Way Down in the Hole: Adaptation to Long-Term Water Loss in Rural India

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Introduction

- Groundwater depletion in southern India
- How do rural households in India adapt to long-term water loss caused by groundwater depletion?
- What role does labor reallocation to non-agricultural sectors play in maintaining household income?
- Important:
    - Groundwater depletion is a critical threat to agriculture-dependent livelihoods
    - Coping mechanisms (labor reallocation, income diversification)
    - Socioeconomic impacts of environmental degradation
    - Inform sustainable development policies
- Methodology:
    - Quasi-random variation in geological factors causing borewell failure, as an exogenous shock
    - Compare HH with functional borewells to HH who experienced borewell failure, within villages
    - Include household and village fixed effects

Methodology

- Quasi-Random groundwater access in Karnataka's hard-rock geology: spatially random subsurface water pockets determine whether a drilled borewell succeeds or fails
- Household borewell failure is used as the central comparison, focusing only on the first borewell to avoid confounding effects of wealthier households drilling additional borewells
- Only households within the same village are compared, isolating quasi-random geological variation and excluding broader village-level trends or differences
- Geological validation: specialized cameras confirm that fine-scale geological differences drive borewell failures, validating exogeneity
- Key Identifying Assumptions:
  - Borewell failure is exogenous to household attributes, with fixed effects for the year of drilling and pre-drilling characteristics (e.g., income, education)
  - Robustness tests show no pre-existing correlation between borewell age, depth, or cost and household socioeconomic conditions
- Regressions estimate outcomes (e.g., income, labor shifts) as a function of borewell failure, using household controls and fixed effects for village and year of drilling

Data

- Household survey data: 1,408 households from 102 villages in Karnataka that rely primarily on groundwater for irrigation
- Data on every borewell drilled, its functionality status, costs, depths, and drilling year. About 62% of first borewells had failed, on average 5 years after drilling
- Household characteristics, including cropping patterns, income sources (farm and off-farm), assets
- Supplementary village-level data from the 2013 Economic Census, used to measure the presence of firms and local industry

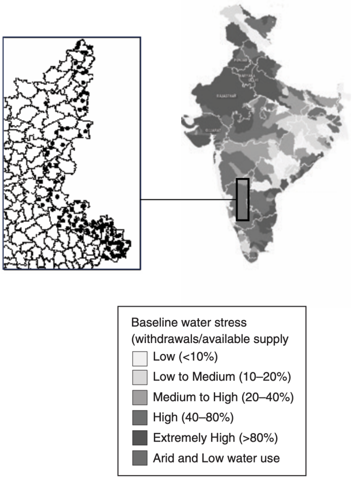


Figure Baseline water stress (withdrawals/available supply)

Results Preview

- Significant drop in farm income with little evidence of agricultural adaptation
- Households shifted labor to off-farm employment to offset income losses; better outcomes in regions with developed manufacturing sectors
- Total income maintained through employment shifts; increased debt and asset liquidation
- Older children more likely to drop out of school to supplement household income
- Younger children's enrollment increased as potential preparation for future non-agricultural jobs

Literature Review (in 30 seconds)

- Severe detrimental effects of climate change on agricultural livelihoods and a host of social outcomes
  - Auffhammer et al. 2013
  - Dell, Jones, and Olken 2014
  - Carleton and Hsiang 2016
- Households' coping strategies in response to such transient income shocks, including asset sales, income diversification, and migration
  - Alderman and Paxson 1994
  - Morduch 1995
  - Dercon 2002
- Shifts to non-agricultural employment in response to transient weather shocks
  - Kochar 1999
  - Macours, Premand, and Vakis 2012
  - Colmer 2016

Overview

1. Background
2. Data
3. Empirical Strategy
4. Results
5. Conclusion
6. Thesis

Background

- Groundwater use has grown by 105% since the 70s, in contrast to 28% growth in surface water use; its access, use, and depletion is dependent on characteristics of the subsurface hydrogeology
- Over-extraction (in excess of local recharge) largely concentrated in two parts of India:
  - The Northwest, where aquifers are deep and alluvial
  - Central-southern India, where aquifers occur within a hard-rock geology

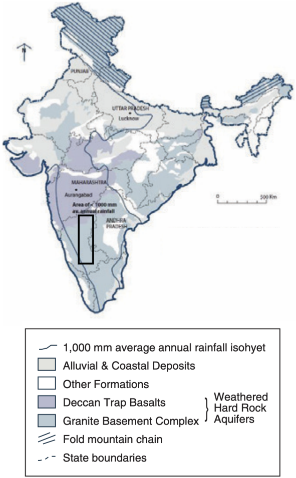


Figure Classification of aquifer systems; light grey shades mark alluvial aquifers, else: hard-rock aquifers

Background

- The bulk of the subsurface consists of impermeable rock interspersed with networks of fractures and pockets of permeable material, which is where groundwater is stored
- Borewells drilled into the hard rock yield water by tapping into these water-bearing pockets, intersect 0—5 sources, each just a few decimeters thick
- The fractures' exact location and spacing cannot be determined by surface features, and their patterns are highly heterogeneous and unpredictable
- Until 60s: mostly shallow, dug wells. Late 60s: "down-the-hole" (DTH) drilling enabled access to deeper sources of water at high cost. 90s: rising incomes enabled a proliferation of DTH

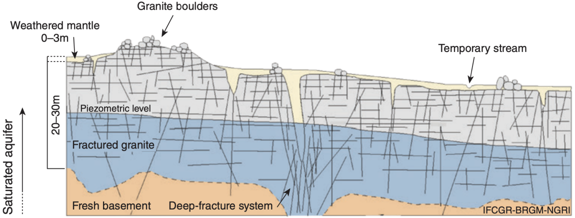


FIGURE 2. HARD ROCK HYDROGEOLOGY

Notes: Simplified geological profile of a hard rock aquifer. Water accumulates in fractures (solid lines) that are interspersed within the subsurface at varying locations and depth, and are being recharged from various sources.

Figure

Background

- Important to our study:

1. Local aquifers have limited storage, exhaust more rapidly than alluvial aquifers of NW India; water levels dropping since 90s, many dried up
2. High degree of quasi-random spatial variation, even at small distances, in rate of hitting water and operation time before it dries up
3. Drilling is a costly (more than double median household annual income) and risky investment

Data

- 2016: 1,408 land-owning households from 102 villages randomly selected from 31 districts in Karnataka, not served by surface irrigation
- Supplemented with village-level admin data from 2013 Economic Census, which provides information on the number and size of firms within each village and in adjacent area

TABLE 1—DESCRIPTIVE STATISTICS

Panel A. Sample sizes	
Number districts	10
Number villages	102
Number households	1,408
Number HHs ever drilled BW	893
Panel B. First borewell characteristics	
Year drilled	2001 [10]
Depth (feet)	423 [225]
Cost (10,000 Rs)	7.463 [5.690]
Failed	0.615 [0.487]
Year failed	2006 [8]

Data

- Households with functioning borewells have much higher farm and total income, and own more land and other assets
- Greater wealth can enable households to retain access to water by drilling more and deeper wells
- Therefore, these differences cannot be interpreted as being caused by access to water

Panel C. Household characteristics

	Household has functional borewell		
	Yes	No	Difference
HH head non-marginal caste	0.532	0.476	−0.055 [0.032]
HH head literate	0.643	0.577	−0.067 [0.027]
HH head age	51.961	51.548	−0.413 [0.809]
Brick house	0.437	0.340	−0.098 [0.028]
Electricity	0.974	0.968	−0.006 [0.010]
Below poverty line (BPL)	0.871	0.892	0.020 [0.020]
Inherited land (acres)	5.720	4.554	−1.166 [0.408]
Asset value without land (10,000 Rs)	28.529	17.465	−11.064 [2.044]
Income, 2015 (1,000 Rs)			
Total	85.374	54.711	−30.663 [7.276]
On-farm	61.005	24.817	−36.188 [4.775]
Off-farm	24.369	29.894	5.525 [4.814]
Fraction of HH members (dry season)			
Own-farm	0.492	0.301	−0.191 [0.023]
Off-farm, agricultural labor	0.126	0.229	0.103 [0.016]
Off-farm, non-agricultural labor	0.041	0.111	0.069 [0.011]
Not working	0.097	0.147	0.050 [0.011]
Working outside village	0.074	0.098	0.024 [0.010]
Semi-permanent migrant	0.015	0.021	0.006 [0.005]

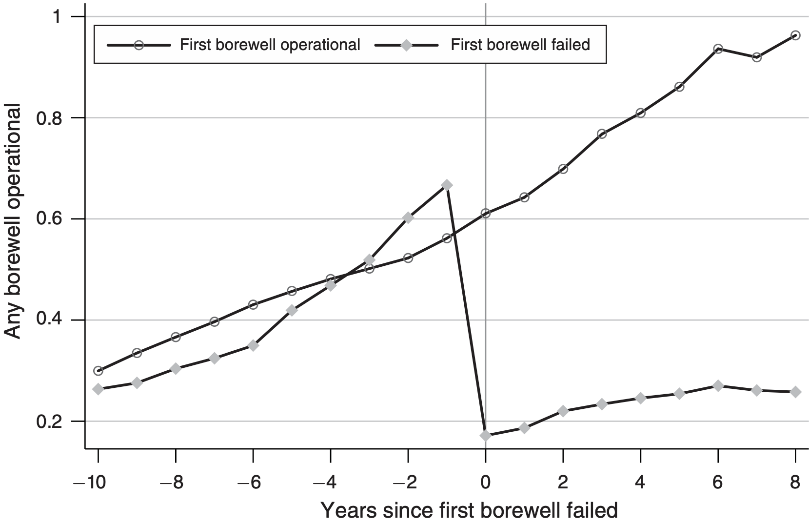
Empirical Strategy

- Regression:

$$y_{i,v} = \alpha_1 + \underbrace{\alpha_2 F_i}_{\text{effect of borewell failure}} + \underbrace{X_i \Phi}_{\text{household characteristics}} + \underbrace{A_v}_{\text{village fixed effects}} + \underbrace{B_t}_{\text{year fixed effects}} + u_i \quad (1)$$

- Household characteristics include age, caste, literacy of HH head, total land inherited by HH
- Robustness tests: depth and cost of the first borewell, alternative specs of first borewell age
- All regressions incorporate sampling weights that reflect the relative share of HH in the village that belong to each type (with/without first borewell)
- Identifying assumption: conditional on year of drilling, failure of first borewell is exogenous, within villages, to any other correlates of the outcomes
- Hypothesis: remaining determinants of failure primarily depend on highly variable and quasi-random hydrogeological characteristics (such as number of sources the well intersects)

Results


First borewell operational
First borewell failed
Any borewell operational
Years since first borewell failed
1
0.8
0.6
0.4
0.2
−10
−8
−6
−4
−2
0
2
4
6
8

Results

TABLE 3—WATER ACCESS AND AGRICULTURE

	Control mean	Impact of BW failure	
	(1)	(2)	(3)
Panel A. Water use			
Operational borewell	1.000	−0.626	−0.634
		[0.027]	[0.026]
Irrigation, rainy season (any)	0.701	−0.443	−0.458
		[0.031]	[0.029]
Irrigation, dry season (any)	0.508	−0.332	−0.336
		[0.035]	[0.034]
Irrigation, dry season (pct. land)	0.317	−0.218	−0.210
		[0.028]	[0.028]
Panel B. Rainy season			
Any cultivation	0.993	−0.020	−0.021
		[0.009]	[0.009]
Total land (acres)	4.451	−0.093	−0.124
		[0.219]	[0.266]
Field crops (acres)	3.730	0.190	0.179
		[0.209]	[0.250]
Horticulture (acres)	0.720	−0.282	−0.303
		[0.096]	[0.099]
Panel C. Dry season			
Any cultivation	0.596	−0.286	−0.303
		[0.037]	[0.038]
Total land (acres)	1.204	−0.466	−0.479
		[0.239]	[0.249]
Field crops (acres)	0.826	−0.291	−0.286
		[0.182]	[0.211]
Horticulture (acres)	0.378	−0.175	−0.193
		[0.098]	[0.089]
Village fixed effects		Yes	Yes
First-BW year-drilled fixed effects			Yes

Results

TABLE 4—LABOR REALLOCATION

	Control mean	Impact of BW failure	
	(1)	(2)	(3)
Panel A. Rainy season			
Occupations per member	1.380	−0.005	−0.013
		[0.047]	[0.044]
Fraction of HH members			
Working on own farm	0.527	−0.040	−0.048
		[0.024]	[0.024]
Working off-farm, agriculture	0.102	0.049	0.048
		[0.019]	[0.020]
Working off-farm, non-agriculture	0.038	0.026	0.027
		[0.011]	[0.012]
Not working	0.100	0.014	0.019
		[0.012]	[0.012]
Panel B. Dry season			
Occupations per member	1.375	−0.025	−0.026
		[0.047]	[0.044]
Fraction of HH members			
Working on own farm	0.489	−0.094	−0.104
		[0.025]	[0.025]
Working off-farm, agriculture	0.119	0.061	0.064
		[0.021]	[0.021]
Working off-farm, non-agriculture	0.045	0.040	0.042
		[0.012]	[0.014]
Not working	0.102	0.022	0.029
		[0.014]	[0.014]
Panel C. Location			
Fraction of HH members			
Semi-permanent migrant	0.010	0.013	0.014
		[0.006]	[0.007]
Non-migrant working outside village			
Rainy season	0.058	0.030	0.027
		[0.013]	[0.014]
Dry season	0.060	0.028	0.028
		[0.013]	[0.014]
Village fixed effects		Yes	Yes
First-BW year-drilled fixed effects			Yes

Results

TABLE 5—CHILD EMPLOYMENT AND SCHOOLING

	Control mean	Impact of BW failure	
	(1)	(2)	(3)
Children, 6–11 years old			
Fraction enrolled	0.542	0.120	0.122
		[0.058]	[0.060]
Fraction employed	0.005	−0.002	−0.004
		[0.003]	[0.005]
Children, 12–18 years old			
Fraction enrolled	0.817	−0.096	−0.110
		[0.043]	[0.042]
Fraction employed	0.130	0.052	0.073
		[0.034]	[0.037]
Village fixed effects		Yes	Yes
First-BW year-drilled fixed effects			Yes

Results

TABLE 6—INCOME

	Control mean	Impact of BW failure	
	(1)	(2)	(3)
Any income			
On-farm	0.800	0.002	0.003
		[0.024]	[0.026]
Government transfers	0.204	0.004	0.028
		[0.031]	[0.033]
Business	0.039	−0.004	−0.010
		[0.012]	[0.012]
Remittances	0.062	0.002	0.009
		[0.019]	[0.020]
Off-farm employment	0.291	0.084	0.118
		[0.038]	[0.038]
Income (1,000 Rs.)			
On-farm	59.141	−16.684	−14.083
		[5.854]	[6.325]
Off-farm	21.850	8.623	12.182
		[5.549]	[6.017]
Total	80.991	−8.061	−1.900
		[8.773]	[9.500]
Village fixed effects		Yes	Yes
First-BW year-drilled fixed effects			Yes

Results

TABLE 7—ASSETS AND DEBT

	Control mean	Impact of BW failure	
	(1)	(2)	(3)
Assets			
Total land (acres)	5.510	0.091	0.045
		[0.216]	[0.226]
Land value (10,000 Rs)	316.816	−18.289	10.593
		[60.519]	[64.742]
Brick house	0.412	−0.055	−0.059
		[0.036]	[0.037]
Number rooms	3.160	−0.062	−0.075
		[0.114]	[0.119]
Asset value without land (10,000 Rs)	27.758	−6.523	−6.750
		[2.363]	[2.464]
Debt			
Any	0.352	0.074	0.073
		[0.032]	[0.031]
Size of total debt (10,000 Rs)	9.270	4.599	5.572
		[2.271]	[2.294]
Village fixed effects		Yes	Yes
First-BW year-drilled fixed effects			Yes

Conclusion

- Provides early evidence on medium- to long-term impacts of large-scale, permanent environmental deterioration in developing countries
- Persistent loss of access to irrigation water reduces agricultural viability; minimal adaptation observed in farming practices
  - Affected land often left fallow or cultivated with low-value crops
  - Raises concerns about aggregate food production
- Households offset agricultural income losses by reallocating labor to off-farm employment
  - Limited migration or employment in nearby villages
  - Worsening groundwater trends unlikely to induce large-scale "environmental refugees"
- Income adaptation depends on local non-agricultural economy:
  - Regions with large firms: higher off-farm employment, slight total income increase
  - Regions with few firms: total income declines
- Rural industrialization and non-agricultural development can mitigate income-related impacts of environmental degradation but involve trade-offs:
  - Asset liquidation, debt accumulation, reduced food expenditures
  - Lower human capital investments for young adolescents

Thesis

- Micro Irrigation (drip and sprinkler systems) can improve agricultural efficiency by saving 30—70 percent of water compared to conventional methods
- Adoption levels remain low in India due to a lack of incentives for efficiency; water and electricity is unpriced or heavily subsidized
- All-India Data Set: Village-level panel data from the Minor Irrigation Census (1993—2017) is used to assess adoption patterns and water scarcity correlations, merging this information with climatic data, socio-economic indicators, and satellite-based irrigation estimates
- Gujarat Data Set: High-resolution data from Gujarat-based GGRC tracks more than 400,000 geo-referenced MI adopters (2006—2013) and includes detailed subsidy variations, enabling analysis of adoption determinants, social learning effects, and water conservation outcomes

Figure Map of India

Thesis

- Working Hypotheses:
  1. Adoption rates are correlated, across villages and farmers, with indicators of economic development and water scarcity, and these correlations are higher at early stages of diffusion. Earlier adopters are larger farmers, but MI diffuses to smaller farmers in the village over time.
  2. Variation in water scarcity has causal impacts on the rate of adoption.
  3. Variation in (subsidy driven) MI cost has causal impacts on the rate of adoption and particularly by smaller farmers.
  4. Subsidized adoption has spillover effects on adoption in adjacent areas (presumably through social learning), but these are limited by crop type and social groups (castes).
  5. Subsidized adoption has varying effects on water and power use for pumping, depending on the extent of overall irrigation coverage in the village and the existence of informal water markets.