Groundwater Externalities with Endogenous Well Capacity Investment

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Motivation and Context

- Dramatic expansion of groundwater irrigation, especially in developing countries, has led to widespread concern about falling groundwater levels and the sustainability of irrigation.
- Economic literature (e.g. Gisser and Sanchez 1980) general concludes that the common property externality is small.
  - Expansion of irrigation has led to substantial reductions in poverty.
  - An important exception: Brill and Burness (1994)
    - If demand is growing over time, the common property externality can be substantial.
Role of “Entry” through Investment

- Expansion of groundwater irrigation driven by investment on two margins
  - Groundwater irrigated acreage in India increased 500% between 1960 and 2010
  - Movement from dug wells to tubewells (0% tubewells in 1960 to 40% tubewells in 2010)
  - Tubewells allow the extraction of more water from greater depths
- Expected overinvestment in addition to overexaction under common property
  - Liu et al (2014) evidence of over-entry in an experimental setting

Our Question
How large are the potential gains from optimally managing both groundwater extraction and on-going investment in new well technology?
Basic Model

- $N$ farms that are either traditional ($T$) or modern ($M$)
  - Share modern is $k_t$
  - Farms differ only in their cost ($\chi_{nt}$) of converting from $T$ to $M$ and their current status
- Instantaneous benefit of water use is $b_i(w_{it})$
- Instantaneous cost of water use is $w_{it}e_i(\bar{h} - h_t)$
- Maximum water use $L_i(h_t)$ depends on the water level and the well characteristics
  - Traditional farms cannot pump water more than 8m
- Groundwater levels evolve according to a “bathtub” model

\[
h_{t+1} = h_t + \frac{r - (1 - \theta)N(k_tw_{Mt} + (1 - k_t)w_{Tt})}{\phi}
\]
Optimal Management

A regulator optimally selects water use $w_{it}$ on both farm types and the share of farms ($\gamma_t$) converting from traditional to modern agriculture in each period yielding the present-value Hamiltonian

$$H(t) = \delta^t \left[ N \sum_k \kappa_{it} \left[ b_i(w_i) - w_{it}e_i(\bar{h} - h_t) \right] - C_t(\gamma_t, k_t) \right] + \sum_{i=T,M} \mu_{it} (L_i(h_t) - w_{it})$$

$$+ \lambda_{kt+1} \gamma_t + \lambda_{ht+1} \frac{r - (1 - \theta)(k_t w_{Mt} + (1 - k_t) w_{Tt})}{\phi}$$

where $C_t(\gamma_t, k_t)$ is the total cost of $N\gamma_t$ farms converting at time $t$, given that the $Nk_t$ cheapest farms have already converted.
Common Property

- Farmers take $h$ as given, choose $w_{nt}$ and investment time $\tau_n$
- Water use problem Lagrangian
  \[ b_i(w_{it}) - w_i e_i (\bar{h} - \hat{h}_t) + \nu_{it} \left( L_i (\hat{h}_t) - w_{it} \right) \]
  - Solution $w_i^{*CP} (\hat{h}_t)$ yielding optimized value $B_i^{*CP} (\hat{h}_t)$
- Farmer $n$’s investment problem is
  \[
  \max_{\tau=1, \ldots, \infty} \sum_{t=0}^{\tau} \delta^t B_T^{*CP} (\hat{h}_t) - \delta^\tau \chi_n \tau + \sum_{t=\tau+1}^{\infty} \delta^t B_M^{*CP} (\hat{h}_t)
  \]
  - Local optimality condition requires investment at $\tau$ to be preferred to investment at $\tau + 1$ and $\tau - 1$
- Farmers have rational expectations about future water levels so
  \[
  \hat{h}_{t+1} = \hat{h}_t + \frac{r - (1 - \theta) N (k_t w_M^{*CP} + (1 - k_t) w_T^{*CP})}{\phi}
  \]
Comparing Solutions

- Water use on type $i$ satisfies
  \[
  \text{CP: } \frac{\partial b_i}{\partial w_i} (w^\ast_{i \text{CP}}) - e_i \left( \bar{h} - \hat{h}^\ast_{CP} \right) = \nu_{it}
  \]
  \[
  \text{OPT: } \frac{\partial b_i}{\partial w_i} (w^\ast_{i \text{OPT}}) - e_i \left( \bar{h} - h^\ast_{OPT} \right) = \frac{\mu_{it}}{\delta^t N \kappa_i (k^\ast_{OPT})} + \frac{\lambda_{ht+1} (1 - \theta)}{\phi}
  \]

  Marginal Private Benefit = Shadow Value of Capacity Constraint (+ User Cost of Water)

- Highest cost farm that invests in period $t$ satisfies
  \[
  \text{CP: } \delta \Delta B^\ast_{CP} \left( h_{CP}, t+1 \right) = \chi_{nt} - \delta \chi_{nt+1}
  \]
  \[
  \text{OPT: } \delta \Delta B \left( w_{t+1}^\ast_{OPT}, h_{t+1}^\ast_{OPT} \right) = \chi_{nt} - \delta \chi_{nt+1}
  \]
  \[
  + \lambda_{ht+2} N \frac{(1 - \theta)}{\phi} \left( w^\ast_{OPT_{Mt+1}} - w^\ast_{OPT_{Tt+1}} \right)
  \]

  Discounted Gain Next Period = Reduction in PV Cost by Waiting (+ User Cost of Water $\times$ Extra Water Use)
Case Study: Odisha (Orissa), India

- CWGB estimates current use is 25% of renewable use
- Low penetration of tubewells and submersible pumps (~5%)
- Active encouragement of irrigation expansion
- Renewable flows not sufficient to sustain full conversion
Model Conditions

Traditional Farms
- Rice grown during kharif only
- Water consumption \(\sim 3,000\text{ m}^3/\text{ha}\)
- Dug wells & centrifugal pumps
  - Limits on extraction increase with depth
  - Max depth is 8m

Modern Farms
- Rice grown during kharif and rabi
- Water consumption (total) \(\sim 15,000\text{ m}^3/\text{ha}\)
- Physical limits on pumping not binding
- Conversion costs roughly 7 years of profit difference
## Specific Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>δ</td>
<td>Discount factor 0.95</td>
</tr>
<tr>
<td>$\bar{h} - h_0$</td>
<td>Initial pumping lift 2m</td>
</tr>
<tr>
<td>$\phi_T$</td>
<td>Inverse demand intercept ($T$)</td>
</tr>
<tr>
<td>$\psi_T$</td>
<td>Inverse demand slope ($T$)</td>
</tr>
<tr>
<td>$\phi_M$</td>
<td>Inverse demand intercept ($M$)</td>
</tr>
<tr>
<td>$\psi_M$</td>
<td>Inverse demand slope ($M$)</td>
</tr>
<tr>
<td>$r$</td>
<td>Natural inflow per hectare 4,680 m$^3$/ha</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Return flow coefficient 35%</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Water released per 1m drop in aquifer 1,600 m$^3$/ha/m</td>
</tr>
<tr>
<td>$e_T$</td>
<td>Energy cost per m on traditional farms 0 Rs/m$^3$/m</td>
</tr>
<tr>
<td>$e_M$</td>
<td>Energy cost per m on modern farms 12 Rs/m$^3$/m</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>Initial common investment cost per ha 13,555 Rs/ha</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Annual percentage decline in $\nu$ 10%</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Mean of $\chi$ distribution 25,394 Rs/ha</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of $\chi$ distribution 10,000 Rs/ha</td>
</tr>
<tr>
<td>$k_0$</td>
<td>Initial share modern 5%</td>
</tr>
<tr>
<td>$L_T(h_0)$</td>
<td>Dug well extraction limit 3,000 m$^3$/ha</td>
</tr>
</tbody>
</table>
Preliminary Results

NPV of water benefits roughly doubles from ~13,000 Rs/ha to ~26,000 Rs/ha under optimal management.

![Graphs showing NPV increase under optimal management and common property.](image-url)
Impact on Different Farms

![Graph showing impact on different farms.]

The top graph displays the NPV of benefits (kRs/ha) against investment cost percentile. The bottom graph shows the percentage gain (loss) over common property against investment cost percentile.
Conclusions and Extensions

- Benefits of implementing optimal management can be substantial when there is endogenous investment in irrigation capacity through changes in well technology
  - Common property: farms with high investment costs driven to dryland farming
  - Optimal management: investment and extractions kept low enough to maintain depths below 8m
- Equity implications
  - In our examples, farms on the two ends of the investment cost distribution benefit from management while farms in the middle are hurt
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