Natural Resource Topic I: Groundwater Markets & Governance

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Natural Resources

Non-renewable natural resources (Perman et al. Ch. 15):

- Fossil-fuel energy supplies (e.g. oil, coal, diamond)
- Minerals (e.g. copper, nickel)
- Forestry (old growth)
- What else?

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Renewable natural resources (Perman et al. Ch. 17):

- Biological resources (e.g. fishery)
- Forestry (including secondary)
- Rangeland
- What else?

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How about **groundwater from aquifer?**

Readings

Groundwater: Overview

Jacoby (2017) and many other sources

Jacoby et al. (2004)

"Monopoly power and distribution in fragmented markets: The case of groundwater"

Sekhri (2011)

"Public protection and protection of natural resources: Groundwater Irrigation in Rural India"

Others

Foster & Rosenzweig (2008); Gine & Jacoby (2020); O'Keeffe-O'Donovan (2022)

Groundwater: Renewable or Non-Renewable?

In theory, it is **renewable**:

- The aquifer is replenished by rainfall or surface water sources
- The change in water level depends on the rate of these recharges and on the rate of ground extraction by pumping

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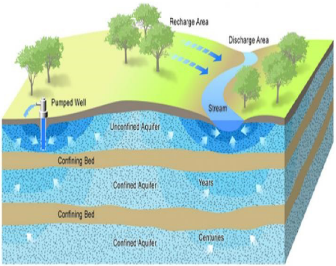
In practice, it depends on:

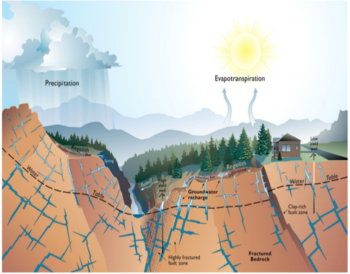
- Geographic scale
- Time scale
- Various environmental and hydrogeological conditions

In many situations, groundwater has a **non-renewable** nature as well

E.g. Aquifer Systems Matter



(a) Permeable Aquifer system



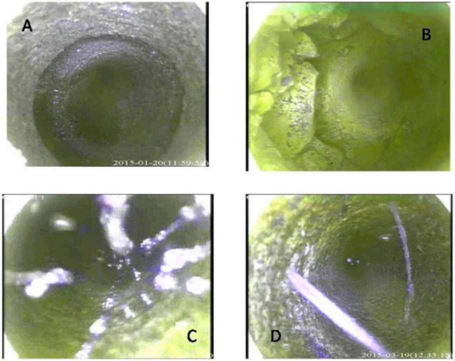
(b) Non-Permeable Aquifer Systems

Source: Colorado Water Knowledge

Source: Bhogale & Khedgikar (2022)

- With a permeable aquifer system, available water levels could be affected by those in a neighboring district (Bhogale & Khedgikar 2022)
- Water could be **renewable** in this system, depending on, for example, rainfall in a neighboring district

E.g. Aquifer Systems Matter



Notes: Figure A2 shows images taken from four borewells in the study area. A: Dry fracture in bedrock. B: Cavity formed in a fracture, now dried up. C: Fracture with cavity below the water level. D: Water-bearing shallow fracture, spout cascading down the well.

Source: Blakeslee et al. (2020)

- Blakeslee et al. (2020):
  - Groundwater in Karnataka, India, is stored in small, scattered pockets located within a hardrock subsurface
  - Households suffer a drying up or (permanent) “failure” of their borewell: **non-renewable** water resource

Externalities Associated with Groundwater Exploitation

Regional scale:

- **Negative**: Pumping groundwater may impose external costs through seawater intrusion in coastal zones or through secondary salinity
  - A serious problem in Pakistan's Punjab
- **Positive**: Vertical drainage afforded by groundwater pumping, which alleviates waterlogging (also in the Punjab)

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Local scale:

- Groundwater becomes a **common-pool resource** when many well owners pump from an aquifer under the rule of capture
  - Each well owner only takes into account the impact of their extraction on their *own* future pumping costs
  - The steady-state water level in the aquifer will be lower when there are many well owners than when there is a single owner
- Models from the previous slides apply to this problem, too!

Bardhan (2000)

"Irrigation and cooperation: An empirical analysis of 48 irrigation communities in South India"

Significant variation in the degree of villagers' cooperation in the management and maintenance of irrigation among villages with similar historical and agricultural production environment

More cooperation is achieved as:

1. Inequality in land ownership is smaller
2. Access to a market and city is more limited
3. Villagers in the same community are more socially homogeneous
4. There are more inter-village conflicts over water
5. Village size is smaller

Evolution of Groundwater Markets

- The "Green Revolution": Asian agriculture experienced a remarkable increase in productivity since the 1980s
- This is triggered by the introduction of a package of new inputs, including high-yielding varieties, chemical fertilizers, and irrigation
- Accelerated diffusion of private tubewells/borewells

Evolution of Groundwater Markets

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- Under the legal systems of South Asian countries, groundwater pumped from wells was treated as entirely private property without any restriction on its use
  (That is why groundwater is a common-pool resource if no market exists)

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- Under the legal systems of South Asian countries, groundwater pumped from wells was treated as entirely private property without any restriction on its use
  (That is why groundwater is a common-pool resource if no market exists)
- As a result, private transactions in irrigation water emerged as a new production factor market
- The emergence of water markets has been significantly higher in areas with higher rates of HYV productivity growth (Foster & Rosenzweig 2008)

Localized and Fragmented Groundwater Markets

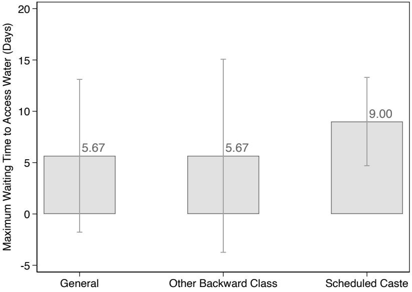
- Groundwater transfers are typically limited to neighboring plots through unlined field channels with high seepage losses
  - Some exceptions: extensive underground pipeline networks connecting well owners and water buyers in Gujarat, India
  - Intermediate cases: plastic pipes

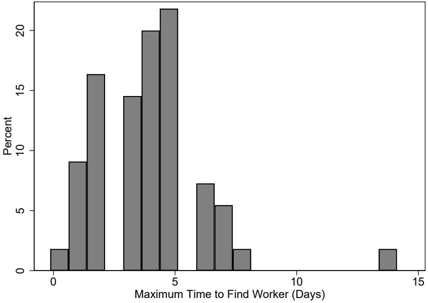
E.g. An Irrigation Tubewell in Bihar, India

E.g. Accessing Irrigation Water in Bihar, India

- Pump up groundwater using electricity or diesel
- Convey the water using plastic pipes


Challenges Accessing Irrigation Water: Time Cost





Source: The author's own agricultural household survey in Bihar, India (August 2023)

- Long waiting time when water is needed for crop production
  → Significantly affects productivity (Left)

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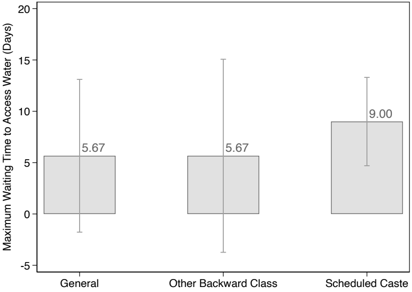
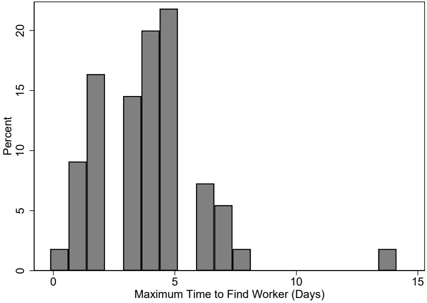
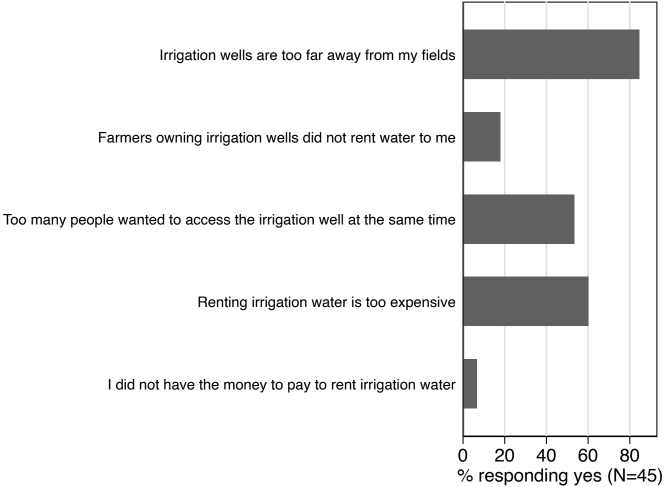




Source: The author's own agricultural household survey in Bihar, India (August 2023)

- Long waiting time when water is needed for crop production
  → Significantly affects productivity (Left)
- This negative effect might be exacerbated if difficult to coordinate between access to water and other inputs
- Especially true for labor as labor demand is high when water is available, but labor search cost also seems high (Right)

Challenges Accessing Irrigation Water: Location Matters



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Localized and Fragmented Groundwater Markets

- Groundwater transfers are typically limited to neighboring plots through unlined field channels with high seepage losses
  - Some exceptions: extensive underground pipeline networks connecting well owners and water buyers in Gujarat, India
  - Intermediate cases: plastic pipes
- Wells tend to be scattered, albeit clustered to some degree

$\Rightarrow$ Groundwater markets may not exhibit perfectly competition, under which the market price of groundwater equals to the marginal cost of extracting it

- An extreme case is **monopoly**: if there is only one well owner who sells water to other farmers in the same village

Irrigation Water Market under Monopoly: Setup

- Suppose one tubewell (TW) owner sells irrigation water to other farmers not owning TWs
- The profit maximization problem of the TW owner:

$$\max_{A} \quad \pi = w(A)A - c(A)$$

  - A: amount of water (in terms of the acreage of irrigated area)
  - $w()$: water charge per acre
  - $c()$: cost (fixed cost + variable cost)
    (A well owner first needs to pay a **fixed cost** to build a well. We will come back to this point with empirical research papers.)

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  - $c()$: cost (fixed cost + variable cost)
    (A well owner first needs to pay a **fixed cost** to build a well. We will come back to this point with empirical research papers.)
- $w(A)$: the (inverse) demand curve of irrigation water
  - Amount of water produced $\uparrow \Rightarrow$ Price of water $\downarrow$
  - The monopolist TW owner acts taking into account this pricing power i.e. The TW owner is no longer a price taker
- $R(A) = w(A)A$: the TW owner's revenue

Irrigation Water Market under Monopoly: Equilibrium

- The condition for the TW owner's profit maximization:

$$\frac{d\pi}{dA} = w(A) + w'(A)A - c'(A) = 0$$
$$\Leftrightarrow w(A) + w'(A)A = c'(A)$$

i.e. **Marginal revenue = Marginal cost**

Irrigation Water Market under Monopoly: Equilibrium

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i.e. **Marginal revenue = Marginal cost**

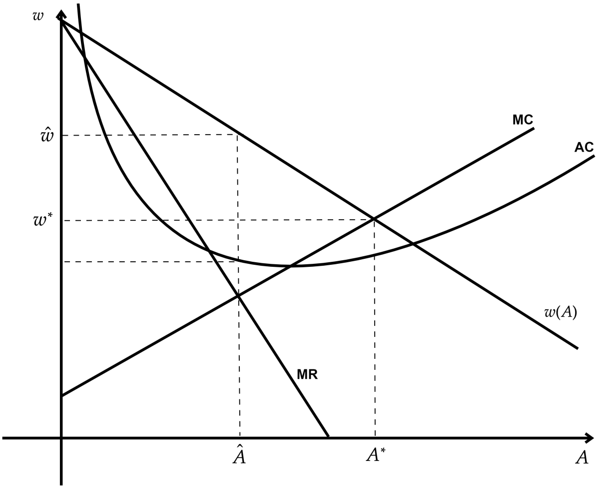
- Rearranging this condition yields the equilibrium water price:

$$\begin{aligned} w(A)\left(1 + w'(A)\frac{A}{w(A)}\right) &= c'(A) \\ \Leftrightarrow \hat{w} &= \frac{e}{e-1}c'(\hat{A}) \end{aligned}$$

where $e \equiv -\frac{dA}{dw}\frac{w}{A}$:

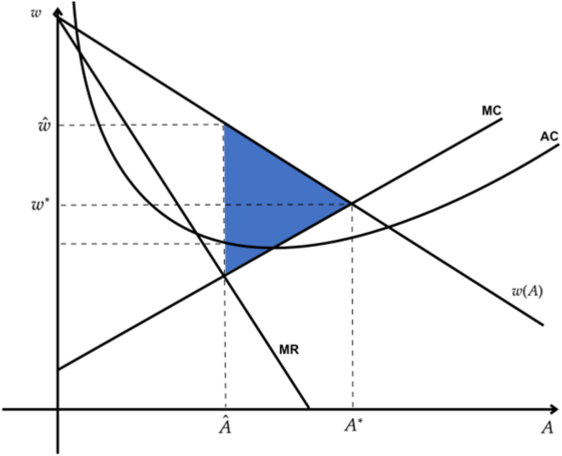
- Price elasticity of water demand (> 1 under monopoly)
- % change in demand when price is increased by 1%

Irrigation Water Market under Monopoly: Equilibrium



- $\hat{A}$: the equilibrium water output is determined at MR = MC
- $\hat{w}$: the corresponding monopoly price is determined from the monopoly output and the demand curve

Irrigation Water Market under Monopoly: Efficiency Loss



Compared to (w^*, A^*) under perfect competition, monopoly leads to:

1. Output amount ↓ & price increases ↑
2. **Unequal distribution**: Producer's profit ↑ & Consumer surplus ↓
3. **Inefficient allocation**: The loss to consumers is always be greater than the increase in profits, and thus total surplus decreases

Market Power

Indicators of the market power or the degree of monopoly:

- Price-cost margin: $\frac{w-c'(A)}{w} = \frac{1}{e}$
- Markup: $\frac{w}{c'(A)} = \frac{e}{e-1}$

where $e \equiv -\frac{dA}{dw}\frac{w}{A}$: price elasticity of demand

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The industrial organization of groundwater markets (i.e. how competitive they are) is a key research agenda → Jacoby et al. (2004)

Groundwater and Well-Drilling

- Wells are strategic substitutes: once every farmer has one, little scope remains for groundwater sales
- Constructing a well requires a high fixed cost
- The choice to drill by a pair of neighboring farmers can be considered a coordination game

Coordination between Neighboring *Rich* Farmers?

Coordination failure

		Farmer 2's action	
		Drill	Not drill
Farmer 1's action	Drill (C)	**(12, 12)**	(20, 10)
	Not drill (O)	(10, 20)	(0, 0)

- **Social optimum**: either one of the farmers drills a well and the other buys water
- **NE**: both farmers drill
- This inefficiency is due to the inequitable allocation of rents (as we have seen in the monopoly model)

Coordination between Neighboring *Rich* Farmers?

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$\downarrow$?

Well co-ownership to achieve efficiency and equity

		Farmer 2's action	
		Drill	Not drill
Farmer 1's	Drill (C)	(12, 12)	**(15, 15)**
action	Not drill (O)	**(15, 15)**	(0, 0)

Coordination between Neighboring *Poor* Farmers?

Coordination failure

		Farmer 2's action	
		Drill	Not drill
Farmer 1's action	Drill (C)	(-1, -1)	(-2, 6)
	Not drill (O)	(6, -2)	**(0, 0)**

- **Social optimum**: either one of the farmers drills a well and the other buys water
- **NE**: neither farmer drills
- This may be because each farmer is too poor to build his own well alone without any cooperation

Coordination between Neighboring *Poor* Farmers?

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↓ ?

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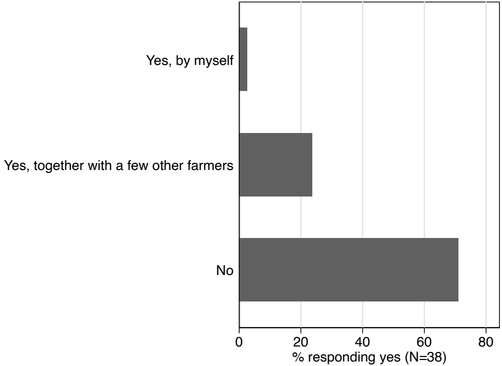
Underinvestment & Interest in Collective Investment in Wells

Have you considered building your own well for irrigation?
(among land owners without irrigation wells)



Source: The author's own agricultural household survey in Bihar, India (August 2023)

⇒ Open questions:

- How can we promote the collective action on lumpy investment?
- Are caste differences in neighboring farmers are hampering collective investment in irrigation wells? (cf. Anderson 2011)

Readings

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Jacoby (2017) and many other sources

Jacoby et al. (2004)

"Monopoly power and distribution in fragmented markets: The case of groundwater"

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Others

Foster & Rosenzweig (2008); Gine & Jacoby (2020); O'Keeffe-O'Donovan (2022)

Motivation

Q. What is the nature of the pricing and allocation of a resource when the asset producing the resource is **lumpy**?

- Given credit constraints and other limitations on spreading ownership of the asset across the users of the resource, markets are likely to develop
- Asset: a tubewell & Resource: groundwater

Summary

- Examines monopoly power in the market for groundwater
- The market is characterized by barriers to entry and spatial fragmentation
- Groundwater and tenancy contracts are often interlinked, with share-tenants gaining access to water through the use of their landlord's tubewell
- Tubewell owners are charging their own share-tenants a price equal to MC and all other water-buyers a substantial markup over MC
- Moving to universal MC pricing does not alter the wealth distribution very much

Data

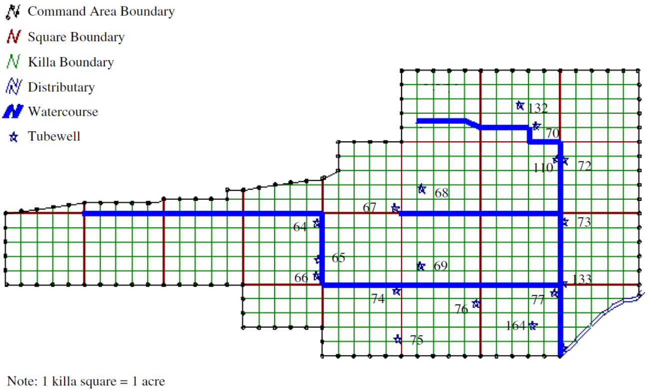

FIGURE 1
Fd14R watercourse map

- Survey of irrigation practices in the Fordwah-Eastern Sadiqia irrigation system of southern Punjab, Pakistan from 1993 to 1995
- Focuses on a single typical watercourse
- Information on every groundwater transaction

Determinants of groundwater prices

	Means (S.D.)	(1)	(2)	(3)
Transaction characteristics				
Buyer is tenant of tubewell owner	0·33	−10·60	−9·55	−9·12
		(6·21)	(3·30)	(3·40)
Buyer provided fuel	0·01	−16·8	−14·6	—
		(7·36)	(5·78)	
Buyer provided engine and fuel	0·06	−31·9	−30·5	−22·8
		(20·5)	(19·3)	(5·11)
Aggregate tubewell operating hours on	37·1	0·002	−0·006	0·029
day of transaction	(22·6)	(0·12)	(0·38)	(1·19)
Canal water endowment (m^3 $acre^{-1}$) in	30·1	−0·005	−0·006	−0·001
week of transaction	(39·0)	(0·60)	(0·79)	(0·07)
Rabi season 1994–1995	0·27	0·71	0·60	−0·14
		(0·76)	(0·64)	(0·21)
Kharif season 1995	0·33	1·79	1·05	0·10
		(1·89)	(1·25)	(0·11)
Buyer (plot) characteristics				
Sharecropped (% cultivated area)	0·52	0·58	0·52	0·09
	(0·49)	(0·26)	(0·24)	(0·01)
Owner-cultivated (% cultivated area)	0·37	0·23	−1·22	0·77
	(0·47)	(0·10)	(0·56)	(0·09)
Distance to head of watercourse	14·7	0·270	0·091	0·038
(acre-lengths)	(8·5)	(3·23)	(0·91)	(0·30)
Tubewell characteristics				
5-inch (vs. 4-inch) pipe diameter	0·47	4·17	—	1·81
		(3·30)		(0·54)
Distance to main watercourse channel	0·47	−1·04	—	−1·29
(acre-lengths)	(1·17)	(2·84)		(0·90)
EC of groundwater (dS m^{-1})[a]	1·82	−0·72	—	−3·86
	(0·92)	(0·74)		(1·36)
Fixed effects	—	None	Tubewell	Farmer
No. of observations	886	886	886	320
Adj. R^2	—	0·557	0·608	0·595

Notes: Robust absolute t-values (in parentheses) adjusted for clustering on buyer (*warabandi* id)—seller (tubewell) pair. Dependent variable is the price of groundwater in rupees h^{-1}. All regressions

Determinants of plot-level groundwater use

	Kharif 1994		*Rabi 1994–1995*		
	Tobit	**SCLS**	**Tobit**	**SCLS**	**Tobit**
Tubewell owner	760	685	386	371	961
	(3·57)	(3·75)	(2·80)	(2·89)	(7·10)
Tubewell tenant	723	527	568	541	548
	(2·37)	(1·90)	(2·63)	(2·32)	(2·87)
Sharecropped	−97	−17	−111	−100	46
(% cultivated area)	(0·39)	(0·12)	(0·67)	(0·82)	(0·27)
Owner-cultivated	120	9	169	74	175
(% cultivated area)	(0·58)	(0·07)	(1·24)	(0·86)	(1·21)
Canal water use (m^3 $acre^{-1}$)	0·073	0·055	−0·045	−0·060	−0·022
	(0·68)	(0·40)	(0·38)	(0·59)	(0·13)
Distance to nearest tubewell (acre-lengths)	−50	−51	−50	−27	−23
	(2·46)	(2·23)	(3·38)	(2·51)	(2·05)
H_0: equality of owner and tenant variables (p-value)	0·91	0·59	0·44	0·41	0·06
Smith–Blundell test: exogeneity of canal water use (p-value)	0·25	—	0·67	—	0·29
Log-likelihood [R^2]	−652·2	[0·211]	−559·9	[0·253]	−535·0
No. censored observations	12		19		
No. observations	93		92		

Notes: Absolute t-values reported in parentheses. Dependent variable is the total groundwater use during a season on a plot (m^3 $acre^{-1}$)

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1. Tubewell tenants pay significantly less (9.6 rupees per hour less) for groundwater coming from their landlord's tubewell
   (The authors carefully argue the presence of the monopoly power by eliminating alternative possible explanations)
2. Large and significant difference between groundwater use of tubewell owners/their tenants and that of other buyers

$\Rightarrow$ Indicative of substantial resource misallocation; Estimated markup $\approx \frac{32}{22}$

Access to groundwater through efficient markets need not imply an equitable distribution of resource rents

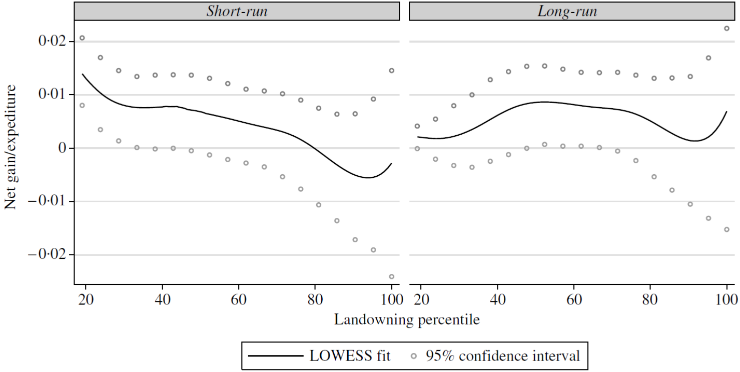

FIGURE 3

Distribution of net gains form marginal cost pricing

In the long run:

- Surrounding landowners benefit from the elimination of their neighbors' monopoly power
- Landless households do not benefit from MC pricing

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Summary

Q. What is the impact of public provision of groundwater through large-capacity wells on overall water tables?

Hypothesis: Public access could lead to sustainable use of groundwater when the **fixed costs for private wells are high**

- Negative side: water use $\uparrow$ by expanding access to farmers who are too poor to sink a well
- Positive side: public provision can crowd out the installation of private wells by large farmers because they are substitutes $\Rightarrow$ water use $\downarrow$ if price charged for the public water is higher than the MC of private water extraction

Context: a deep public tube-well program in Uttah Pradesh, India

Results: heterogeneous treatment effects by the cost of extraction (using 8 meters cutoff of water table depth) confirmed her hypothesis

Table 4—Differences-in-Differences Estimates of Public Tube well on Local Water Table Depth by Category of Fixed Cost (*Differences-in-differences with matching*)

Dependent variable: Depth of water table below ground level	Benchmark (1)	DID with matching (2)	(3)
Panel A			
Public tube well × *post* × Low cost	−0.8	−0.8	−0.5
	(0.8)	[0.8]	[0.8]
Public tube well × *post* × High cost	−5.53	−5.4	−5.21
	(2.3)	[1.9]	[2.10]
Demographic and economic time varying controls	Yes	Yes	No
Geographical time varying controls	Yes	Yes	Yes
Observations	14,202	14,002	14,202
R^2	0.17	0.16	0.17
Panel B. Heterogeneity in impact of public tube well program between high- and low-cost category			
Difference between point estimates from panel A	−4.73	−4.6	−4.71
F-statistic (testing if the difference is 0)	3.85	6.06	4.24
Significance level	0.049	0.013	0.0395

- Public provision led to a > 5m less decline of water table depth in the high fixed cost category
- Significant difference from the low fixed cost category
- Not tested here, but the water saving impact will be stronger in locations with a thick-tail land distribution (more large-scale farmers)

Readings

Groundwater: Overview

Jacoby (2017) and many other sources

Jacoby et al. (2004)

"Monopoly power and distribution in fragmented markets: The case of groundwater"

Sekhri (2011)

"Public protection and protection of natural resources: Groundwater Irrigation in Rural India"

Others

Foster & Rosenzweig (2008); Gine & Jacoby (2020); O'Keeffe-O'Donovan (2022)

Foster & Rosenzweig (2008)

"Inequality and sustainability of agricultural productivity growth: Groundwater and the Green Revolution in rural India"

Q. How does inequality in landholding impact groundwater extraction?

Foster & Rosenzweig (2008)

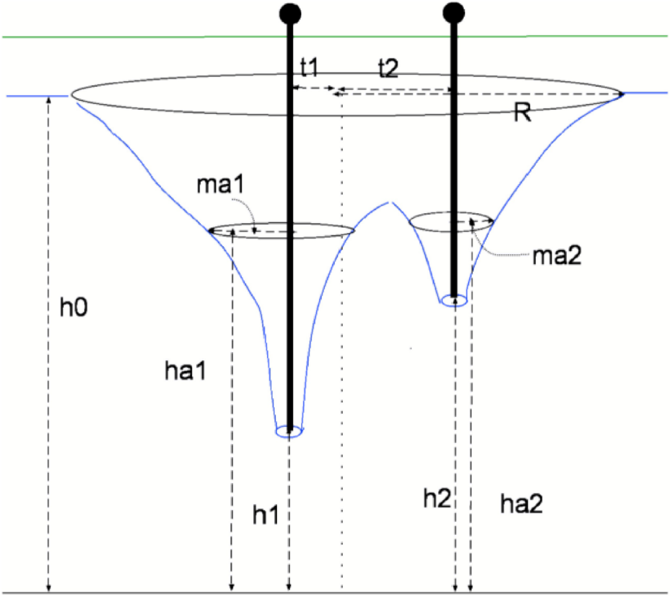
"Inequality and sustainability of agricultural productivity growth: Groundwater and the Green Revolution in rural India"

Q. How does inequality in landholding impact groundwater extraction?

Coordination failure among well owners as a result of interference:

- Negative spillovers onto farm profitability:
  - Your profitability decreases with neighbors' water usage
- Strategic complementarity in input choice:
  - Your groundwater use increases with neighbors water use
  - Marginal cost of your water extraction is lower as neighbors' pumping rate is higher

Model of Two Well Interference



Foster & Rosenzweig (2008): "Concavity effect"

More equal distribution of land size leads to greater overall extraction of water resources:

- Small farmers do not find it profitable to sink a well because of its high fixed cost
- Large farmers use less water per irrigated area, because they cannot effectively poach the water from neighboring farmers (less chance to free-ride on common aquifer)
- Medium farmers do not fully internalize the cost of pumping, leading to the highest water use

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Trade-off between inequality, productivity growth, and environmental sustainability

Gine & Jacoby (2020)

Contracting under uncertainty: Groundwater in South India

- A model of contracting under payoff uncertainty
- Uncertainty arises from unpredictable fluctuations in groundwater supply during the agricultural dry season
- Trade-off between the ex-post inefficiency of long-term contracts and the ex-ante inefficiency of spot contracts

Hold-up Problem

Definition:

- A and B can work most efficiently through cooperation
- But it cannot be achieved due to concerns that A's pre-commitment makes B's bargaining power stronger (B holds up A)

When this happens:

- Needs relationship-specific investments before the transaction takes place
- A scope for deviation from commitment (opportunistic behavior)

The groundwater context:

- Water buyers need to choose area irrigated before the water transaction (pre-commitment)
- If buyers decide that a larger portion of lands are irrigated, their position will become weaker. So this leads to underinvestment in irrigated lands

Trade-offs between Long-Term vs. Spot Contracts

Long-term contracts (Commitment):

- Commits the well-owner to irrigate a buyer's field or some portion, for the whole season at a pre-determined price
- Pros: no scope for quasi-rents generated by relationship-specific investments $\Rightarrow$ ex-ante efficiency
- Cons: contractual rigidity $\Rightarrow$ misallocation

Spot contracts (Nash-bargaining on the spot):

- Pros: flexible to changing conditions $\Rightarrow$ state contingent $\Rightarrow$ ex-post efficiency
- Cons: scope for opportunistic behavior $\Rightarrow$ underinvestment in planting of water-buyers (hold-up problem)

Gine & Jacoby (2020): Summary

- A model of contracting under payoff uncertainty
- Uncertainty arises from unpredictable fluctuations in groundwater supply during the agricultural dry season
- Trade-off between the ex-post inefficiency of long-term contracts and the ex-ante inefficiency of spot contracts
- Data: payoff uncertainty and relationship-specific investment from a large sample of well-owners in Andhra Pradesh, India
- Estimates: spot contracts entail a 3% efficiency loss due to hold-up
- Counterfactual simulations reveal that the equilibrium contracting distortion reduces:
  - the overall gains from trade by about 4%
  - the seasonal income of the median borewell owner by 2%

  with proportionally greater costs borne by smaller landowners

O'Keeffe-O'Donovan (2022)

"Water, spillovers, and free riding: Provision of local public goods in a spatial network"

Model the role of strategic complementarity among nearby communities in the context of pump maintenance in Tanzania:

- Free riding: less likely to be functional, if there are more non-pump water sources (e.g. community taps)
  - Even if your own pump is not functional, you can use a neighbor's water source
- Positive maintenance spillovers: more likely to be functional if there are many pumps of the same technology nearby
  - Emergence of markets for spare parts, skill development, and information sharing

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Empirical results:

- Standardization of pumps would increase the functionality rate
- Water collection fees at alternative water sources would be a effective policy to discourage free-riding