Monitoring groundwater abstraction using electric energy as proxy in an area of intensive agricultural pumping

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Background and Study Area

- Groundwater abstraction monitoring is usually absent in areas of intensive agricultural pumping.
- Large number of users operating small-scale wells with primitive equipment.
- Electricity consumption for pumping is metered by existing electricity monitoring grid.

**Guantao County in the North China Plain**

- Groundwater is overpumped due to the irrigation of winter wheat.
- Groundwater control policy: Water tax is generated when users pump a volume of groundwater exceeding the prescribed quota.
- All irrigation wells are equipped with electricity meters.

Guantao County

- Area: 456 km²
- Number of wells: > 8000
- Irrigation area per well: ~ 3.3 ha
- Water quota: 296 m³/mu/year (1 mu=1/15 ha)
Indirect groundwater abstraction monitoring using electricity consumption as proxy

Key questions to be answered

1. How to convert the proxy of electric energy consumption to groundwater abstraction?
   - Electricity-to-water conversion factor measured by field tests: \( c_f \) (m\(^3\)/kWh)
     \[ V = E \cdot c_f \]

2. What is the accuracy of the conversion?
   - Trade-offs between accuracy and efforts in data collection

3. Is the monitoring method feasible and sustainable?
   - Comparison of monitoring methods regarding cost, ease of implementation, etc.
Q1 Converting the proxy of electricity consumption to groundwater abstraction

- Pumping tests for measuring Electricity-to-Water Conversion Factor, $c_f$ (m³/kWh)
  - Electricity-to-water pumping tests on single wells [at 281 locations]
  - Continuous pseudo pumping tests using smart flow meters and electricity meters [at 6 locations]

- A uniform conversion factor will lead to large errors in the abstraction estimates of single wells.

- Pumping tests performed in whichever irrigation season result in a conversion factor with a relative error of less than 20% for a single well.
Q2 Accuracy of the electricity-to-water conversion
Trade-off between accuracy and efforts in data collection

More wells tested  ➔  More accurate

- How many wells in a region should be tested to obtain an average conversion factor with a relative error less than a threshold $\varepsilon$, e.g., 20% or 10%?
- Analysis using the theory of interval estimation

<table>
<thead>
<tr>
<th>Regions</th>
<th>Total Number of Wells</th>
<th>Number of Samples $n$</th>
<th>Number of Wells to Be Tested (Confidence Level: 95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\varepsilon &lt; 20%$</td>
</tr>
<tr>
<td>Village 1</td>
<td>49</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td>Village 2</td>
<td>66</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>Village 3</td>
<td>51</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>Village 4</td>
<td>41</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Shoushansi District</td>
<td>600</td>
<td>281</td>
<td>14</td>
</tr>
</tbody>
</table>

- Taking the average conversion factors of 17 measurements evenly distributed over the county, the average conversion factor of shallow wells in Guantao County is estimated as 2.62 m$^3$/kWh ($\varepsilon < 20\%$).
Q3 Is the monitoring method sustainable? – Method Comparison

- Direct water monitoring by smart water meters
- Indirect monitoring using electric energy as proxy
  - Pumping tests at **All** wells or at **Selected** wells

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Direct Water Metering</th>
<th>Energy Metering + Pumping Tests on All Wells</th>
<th>Energy Metering + Pumping Tests on Selected Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>(Investment: 9.6 Mio. CNY/a Maintenance: 17.2 Mio. CNY/a)</td>
<td>(Operation cost: 3.6 Mio. CNY/a)</td>
<td>(Operation cost: 6300 CNY/a)</td>
<td></td>
</tr>
<tr>
<td>Ease of implementation</td>
<td>Very difficult</td>
<td>Medium</td>
<td>Easy</td>
</tr>
<tr>
<td>Accuracy</td>
<td>High (±5%)</td>
<td>Medium</td>
<td>Low (±50%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(or Median for areal abstraction at county level, ±20%)</td>
</tr>
<tr>
<td>Equitability</td>
<td>Equitable</td>
<td>Equitable</td>
<td>Low equitability (regarding abstraction estimates) or Equitable (regarding energy-saving)</td>
</tr>
</tbody>
</table>

- Guantao County in 2018
  Water volume exceeding water quota: 11.7 million m³
  Water tax: 2.34 million CNY.
Conclusions

• Direct water metering is presently infeasible in the North China Plain.

• Indirect groundwater abstraction metering using energy consumption as proxy substantially reduces the investment and efforts required in system maintenance and data collection.

• Field tests in Guantao revealed the large variability of the electricity-to-water conversion factors between individual wells. But the error of electricity-to-water conversion for an individual well based on field test is within 20%.

• A trade-off between data accuracy and efforts in data collection can be made by selecting the number of pumping tests.
Thank you!

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