AWRA Annual Conference
November 8, 2017

The Effects of Source Water Quality on Drinking Water Treatment Costs:

A Review and Synthesis of Empirical Literature

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Source Water Protection

Source Water Protection: Actions that safeguard source water conditions from adverse impacts prior to intake

- Land acquisition and management
- Incentivizing best-management practices
- Public education

Ohio Environmental Protection Agency. http://epa.ohio.gov/ddagw/swap.aspx

Source Water Protection

Source water protection has received growing attention as an approach to mitigating health risks and avoiding treatment costs

- Safe Drinking Water Act
- California Water Code
- Municipal engagement

Source Water Protection

- Benefit-cost analysis provides a framework for evaluating source water protection programs
- Benefits (Beneficiaries)
  - **Avoided operation and maintenance (O&M) costs (Drinking water treatment plants)**
  - **Avoided capital upgrades (Drinking water treatment plants)**
  - Improved recreational experiences (Recreationists)
  - Higher home prices (Homeowners)
  - Avoided wildland firefighting costs (Municipality/tax payer)
- Costs
  - Expenditures on source water protection activities
  - Opportunity cost of source water protection activities (e.g., capital upgrades)

Literature Review

- We conduct a literature search for studies that quantify the relationship between treatment costs and source water quality
  - Peer-reviewed and gray literature
  - Multiple disciplines
- **Search Criteria**

  1) Establish an original, quantitative functional relationship between costs and source water quality or select proxies for water quality

  2) Use historic cost information obtained from community water systems

  3) Clearly describe data sources, methodological procedures, and results

Theoretical Framework

- Short-run cost function (variable costs)

$$Treatment\ Costs = f(Y, P_X, K, WQ)$$

$$Y = Output$$

$$P_X = Input\ prices$$

$$K = Capital\ stock$$

$$WQ = Water\ quality$$

- Long-run cost function (total costs)
- Rate function (long-run average costs)
- Usage function

Geography and Motivation

- Country (# of studies)
  - United Sates (15)
  - Canada (2)
  - France (2)
  - Malaysia (2)
  - India (1)
  - Japan (1)
  - Spain (1)
- Motivating factor
  - Nonpoint source pollution from agricultural runoff
  - Forest landscapes and associated disturbances
  - Water quality standards
  - Omitted variable bias in cost efficiency estimates
  - Welfare implications of source water quality changes
  - Endogeneity between technology choice and ecosystem service values

Data Structure

- Unit of analysis
  - Drinking water treatment plants
  - Community water systems
  - Political entities
- Data structure (Range of obs.)
  - Cross-sectional (37 – 994 obs.)
  - Time series (144 – 1826 obs.)
  - Panel (75 – 7380 obs.)
- Source water type (# of studies)
  - Surface water (18)
  - Surface water and groundwater (6)
  - No studies exclusively evaluate groundwater facilities

Cost and Water Quality

- Cost measures
  - Single input expenditures (e.g., chemical, electricity)
  - O&M expenditures
  - Total expenditures

- Water quality measures
  - **Water quality parameter:** the physical, chemical, and microbiological traits of source water
  - **Watershed loading:** the quantity of sediment, nutrients, or pesticides entering surface water due to runoff
  - **Land use characteristics:** the proportion of land within a designated area (e.g., watershed) with a particular land cover or land use designation.

Control Variables

Control variables: Covariates other than water quality measures included in the analysis

- Treated water volume
- Chemical, energy, and labor prices
- Capital stock/prices
- Network/population characteristics (e.g., density)
- Treatment technology
- Source water type

Modeling Approach and Estimation

- Modeling approach
  - Single equation models
  - System of equations

- Statistical estimator/model
  - Ordinary least squares
  - Three stage least squares
  - Stochastic cost frontier
  - Spatial regression
  - Error correction model
  - Panel fixed-effects

Elasticity

- **Elasticity:** Responsiveness of treatment costs to changes in source water quality

$$\eta = \frac{\%\Delta\, Treatment\ Costs}{\%\Delta\, Source\ Water\ Quality}$$

  - η=0.1 (Turbidity): a 1% increase in turbidity leads to a 0.1% increase in costs
  - η=-0.3 (Forestland): a 1% increase in forest land leads to a 0.3% decline in costs

- Comments/caveats
  - Elasticities are only relevant for small changes in water quality
  - Elasticities reported here are averages and are unlikely to accurately reflect conditions at particular treatment facility

Estimated Elasticities

- Water quality parameter (# of elasticities)
  - Turbidity (21)
  - TOC (6)
  - pH (4)
  - Nitrate (2)
  - Calcium carbonate (1)
  - Conductivity (1)
  - Temperature (1)
- Watershed loading (# of elasticities)
  - Sediment (3)
  - Pesticide (2)
  - Phosphorous (2)
- Land use (# of elasticities)
  - Forestland (11)
  - Agriculture (7)
  - Other (7)
  - Urban (6)

Average Elasticities

		Elasticities		Elasticities (w/ key covariates)	
		Est.	Mean (SE)	Est.	Mean (SE)
Turbidity	US	9	0.14 (0.03)*	4	0.12 (0.01)*
	Non-US	3	0.12 (0.03)*	1	0.10 (0.02)*
	Total	12	0.14 (0.02)*	5	0.12 (0.01)*
TOC	US	3	0.44 (0.14)*	1	0.10 (0.29)
	Non-US	1	0.06 (0.02)*	1	0.06 (0.02)*
	Total	4	0.35 (0.10)*	2	0.08 (0.29)
Nitrate	US	1	0.02 (0.01)*	1	0.02 (0.01)*
	Non-US	1	0.05 (0.01)*	0	
	Total	2	0.04 (0.01)*	1	0.02 (0.01)*
Sediment load	US	2	0.23 (0.01)*	1	0.05 (0.02)*
	Non-US	0		0	
	Total	2	0.23 (0.01)*	1	0.05 (0.02)*
Phosphorus load	US	1	0.02 (0.01)*	1	0.02 (0.01)*
	Non-US	0		0	
	Total	1	0.02 (0.01)*	1	0.02 (0.01)*
Forest (non-forest, agriculture, urban)	US	2	-0.35 (0.16)*	0	
	Non-US	4	-0.70 (0.21)*	2	-0.58 (0.10)*
	Total	6	-0.58 (0.15)*	2	-0.58 (0.10)*

Benefits vs. Costs

- Whether avoided treatment costs justify source water protection is highly contextual, depending on site-specific ecologic, hydrologic, and treatment plant characteristics

- Annual benefit for representative treatment facilities (2015 USD)
  – A 1% reduction in turbidity: $121 – $13,060
  – A 1% increase in forestland: $201 – $63,293

- Costs for representative treatment facilities
  – A 1% increase in forestland: 955 – 22,680 hectares
  – Costs of forestland conversion and protection at least several hundred dollars per hectare

Conclusions

- Marginal changes in water quality lead to statistically significant but modest gains in avoided treatment costs
  - Elasticities for turbidity are relatively robust
  - Elasticities for other water quality measures are more varied (TOC, phosphorus load, sediment load, forestland)
  - Average elasticities are smaller and ranges often narrower for studies that incorporated control variables consistent with economic theory in their models
- Evidence suggests that source water protection will not be cost effective in many situations where estimated benefits are limited to avoided treatment expenditures

Knowledge Gaps

- Capital costs and water quality (long-run cost function)
- Sludge disposal costs and water quality
- Treatment costs and key water quality measures: TOC, nutrients, algae blooms, and cyanobacteria
- Treatment costs and various agricultural, forestland, and storm water management practices
- Treatment costs and water quality in small ground water systems
- Treatment costs and water quality for various treatment technologies
- Nonlinearities and threshold effects on the relationship between treatment costs and water quality

Suggestions for Future Research

- Multi-pronged approach
  - Some issues better suited to cross-sectional or panel data that exhibit variation in treatment technologies and source water characteristics
  - Other issues better suited to time-series analysis that can account for context-specific aspects of water treatment
- Data availability is the main obstacle
  - Targeted surveys of multiple of treatment plants
  - Partnerships with individual treatment plant

Supplementary Material

Background

- Concerns about water quality and drinking water safety
  - Wichita, KS constructed an ozone treatment facility to address taste and odor problems caused by algae in the source reservoir (KDHE 2011)
  - Celina, OH incurred considerable costs, including testing treated water for microcystins, as a result of severe toxic algal blooms (Davenport & Drake 2011)
  - Denver, CO incurred considerable treatment and watershed restoration costs following wildfire induced sediment loading (Gartner et al. 2013)
  - Toledo, OH, residents told not to drink water due to toxins from harmful algal blooms (HABs) in Lake Erie (Snider 2014)
  - Waco, TX installed a dissolved air flotation plant and ozone treatment to, in part, address persistent taste and odor problems caused by algal blooms (Dunlap et al. 2015)
  - Des Moines Water Works suit seeks to make agricultural drainage districts address nitrate problems (Hanson et al. 2016)

Partial List of US Municipalities Engaged in Source Water Protection		
Auburn, MA	Flagstaff, AZ	Raleigh, NC
Aurora, CO	Forest Grove, OR	Salt Lake City, UT
Austin, TX	Hoquiam, WA	San Antonio, TX
Boston, MA	Ilwaco, WA	San Francisco, CA
Brooktrails Twp, CA	Little Rock, AR	Santa Fe, NM
Charlottesville, VA	New York, NY	Seattle, WA
Cold Spring, MN	Oakland, CA	Syracuse, NY
Denver, CO	Portland, ME	Tulsa, OK
Eugene, OR	Portland, OR	Willits, CA

Sources: Bennet et al. (2014); Gartner et al. (2013); Herbert (2007)

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