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Economic drivers of additional borewell investment in Karnataka's Central Dry Zone

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Abstract
Repeated borewell failure is a defining economic risk of groundwater irrigation in the hard-rock aquifers of peninsular India, yet little is known about what drives farmers' investment in additional or replacement borewells after an initial failure, or whether micro-irrigation lowers or raises that investment. Using primary data for 2025-26 from 120 farmers in Chitradurga and Davanagere districts of Karnataka's Central Dry Zone (53 drip, 37 sprinkler and 30 conventionally irrigated farms), a Tobit model was estimated for investment in additional borewells, which is bounded below at zero. Gross irrigated area (₹1,13,903.70 per acre) and the variable cost of irrigation water (₹135.38 per rupee) significantly increased latent investment, whereas each additional year of successful borewell operation reduced it (₹79,769.33); all three effects were significant at the one per cent level. The drip dummy was positive (₹2,50,638.90) and the sprinkler dummy negative (₹74,327.69), but neither was statistically significant *and* groundwater used per farm was also non-significant. At mean values, predicted investment was ₹3,89,732 per drip farm, while latent investment was negative for sprinkler and conventional farms. The results suggest that pressure for further drilling operates mainly through the expansion of irrigated area and rising water costs rather than through irrigation technology itself, which is consistent with rebound-effect concerns. Policies that promote micro-irrigation should therefore be coupled with measures that limit area expansion and reduce the risk of well failure.

Keywords: Tobit model, Groundwater, Borewell failure, Drip irrigation, Rebound effect, Central Dry Zone, *Karnataka*

Introduction

Groundwater has become the backbone of Indian agriculture. India is the largest user of groundwater in the world, extracting roughly a quarter of the global total *and* groundwater supplies well over half of the country's irrigation (Shah, 2009) [1]. The most recent national assessment puts annual groundwater recharge at 446.90 billion cubic metres (bcm), annual extractable resources at 406.19 bcm and annual extraction at 245.64 bcm, giving an average stage of extraction of 60.47 per cent (Central Ground Water Board, 2024) [2]. National averages conceal severe local stress *and* satellite-based estimates have documented rapid groundwater depletion across large parts of the country (Rodell *et al*., 2009) [3].

The problem is sharpest in the hard-rock regions of peninsular India. Aquifers in granitic and gneissic terrain store water mainly in weathered and fractured layers (Dewandel *et al*., 2006) [4], so storage is limited, recharge is only a small fraction of rainfall and well yields are highly uncertain (Anitha *et al.*, 2017) [5]. Farmers therefore drill repeatedly and deeper *and* many wells fail prematurely or never yield water. Studies from *Karnataka* and Andhra Pradesh show that well failure and well interference impose externality costs on neighbouring farmers, that small farmers are among the worst affected *and* that the cost of groundwater irrigation rises as the resource is mined (Reddy, 2005; Anantha, 2013; Chandrakanth, 2015) [7, 6, 8]. Using household data from the drier eastern parts of *Karnataka*, Blakeslee *et al.* (2020) [9] show what is at stake: households whose first borewell dried up cultivated less land and shifted towards off-farm work *and* although drilling an additional well could in principle offset the loss, its cost and risk deterred most households from doing so. Investment in an additional borewell after a failure is thus a costly, risky and unevenly taken decision.

Governments have promoted drip and sprinkler irrigation as a way to save water and relieve pressure on aquifers. Micro-irrigation has been shown to raise yields and reduce the water applied per unit area, particularly for widely spaced horticultural crops (Narayanamoorthy, 2004; Namara *et al.*, 2007) [11, 10]. Field-level savings, however, do not automatically translate into lower aggregate extraction. Because greater efficiency lowers the effective cost of water, farmers may expand the irrigated area, switch to more water-intensive crops or intensify cultivation, an outcome described as the rebound effect or Jevons paradox (Ward *et al.*,

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2008; Perry *et al.*, 2009; Grafton *et al.*, 2018; Sears *et al.*, 2018) [13, 14, 12, 15]. Empirical work reinforces the concern. Efficient irrigation technology increased groundwater extraction in Kansas through reduced fallowing and a shift to more water-intensive crops (Pfeiffer *et al.*, 2014) [16]; simulations for India suggest that about half of the potential reduction in over-extraction from drip and sprinkler adoption would be lost to expansion of irrigated area (Fishman *et al.*, 2015) [17]; and a randomised trial in Andhra Pradesh found that subsidised drip adoption raised farm profit and moved farmers into horticulture without any reduction in groundwater pumping (Fishman *et al.*, 2023) [18]. Birkenholtz (2017) [19] likewise questions whether India's drip-irrigation boom will deliver groundwater savings.

If micro-irrigation sustains or expands irrigated area, it may also raise farmers' dependence on an assured water supply and thereby the financial pressure to drill again after a failure. Yet microeconomic evidence on what determines investment in additional or replacement borewells in hard-rock regions is thin *and* very little of it compares drip, sprinkler and conventionally irrigated farms. The outcome is also a limited dependent variable: many farmers incur no additional expenditure, so observations accumulate at zero while the remainder take positive values. Ordinary least squares applied to such data yields biased and inconsistent estimates *and* the Tobit model (Tobin, 1958) [20] is the standard remedy (McDonald *et al.*, 1980; Amemiya, 1984) [22, 21]. Censored regression is also a common tool in studies of the extent and intensity of farm technology adoption, a literature surveyed by Feder *et al.* (1985) [23] and Doss (2006) [24].

This paper therefore estimates a Tobit model of investment in additional or replacement borewells following initial well failure for drip, sprinkler and conventionally irrigated farms in Chitradurga and Davanagere districts of Karnataka's Central Dry Zone. It examines whether irrigation technology, the scale of irrigation (gross irrigated area), groundwater use, the variable cost of irrigation water and the number of successful well years significantly influence such investment.

Materials and Methods

Study area, sampling and data

The study was conducted in Chitradurga and Davanagere districts, which lie in the Central Dry Zone of *Karnataka*, a hot semi-arid and drought-prone agro-climatic zone with low and erratic rainfall (about 450 to 890 mm a year), shallow red and black soils and hard-rock geology. Agriculture is predominantly rainfed *and* irrigation depends heavily on borewells and minor tanks. An ex-post-facto research design was adopted because the events under study had already occurred and the researcher had no control over the variables. A total of 120 farmers using groundwater irrigation were randomly selected and then post-stratified into 53 drip-irrigated farms (DIF), 37 sprinkler-irrigated farms (SIF) and 30 conventionally irrigated farms (CIF). Primary data for the agricultural year 2025-26 were collected through a pretested, structured interview schedule covering borewells drilled, year of drilling, depth, functioning wells, investment in drilling, casing, pumpsets and conveyance, irrigation technology *and* groundwater use, which was estimated from the number of irrigations, the time taken to irrigate an acre, the discharge of drippers or sprinklers and borewell yield. Of the 120 farmers, 82 had experienced the initial failure of one or more borewells.

Tobit specification

Investment in additional or replacement borewells contingent on initial failure cannot be negative and equals zero for farmers who made no such investment. It was therefore modelled as a censored dependent variable using a Tobit model, in which an unobserved latent investment I^* is linearly related to the explanatory variables:

$I^*_i = \alpha + \beta_1 D_{1i} + \beta_2 D_{2i} + \beta_3 X_{1i} + \beta_4 X_{2i} + \beta_5 X_{3i} + \beta_6 X_{4i} + \varepsilon_i$, $\varepsilon_i \sim N(0, \sigma^2)$

$I_i = I_i$ *if* $I_i > 0$ *and* $I_i = 0$ otherwise.

Variable	Definition
I	Investment in additional or replacement borewells per farm after initial failure (₹)
D_1	Drip dummy (1 = drip irrigation, 0 = conventional)
D_2	Sprinkler dummy (1 = sprinkler irrigation, 0 = conventional)
X_1	Gross irrigated area (acres)
X_2	Number of successful borewell years
X_3	Groundwater used per farm (acre-inches)
X_4	Variable cost of irrigation water (₹)

Conventional irrigation is the reference category. The model was estimated by maximum likelihood in EViews. The coefficients (β) measure the effect of each variable on latent investment; the effect on observed expected investment equals β multiplied by the probability of being uncensored (McDonald *et al.*, 1980) [22], so the signs and significance levels are the same, but the magnitudes on the observed outcome are smaller.

Results and Discussion

Overall model

The maximum likelihood estimates are presented in Table 1. The log-likelihood of the model was −1,233.51. Three of the six explanatory variables, namely gross irrigated area, the number of successful well years and the variable cost of irrigation water, were significant at the 1 per cent level, whereas the technology dummies and groundwater used per farm were not. The estimated equation was:

$$I = -53,727.42 + 2,50,638.90D_1 - 74,327.69D_2 + 1,13,903.70X_1 - 79,769.33X_2 - 2,167.88X_3 + 135.38X_4$$

Table 1. Tobit estimates of the determinants of investment in additional borewells contingent on initial borewell failure (n = 120)

Variable	Coefficient (₹)	*p*-value	Significance
Intercept	−53,727.42	0.82	NS
Drip technology dummy (D_1)	2,50,638.90	0.14	NS
Sprinkler technology dummy (D_2)	−74,327.69	0.67	NS
Gross irrigated area, acres (X_1)	1,13,903.70	0.002	**
Number of successful well years (X_2)	−79,769.33	0.007	**
Groundwater used per farm, acre-inches (X_3)	−2,167.88	0.31	NS
Variable cost of irrigation water, ₹ (X_4)	135.38	0.003	**
Log-likelihood	−1,233.51		

*Note: ** significant at 1 per cent; NS = not significant. Conventional irrigation is the reference category.*

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Scale of irrigation

Gross irrigated area had a positive and highly significant effect: each additional acre was associated with ₹1,13,903.70 more latent investment in additional or replacement borewells. A larger irrigated area raises the quantity of water that must be drawn from a limited fractured-rock aquifer, increases the number of wells needed to meet demand and intensifies interference between neighbouring wells, which in turn raises the likelihood and cost of failure (Anantha, 2013; Chandrakanth, 2015) [6, 8]. Larger farms may also have greater capacity to finance repeated drilling, a pattern commonly reported in the technology-adoption literature (Feder *et al.*, 1985; Doss, 2006) [23, 24]. The result is also consistent with the rebound argument: when the cost of water falls or its supply seems assured, farmers expand irrigated area *and* the expansion, not the efficiency of the technology, determines the pressure on the aquifer (Pfeiffer *et al.*, 2014; Fishman *et al.*, 2015; Grafton *et al.*, 2018) [16, 17, 12]. Area expansion appears to be the main channel through which agricultural intensification translates into further investment in wells.

Successful well years

The number of successful well years had a negative and significant effect: one additional year of successful borewell operation reduced latent investment by ₹79,769.33. A durable well allows the farmer to defer drilling *and* the capital sunk in it is recovered over a longer period, which lowers the annual burden of groundwater irrigation. The finding is in line with the observation that well life in hard-rock aquifers has been shortening as water tables fall and wells interfere with one another (Anitha *et al.*, 2017; Chandrakanth, 2015) [5, 8] *and* with evidence that the burden of well failure is greatest where well interference is high (Anantha, 2013) [6]. It also highlights why premature failure is costly: it brings forward replacement expenditure that farmers, as Blakeslee *et al.* (2020) [9] show, find expensive and risky to undertake.

Variable cost of irrigation water

The variable cost of irrigation water had a positive and significant effect: each additional rupee of variable cost was associated with ₹135.38 more latent investment. Variable costs rise when water tables fall, pumping lifts increase and wells deliver less water per hour of pumping, so a higher variable cost can be read as a signal of deteriorating well performance, which pushes the farmer towards deepening or replacing a borewell. This is the cost-escalation mechanism emphasised in the groundwater externality literature (Reddy, 2005; Anantha, 2013) [7, 6]. The relationship may also run in both directions, since recently drilled deeper wells carry higher energy costs *and* the coefficient should therefore be read as an association rather than a strict causal effect.

Irrigation technology

The drip dummy was positive (₹2,50,638.90) but not statistically significant (p = 0.14) *and* the sprinkler dummy was negative (₹74,327.69) and clearly non-significant (p = 0.67). Relative to conventional irrigation, there is therefore no statistically reliable evidence that either technology reduces investment in additional borewells after an initial failure. This matters for the water-saving argument: if micro-irrigation really relieved pressure on the aquifer, drip and sprinkler farms would be expected to invest significantly less in additional wells *and* this was not observed. The large positive but imprecise drip coefficient is nevertheless suggestive. Drip systems are typically adopted for high-value horticultural crops (Narayanamoorthy, 2004; Namara *et al.*, 2007) [11, 10] *and* Fishman *et al.* (2023) [18] found that drip adopters moved into more remunerative, irrigation-dependent horticulture without reducing pumping. Farmers who have sunk capital into drip systems and perennial crops depend on an assured water supply and may therefore be more willing to re-drill after a failure. The insignificance of the technology dummies once area and water cost are controlled suggests that the effect of technology, if any, works through scale and cost rather than directly, a pattern in line with the rebound literature (Birkenholtz, 2017; Sears *et al.*, 2018) [19, 15]. Given the modest size of the sub-samples, particularly the 30 conventional farms, this result should be treated as indicative.

Groundwater used per farm

Groundwater used per farm had a negative but non-significant coefficient (−₹2,167.88 per acre-inch; p = 0.31). Farm-level water use is largely determined by irrigated area and cropping pattern, so much of its variation may already be captured by gross irrigated area, leaving little independent explanatory power. The volume of water drawn is also estimated from irrigation schedules and discharge rather than metered, which introduces measurement error that biases coefficients towards zero. It is the area irrigated *and* the cost of getting water, rather than the volume estimated to be pumped, that explains additional well investment in this sample.

Predicted investment and policy implications

At the mean values of the explanatory variables, the model predicted investment of ₹3,89,732 per farm for drip-irrigated farms. For sprinkler and conventional farms the predicted latent investment was negative, which in a Tobit framework means that a large share of such farms is expected to be at the censoring limit of zero additional investment. Drip farms, which tend to be larger, more capital-intensive and more dependent on assured water, thus carry the highest expected financial exposure to well failure.

Three implications follow. First, because area expansion is the main driver of further investment, subsidies for micro-irrigation should be accompanied by farm-level water budgets or limits on the area brought under irrigation, so that efficiency gains are not converted into additional extraction (Fishman *et al.*, 2015; Grafton *et al.*, 2018) [17, 12]. Second, regulating well spacing, enforcing groundwater legislation such as the *Karnataka* Ground Water (Regulation and Control of Development and Management) Act *and* restoring surface water bodies for recharge would reduce interference and prolong well life (Anantha, 2013; Anitha *et al.*, 2017) [6, 5]. Third, because the cost and risk of re-drilling fall heavily on farmers (Blakeslee *et al.*, 2020) [9], hydrogeological siting support and risk-sharing mechanisms for well failure could reduce the repeated-drilling spiral, especially for small and marginal farmers.

Limitations

The analysis rests on a single agricultural year and a cross-section of 120 farmers, with relatively small technology sub-samples. Investment, irrigated area and water costs are determined jointly, so the estimates describe associations rather than causal effects *and* farm-level groundwater use is calculated rather than metered. Panel data with hydrogeological controls such as well depth, aquifer type and well density would allow stronger inference.

Conclusions

A Tobit analysis of investment in additional or replacement borewells following initial failure in the Central Dry Zone of *Karnataka* shows that gross irrigated area and the variable cost of irrigation water significantly increase such investment, whereas longer successful operation of existing wells significantly reduces it. Neither drip nor sprinkler irrigation had a statistically significant effect relative to conventional irrigation *and* groundwater used per farm was also non-significant, although drip farms had the highest predicted investment. Micro-irrigation by itself therefore does not appear to relieve the pressure to drill additional wells; what matters is how far it is accompanied by expansion of irrigated area and by rising water costs. Policies that combine micro-irrigation support with limits on area expansion, well-spacing regulation, aquifer recharge and risk-sharing against well failure are more likely to translate field-level efficiency into real groundwater conservation.

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