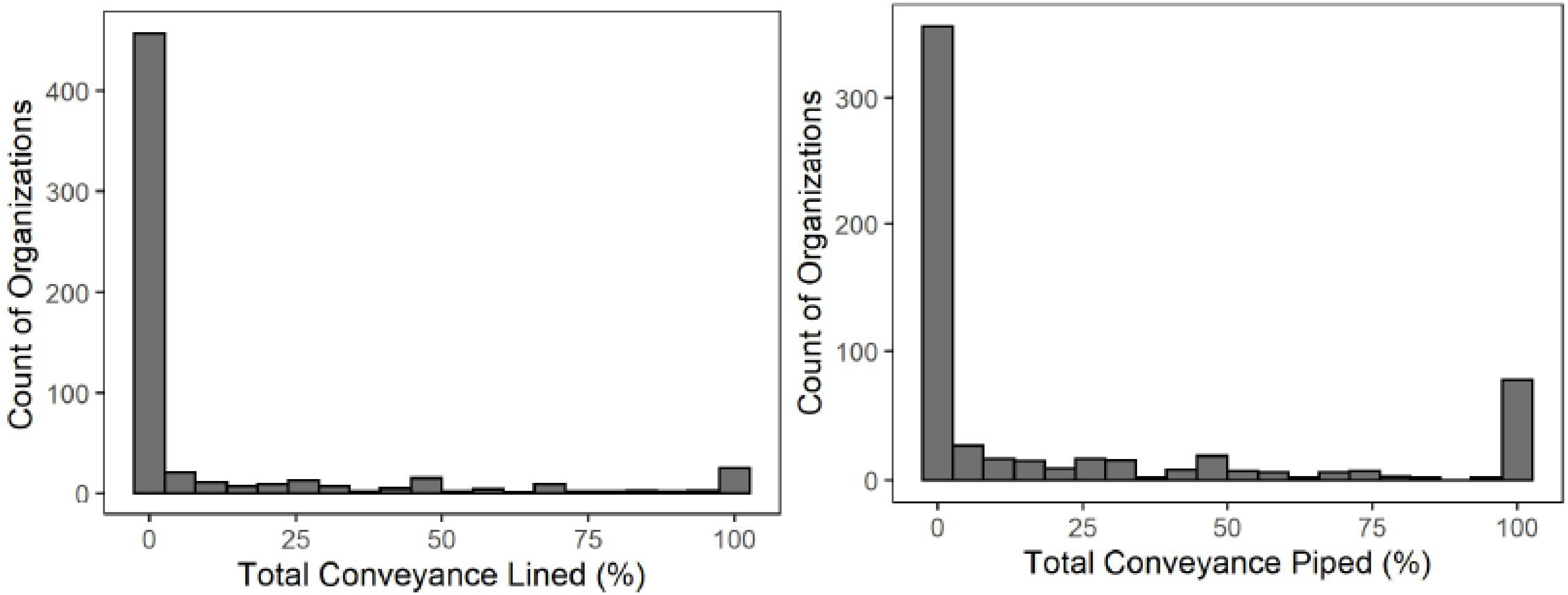
- Asked respondents to report on total water supplies, conveyance losses, and lined, piped, and unimproved conveyance infrastructure

Conveyance losses



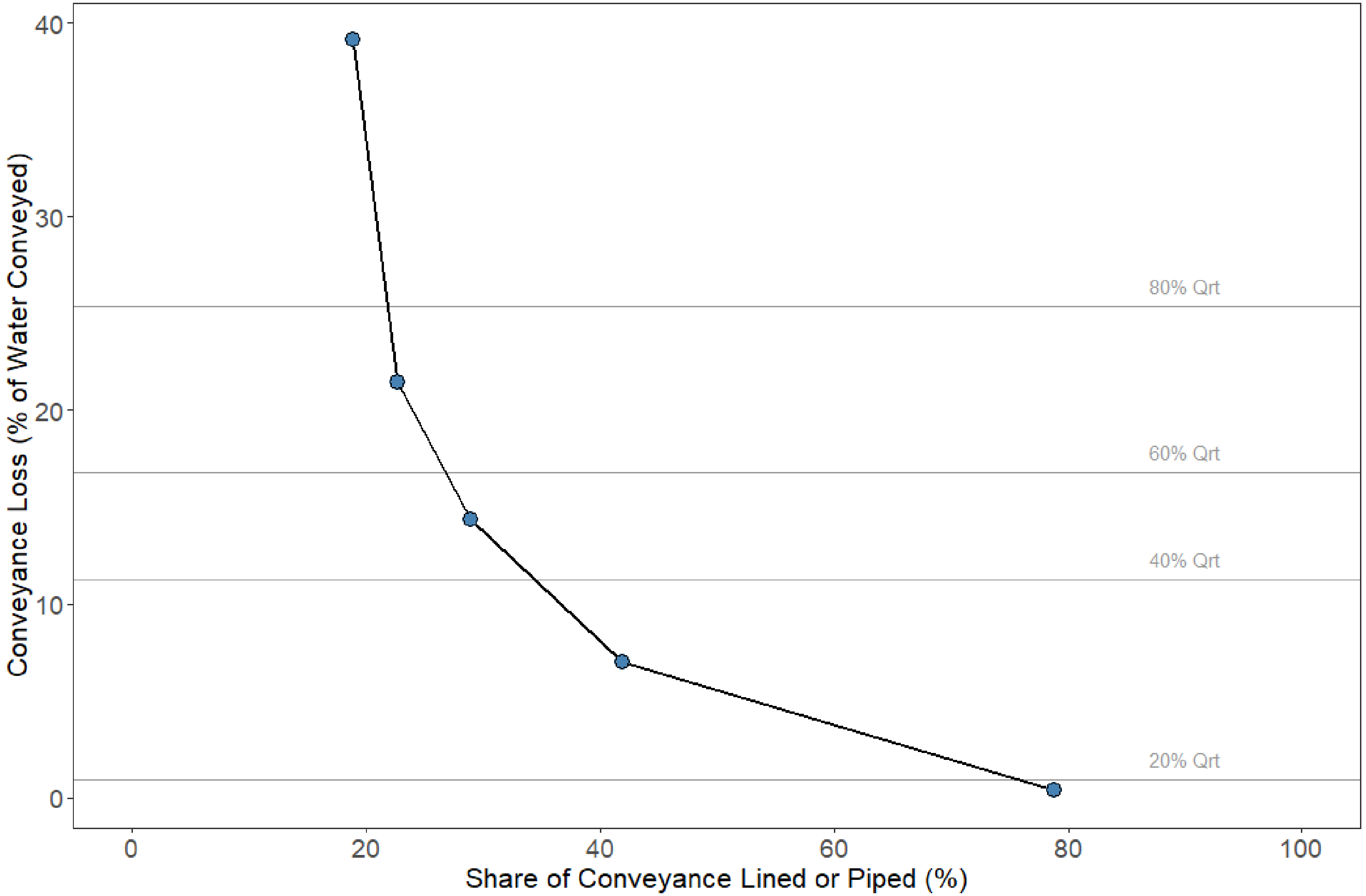
Note: Excludes zero-conveyance loss responses unless fully piped.
Source: USDA Economic Research Service analysis of 2019 SIO data.

Conveyance lining and piping



Note: Excludes zero-conveyance loss responses unless fully piped.
Source: USDA Economic Research Service analysis of 2019 SIO data.

Quintile means of conveyance loss vs. conveyance lined and piped



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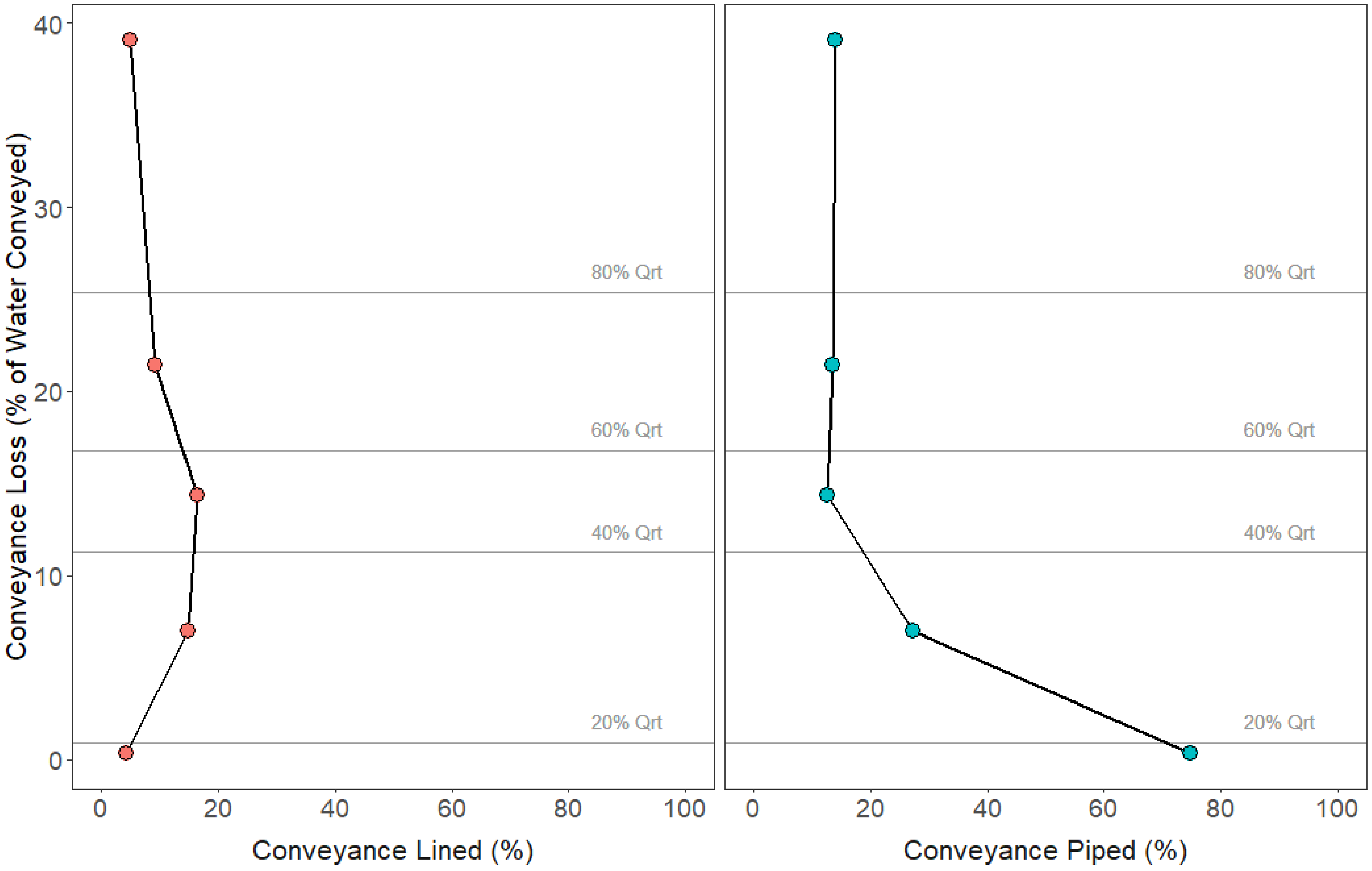
Quintile means of conveyance loss vs. conveyance lined and conveyance piped



Note: Excludes zero-conveyance loss responses unless fully piped.
Source: USDA Economic Research Service analysis of 2019 SIO data.

Summary data: instruments

Statistic	Mean	St. Dev.
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

Source: USDA Economic Research Service analysis of 2019 SIO data.

Summary data: instruments

Restricted set of IVs

Statistic	Mean	St. Dev.
Instruments		
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Source: USDA Economic Research Service analysis of 2019 SIO data.

Results

Regression estimates

	(1) Linear	(2) Logistic	(3) Logistic Control Function	(4) Logistic Control Function
	Uninstrumented	Uninstrumented	Restricted IVs	Full IVs
Lined	−0.0747***	−0.0686**	0.0771	−0.0306
	(0.0213)	(0.0248)	(0.0628)	(0.0519)
Piped	−0.1066***	−0.1385***	−0.1906***	−0.1580***
	(0.0147)	(0.0189)	(0.0314)	(0.0292)

Source: USDA Economic Research Service analysis of 2019 SIO data.

Regression estimates

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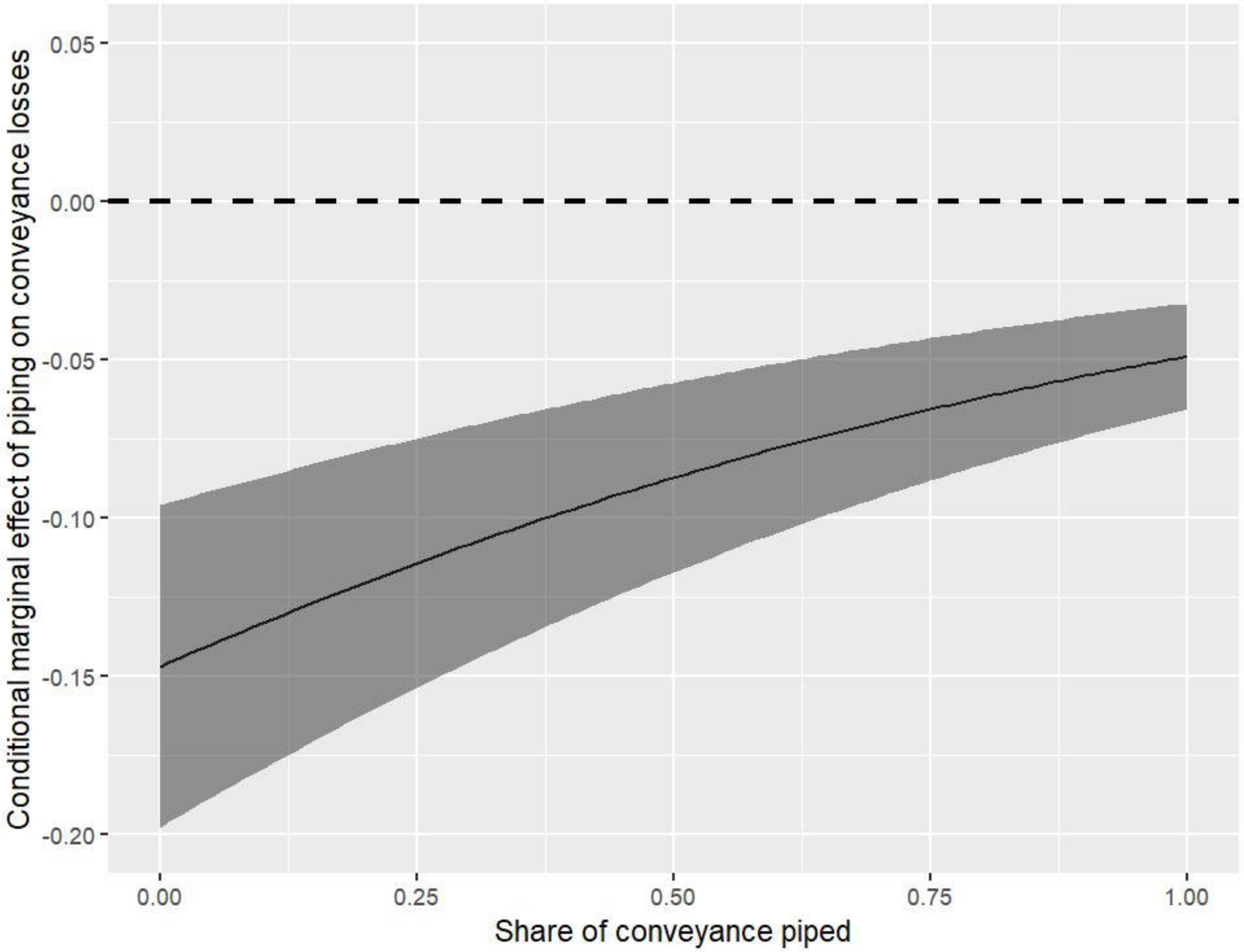
Source: USDA Economic Research Service analysis of 2019 SIO data.

Marginal Effect of Conveyance Piped



Source: USDA Economic Research Service analysis of 2019 SIO data.

What is the water conservation potential of piping?

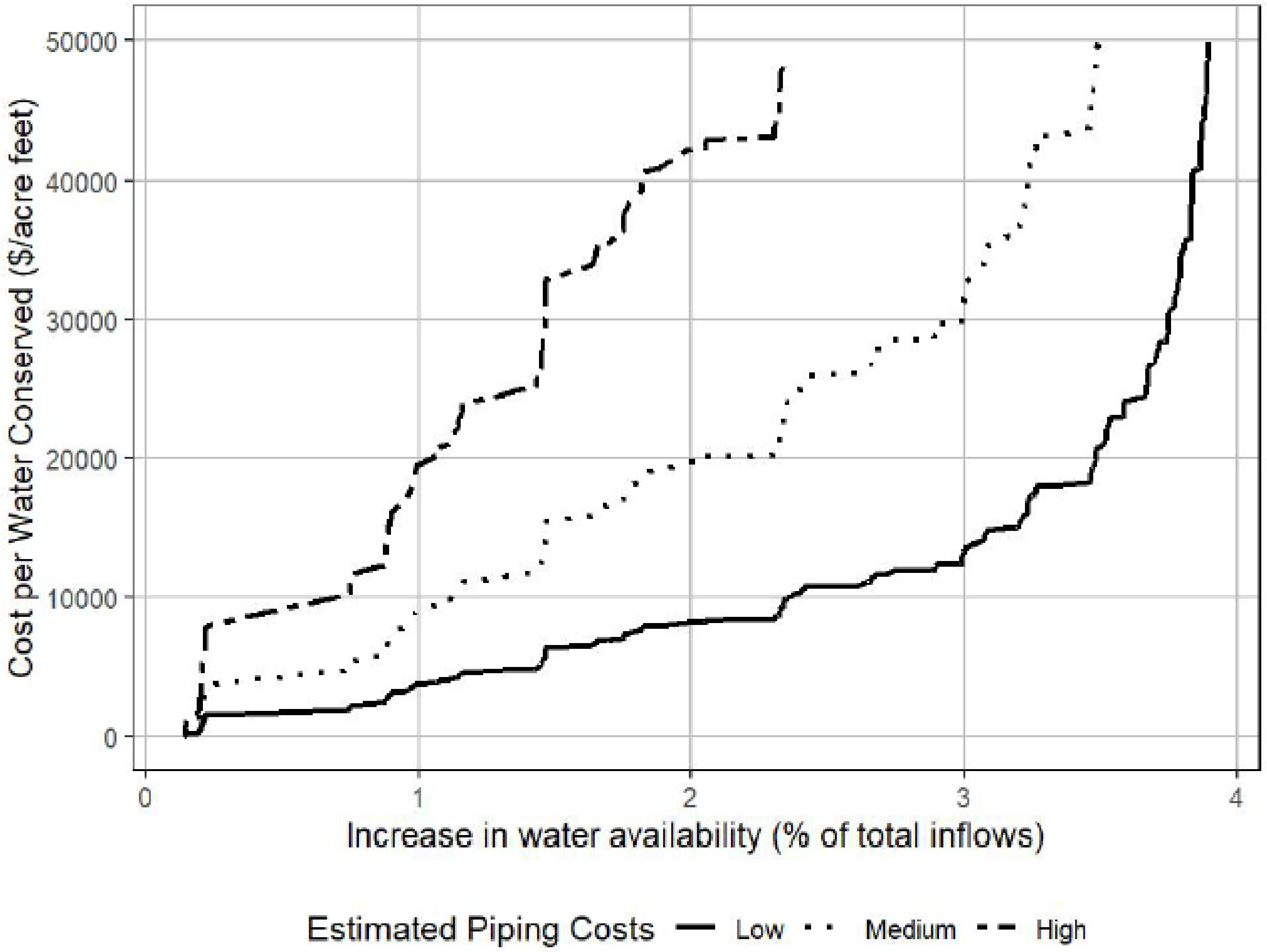
We construct a “supply curve” of water conserved per unit cost

For each organization we:

- Estimate the reduction in losses from moving from current piping level to 100% piped using the marginal effect of piping (-0.158)
- Apply a per mile cost of conveyance piping (USDA-NRCS, 2020) to the conveyance to be piped

A cumulative cost of water conserved is obtained by ordering organizations by marginal cost of piping per acre-foot of water

Supply Curve of Water Conserved by Piping



Per mile piping cost:

Low: $629,000

Medium: $1,512,000

High: $3,239,000

Source: USDA Economic Research Service analysis of 2019 SIO data.

Conclusions

- At the mean, piping an additional ten percentage points of conveyance reduces conveyance losses by between one and two percentage points.

- Conveyance lining may also reduce conveyance losses, but estimated effects are imprecise. Accounting for the relationship between lining and piping is important.

- At a marginal cost between $8,000 and $43,000 per AF, about 2% of inflows (13% of all conveyance losses) would be conserved.

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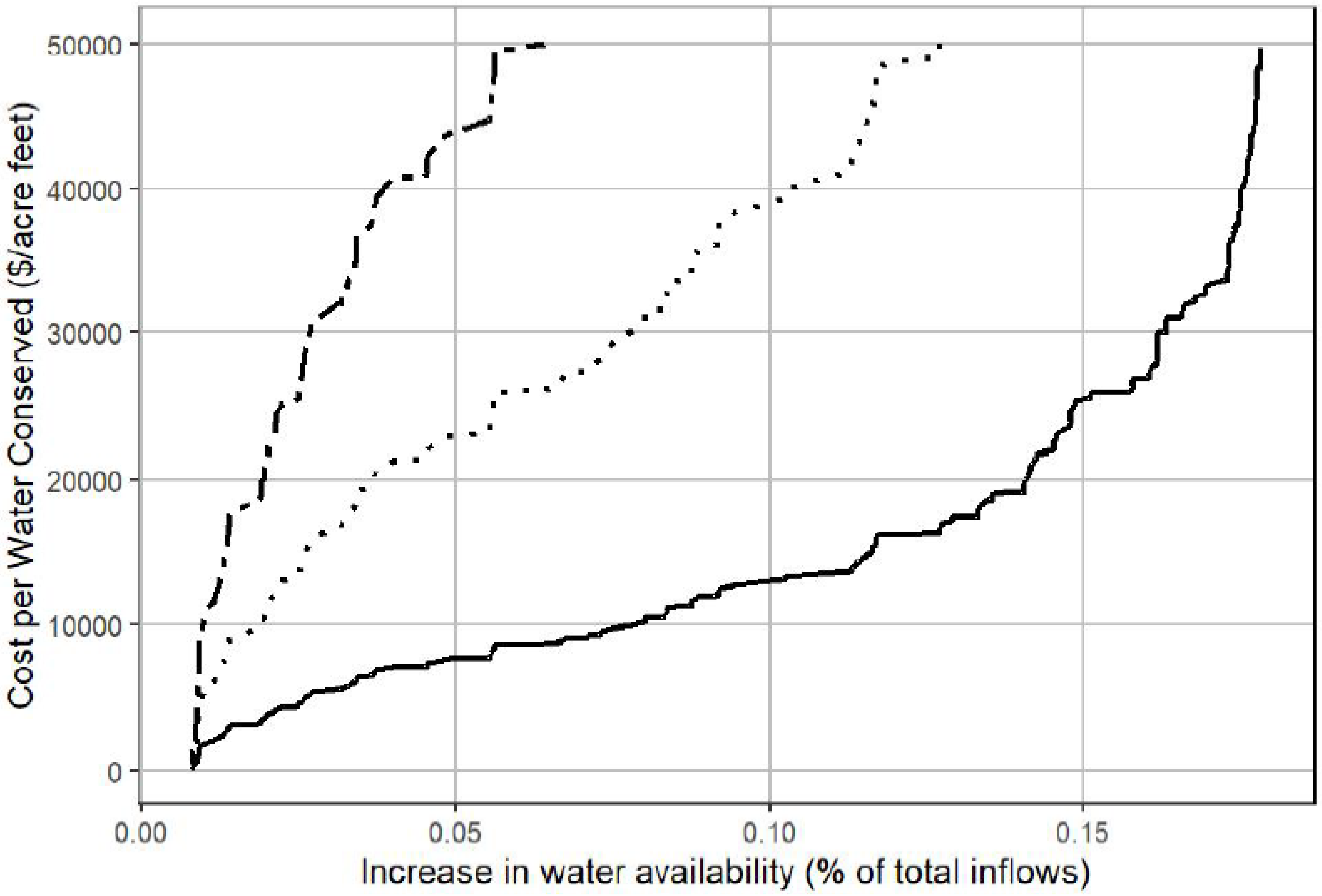
Appendix

Regression Estimates

	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

Source: USDA Economic Research Service analysis of 2019 SIO data.

Supply Curve of Water Conserved by Lining



Source: USDA Economic Research Service analysis of 2019 SIO data.

First Stage Results

	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)

Note: See working paper for full table.
Source: USDA Economic Research Service analysis of 2019 SIO data.

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

Source: USDA Economic Research Service analysis of 2019 SIO data.

Restricted IV Regression Estimates for Difference 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)

Samples Definitions:

- *Loss > 0* includes those observations with conveyance losses greater than 0
- *Loss ≥ 0 & C1* includes responses with zero conveyance loss and 100% conveyance piped
- *Loss ≥ 0 & C2* includes responses with zero conveyance loss and at least 50% conveyance piped
- *Loss ≥ 0 & C3* includes responses with zero conveyance loss and at least 50% conveyance lined or piped

Source: USDA Economic Research Service analysis of 2019 SIO data.

Full IV Regression Estimates for Different 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)

Samples Definitions:

- *Loss > 0* includes those observations with conveyance losses greater than 0
- *Loss ≥ 0 & C1* includes responses with zero conveyance loss and 100% conveyance piped
- *Loss ≥ 0 & C2* includes responses with zero conveyance loss and at least 50% conveyance piped
- *Loss ≥ 0 & C3* includes responses with zero conveyance loss and at least 50% conveyance lined or piped

Source: USDA Economic Research Service analysis of 2019 SIO data.

Sample Restrictions

Include survey responses from irrigation organizations that

- Are not engaged only in groundwater management
- Have some conveyance infrastructure (canals, ditches, pipes, etc…)
- Have less than one mile of conveyance per irrigable acre
- Have a share of conveyance loss between 0 and 75%, or are 100% piped
- Are in a state with at least five responses

2019 Survey of Irrigation Organizations

3. What is the total amount of water brought into this system's storage and conveyance facilities in 2019? This total will be broken down by water source in items 3a and 3b below. This total should equal the sum of items 3ai-v and 3bi-iv.. =

	Acre-Feet
3. Total	0061
d. Conveyance losses...	0087

	Percent of Water Diverted
25. What are the estimated conveyance losses within this organization's delivery system (in percent of water diverted)?...	0165

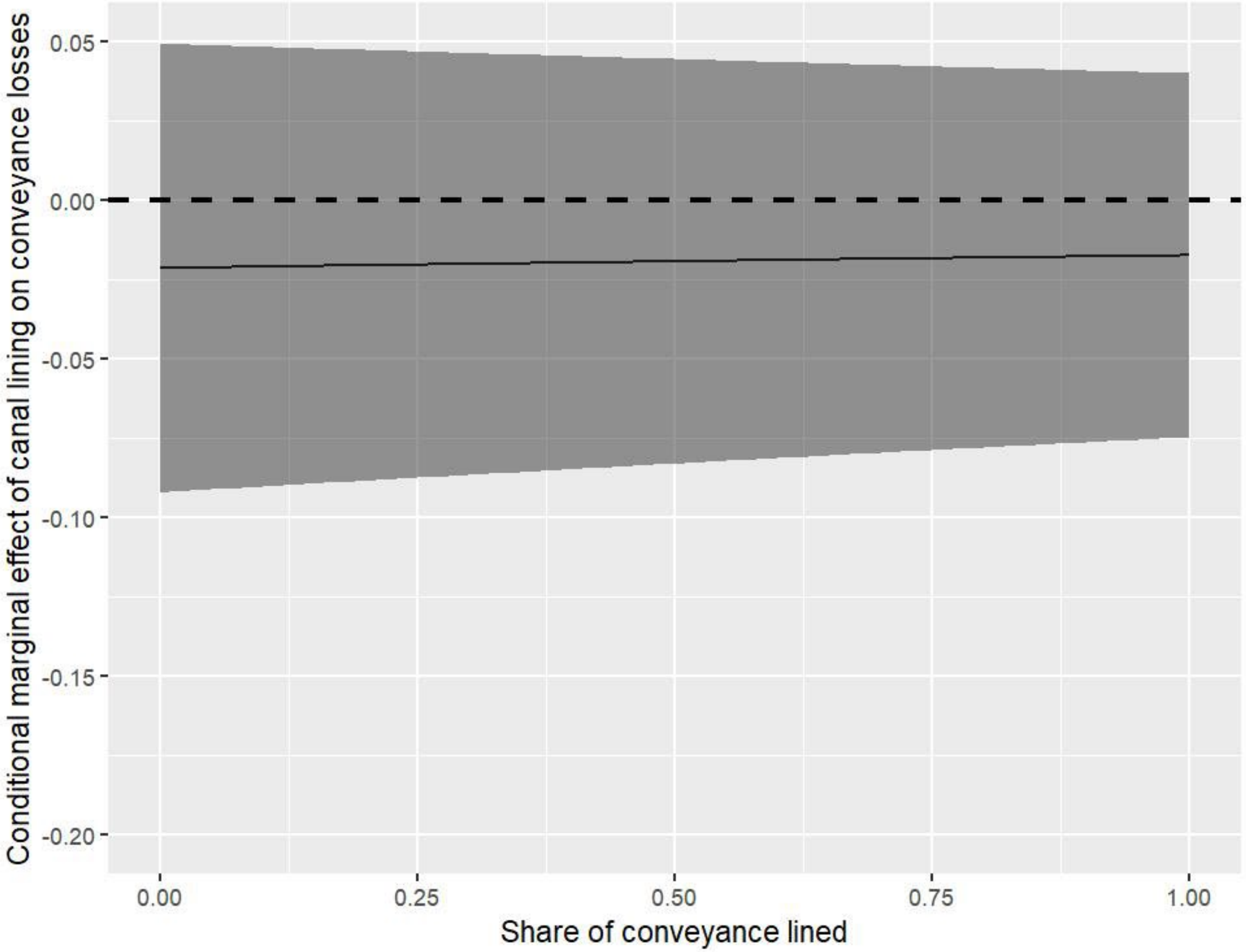
Source: 2019 Survey of Irrigation Organizations.

Summary data: Outcome and covariates of interest

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

Note: Excludes zero-conveyance loss responses unless fully piped.
Source: USDA Economic Research Service analysis of 2019 SIO data.

Marginal Effect of Conveyance Lined



Source: USDA Economic Research Service analysis of 2019 SIO data.