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

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

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https://commons.wikimedia.org/wiki/File:Newark_reservoir.jpg
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
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
• Short-run cost function (variable costs)

\[ \text{Treatment Costs} = f(Y, P_X, K, WQ) \]

\( Y = \text{Output} \)

\( P_X = \text{Input prices} \)

\( K = \text{Capital stock} \)

\( WQ = \text{Water quality} \)

• Long-run cost function (total costs)

• Rate function (long-run average costs)

• Usage function
Geography and Motivation

- Country (# of studies)
  - United States (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: 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
  
  \[ \eta = \frac{\% \Delta \text{Treatment Costs}}{\% \Delta \text{Source Water Quality}} \]

  - \( \eta = 0.1 \) (Turbidity): a 1% increase in turbidity leads to a 0.1% increase in costs
  - \( \eta = -0.3 \) (Forestland): a 1% increase in forestland 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

<table>
<thead>
<tr>
<th></th>
<th>Elasticiesty (w/ key covariates)</th>
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<tbody>
<tr>
<td></td>
<td>Est.</td>
<td>Mean (SE)</td>
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<tr>
<td><strong>Turbidity</strong></td>
<td></td>
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<tr>
<td>US</td>
<td>9</td>
<td>0.14 (0.02)*</td>
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<tr>
<td>Non-US</td>
<td>3</td>
<td>0.12 (0.03)*</td>
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<tr>
<td>Total</td>
<td>12</td>
<td>0.14 (0.02)*</td>
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<tr>
<td><strong>TOC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>3</td>
<td>0.44 (0.14)*</td>
</tr>
<tr>
<td>Non-US</td>
<td>1</td>
<td>0.06 (0.02)*</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>0.35 (0.10)*</td>
</tr>
<tr>
<td><strong>Nitrate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>1</td>
<td>0.02 (0.01)*</td>
</tr>
<tr>
<td>Non-US</td>
<td>1</td>
<td>0.05 (0.01)*</td>
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<tr>
<td>Total</td>
<td>2</td>
<td>0.04 (0.01)*</td>
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<tr>
<td><strong>Sediment load</strong></td>
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</tr>
<tr>
<td>US</td>
<td>2</td>
<td>0.23 (0.01)*</td>
</tr>
<tr>
<td>Non-US</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
<td>0.23 (0.01)*</td>
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<tr>
<td><strong>Phosphorus load</strong></td>
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<td></td>
</tr>
<tr>
<td>US</td>
<td>1</td>
<td>0.02 (0.01)*</td>
</tr>
<tr>
<td>Non-US</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>0.02 (0.01)*</td>
</tr>
<tr>
<td><strong>Forest (non-forest, agriculture, urban)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>2</td>
<td>-0.35 (0.16)*</td>
</tr>
<tr>
<td>Non-US</td>
<td>4</td>
<td>-0.70 (0.21)*</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>-0.58 (0.15)*</td>
</tr>
</tbody>
</table>
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