Challenges in Evaluating Drinking Water Quality in Agricultural Areas

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Overview

• Private wells/small systems
  ❖ Regulations in US and EU
  ❖ Water quality issues

• Exposure assessment approaches: examples from the USA:
  ❖ Arsenic in New England
  ❖ Nitrate in Iowa and North Carolina

• Considerations for future studies
U.S. Drinking Water Regulations

- Regulated by U.S. EPA under Safe Drinking Water Act (SDWA) since 1974
  - Community water supplies (serving 25+ or 15+ connections)

- Private wells & very small systems exempt
  - Monitoring data sparse
  - Located in rural/agricultural areas
  - Affected by non-point source pollution
    - Fertilizer applications, manure
    - Pesticide applications (herbicides, seed treatments)
    - Septic systems often close to wells

- Agricultural chemicals less regulated than EU
  - Nutrient reduction strategy is voluntary
  - 72 pesticides used in U.S. banned in the EU
    - >25% of agricultural pesticide use

Donley Env Health; 2019
Density of private drinking water wells (1990)

- 130 million (~50%) of US population uses groundwater
- ~43 million people (15% of population) use unregulated drinking water sources – mostly private wells
- Private wells located in agricultural areas, suburban/rural northeast

US Geological Survey
https://www.sciencebase.gov/
E.U. Drinking Water Regulations

  - Regulates supplies serving 50+ people or >10 m$^3$/day
  - ~50% of population uses groundwater

- Small scale water supplies (SSWS) including private wells:
  - <5000 population, 22% of EU (~109 million)
  - ~7% served by private wells
  - Range from 0 (Netherlands) to >1 million (Romania)
  - Mostly located in rural/agricultural areas
  - Monitoring data are sparse

Gunnarsdottir et al. IJERPH 2017; WHO report on SSWS, 2011
U.K. private vs. public water supplies – water quality

Fig. 11.1. Tests failing drinking-water standards in public and private supplies

WHO report on SSWS, 2018
Regulations vary by EU country & U.S. state

Center for Progressive Reform 2021. Tainted Tap

WHO report on SSWS, 2011
Water quality in U.S. groundwater

- 62 principal aquifers in 50 states (1991-2010)
  - Private wells in 30 aquifers
  - Measured inorganics, nutrients, pesticides, VOCs, microbes

- 22% of wells had 1+ contaminants above maximum contaminant level (MCL) or human-health benchmarks
  - Most were inorganics (As, Mn, U, Ra)
  - Nitrate >10 mg/L NO₃-N: 4 percent of wells

- Organics in ~60% of private wells

- Microbial contaminants ~33% of private wells

- *Contaminants usually co-occurred with other contaminants as mixtures*

DeSimone et al. 2009; 2014. USGS Circulars 1332, 1360,
PFAS in groundwater - USA

• 5 principal aquifers in eastern states:
  – Measured 24 PFAS, VOCs, nutrients, ions, tritium (groundwater age)
  – 60% of public wells had 1+ PFAS
  – 20% of private wells

• Urban land (<500 m), fire training, VOCs, groundwater age (post-1953) were important predictors

• **PFAS often occurred with other contaminants as mixtures** – VOCs, pharmaceuticals, nitrate

McMahon et al. ES&T, 2022
Drinking water quality exposure disparities

• US national scale study of 40,000 public water supplies (Schraider et al. Env Health; 2019)
  – 5.6 million exposed 5 mg/L NO₃-N or above
  – 3x higher probability for Hispanic/Latinos
  – Served by smaller public supplies

• Review of disparities in drinking water exposures (Vanderslice AJPH; 2011) – water quality issues:
  – Tribal lands, Alaskan Native villages, colonias US/Mexico border, small communities in agricultural areas
  – High cost of nitrate & As removal exacerbates socioeconomic disparities

• Eastern shore of Maryland (Minovi & Schmitt, Center for Progressive Reform. 2020)
  – Highest nitrate in counties with high poverty, African-Am population
Private drinking water wells and small supplies: Exposure assessment considerations

• Typically pump groundwater from relatively shallow depths vs. public supply wells

• Private wells often have higher contaminant concentrations than public supplies, occurring as mixtures

• Treatment not common

• Contaminant movement to groundwater usually takes years

• Few regulations – limited monitoring data

DeSimone et al. USGS Circular 1332; 2009; Center for Progressive Reform, Tainted Tap; 2020
How do we move forward to assess exposure?

- New methods of surveillance and monitoring (Tools and Technologies Session)
- Modeling approaches for private wells in rural and agricultural areas:
  - Two examples from epidemiologic studies of drinking water contaminants and cancer
  - Multi-year, interdisciplinary collaborations of exposure scientists, epidemiologists, hydrogeologists, statisticians
Example 1: Bladder cancer in Northern New England

Mortality rates among white women
1980-2004

Red=high rates, Blue=low
New England Bladder Cancer Study

• Popn-based case-control study (1213 cases, 1418 controls)
  Maine, New Hampshire, Vermont
  – Newly diagnosed cases 2001-2004, ages 30-79

• Home interviews
  – Residence and workplace water source histories
  – Private well depth, type of well (drilled, dug)
  – Tap water intake
  – GPS of current home, geocoded past addresses

• Water samples for private wells (46%), some past homes on private wells

• Measured & modeled known or suspected bladder carcinogens in water:
  – Arsenic
  – DBPs
  – Nitrate

Baris et al JNCI; 2016; Nuckols et al. EHP; 2001
### GIS-based prediction Models for Assigning Arsenic Concentrations for Residences and Workplaces on Private Wells

<table>
<thead>
<tr>
<th>Model Categories</th>
<th>Description of Measurements</th>
<th>Model Description</th>
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<tbody>
<tr>
<td><strong>Private Water Supply (6-State Region)(^7)</strong></td>
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</tbody>
</table>
| Wells - Bedrock Aquifer Source                       | N = 3,527                                                                                    | Model: ln(As) = β x + ε  
Model includes 12 geographic-based variables (x) based on geologic provinces, litho chemistry and surficial geology of bedrock units (Table 2). |
| Wells - Unconsolidated Materials Aquifer Source       | N = 1,557                                                                                    | Model: ln(As) = β x + ε  
Model includes 13 geographic-based variables (x) based on geologic provinces, litho chemistry and surficial geology of bedrock units (Table 2). |
| **Private Water Supply (outside 6-State Region)**    |                                                                                             |                                                                                                                          |
| USGS Hydroregion Subbasin (Watermolen, 2005) modeling unit | N = 18,651; H = 934 subbasins where residences/workplaces located                           | Model: ln(As) = \( \sum_{h=1}^{H} \beta_h x_{h} + \varepsilon \)  
\( \beta_h \) is the parameter estimate (mean measurement data for \( h \)), and \( \varepsilon \) is the error, derived from normally distributed measurements N, mean 0 and variance \( \sigma^2 \) |
| Principal Aquifer Modeling Unit                      | N = 15,687; P = 64 Principal Aquifer boundaries (USGS 2008) where hydroregion subbasins with residences/workplaces located | Model: ln(As) = \( \sum_{p} \beta_p x_{p} + \varepsilon \)  
USGS Principal Aquifer-specific model using measurements from all study hydroregion subbasin wells located within each aquifer boundary |

Nuckols et al; EHP; 2011
Modeled Probability of Arsenic >5 ug/L in Bedrock Wells

Nuckols et al. EHP; 2011
Results

- Significant exposure-response for bladder cancer risk with cumulative arsenic, elevated risk for high average concentrations lagged 40 years
- Consumption of water from dug wells during period of arsenical pesticide use (<1960) associated with 2.3x bladder cancer risk

Baris et al, J Natl Cancer Inst; 2016
Conclusions and challenges

• Regulatory limit 10 µg/L (as of 2001, previously 50 µg/L)
  – Public supplies were mostly in compliance
  – Levels were higher in private wells

• Cancer (especially of internal organs) has a long latency requiring lifetime water source histories

• Exposures mostly low, required large study with good exposure assessment

• Models required accurate geocodes, well depth, type, measurement data from study area and other US states
Example 2: Nitrate in private wells

- Regulatory limit (Maximum Contaminant Level [MCL]):
  - 10 mg/L as $\text{NO}_3\text{-N}$ (USA)
  - 50 mg/L as $\text{NO}_3$ (EU)

- Highest exposures:
  - Residents on private wells in agricultural areas
  - $N$ fertilizers, animal feeding operations
Agricultural Health Study

- Cohort study of pesticide applicators and spouses in Iowa and North Carolina (58,563 from Iowa; 31,092 from North Carolina)

- Residence histories, drinking water source at enrollment (1993-97) & follow-up interviews

- Developed separate random forest models for Iowa and North Carolina (Wheeler/Nolan et al. STOTEN; 2015; Messier/Wheeler et al. STOTEN; 2018)

Drinking water source by state

- Manley et al. Env Epidemiol. 2021
GIS-based model of nitrate in Iowa private wells

- ~34,000 nitrate measurements (1980-2000s)
- Evaluated >150 variables (e.g., land use, animal feeding operations, geology, soils, slope, precipitation)

Wheeler/Nolan et al. STOTEN; 2015
- 66 variables explained 77% of variation in training dataset:
  - Well depth
  - Geologic features – karst geology, sinkholes
  - Slope, elevation
  - Animal feeding operations
  - Agricultural land (1990)
  - Precipitation
  - Soil characteristics at well screen
  - Year

Wheeler/Nolan et al. STOTEN; 2015
Observed and predicted nitrate sensitivity and specificity (5 mg/L)

<table>
<thead>
<tr>
<th>NO₃-N Predicted</th>
<th>NO₃-N Observed</th>
<th>Sensitivity</th>
<th>Specificity</th>
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<tbody>
<tr>
<td>≥5 mg/L</td>
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<td>2615 (67%)</td>
<td>15660 (86%)</td>
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<tr>
<td></td>
<td>&lt;5 mg/L</td>
<td>2598 (14%)</td>
<td></td>
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<tr>
<td>&lt;5 mg/L</td>
<td>≥5 mg/L</td>
<td>1280 (33%)</td>
<td></td>
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Wheeler/Nolan et al. STOTEN; 2015
USGS National Models of Nitrate in Groundwater

- Domestic & public supply well depths
- Machine learning methods: 3D extreme gradient boosting
- 76 variables: well depth, soils, land use, climate were most important
- Fertilizer & manure inputs in ag areas
- Utility for exposure assessment?
  - 1 km scale
  - Compare with regional/state models

Ransom et al. STOTEN; 2022
Exposure Assessment Challenges

- Lack of publicly available measurement data for private wells and small water systems

- Modeling is feasible:
  - Representative measurement data
  - Accurate location
  - Well depth, type
  - GIS-based variables for study area (e.g. land use, pollutant sources, soils, aquifer characteristics, slope, meteorologic data)

- Challenges for modeling exposure:
  - Hydrogeology and geochemistry may not be well understood
  - Multidisciplinary effort
  - Can be expensive especially if monitoring required
  - Modeling contaminant mixtures
Exposure Assessment Challenges

• Health risks likely from low level exposures over lifetime
  – Lifetime history including water treatment, well depth
  – Historical recall is challenging

• Route of exposure
  – Ingestion: Tap water intake may vary over time, likely misclassification
  – Dermal, inhalation for DBPs, volatile organic contaminants (e.g. trichloroethylene)

• Susceptible subgroups - pregnant women, infants, children
  – Many contaminants cross the placenta
Collaborators on AHS and NEBCS

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