WELL-FARE ECONOMICS OF GROUNDWATER DEVELOPMENT

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OLD NEWS IN INDIA
GROUNDWATER FACTS
WHAT IS IT?

Hard rock aquifer

Alluvial aquifer

Water (not ground water) held by molecular attraction surrounds surfaces of rock particles

Approximate level of the water table

All openings below water table full of ground water

Creviced rock

Gravel

Unsaturated zone

Saturated zone

Land surface

Surface water
HOW IS IT PUMPED?

Centrifugal
- Surface motor, typically diesel, sometimes electric.
- Uses suction ⇒ Max lift 7-8 m.
- But pump can be underground.

Submersible
- Integrated pump/motor
- Always electric
- 100+ m depth
- More expensive

Diesel motor deep set centrifugal pump with belt drive. Pump may be up to 7 meters below ground!
WHERE IN THE WORLD ARE FARMERS PUMPING GROUNDWATER?

Source: Siebert et al. (2010)

% of grid-cell equipped for GW irrigation

South Asia accounts for 48% of global GW use for irrigation
CONTEXT MATTERS...

- A tale of two Punjabs
  - Punjab, India: Deep alluvial aquifer
  - Punjab, Pakistan: "" + dense canal network

- Andhra Pradesh
  - Shallow hard-rock aquifer
SOUTH ASIA’S BOREWELL REVOLUTION
PRIVATE SECTOR DEVELOPMENT ON A GRAND SCALE

<table>
<thead>
<tr>
<th></th>
<th>No. of borewells (millions)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Census year</td>
</tr>
<tr>
<td>Punjab, PK</td>
<td>1994</td>
</tr>
<tr>
<td></td>
<td>2004</td>
</tr>
<tr>
<td>Punjab, IN</td>
<td>1995</td>
</tr>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Andhra Pradesh</td>
<td>1995</td>
</tr>
<tr>
<td></td>
<td>2010</td>
</tr>
</tbody>
</table>

- Growth in India is in submersible pumps
- Growth in PK is in centrifugal pumps
- Why? India has lower WT and ‘free’ electricity!

Source: Shah (2009)
PAKISTAN: CONJUNCTIVE USE

Cultivated Area of Punjab, PK

- Canal & tubewell: 18%
- Canal only: 1%
- Tubewell only: 18%
- Other irrigated: 15%
- Rainfed: 48%

Source: Ag census, 2010
GROUNDWATER AS A BUFFER
EVEN IN DRY SEASON

Figure 2. Weekly Irrigation Supply in Fd14R: Apr. 94-Oct. 95
(vertical lines = season boundaries)

Jacoby, Murgai, Rehman (2004)
SHARED PROSPERITY?

Source: Ag Machinery Census, 2004 (PK); Ag Census, 2010 (IN)
A DISTRIBUTIONAL SHIFT: PUNJAB, PK

Source: Ag Machinery Census, 1994 & 2004
SHARED ACCESS: PUNJAB, PK

Source: Ag census, 2010
GROUNDWATER DEPLETION IN SOUTH ASIA
NASA GRACE satellite shows that groundwater withdrawals in Rajasthan, Punjab, & Haryana led to water table decline of 33 cm/year for 2002-2008 (source: Rodell et al. 2009).
ANDHRA PRADESH

- High intra-year variability as monsoonal recharge is extracted during dry season, but...

- Piezometer data show virtually zero trend 1998-2012.
- GRACE data show GW gains from 2002-2008.
Historically

Rising groundwater levels after the introduction of canal irrigation (Wolters and Bhutta, 1997).

Recently

~3000 piezometers in canal command areas reveal a minimal depletion trend of 0.5 cm/year.
But, depletion is concentrated in 6 high depth to water-table districts of south-central Punjab.
Establishing causality is tricky!

Ag Machinery Census, 2004: WT changes matched to no. of tubewells by year of installation in corresponding Union Council.

Conclusion: faster tubewell development leads to faster depletion, but only in areas with initially high depth to WT.

In zones of plentiful recharge, tubewell development has not created problems (circa 2004).
SOUTH ASIA’S GROUNDWATER DILEmma
IN A NUTSHELL

Democratization

Depletion
4 WELL-FARE ECONOMICS QUESTIONS

(1) WHAT IS THE ECONOMIC RETURN TO WELL-DRILLING?
WELL-DRILLING IN AP

- 2010 weather insurance survey (~1500 hhs/44 villages) in two drought-prone districts of interior AP (w/Xavi Giné).
- Estimate gross return to a borewell.
- Estimate private cost of a borewell.
### Hedonic Estimate

<table>
<thead>
<tr>
<th></th>
<th>log(value/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functioning owned wells/acre</td>
<td>0.487</td>
</tr>
<tr>
<td></td>
<td>(0.113)</td>
</tr>
<tr>
<td>(accounting for fractional ownership)</td>
<td>0.459</td>
</tr>
<tr>
<td></td>
<td>(0.066)</td>
</tr>
<tr>
<td>log plot area</td>
<td>0.095</td>
</tr>
<tr>
<td></td>
<td>(0.025)</td>
</tr>
<tr>
<td>soil depth</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>(0.025)</td>
</tr>
<tr>
<td>black soil</td>
<td>0.137</td>
</tr>
<tr>
<td></td>
<td>(0.052)</td>
</tr>
<tr>
<td>Number of groups</td>
<td>44</td>
</tr>
<tr>
<td>Observations</td>
<td>3,018</td>
</tr>
<tr>
<td>Fixed effects</td>
<td>Village</td>
</tr>
<tr>
<td></td>
<td>Household</td>
</tr>
</tbody>
</table>

Notes: Cluster-robust standard errors in parentheses.

“If you were to sell this plot today, including the associated water rights, how much would you receive in `000 Rs./acre?”
HARD ROCK LOTTERY

The man with 48 borewells in drought-hit Marathwada

HT: Ram Fishman, GWU
“The rapid spread of groundwater irrigation throughout the dry-land areas has been gradually increasing the density of green specks in this otherwise brown terrain” (Shah, 2009)
## Consumption-Based Estimate

<table>
<thead>
<tr>
<th></th>
<th>log(total hh expenditure)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>No. of attempts &gt; 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>functioning owned wells/acre</td>
<td>0.191</td>
<td>0.220</td>
<td>0.161</td>
<td></td>
</tr>
<tr>
<td>(accounting for fractional ownership)</td>
<td>(0.039)</td>
<td>(0.045)</td>
<td>(0.046)</td>
<td></td>
</tr>
<tr>
<td>log(hh size)</td>
<td>0.481</td>
<td>0.424</td>
<td>0.425</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.022)</td>
<td>(0.042)</td>
<td>(0.042)</td>
<td></td>
</tr>
<tr>
<td>log(area owned)</td>
<td>0.139</td>
<td>0.180</td>
<td>0.230</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.013)</td>
<td>(0.024)</td>
<td>(0.025)</td>
<td></td>
</tr>
<tr>
<td>log(no. drilling attempts/acre)</td>
<td></td>
<td></td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.016)</td>
<td></td>
</tr>
<tr>
<td>No. of groups</td>
<td>44</td>
<td>44</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>1,484</td>
<td>891</td>
<td>891</td>
<td></td>
</tr>
<tr>
<td>Fixed effects</td>
<td>Village</td>
<td>Village</td>
<td>Village</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Cluster-robust standard errors in parentheses.
SIMPLE ARITHMETIC OF WELL-DRILLING

- What discount rate reconciles hedonic (capitalized) and consumption-based (income flow) gross return estimates? Answer: 5.6%

- What is the cost of a successful borewell?
  - Installation cost (drilling, casing, connection) = $C (= 23$ thousand Rs.)
  - Cost per failed attempt = $0.5 \times C$ (only bear cost of drilling)
  - Expected private cost = $C + 0.5 \times C \times E[\text{no. failures | success}]

- In this example:
  - Gross return (p.v.) to well ownership = 79.8 thousand Rupees
  - Private cost = 45.7 (≫ 23!)
  - Net private return = 34.1
  - Equivalent to around 3% of permanent income.
What if electricity to run pump is priced at cost rather than free?

Assume:
- Pump uses 4.7 kwh per hour of operation
- Operates 900 hours per year
- Cost of electricity = 0.75 Rs./kwh (off-peak ag. power tariff in W. Bengal)

→ Capitalized power subsidy = 56.6

→ Net private return = -22.6!

Conclusion: Without the heavy power subsidy, the marginal borewell would not be economically viable.
Standard DWL is fiscal cost (C+D) – gain in surplus (C) = D
Insofar as subsidy results in wells that would not otherwise have been drilled, there is an additional DWL of B – A.

Better to transfer C+D unconditionally than to condition on well-drilling!
4 WELL-FARE ECONOMICS QUESTIONS

(2) IS GROUNDWATER BEING EXTRACTED TOO QUICKLY?
Why? Optimal control of aquifer: maximize p.v. of revenue stream
- subject to law of motion for water level (WL) in aquifer
- taking account that extraction cost is a function of WL.
- Solution is steady-state WL*

WL* < WL₀ ⇒ optimal to deplete aquifer

So what is over-exploitation?...
TRAGEDIES OF THE COMMONS
EXTERNALITIES ASSOCIATED WITH GROUNDWATER

- **Strategic externality**
  - Does open access ("use-it-or-lose-it") ⇒ race to exhaustion?
  - **Not** if rising pumping costs eventually make extraction prohibitive.

- **Pumping cost externality**
  - Marginal extraction cost is the binding constraint.
  - Each irrigator only takes into account the (typically infinitesimal) impact of their extraction on their **own** future pumping cost, not on the future pumping costs of others.
  - Compared to WL*, steady state WL will be too low in a free-for-all.
TRAGEDIES OF THE COMMONS
EXTERNALITIES ASSOCIATED WITH GROUNDWATER

- **Uncertainty (risk) externality**
  - Amount of groundwater extracted varies stochastically depending on WL. (Alternatively, surface water is stochastic in a conjunctive use environment).
  - Individual irrigators do not fully internalize the cost of higher production uncertainty (or income risk) and thus over-extract relative to a managed aquifer.

- **Environmental externalities**
  - Land subsidence
  - Seawater intrusion or secondary salinity (important in Punjab, PK)
  - Positive externality: Vertical drainage alleviates waterlogging (Punjab, PK)
Welfare gains to groundwater management are negligible!
- When calibrated to a U.S. aquifer, $WL^* \approx WL$ under “free-for-all” pumping scenario.
- i.e., the pumping cost externality is vanishingly small.

Is this result applicable to the South Asian context(s)?

Gisser-Sanchez assumes
- No uncertainty in irrigation supply
- Single-cell (bathtub) aquifer $\Rightarrow$ pumping cost externality is global
- Number of wells exogenously fixed

Let’s return to the last two assumptions after some investigation in AP.
DEMISE OF THE DUGWELL

- Once the dominant well-type in peninsular India, shallow dugwells have reportedly been drying up at a prodigious rate over the last decade.

- Results from our 6-district 2012 GW markets survey (GWMS) for 62 villages having at least one dugwell in 2007.

<table>
<thead>
<tr>
<th>Mean number of</th>
<th>2007</th>
<th>2012</th>
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</thead>
<tbody>
<tr>
<td>Functioning dugwells</td>
<td>16.1</td>
<td>4.2</td>
</tr>
<tr>
<td>Non-functioning dugwells</td>
<td>9.9</td>
<td>20.9</td>
</tr>
</tbody>
</table>

In the mid 2000’s, there were more than 9 ml. open dugwells with mechanized pumps.

About a million alone in AP.
GWMS survey covers ~2400 borewells in 144 villages.

Since borewells may have been sunk first in villages with high WT (⇒ early wells are shallower), control for village fixed effects.

Conclusion: within a village, more recently sunk borewells are deeper. Trend is accelerating!

⇒ drilling cost ↑, pump HP ↑
OLDER BOREWELLS ALSO FAILING
SUGGESTIVE OF FALLING WATER TABLE
RECONCILING THE FACTS

“Groundwater, in hard rock areas is a local resource and [the] influence of [a] cluster of wells (which are about 30 or 40 metres deep) will be marginal beyond a radius of 2 or 3 km.” (AP Groundwater Dept., 2007).
BORREWELL CLUSTERING
GETTING A PIECE OF THE ACTION!

Village fixed effects included
**WELL INTERFERENCE**

**LOCALIZED PUMPING COST EXTERNALITY**

In AP,
- Pumps run continuously for the few hours/day electricity is available.
- Low transmissivity ⇒ greater drawdown

Combined discharge $\ll 2 \times$ individual
CLUSTERING AND WELL DISCHARGE

- “Circle” survey: Census of borewells within 100 meter radius of 369 randomly chosen reference borewells.
- Median of 2 other wells/circle.
- Conclusion: greater clustering attenuates well discharge.

⇒ In hard-rock zone, widespread well failure & well deepening is consistent with zero trend in static WL.
GISSER-SANCHEZ REVISITED
CONSEQUENCES OF WELL INTERFERENCE

- Localized pumping cost externality
  - “...if wells are clustered together in a relatively small area within an aquifer with much larger surface area, then a spatially explicit model will predict much larger welfare gains from optimal management than a single-cell model.” (Brozović et al. 2010)
  - i.e., given well interference, the external costs of any single well’s pumping are no longer diluted across the entire extent of the aquifer.

- Rent-seeking
  - Well interference ⇒ marginal well adds little to net extraction
  - but it entails a large fixed cost ⇒ surplus dissipated as more wells are sunk.
  - So, welfare losses from “free-for-all” may ultimately be huge.

- In sum, there may yet be an economic rationale for public intervention in groundwater management!
4 WELL-FARE ECONOMICS QUESTIONS

(3) HOW WELL DO GROUNDWATER MARKETS FUNCTION?
Markets in groundwater are inherently fragmented and local.

Jacoby, Murgai, Rehman (2004): sellers in Fd14R charge lower prices (\(= MC\)) to their share-tenants than to other buyers.

Inefficiency: deadweight loss 7% of total groundwater expenditures in watercourse.

Inequity: monopoly pricing has small distributional impact.

Conclusion: shared access \(\not\Rightarrow\) shared prosperity
WHAT’S THE CONTRACTING FAILURE?

- Why can’t farmers contract around deadweight loss?
  - E.g., why not price groundwater at marginal cost and charge buyers a lump-sum fee equal to their consumer surplus.

- Conjecture: demand uncertainty ⇒ renegotiation/hold-up problem (contracting breaks down).

- More generally, can uncertainty (in demand or supply) explain the organization of groundwater markets?
EFFICIENT MARKETS? AP

- Efficient groundwater market ⇒
  - small plots (without a borewell, but adjacent to one) should be just as likely as large plots to be left fallow.
  - But this is not the case in AP…

- Giné and Jacoby (2015): uncertainty about end-of-season borewell discharge
  - Influences form of groundwater contracts
  - Accounts for lack of groundwater sales—up to a point.
**How do groundwater markets interact with well-drilling?**

<table>
<thead>
<tr>
<th></th>
<th>Drill</th>
<th>Not drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill</td>
<td>12, 12</td>
<td>20, 10</td>
</tr>
<tr>
<td>Not drill</td>
<td>10, 20</td>
<td>0, 0</td>
</tr>
</tbody>
</table>

Coordination failure

- Farmer that doesn’t drill must buy water from farmer that does drill.
- Seller always has monopoly power, hence unequal surplus.

<table>
<thead>
<tr>
<th></th>
<th>Drill</th>
<th>Not drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill</td>
<td>12, 12</td>
<td>15, 15</td>
</tr>
<tr>
<td>Not drill</td>
<td>15, 15</td>
<td>0, 0</td>
</tr>
</tbody>
</table>

Anti-coordination success

- Same total surplus but divided equally, as through co-ownership.
- No wasteful drilling—equity enhances efficiency!
WELL DENSITY AND CO-OWNERSHIP

Data from 369 “circles” in AP
4 WELL-FARE ECONOMICS QUESTIONS

(4) WHAT POLICIES CAN ARREST GROUNDWATER DEPLETION?
We have seen that, in some contexts, controlling groundwater depletion may be economically justified.

But not in all contexts....

- Canal commands of Punjab, PK with reliable surface water
- Parts of northeastern India and W. Bengal
- In these places, we may want to encourage access to groundwater
  - Credit constraints may limit profitable well investment opportunities.
  - Positive vertical drainage externalities.
ANTI-DEPLETION POLICIES

- Remove price subsidies for groundwater-intensive crops (rice, wheat)
- Meter electricity and charge per kwh
  - Voltage stability mitigates pump burnout (WB, 2001).
- Permit system for well-drilling or power connections.
  - Enforcement of existing regulation virtually non-existent
- Public tubewells?
  - Governance problems (as in public surface irrigation).
  - Can’t put private genie back in the bottle!
- Artificial recharge (a local solution in hard-rock areas).
COMMUNITY GROUNDWATER MANAGEMENT

- APFAMGS: Community monitors groundwater balance in local aquifer to inform dry season planting decisions.

- Essentially tightens priors around variance of end-of-season groundwater supply.

- Giné and Jacoby (2015): Higher variance $\Rightarrow$ less area planted in the dry season (“precautionary planting”)

- Although pilot looks promising, jury is still out on whether this intervention is cost-effective and sustainable.
SOLAR-POWERED PUMPSETS TO SUBSIDIZE OR NOT?

- Subsidy likely to encourage depletion.
- But drilling incentives are already distorted
  - 5-hour daily power ration ⇒ 2 borewells needed to pump 10 hrs/day!
  - Solar pump ⇒ only one borewell needed to pump 10 hrs/day.
- Solar subsidy may reduce rent-seeking (wasteful drilling) even as it increases depletion (more drilling/pumping overall).
- Punjab (IN) will condition its solar subsidy on adopting drip irrigation.
DRIP IRRIGATION

- Given that policies to raise the cost of groundwater extraction are political landmines, what about subsidizing water-saving technology?
- Drip irrigation uses water more efficiently, but will it save water?
- Insofar as farmers expand irrigated area, it may not!
  - Depends on organization of groundwater markets
- RCT planned in AP will examine this question.
- Results (hopefully) in near future!
THANK YOU!