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 (χ_{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 $w_{it}e_i\left(\bar{h} - h_t\right)$
- 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

$$h_{t+1} = h_t + \frac{r - (1-\theta)N(k_t w_{Mt} + (1-k_t)w_{Tt})}{\phi}$$

Optimal Management

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

$$
\begin{aligned}
H(t) &= \delta^t \left[N \sum_i \kappa_{it} \left[b_i(w_i) - w_{it} e_i \left(\bar{h} - h_t \right) \right] - C_t(\gamma_t, k_t) \right] \\
&+ \sum_{i=T,M} \mu_{it} \left(L_i(h_t) - w_{it} \right) \\
&+ \lambda_{kt+1} \gamma_t + \lambda_{ht+1} \frac{r - (1-\theta)(k_t w_{Mt} + (1-k_t) w_{Tt})}{\phi}
\end{aligned}
$$

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 $\hat{\mathbf{h}}$ as given, choose w_{nt} and investment time τ_n
- Water use problem Lagrangian

$$b_i(w_{it}) - w_i e_i\left(\bar{h} - \hat{h}_t\right) + \nu_{it}\left(L_i\left(\hat{h}_t\right) - w_{it}\right)$$

  - Solution $w_i^{*CP}\left(\hat{h}_t\right)$ yielding optimized value $B_i^{*CP}\left(\hat{h}_t\right)$
- Farmer n's investment problem is

$$\max_{\tau=1,\ldots,\infty} \sum_{t=0}^{\tau} \delta^t B_T^{*CP}\left(\hat{h}_t\right) - \delta^\tau \chi_{n\tau} + \sum_{t=\tau+1}^{\infty} \delta^t B_M^{*CP}\left(\hat{h}_t\right)$$

  - Local optimality condition requires investment at τ to be preferred to investment at $\tau+1$ and $\tau-1$
- Farmers have rational expectations about future water levels so

$$\hat{h}_{t+1} = \hat{h}_t + \frac{r - (1-\theta)N\left(k_t w_{Mt}^{*CP} + (1-k_t)w_{Tt}^{*CP}\right)}{\phi}$$

Comparing Solutions

- Water use on type *i* satisfies

$$
\begin{aligned}
\text{CP:}\quad & \frac{\partial b_i}{\partial w_i}\left(w_i^{*CP}\right) - e_i\left(\bar{h} - \hat{h}_t^{CP}\right) = \quad \nu_{it} \\
\text{OPT:}\quad & \frac{\partial b_i}{\partial w_i}\left(w_i^{*OPT}\right) - e_i\left(\bar{h} - h_t^{*OPT}\right) = \quad \frac{\mu_{it}}{\delta^t N \kappa_i\left(k_t^{*OPT}\right)} + \frac{\lambda_{ht+1}}{\delta^t}\frac{(1-\theta)}{\phi}
\end{aligned}
$$

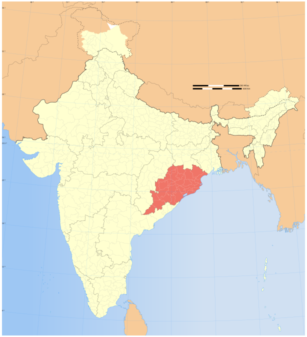
  Marginal Private Benefit = Shadow Value of Capacity Constraint (+ User Cost of Water)

- Highest cost farm that invests in period *t* satisifes

$$
\begin{aligned}
\text{CP:}\quad & \delta \Delta B^{*CP}\left(\mathbf{h}^{CP}, t+1\right) = \quad \chi_{nt} - \delta \chi_{nt+1} \\
\text{OPT:}\quad & \delta \Delta B\left(\mathbf{w}_{t+1}^{*OPT}, h_{t+1}^{*OPT}\right) = \quad \chi_{nt} - \delta \chi_{nt+1} \\
& \qquad + \lambda_{ht+2} N \frac{(1-\theta)}{\phi}\left(w_{Mt+1}^{*OPT} - w_{Tt+1}^{*OPT}\right)
\end{aligned}
$$

  Discounted Gain Next Period = Reduction in PV Cost by Waiting (+ User Cost of Water × 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 ~3,000 m^3/ha
- Dug wells & centrifugal pumps
  - Limits on extraction increase with depth
  - Max depth is 8m

Modern Farms

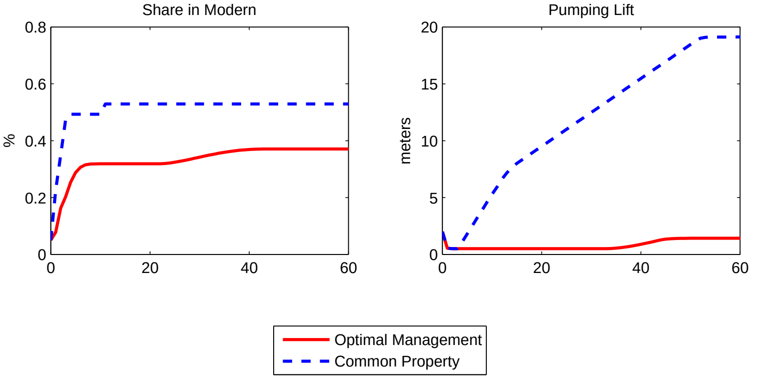
- Rice grown during kharif and rabi
- Water consumption (total) ~15,000 m^3/ha
- Physical limits on pumping not binding
- Conversion costs roughly 7 years of profit difference

Specific Parameters

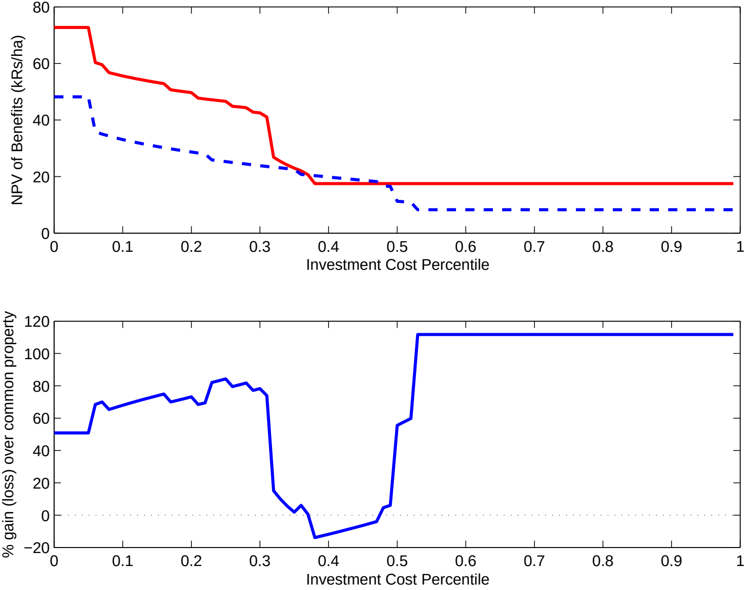
	Description	Value
δ	Discount factor	0.95
$\bar{h} - h_0$	Initial pumping lift	2m
φ_T	Inverse demand intercept (T)	0.3107 Rs/m^3
ψ_T	Inverse demand slope (T)	12.87×10^{-6} Rs/m^3/m^3
φ_M	Inverse demand intercept (M)	0.2788 Rs/m^3
ψ_M	Inverse demand slope (M)	3.63×10^{-6} Rs/m^3/m^3
r	Natural inflow per hectare	4,680 m^3/ha
θ	Return flow coefficient	35%
ϕ	Water released per 1m drop in aquifer	1,600 m^3/ha/m
e_T	Energy cost per m on traditional farms	0 Rs/m^3/m
e_M	Energy cost per m on modern farms	12 Rs/m^3/m
v_0	Initial common investment cost per ha	13,555 Rs/ha
α	Annual percentage decline in v	10%
μ	Mean of χ distribution	25,394 Rs/ha
σ	Standard deviation of χ distribution	10,000 Rs/ha
k_0	Initial share modern	5%
$L_T(h_0)$	Dug well extraction limit	3,000 m^3/ha

Preliminary Results

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



Impact on Different Farms



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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