Groundwater Depletion and Land Reallocation*

Talha Naeem†

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Abstract

I estimate the effect of groundwater depletion on agricultural organization, land markets, and household welfare using over two decades of plot-level administrative land records in Haryana, India. I instrument for groundwater depth using predetermined variation in soil texture and subsurface geological characteristics, which govern the differential pass-through of rainfall to groundwater stocks. Outcomes respond non-linearly to groundwater depth: production first shifts away from dry-season water-intensive crops toward monsoon-season crops; as depth increases further, land exits agriculture through market sales and non-market transfers such as family partitions, encumbered inheritance, and near-zero-price transfers. These reallocations are not distributionally neutral: small farmers disproportionately exit, holdings consolidate, and non-agricultural and institutional buyers increasingly dominate, with the share of market transactions involving an institutional buyer rising from roughly 3 percent at shallow depths to 14 percent at extreme depths. A financial channel amplifies these transitions: loan take-up rises with scarcity, while mortgaged plots are sold or passed on to heirs, with debt attached. These patterns are consistent with a credit-collateral trap in which land pledged for adaptation loans is lost when farm revenues fall short of debt obligations, with agricultural income shares falling as households shift away from farming. The findings point to collateralized credit and land markets as the channels through which environmental risk generates structural and distributional change.

JEL Codes: Q15, Q25, O12, R14, G21.
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†University of British Columbia. Email: naeemtal@student.ubc.ca

1 Introduction

Climate change not only increases risks for farming but also gradually alters who farms, how farms are organized, and how land and labour are allocated. In northern India, known as the country's food bowl, this reorganization is already underway, driven by rapidly depleting groundwater. Two-thirds of irrigated land in India relies on groundwater, and extraction rates are now unsustainable across large swaths of South Asia. As water tables fall, groundwater is not merely a depleting input: it is a shared, unregulated resource whose extraction imposes externalities on others without being priced in. This commons problem means that without policy intervention, farmers continue to pump even as the collective stock deteriorates.

As water tables drop, farm households face mounting costs: they must upgrade extraction technology to survive, switch to less water-intensive crops, or leave farming altogether. Upgrading technology requires access to credit, and credit is typically secured by land. This creates a debt cycle: rising irrigation costs increase borrowing; falling farm revenues make debt hard to service; default or near default conditions transfers land to lenders, family, and market; and credit-constrained households are permanently excluded from agriculture, their descendants losing their inheritance. What begins as a shared resource problem thus becomes a private financial crisis, reshaping who owns land and who remains in farming.

Despite the scale and speed of this depletion, our understanding of how economies adapt when a vital resource diminishes remains limited. This paper traces how groundwater scarcity propagates from production decisions through land markets and collateralized credit to labour reallocation and household welfare.

Related literature. A growing body of research studies water access and irrigation, documenting their effects on yields, cultivation intensity, climate resilience, and agricultural productivity (Cisse et al., 2026; Asher et al., 2022; Blakeslee et al., 2023; Proctor et al., 2025). Related work on groundwater emphasizes its shared-resource nature, where weak regulation and policy distortions shape extraction decisions and amplify scarcity

(Badiani-Magnusson and Jessoe, 2018; Burlig et al., 2021; Basavappa and Pommer Muñoz, 2025). A separate literature studies land institutions and land market frictions, highlighting how restrictions on transactions and conversion can generate persistent misallocation and limit sectoral mobility (de Janvry et al., 2015; Adamopoulos et al., 2024; Bolhuis et al., 2025). Yet these literatures have largely remained separate: work on water scarcity treats agricultural organization as static, while the land market literature largely abstracts from environmental constraints.

Recent work by Donna and Espín-Sánchez (2026) provides upstream evidence that frictions in water access generate productive inefficiencies, even when water is allocated through market mechanisms, showing that liquidity constraints distort water allocation during critical growing periods. This paper complements that work by tracing the *downstream* consequences of persistent water scarcity, documenting how groundwater depletion reshapes land use, land markets, farm size distribution, and labour allocation over time.

Understanding these mechanisms is also central to the literature on agricultural organization and structural transformation. Farm size distribution and land reallocation are key determinants of productivity differences across countries (Caselli, 2005), and prior work emphasizes the role of credit, labour markets, technology adoption, and urbanization in shaping agricultural structure (Eswaran and Kotwal, 1986; Foster and Rosenzweig, 2022; Dwyer, 2024). More recent evidence suggests that climate change may slow or reverse structural transformation as subsistence constraints bind (Nath, 2025), with limited on-farm adaptation (Hultgren et al., 2025). Yet it remains unclear whether these patterns reflect stagnation or instead mask substantial reorganization within agriculture mediated by land markets. Recent land digitization efforts have begun to relax data constraints (Rao et al., 2022; Arteaga et al., 2025). This paper builds on that work by assembling a plot-level panel to trace how groundwater scarcity propagates from production decisions to land markets, ownership structure, labour allocation, and household welfare.

I assemble newly digitized administrative land records from Haryana, India, covering plot-level ownership and transaction activity from 2000 to 2025. These data are matched to groundwater monitoring data from the Central Ground Water Board (CGWB), satellite-

based land-use and crop production measures. I also use household survey data from the Indian Human Development Survey (IHDS) to study the downstream consequences.

Groundwater depth is endogenous to farming decisions. To isolate exogenous variation, I exploit a geological fact: soils differ in their ability to transmit rainfall to groundwater. Because soil composition is predetermined and rainfall is exogenous from farmers' perspectives, differential rainfall pass-through driven by soil characteristics generates plausibly exogenous variation in groundwater depth. Extraction technology introduces nonlinearities: centrifugal pumps fail between 8 and 10.3 meters depth (Sekhri, 2014; Butler and Boudot Reddy, 2023), and submersible pumps become increasingly expensive beyond that. Due to this non-linearity, the standard 2SLS specification is ill-suited. So, I adopt a control function approach that allows a fully non-parametric relationship between groundwater depth and outcomes of interest.

The paper produces three sets of findings. First, the production response to groundwater depletion is nonlinear and sequential: dry-season water-intensive crop production contracts while monsoon-season output expands at the village level. Second, land markets are a central transmission channel: as scarcity intensifies, land exits agriculture through both market sales and non-market transfers (family partitions, encumbered inheritance, and near-zero-price transfers). Two distinct processes drive reallocation: ownership consolidates as small farmers exit to larger individual landowners, and institutional buyers progressively enter the formal market channel, with their share rising from roughly 3 percent at shallow depths to 14 percent at extreme depths; institutional participation in non-market transfers shows no depth gradient. A credit channel mediates these transitions: rising groundwater depth increases loan take-up but concentrates forced sales in the most water-stressed locations, with debt burdens transmitted to heirs through encumbered inheritance and rising land partition. Third, land market stress connects to downstream household outcomes through the asset channel: forced sales, encumbered inheritance, and partition erode land wealth during the transition, with agricultural income shares falling as households shift away from farming.

This paper makes three contributions. First, it contributes to the literature on water

scarcity and agricultural production by showing that the economic effects of groundwater depletion extend beyond crop choice and yields to reshape land use and land markets. While existing work emphasizes extraction behavior and production responses to water scarcity, this paper highlights land markets as the central transmission channel through which persistent groundwater stress propagates to broader economic outcomes. Second, the paper contributes to the literature on land institutions and agricultural organization by providing new evidence that environmental constraints alter which land remains cultivable and who owns it. Persistent groundwater scarcity induces land exits, consolidation, and ownership reallocation toward larger and non-agricultural buyers, demonstrating that land is an endogenous margin of adjustment under environmental stress rather than a fixed productive asset. Third, the paper contributes to the literature on collateral, financial frictions, and household welfare by documenting how environmental risk translates into persistent distributional change through a credit-collateral trap. Water stress compels farmers to borrow against land to finance technology upgrades; but because groundwater is a common-pool resource, ongoing collective extraction continues to deepen the water table even after individual adaptation, eroding the farm revenues that were meant to service the debt. Land changes hands through two related channels: forced market sales to service debt, and non-market transfers (encumbered inheritance, family partition, and near-zero-price transfers) that transmit debt burdens across generations. The result is that the credit market, rather than smoothing the adjustment to resource scarcity, amplifies and concentrates it among the most credit-constrained households.

2 Model

I develop a dynamic model of a village economy in which groundwater is a common-pool resource and land serves as collateral for credit. The model delivers testable predictions about the sequence of economic adjustments documented in the empirical analysis and provides a framework for evaluating policy counterfactuals. Full derivations and proofs are in Appendix B.

2.1 Environment

Time is discrete, $t = 0, 1, 2, \ldots$. A village contains a unit mass of indivisible land plots $j \in [0, 1]$. Each plot has a time-invariant conversion index $q_j \in \{q_L, q_H\}$ with $q_H > q_L$, capturing proximity to urban markets. Farmers differ in credit capacity $\lambda_i \in \{L, H\}$, where $\lambda_H > \lambda_L \geq 0$ governs access to external finance. Non-agricultural buyers value land only for conversion; land sold to non-agricultural buyers exits agriculture irreversibly. A fixed transaction cost $\tau > 0$ must be borne by the seller.

Groundwater depth g_t evolves endogenously with aggregate extra ction X_t and exogenous recharge R_{t+1}:

$$g_t = g_{t-1} + \kappa X_t - R_t, \qquad \kappa > 0. \tag{1}$$

Higher g_t corresponds to deeper, scarcer groundwater. A key feature of the environment is that recharge R_t varies across villages depending on predetermined soil characteristics that govern how surface rainfall percolates into aquifers. This heterogeneity forms the basis of the empirical identification strategy.

2.2 Production and Technology

If a farmer with credit type λ operates one plot in period t, she chooses a crop $c \in \mathcal{C}$, on-farm labour $\ell \in [0, 1]$, a pumping technology $T \in \mathcal{T}(g_t)$, and pumping $x \geq 0$. Output is $y = A_c f_c(\ell, x)$, where f_c is increasing and concave.

The feasible technology set $\mathcal{T}(g)$ changes with depth. Following Sekhri (2014) and Butler and Boudot Reddy (2023), centrifugal pumps face a hard suction limit and become infeasible once groundwater falls below approximately 8 meters below ground level. Submersible (tube-well) pumps do not face a strict depth limit but require increasingly powerful motors as depth increases. Adopting technology T requires a fixed outlay F_T, financed only up to credit capacity: $F_T \leq \lambda$. The per-unit variable pumping cost $\kappa_T(g)$ is increasing in depth.

The maximized per-plot operating return is:

$$\pi(g, \lambda; w) \equiv \max_{c, \ell, x, T \in \mathcal{T}(g),\, F_T \leq \lambda} \{p_c A_c f_c(\ell, x) - \kappa_T(g)\, x - w\ell - F_T\}, \tag{2}$$

where w is the prevailing non-agricultural wage.

Three properties of π follow directly from this definition.

Lemma 1. *The maximized return $\pi(g, \lambda; w)$ satisfies:*

(i) π is weakly decreasing in g: deeper groundwater raises pumping costs and, at sufficiently large g, forces adoption of costlier technologies.

(ii) π is weakly increasing in λ: higher credit capacity expands the feasible technology set and generates higher net returns.

(iii) The return differential $\pi(g, H; w) - \pi(g, L; w)$ is weakly increasing in g: as depth increases, the return advantage of high-credit farmers widens.

The third property is key: as groundwater deepens and expensive technology becomes necessary, only high-credit farmers can afford the required adoption cost, so the profitability gap between high- and low-credit farmers widens with scarcity.

2.3 Land Market and Value Functions

Farmers are risk-neutral with discount factor $\beta \in (0, 1)$. At the start of each period, a farmer draws a transitory liquidity obligation $b \geq 0$ (e.g., debt repayment or subsistence need). A farmer can raise up to $B(\lambda)$ without selling land, with $B(H) > B(L) \geq 0$. The *distress constraint* binds when:

$$\pi(g, \lambda; w) + B(\lambda) < b, \tag{3}$$

forcing a sale if market proceeds net of transaction costs cover b.

The value of owning one plot satisfies:

$$V_t^1(g,q,\lambda,b) = \max\Big\{ \underbrace{[P_t(g,q) - \tau - b]}_{\text{sell}} + \beta\,\mathbb{E}[V_{t+1}^0(g',\lambda,b')], \\ \underbrace{[\pi(g,\lambda;w_t) - b]}_{\text{keep \& operate}} + \beta\,\mathbb{E}[V_{t+1}^1(g',q,\lambda,b')]\Big\}, \tag{4}$$

and the value of being landless is:

$$V_t^0(g,\lambda,b) = \max\Big\{ \underbrace{[w_t - b]}_{\text{no purchase}} + \beta\,\mathbb{E}[V_{t+1}^0(g',\lambda,b')], \\ \max_{q\in\mathcal{Q}_t} \underbrace{[w_t - b - P_t(g,q)]}_{\text{buy plot } q} + \beta\,\mathbb{E}[V_{t+1}^1(g',q,\lambda,b')]\Big\}. \tag{5}$$

A farmer's willingness to pay is $W_t^F(g,q,\lambda) \equiv V_t^1(g,q,\lambda,0) - V_t^0(g,\lambda,0)$, which is decreasing in g through π. Non-agricultural buyers' willingness to pay is $W_t^N(q) = z_t q$, where $z_t > 0$ captures local non-agricultural demand, orthogonal to groundwater. The competitive land price is:

$$P_t(g,q) = \max\Big\{W_t^N(q),\ \sup_{\lambda} W_t^F(g,q,\lambda)\Big\}. \tag{6}$$

When agricultural value dominates, farmers are the marginal buyer and prices track groundwater. When non-agricultural value dominates, especially for high-q plots as g rises, non-agricultural buyers set prices, decoupling price from groundwater depth.

2.4 Equilibrium Predictions

The model delivers the following predictions, which motivate the empirical design. The flexible non-parametric empirical specification in Section 4 is designed to recover the shape of these relationships across the full depth distribution without imposing specific parametric forms.

Proposition 1 (Crop switching)**.** *Rising pumping costs reduce the relative profitability*

of water-intensive crops. As g increases, the optimal crop mix shifts away from water-intensive dry-season crops toward less water-intensive alternatives, with the shift accelerating as depth rises and extraction costs grow.

Proposition 2 (Land exit and market activity)**.** *As g rises, W_t^F falls through π while W_t^N does not. Land market activity and non-agricultural acquisitions increase monotonically in depth, with the response accelerating as more farmers hit the distress constraint* (3)*.*

Proposition 3 (Consolidation and small-farm exit)**.** *Because the credit advantage of high-λ farmers widens as g increases (Lemma 1(iii)), conditional on within-agricultural trade, plots flow toward high-credit, larger farmers. Small farms are disproportionately likely to exit as depth rises.*

Proposition 4 (Land prices and non-agricultural buyers)**.** *Because W_t^N is independent of g, land prices need not fall proportionally to agricultural value losses: non-agricultural buyers increasingly set prices as g rises, particularly for high-q plots in well-connected locations. Transaction prices therefore depend on the composition of buyers and may be non-monotone in groundwater depth.*

Proposition 5 (Financial stress and inheritance)**.** *The probability that the distress constraint* (3) *binds is increasing and convex in g. Default, forced sales, and declines in intergenerational inheritance all increase as depth rises, with larger responses for low-credit, smaller farmers.*

Remark 1. The model abstracts from the commons externality in extraction to focus on land market mechanisms. In the background, each farmer's individual extraction contributes to the aggregate X_t that drives the law of motion (1).

3 Data

I combine administrative groundwater monitoring data with detailed land records, land-use and crop production data, weather variables, hydrogeological information, and household surveys. These datasets are harmonized at the village level (excluding the household

panel, which is available at the district level) using village shapefiles from the Socioeconomic High-resolution Rural–Urban Geographic (SHRUG) database.

3.1 Groundwater Depth

I retrieve groundwater depth data from the Central Groundwater Board (CGWB) portal spanning 1996–2025. The CGWB measures groundwater depth in meters below ground level on a quarterly basis, with readings in January, May, August, and November. Monitoring stations are distributed across India, with approximately 1,800 stations in Haryana (Figure A1). Figure A2 presents state-level averages for selected years and shows that Haryana is among the states experiencing the most pronounced increases in groundwater depth over time.

For each monitoring well in Haryana, I construct a five-year rolling median of groundwater depth. These well-level measures are spatially matched to plot-level centroids using the nearest monitoring station and aggregated to the village level by taking the maximum depth across matched plots within each village–period cell.

3.2 Administrative Land Records

I compile plot-level land records from Haryana's integrated land records and registration system (Web-HALRIS), which integrates deed registration and core land record modules, including Jamabandi (record of rights and ownership), mutation (title updates), and khasra girdawari (crop inspection). I draw upon three complementary sources.

Ownership records are updated every three to five years at the village level. They contain household–owner–plot information: for each plot, I observe all owners and their ownership shares, land classification (agricultural, irrigated, rainfed, or non-agricultural), and irrigation source (tubewell, dugwell, or canal). It also records loan, inheritance, and loan default events at the household identifier level. These records allow me to construct ownership histories, land size distributions, and the financial standing of the household over time.

Transaction records are embedded within the land registry. For each plot, the data record whether a sale occurred, the buyer's and seller's names, transaction price (including transfers at price zero), and the transaction date. I classify transactions as *market* (recorded price above INR 101) or *non-market* (recorded price at or below INR 101), where the non-market category typically covers inheritance, family partition, and near-zero-price transfers. These records enable annual and five-year measures of land sales, transaction prices, and buyer–seller characteristics. Transaction records cover more than 6,000 villages, representing over 75 percent of all villages in Haryana.

Figure 1 shows buyer and seller composition separately for market and non-market transactions. Individual buyers and sellers dominate both channels. Institutional participants (banks, developers, and state agencies) are a small minority of total volume but are concentrated almost entirely in the market channel; their presence in non-market transfers is near zero. This baseline pattern motivates the analysis of how the institutional buyer share evolves with groundwater depth.

Cadastral maps provide time-invariant plot-level spatial coverage. These maps allow me to link ownership and transaction records spatially and are essential for integrating land records with groundwater monitoring data. Figure 2 illustrates cadastral village boundaries and the spatial coverage of matched ownership and transaction records.

Land markets in India are characterized by substantial institutional frictions, including restrictions on converting agricultural land to non-agricultural uses and multiple layers of approval required for transactions (Banerjee and Iyer, 2005; Bolhuis et al., 2025). Appendix C provides additional details on the data collection process, zoning regulations, and potential concerns related to reporting incentives and moral hazard in land-use classification.

3.3 Satellite Data

Land use and land cover. To measure land use around each plot and village, I use the Global Land Cover and Land Use (GLCLU) products from the University of Maryland's Global Land Analysis & Discovery (GLAD) group, which provide 30-meter gridded mea-

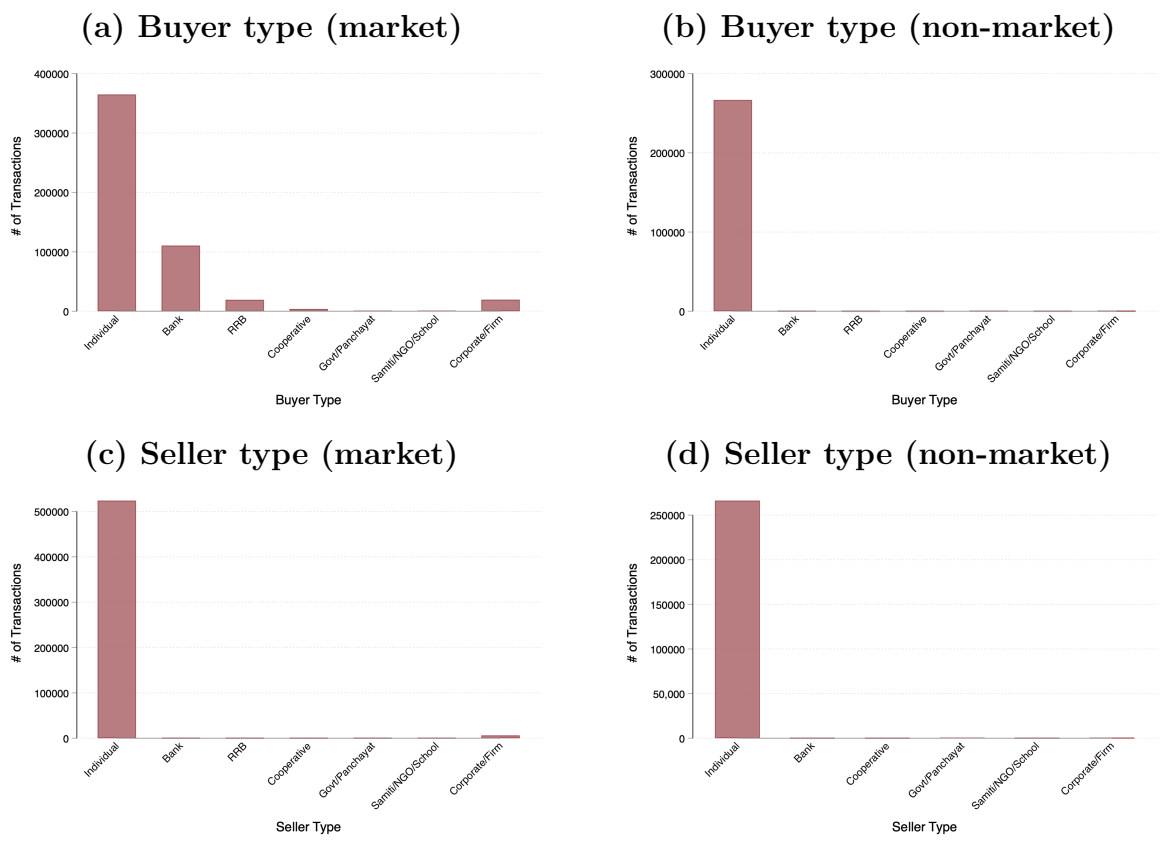
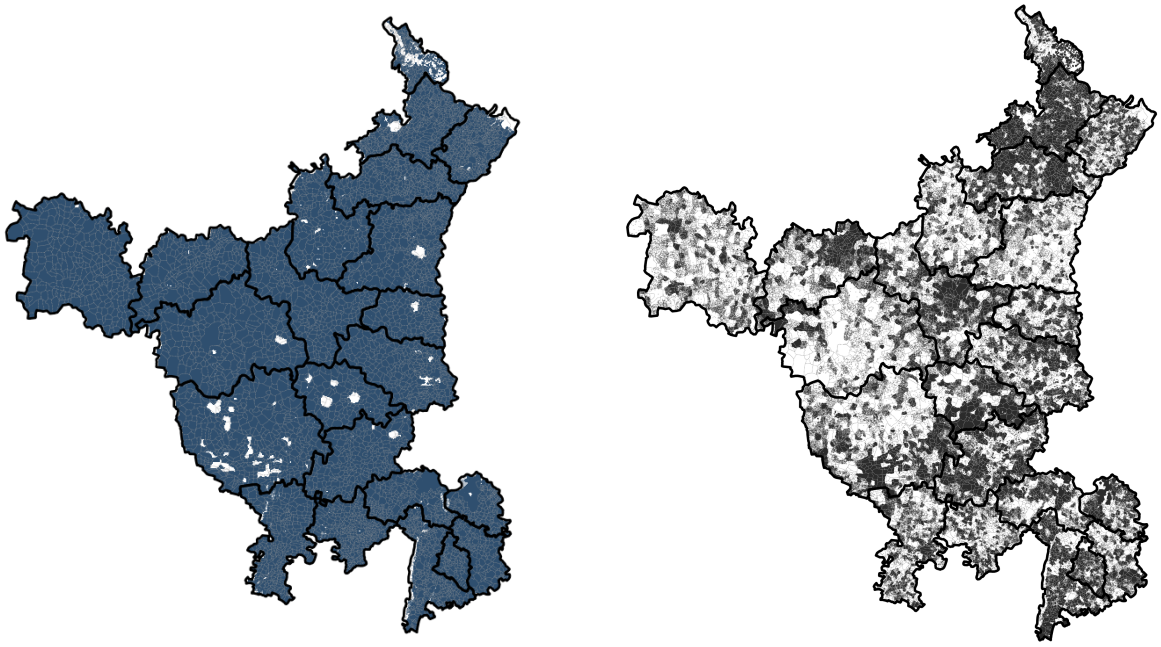


Figure 1: Composition of buyers and sellers by transaction channel

Notes: The figure shows buyer type (top row) and seller type (bottom row) separately for market transactions (recorded price above INR 101, left column) and non-market transfers (recorded price at or below INR 101, right column). Institutional participants include banks, regional rural banks, state agencies, and registered companies.



(a) Cadastral village and district boundaries (b) Coverage of land transaction records

Figure 2: Cadastral boundaries and land transaction coverage in Haryana

Notes: Panel (a) shows cadastral village boundaries overlaid on district boundaries in Haryana. Panel (b) displays the spatial coverage of digitized land transaction records at the village level. White areas indicate plots not covered by the transaction records sample.

sures of cropland, built-up area, and natural land, among other classifications every five years from 2000–2020.[1] I overlay village boundaries on these rasters and compute village-level land shares for cropland, built-up area, and natural land.

Crop production. For wheat, rice, and maize production, I use gridded data from 2010 to 2020 from Qin et al. (2024), matched to each plot using the nearest grid cell and aggregated to the village level.

Water storage anomalies. To provide cross-country validation of the land-use results, I draw on total water storage anomalies from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, aggregated at the district level across South Asian countries from 2002 to 2017. GRACE measures changes in vertically integrated water storage (including groundwater, soil moisture, and surface water) relative to a baseline period.

Rainfall. Rainfall is measured using the Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS), a quasi-global gridded product combining satellite-based infrared observations with in-situ station data at 0.05° resolution ($\approx$ 5.6 km pixels), available from 1981 onward. I extract village-level precipitation by overlaying village polygons on the CHIRPS grid.

3.4 Soil and Hydrogeological Data

I measure soil texture using the Harmonized World Soil Database (HWSD v2.0), which provides globally harmonized, gridded soil data at approximately 1 km resolution. From HWSD, I use the relative shares of sand, silt, and clay, which govern infiltration and percolation of rainfall into aquifers. Clay-rich soils impede vertical water movement due to small pore sizes, while sand-rich soils allow more rapid percolation. Soil composition is determined by long-run geology and does not respond to farming decisions or short-run economic conditions. I aggregate soil characteristics to the village level using area-weighted averages and treat them as time-invariant.

I also use porosity and permeability data from the Global Hydrogeology Maps (GLHYMPS) database at 10 km $\times$ 10 km resolution. Both soil texture measures and GL-

[1] The median village size is 2.32 km^2.

HYMPS porosity and permeability are used as instruments for groundwater depth, described in Section 4.

3.5 Household Surveys

Household outcomes come from the India Human Development Survey (IHDS), a nationally representative multi-topic panel survey implemented by the National Council of Applied Economic Research (NCAER). Wave 1 (2004–05) covers 41,554 households; Wave 2 (2011–12) covers 42,152 households and re-interviews most wave-1 households. This panel enables analysis of crop choice, labour market outcomes, sectoral reallocation, and household welfare. I link district-level groundwater depth measures to households using district identifiers provided in the survey.

3.6 Urban Market Access

To measure access to urban markets, I compute the distance from each village centroid to the nearest urban centre using the Global Human Settlement Urban Centre Database (GHS-UCDB). An urban centre is defined as a contiguous cluster of 1 km^2 grid cells in which each cell contains at least 1,500 persons km^{-2} or at least 50 percent built-up area, and the cluster has a minimum total population of 50,000. Urban centres are identified from GHS-POP population grids and GHS-BUILT built-up extent derived from Landsat and Sentinel imagery, providing a globally consistent, satellite-based delineation that is comparable across countries and independent of administrative boundaries. Village-level distances to the nearest urban centre are treated as time-invariant.

4 Empirical Strategy

4.1 Background: Irrigation Technology and Non-Linearities

Haryana sits primarily on alluvial aquifers, where permeability varies substantially depending on whether local sediment layers are sand and gravel (high permeability) or silt

and clay (low permeability). Extraction costs rise roughly in proportion to pumping depth, so falling water tables translate into higher energy costs per unit of water and, at certain thresholds, discrete jumps in equipment costs when deeper pump technologies are required.

Agricultural groundwater extraction in South Asia relies on two main technologies. *Centrifugal pumps* (used in dug wells) extract water by creating suction at the surface and face a hard mechanical limit: while the theoretical suction limit is 10.3 meters, in practice these pumps become ineffective once groundwater falls below roughly 8 meters (Sekhri, 2014; Butler and Boudot Reddy, 2023). Beyond this depth, centrifugal pumps fail entirely. *Submersible pumps* (used in tube wells) are installed inside the well and push water upward; they do not face a strict depth limit, but extracting from greater depths requires increasingly powerful motors. Horsepower investments are lumpy and involve large fixed costs (e.g., drilling deeper wells, installing higher-capacity pumps) and are often constrained by credit access.

These technological features generate two channels through which groundwater depth affects agricultural outcomes: a *variable cost* channel, when installed capacity is sufficient; and a *discrete feasibility* channel, when existing equipment cannot support adequate irrigation. In Haryana, electricity tariffs for agricultural use are heavily subsidised and have remained low throughout the sample period, which attenuates the variable cost channel: for farmers already equipped with submersible pumps capable of reaching deeper water, per-unit pumping costs change little as the water table falls. The discrete feasibility channel, however, operates independently of electricity prices. Centrifugal pumps physically cannot lift water beyond the suction limit ($\approx$ 8–10 m), so subsidised electricity cannot overcome this hardware constraint; the only options are to invest in a submersible upgrade—a large, lumpy fixed cost—or to exit irrigated production. It is this threshold-based feasibility constraint, rather than rising marginal pumping costs, that generates the nonlinear responses documented in the empirical analysis. Consistent with this mechanism, Figure 3 documents a sharp shift in Haryana's extraction technology mix: government-monitored dug wells declined from 381 to 202 (a 47 percent reduction) between 1996 and

2022, while tube wells increased from 73 to 209 (185 percent), tracking the rise in median groundwater depth. This provides suggestive evidence on the shift towards deeper extraction technology as water tables fall.

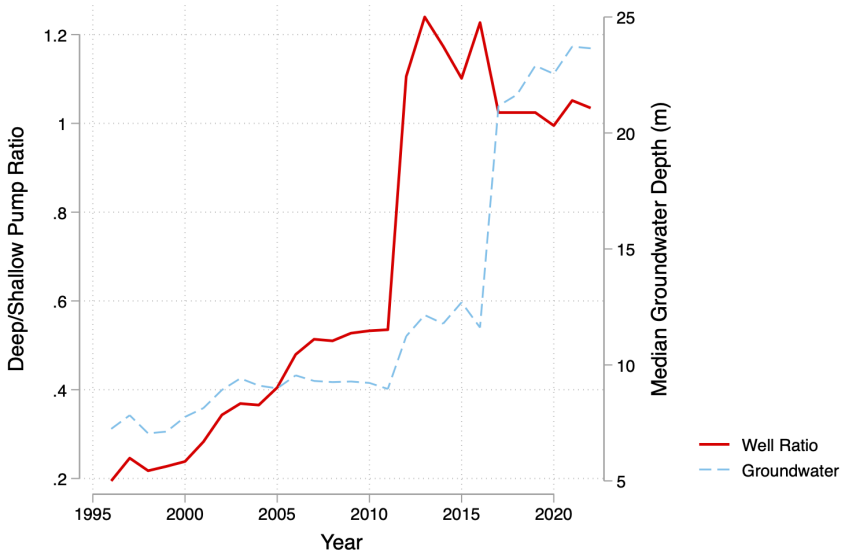


Figure 3: Haryana: well type composition and groundwater depth, 1996–2022

Notes: The figure plots the ratio of deep (tube) wells (tube wells divided by dug wells plus tube wells) and median groundwater depth (meters below ground level, right axis) in Haryana from 1996 to 2022. The shift from dug wells to tube wells tracks the rise in groundwater depth.

4.2 Baseline Specification

I estimate the relationship between groundwater depth and land market outcomes using:

$$y_{vt} = \beta f(g_{vt}) + \gamma X_{vt} + \alpha_v + \delta_t + \varepsilon_{vt}, \tag{7}$$

where y_{vt} denotes the outcome of interest for village v in period t (a five-year interval for most outcomes); g_{vt} measures the five-year rolling median groundwater depth; $f(g_{vt})$ is a set of indicator variables for groundwater depth deciles, allowing fully flexible non-linear effects; X_{vt} includes contemporaneous and five-year lagged rainfall; village fixed effects α_v control for time-invariant local characteristics (e.g., soil texture); and period fixed effects δ_t absorb common shocks (e.g., electricity prices). Standard errors are clustered at the

village level.

4.3 Identification: Instrumental Variable and Control Function

Groundwater depth is endogenous to agricultural and land-market activity. Extraction behavior directly affects groundwater stocks: crop choices, irrigation intensity, and mechanized pumping jointly determine water withdrawal, while land structure shapes extraction capacity. These feedback mechanisms imply that observed groundwater depth is jointly determined with agricultural production, land use, and land-market outcomes, rendering a simple regression non-causal.

Conceptually, groundwater depth evolves according to:

$$g_{v,t} = g_{v,t-1} - \underbrace{\text{Recharge}_v}_{\text{geology}} \times \underbrace{\text{Rainfall}_{t-1}}_{\text{exogenous}} + \underbrace{\gamma X_{v,t}}_{\text{extraction}} + \eta_{v,t}, \tag{8}$$

where Recharge_v captures village-level geological characteristics governing how precipitation translates into groundwater recharge, Rainfall_{t-1} is lagged precipitation, and X_{vt} aggregates individual extraction decisions. Rainfall mechanically replenishes groundwater, but the magnitude and timing of this effect vary sharply across locations depending on subsurface characteristics.

These subsurface characteristics are predetermined i.e., they cannot be influenced by farmers, and the differential pass-through of rainfall to groundwater driven by hydrogeological features provides plausibly exogenous variation in groundwater stocks. The primary channel is permeability: sand and gravel formations have high hydraulic conductivity, allowing rainfall to infiltrate rapidly and recharge the aquifer, whereas clay-rich formations have low permeability, causing rainfall to run off or remain near the surface. Porosity captures a distinct dimension: the fraction of void space available to store infiltrated water, but it does not govern recharge efficiency in the same way. Critically, clay and sand sit at *opposite ends* of both dimensions: clay has high porosity but low permeability, while sand has moderate porosity but high permeability. As a result, the two measures can move in opposite directions across geological units, identifying different

aspects of how subsurface structure moderates the rainfall-to-groundwater relationship. I leverage porosity and permeability (from GLHYMPS) interacted with five-year lagged rainfall as the preferred instruments. The first-stage regression is:

$$g_{vt} = \theta_1(\text{Porosity}_v \times \text{Rainfall}_{t-1}) + \theta_2(\text{Permeability}_v \times \text{Rainfall}_{t-1}) + X_{vt} + \alpha_v + \delta_t + \eta_{vt}. \quad (9)$$

As a complementary instrument, I use soil texture from HWSD at finer spatial resolution (1 km), constructing the proportion of area under clay, sand, and silt. The relevant first-stage is:

$$g_{vt} = \tilde{\theta}_1(\text{Clay}_v \times \text{Rainfall}_{t-1}) + \tilde{\theta}_2(\text{Silt}_v \times \text{Rainfall}_{t-1}) + X_{vt} + \alpha_v + \delta_t + \tilde{\eta}_{vt} \quad (10)$$

A standard two-stage least squares approach is ill-suited here because it imposes linearity in the endogenous regressor. Instead, I adopt the *control-function* approach, which addresses endogeneity by including the first-stage residuals $\hat{\eta}_{vt}$ (or $\hat{\tilde{\eta}}_{vt}$) directly in the second stage, allowing fully non-parametric estimation of the groundwater–outcome relationship:

$$y_{vt} = \beta f(g_{vt}) + \lambda \hat{\eta}_{vt} + \gamma X_{vt} + \alpha_v + \delta_t + \varepsilon_{vt}. \quad (11)$$

This approach relies on the assumption that, conditional on first-stage residuals, controls, and fixed effects, remaining variation in groundwater depth is as good as random, i.e., the identifying variation comes from how predetermined hydrogeology differentially amplifies or attenuates the effect of rainfall on subsequent groundwater depth. Table A1 reports first-stage results using both the porosity-permeability and soil texture instruments; F-statistics are 50.74 for permeability-porosity and 204.16 for soil texture instruments, and the coefficients indicate that these geological characteristics strongly predict groundwater depth.

4.4 Technology Threshold Specifications

As a complementary identification strategy, I follow Butler and Boudot Reddy (2023) to recover a village-specific centrifugal-pump failure depth c_v. Centrifugal pumps cannot lift water beyond c_v; farmers must then adopt submersible technology at substantially higher capital cost. I estimate the average level shift in outcomes at the moment of threshold crossing:

$$y_{vt} = \beta \, \mathbf{1}\{g_{vt} > c_v\} + \gamma X_{vt} + \alpha_v + \delta_t + \varepsilon_{vt}. \tag{12}$$

The coefficient β identifies the average change in y_{vt} when groundwater depth crosses the pump failure threshold, i.e., it captures the reduced-form local effect of the discrete technology switch from centrifugal to submersible pumps.

5 Results

Water is a critical input in agriculture, both for transporting nutrients within plants and enhancing productivity (Asher et al., 2022) and increasingly a form of natural insurance against extreme heat (Cisse et al., 2026). As water becomes scarcer, the viability of agricultural production is threatened. In response, farm households may invest in adaptive technologies (e.g., deeper pumps), adjust their cropping strategies, or exit the sector through changes in land use or market sales or non-market transfers. I organize the results in three subsections. Section 5.1 documents within-agriculture responses. Section 5.2 examines land market responses. Section 5.3 presents downstream consequences for labour markets and household welfare.

5.1 Within-Agriculture Responses

Crop switching. Figure 4 presents coefficient plots from Equation (11), using the IV approach with the porosity–permeability instrument, for village-level total crop production of wheat, rice, and maize over 2010–2020. Wheat and maize production—dry-season crops heavily dependent on groundwater irrigation—decline sharply as the five-year rolling

median groundwater depth rises, in line with Proposition 1. This pattern suggests that binding water constraints reduce the viability of dry-season production. By contrast, rice production increases substantially as groundwater scarcity deepens. Although rice is commonly cited as among the most groundwater-intensive staples in South Asia, its cultivation is concentrated in the monsoon (*kharif*) season when peak rainfall substantially reduces the *marginal* irrigation requirement relative to dry-season crops. As the opportunity cost of groundwater rises with depletion, farmers shift toward crops where rainfall can partially substitute, raising the relative profitability of kharif rice compared with rabi wheat and maize. This is not a water-conserving response: it reflects intertemporal substitution toward the season where the groundwater constraint is less binding.

Estimates of Equation (12) corroborate these patterns: crossing the centrifugal pump failure threshold c_v reduces wheat production (area) by 0.86% (0.34%) and maize production (area) by 7.9% (4.5%), while rice production (area) increases by 3.3% (12.5%) (Table A2).

These intertemporal production responses reveal two margins of adjustment: farmers contract production when groundwater constraints are most binding (dry season) and expand during periods of surface water abundance (wet season), even by adopting more water-intensive crops. Those who cannot smooth risk across seasons, typically small landholders with limited credit access, face a harder margin: changing land use or exiting through market or family channels. The results that follow show this transition is sequential: household finance reorganizes first, the land market reconstitutes second.

5.2 Land Market Responses

Land exits agriculture as groundwater depletes. Figure 5 plots the non-linear effects of instrumented groundwater scarcity on village-level land use in Haryana from 2000 to 2020 (Equation (11)), focusing on the shares of cropland, built-up land, and natural (fallow) land. Cropland shares remain relatively stable under moderate groundwater scarcity but contract sharply once groundwater depth reaches severe scarcity, consistent with rising extraction costs and economic constraints on submersible pump use. This

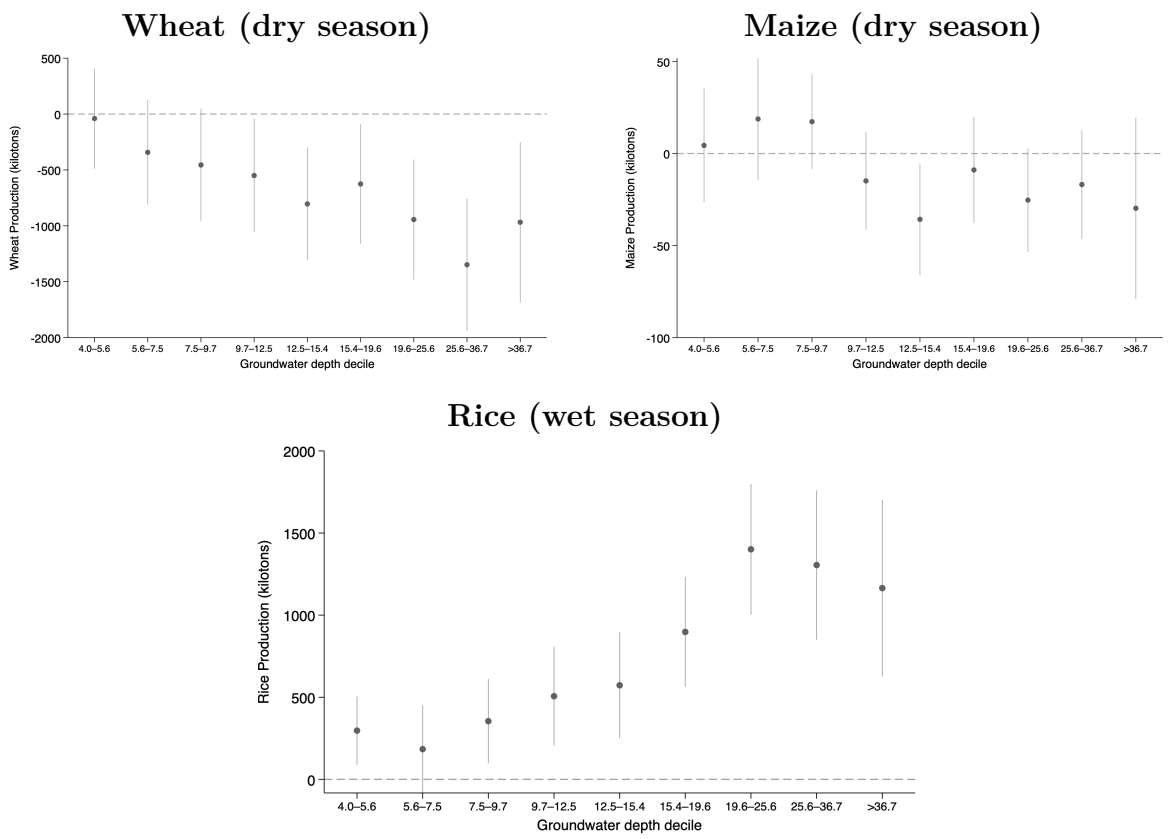


Figure 4: Effects of groundwater depth on crop production across seasons

Notes: The figure reports instrumental variables estimates of the effect of groundwater depth on crop production (kilotons) at the village–year level in Haryana. Groundwater depth is instrumented using the porosity–permeability instrument. Wheat and maize are dry-season crops; rice is a wet-season crop. Coefficients are estimated across groundwater depth deciles relative to the shallowest decile. All specifications include village and period fixed effects. Standard errors clustered at the village level.

contraction is accompanied by a modest expansion in built-up land and a pronounced increase in natural (fallow) land categories. These patterns suggest land is being withdrawn from cultivation, awaiting conversion due to zoning or regulatory constraints, or held by non-agricultural users. Table A3 reports estimates of Equation (12): crossing c_v reduces cropland share by 1% and increases fallow land share by 7.7%.

The land-use contraction documented here is not isolated to Haryana. Complementary district-level evidence from across South Asia corroborates the pattern: using total water storage from the Gravity Recovery and Climate Experiment (GRACE), which captures aggregate water availability across surface and subsurface stocks rather than groundwater depth alone, and operates at district rather than village scale, districts experiencing larger water storage declines exhibit systematic reductions in agricultural land share, partially offset by increases in built-up and natural land (Table A4).

While these land-use changes document reallocation away from agriculture, they do not reveal whether adjustment occurs passively through temporary withdrawal or actively through market transactions or non-market transfers. I therefore turn to land market activity to examine whether groundwater scarcity induces households to sell land, reshaping ownership patterns and facilitating exit from agriculture.

Land market activity. Figure 6 presents estimates of Equation (11) for land market outcomes at the village–year level. The top row plots the total number of market and non-market transactions. The second row plots the cumulative share of village plots transacted up to period t, disaggregated into market transactions (recorded price above INR 101) and non-market transfers (zero or near-zero price, covering inheritance, partition, and family transfers). Panel (e) shows the proportion of plots transacted at a market price. Panel (f) plots log transaction prices per hectare.

While number of market transactions remain stable, overall market activity declines under moderate scarcity, consistent with reduced demand from agricultural buyers as water constraints tighten. As scarcity intensifies, however, market sales and transaction counts increase substantially. Two forces drive this reversal: entry of non-agricultural

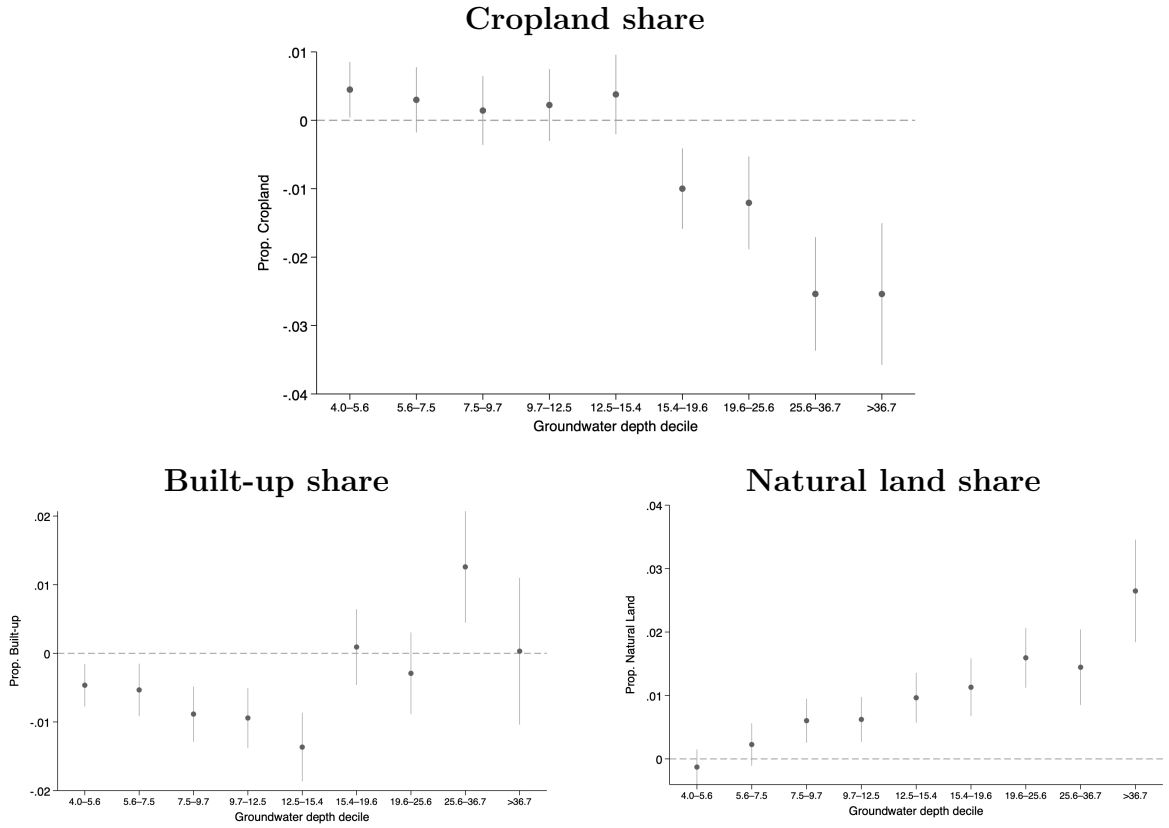


Figure 5: Effects of groundwater depth on land use composition

Notes: The figure reports instrumental variables estimates of the relationship between groundwater depth and land use composition at the village–year level in Haryana from 2000 to 2020. Outcomes are village-level shares of land allocated to cropland, built-up areas, and natural (fallow) land. Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and period fixed effects. Standard errors clustered at the village level.

buyers who value land independently of its irrigation capacity, and distress sales by farmers liquidating holdings to service debt. Non-market transfers follow a distinct pattern: transaction counts peak at moderate groundwater depth (roughly 15–20m) and then decline, while the cumulative share is positive throughout but diminishing. This hump shape reflects family reorganization at an early stage of stress, with partition and within-family transfers rising as households divide holdings before the formal market becomes active. At severe depth, non-market activity recedes as within-family redistribution options narrow and remaining adjustment shifts to the formal market. Panel (e) tracks the proportion of plots sold in the market. At the pump-failure threshold (9.7–12.5m), this share falls sharply, consistent with non-market transfers rising as a fraction of all activity during the reorganization phase. At severe depth (above 19.6m), the market share recovers strongly, reaching roughly 5.5 percentage points above baseline at the extreme tail, consistent with formal-market reconstitution as non-agricultural buyers absorb distress sales.[2]

Transaction prices fall at the threshold: crossing c_v reduces log transaction price by 12 percent and log price per hectare by 10 percent (Table A5, columns 5 and 6, both $p<0.01$). This decline reflects the reorganization phase at intermediate depths, where agricultural buyers are exiting but non-agricultural demand has not yet fully replaced them, leaving a thinner market and downward pressure on prices. At severe groundwater depth, however, the non-parametric estimates show no sustained price trend, consistent with Proposition 4: once non-agricultural buyers dominate the market, they set prices based on non-agricultural use value independently of irrigation capacity, buffering further price declines. The price signal is therefore informative at intermediate depths and attenuated at extreme depths, with the compositional shift in who transacts providing the more consistent marker of stress throughout the distribution.

The aggregate market surge at severe depth is concentrated in a specific segment: agricultural plots served by tubewells and formal irrigation (Appendix Figure A4; Appendix Tables A6). These plots exhibit a U-shaped response. At moderate depths, market sales

[2]The credit channel results in Section 5.3 show that debt-driven transfers concentrate in market sales rather than non-market transactions, pointing to sale-and-loan sequences as the primary credit resolution mechanism rather than foreclosure-type zero-price transfers.

fall as agricultural buyers exit when rising extraction costs compress farm returns. At severe depths, sales recover sharply, reaching roughly 13 percentage points above baseline at the extreme tail. The buyers driving this recovery are non-agricultural: they acquire high-quality agricultural plots for conversion or development, not for their irrigation capacity. Debt obligations force owners to sell regardless of the water table; non-agricultural buyers enter because these plots are now available at values reflecting non-agricultural use rather than irrigation capacity, consistent with Proposition 2. This recovery is absent for non-agricultural, rainfed, and dug-well plots, each for distinct reasons.[3]

The non-market channel shows a different pattern across all land types (Appendix Figure A5; Appendix Table A7). Non-market transfers decline with groundwater depth for agricultural, irrigated, and tubewell plots, with no U-shaped recovery. Non-agricultural and rainfed plots show a similar monotonic decline. This pattern is informative about mechanism. The U-shaped market recovery for irrigated and tubewell plots is driven entirely by outside buyer entry at severe depth; it does not appear in the non-market channel because inheritance and partition do not respond to non-agricultural demand. The monotonic decline in non-market transfers for high-quality agricultural plots reflects the narrowing of within-family redistribution options as stress deepens: once depth passes the reorganization threshold, family resources are exhausted and transfers shift to the formal market.

Taken together, the land market evidence traces a phased adjustment sequence. At moderate groundwater depth, market activity contracts as agricultural buyers exit and families absorb stress through internal transfers: partition, inheritance, and within-family reorganization. At severe depth, the formal market reconstitutes as non-agricultural buyers enter to acquire high-quality agricultural plots, prices stabilize as those buyers set values independently of irrigation capacity, and non-market activity recedes as within-family

[3]Non-agricultural plots are already converted and not targets for buyers seeking agricultural land; their owners also face no groundwater-driven distress pressure. Rainfed plots are lower-quality agricultural land, less attractive for conversion, and have owners facing lower exposure to irrigation costs. Dug-well plots are stranded: their extraction technology becomes inoperable when the water table falls below the shallow-well depth, making the asset difficult to value and unlikely to attract buyers at any price. Relative to rainfed, the decline is modest in dugwell-operated plots, likely because some are viable for conversion to tubewell-operated plots, subject to credit constraints and investment returns.

options are exhausted. The land type and channel evidence reinforces this ordering: the U-shaped recovery in market sales is specific to irrigated and tubewell plots and absent in the non-market channel, confirming that reconstitution is driven by outside demand rather than household-level adjustment. The threshold estimates in Tables A5 and A6 capture effects at the pump-failure boundary (Phase 2); the non-parametric figures trace the full transition through Phase 3, and the two are complementary rather than contradictory.[4][5]

Distributional consequences: who sells, who buys. Figure 7 examines how groundwater scarcity reshapes the land size distribution by estimating Equation (11) separately for small (0–2 ha), medium (2–7.5 ha), and large (7.5+ ha) landholders, and a Herfindahl-Hirschman index (HHI) of land concentration. Small-scale farmers are increasingly likely to exit as groundwater scarcity intensifies, consistent with Proposition 3: facing the binding distress constraint (3) at higher rates, small-scale farmers with limited credit capacity ($\lambda = L$) are forced to exit the market. Their land is absorbed by larger landowners, with the non-parametric estimates showing the HHI of land concentration rising, especially at the right tail of depth distribution. Medium-sized farms (2–7.5 ha) gain modestly at moderate depths but show no sustained trend at severe depths, consistent with partial exposure to consolidation gains without the same pressure as smallholders. At the pump-failure threshold, the share of large landholders rises by 14.3% (Table A8, column 4, $p<0.01$); the small-farm decline and HHI increase are directionally consistent in the non-parametric figures but do not reach conventional significance at the threshold.

I classify buyers and sellers using names recorded in the land transaction data to distinguish institutional participants (banks, regional rural banks, state agencies, and registered companies) from individuals. In this setting, institutional buyers are the empirical counterpart to the non-agricultural buyers in the model: entities that acquire land for

[4]Threshold estimates from Tables A6 and A7 are consistent with this interpretation. For agricultural, irrigated, and tubewell plots, the threshold coefficient is near zero and insignificant in both channels: the early-depth decline and later-depth recovery roughly cancel at the pump-failure threshold, so the average effect is small. Non-agricultural, rainfed, and dug-well plots show significant negative coefficients in both channels, consistent with the monotonic decline in the non-parametric figures.

[5]Dug-well plots are an exception: non-market transfers are elevated at moderate depths before falling at extreme depth, suggesting that technology-stranded owners unable to attract market buyers channel land to family members during the intermediate phase; at extreme depths, even that option closes.

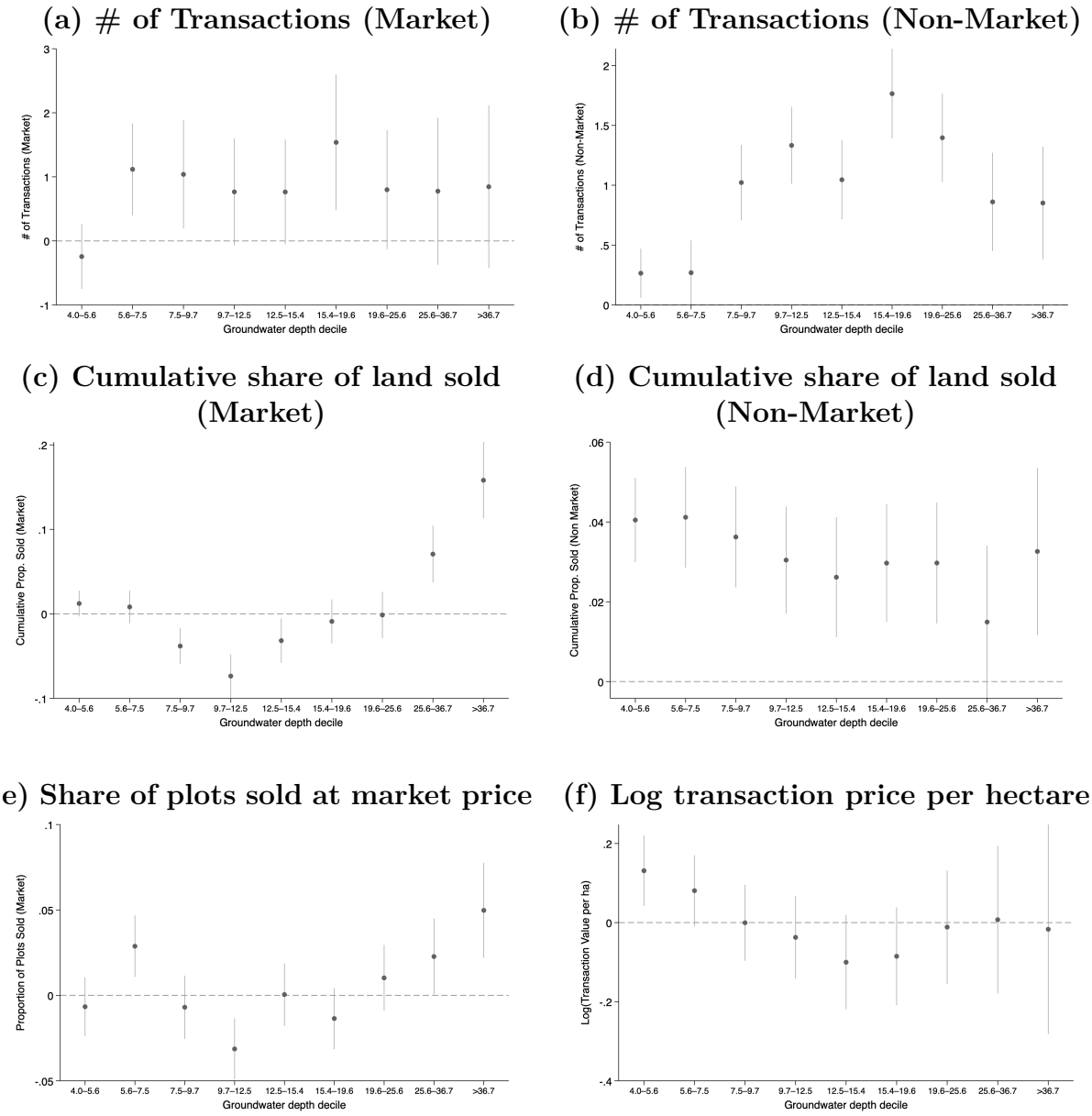


Figure 6: Land market responses to groundwater depth

Notes: The figure plots control-function instrumental variables estimates of the effect of groundwater depth on land market outcomes at the village–year level in Haryana. The top row shows the number of market and non-market transactions. The second row plots cumulative market sales (recorded price above INR 101) and cumulative non-market transfers (recorded price at or below INR 101), which include inheritance, partition, and family transfers. Panel (e) shows the share of all transactions recorded at a market price. Panel (f) shows the log transaction price per hectare. Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and period fixed effects, with standard errors clustered at the village level.

non-farming purposes and whose valuations are independent of groundwater conditions.[6] Appendix Figure A3 shows the baseline split between market and non-market transactions by participant type. Figure 8 shows that institutions are significantly less likely to appear as sellers in either transaction type, consistent with the fact that they have little direct exposure to groundwater constraints and, once land has been acquired by a non-agricultural buyer, it is unlikely to change ownership due to groundwater constraints. Institutional buyer participation rises with groundwater depth in market transactions across the full depth distribution, but shows no depth gradient in the non-market channel.

Appendix Figure A6 and Table A10 decompose transactions by buyer–seller type for both market and non-market channels, estimated on the sample of village-years with at least one recorded transaction. Conditional on market activity, both individual-to-individual (I2I) and individual-to-institution (I2B) market transactions rise significantly at the pump-failure threshold (I2I(M): +0.026, $p<0.01$; I2B(M): +0.021, $p<0.01$), consistent with a broad expansion across transaction types once the market opens. Over the full depth distribution, the non-parametric figures show the I2B share within market transactions rising from roughly 3 percent at shallow depths to 14 percent at extreme depths, while the I2I share falls correspondingly, confirming that the compositional shift toward institutional buyers accumulates gradually beyond the threshold. This is consistent with the market reconstitution narrative: at pump failure, both distress sales between individuals and acquisitions by institutional buyers expand, but as depth increases further, institutional buyers progressively displace individual buyers as the marginal acquirer. The non-market channel is dominated by individual-to-individual transfers throughout (I2I baseline share: 99 percent); threshold estimates show a small but significant shift toward I2B in non-market at pump failure (I2B(N): +0.005, $p<0.10$), consistent with near-zero-price transactions involving institutional counterparties clustering at that point, though the mechanism (foreclosure, administrative transfer, or partition) cannot be cleanly distinguished in the records.[7]

[6]This classification is likely an underestimate of land under institutional and non-agricultural use, as there maybe individuals who bought the plot for that use and thus would be classified as individual despite the non-agricultural motivations.

[7]B2B and B2I transaction types are near zero in both channels and show no significant depth gradient,

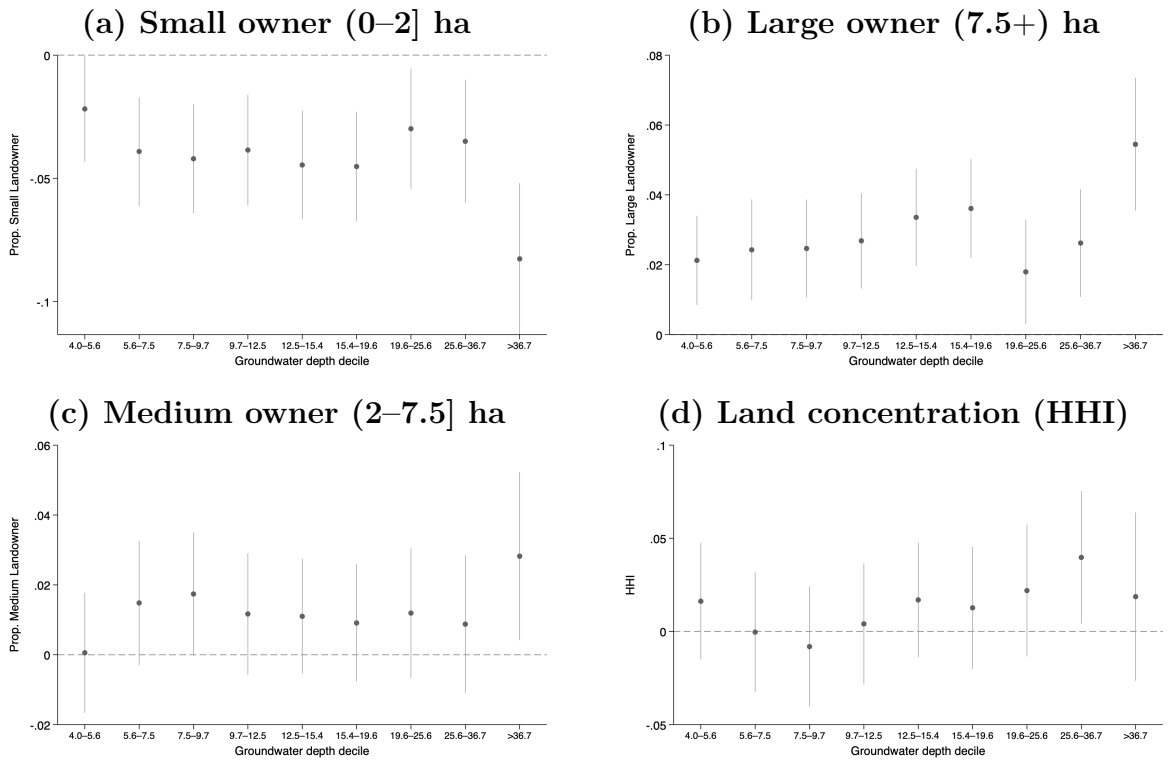


Figure 7: Effects of groundwater depth on land ownership distribution and concentration

Notes: The figure reports control-function instrumental variables estimates of the effect of groundwater depth on the share of landowners in each size category (small: 0–2 ha; medium: 2–7.5 ha; large: 7.5+ ha), and on the HHI of land concentration. Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and period fixed effects. Standard errors clustered at the village level.

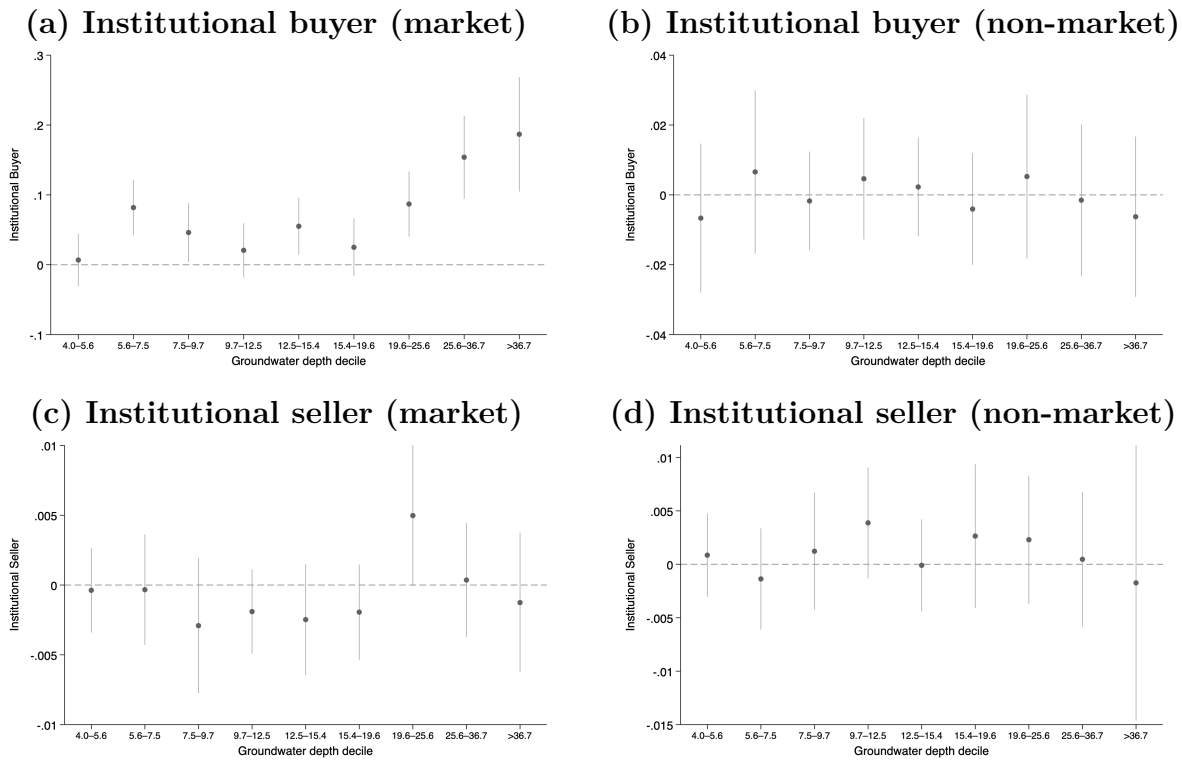


Figure 8: Institutional participation in land transactions

Notes: The figure reports control-function instrumental variables estimates of the effect of groundwater depth on institutional participation. The top row restricts to market transactions (price $>$ INR 101); the bottom row restricts to non-market transfers (price $\leq$ INR 101). Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and period fixed effects, with standard errors clustered at the village level.

Market connectivity and land market responses. Urban proximity shapes the composition of adjustment at the pump-failure threshold rather than its overall volume (Tables A11 and A12). Non-market transfers rise significantly at the threshold across all villages (0.46 additional transactions, $p<0.05$), with the effect modestly larger in more remote locations (0.029 per additional kilometre of urban distance, $p<0.05$). Market transactions show no significant threshold effect and no significant urban gradient.

The key urban distinction is in who transacts, not how much. Institutional buyer participation in market transactions responds significantly to groundwater stress only near urban centres: the threshold effect on institutional buyers declines by 0.0025 per additional kilometre ($p<0.05$), and individual-to-institution (I2B) market transactions fall by 0.042 per km of urban distance ($p<0.05$, Table A12). This is consistent with institutional buyers, the empirical counterpart to non-agricultural buyers in the model, operating where conversion value and legal infrastructure are most developed. Near-urban individual-to-individual non-market transfers also spike at the threshold (1.15 additional transactions, $p<0.01$), consistent with both family reorganizations and creditor-initiated transfers clustering at pump failure in high-value locations.

In remote villages, non-market transfers still rise at threshold, but without institutional involvement. Households in remote areas lack access to institutional buyers and cannot reallocate land through the formal market at the point of pump failure; non-market, family-internal transfers are the primary adjustment channel throughout. Urban market access therefore determines whether groundwater-driven reallocation draws in outside institutional demand or remains confined to within-family redistribution.

5.3 Financial Stress and Downstream Consequences

Collateralizing land: credit stress and forced sales. Figure 9 documents descriptive trends: as groundwater depth rises, both the incidence of household borrowing and the rate of default increase. This pattern is consistent with a mechanism in which de-

indicating that institution-to-institution and institution-to-individual transfers play no material role in groundwater-driven land reallocation.

clining water access raises the cost of irrigation, compresses farm revenues, and pushes households to borrow to sustain production, while simultaneously eroding the income stream needed to service debt.

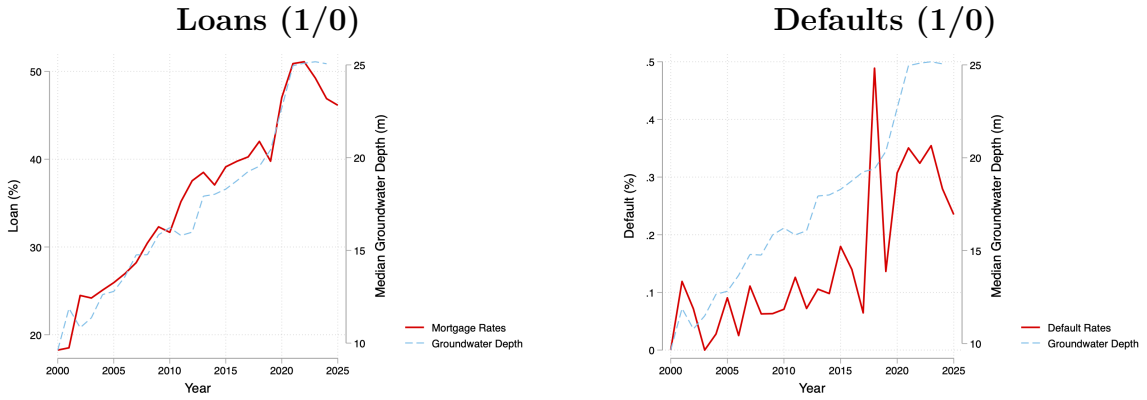


Figure 9: Trends in groundwater depth, borrowing, and default

Notes: This figure plots village–year trend lines over time for loan incidence (left) and default rates (right).

Figure 10 reports IV estimates for the credit channel. Loan take-up rises across depth deciles, peaking at moderate depths (9.7–15.4m) before easing at more severe depths, consistent with households borrowing to finance technology upgrades as centrifugal pumps approach their operational limits and credit capacity becoming exhausted at the extreme tail. The non-parametric estimates show that pure defaults have no depth gradient (Figure 10, panel (b)); the threshold coefficient is also small and not significant (Table A13, column 2), consistent with official defaults remaining rare because households typically sell encumbered land before a formal default is filed.

The bottom panels reveal two pathways through which debt resolves under scarcity. First, the incidence of plots with an active loan that are subsequently sold rises strongly from the middle depth deciles onward, consistent with creditor pressure or the need to service debt, forcing outright land liquidation (+0.0097, $p<0.01$; Table A13, column 3). Second, the incidence of encumbered inheritance rises broadly and spikes sharply at extreme depth (above 36.7m), with a coefficient approximately twice the magnitude of other deciles (Figure 10, panel (d)), consistent with households who cannot resolve debt through

sale passing the obligation to heirs at the point of maximum depletion. Crucially, overall inheritance does not increase (Table A13, column 6; Figure 10 panel (e)): it is the *composition* of succession events that shifts, with a larger share now involving outstanding debt. Land partition also rises (Table A13, column 5; Figure 10, panel (f)), consistent with families formally dividing holdings under financial pressure ahead of partial sales.

Labour market and welfare implications. Appendix Table A14 reports OLS estimates of the effect of a binary groundwater depth indicator ($D_{dt} = \mathbf{1}\{g_{dt} > 8\text{m}\}$) on a range of labour market and welfare outcomes using the IHDS household panel restricted to water-stressed states: Punjab, Haryana, Gujarat, Maharashtra, and western UP. The outcomes include the likelihood that a household grows wheat (Column 1), whether the household head works in agriculture (Column 2), the share of household income derived from agriculture (Column 3), the likelihood of working as an agricultural wage labourer (Column 4), and the household consumption quintile (Column 5).

As groundwater scarcity increases, households are less likely to grow wheat (column 1, $p<0.01$), consistent with the production results in Section 5.1, and the agricultural income share falls by roughly 12 percentage points (column 3, $p<0.01$). Agricultural employment participation and consumption do not show statistically significant changes at the district level (columns 2, 4, and 5). These results should be interpreted as suggestive evidence of the labour market and welfare consequences of groundwater depletion; the analysis is conducted at the district level using two survey waves, and precision is limited accordingly.

6 Discussion

The results point to a structured sequence of economic adjustment to groundwater scarcity. Within agriculture, dry-season water-intensive crop production contracts while wet-season output expands at the village level, consistent with within-agriculture adjustment to binding groundwater constraints; irrigation technology simultaneously upgrades toward submersible pumps. This is broadly consistent with the existing literature documenting how water access shapes yield and cultivation intensity (Asher et al., 2022) and how ground-

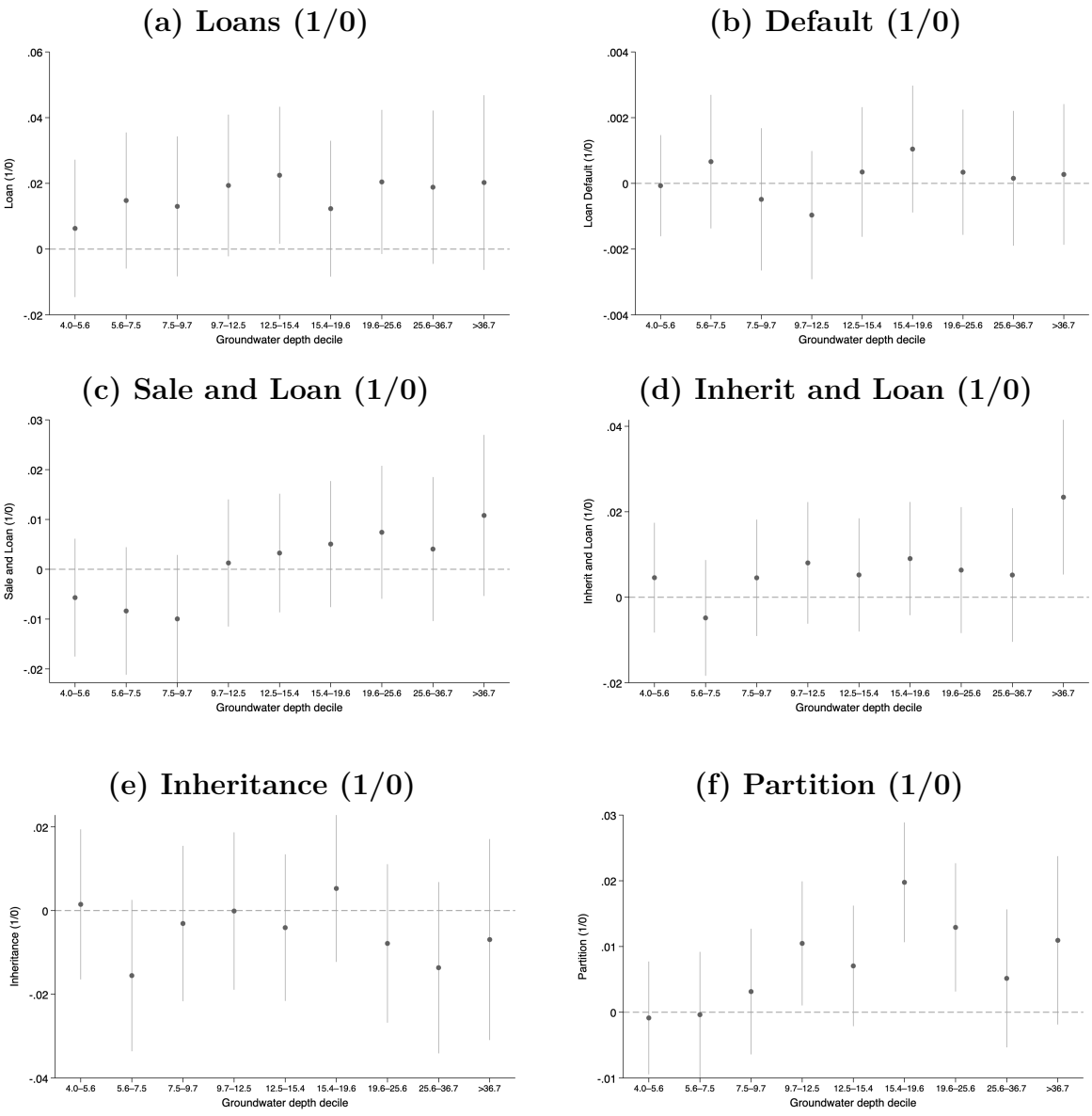


Figure 10: Household financial responses to groundwater depth

Notes: The figure reports control-function instrumental variables estimates of the effect of groundwater depth on household financial outcomes at the village–year level in Haryana. Panels (a) and (b) show broad loan take-up and default. Panel (c) shows the incidence of plots with an active loan that are subsequently sold. Panel (d) shows the incidence of plots with an active loan at the time of succession. Panel (e) shows overall succession incidence, which does not rise, indicating that the pattern in panel (d) reflects a shift in the composition of inheritance events rather than an increase in their frequency. Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and period fixed effects. Standard errors clustered at the village level.

water functions as natural insurance against heat stress (Cisse et al., 2026). What the existing literature has not traced is where this adjustment goes when within-agriculture on-farm margins are exhausted.

As depletion intensifies, technology becomes either too costly or infeasible, and adjustment shifts to land markets. Initially, land is passed within the family or split to the extent that it is viable to remain in agriculture. Eventually, land exits agriculture through changes in use and active sales, with activity concentrated in irrigated parcels and tubewell-dependent plots, those most exposed to rising extraction costs. This is consistent with Donna and Espín-Sánchez (2026)'s finding that liquidity constraints distort land-use decisions when water access is subject to cost uncertainty. The land institutions literature has emphasized how frictions in land transactions and conversion slow reallocation and generate persistent misallocation (de Janvry et al., 2015; Bolhuis et al., 2025); the results here suggest that environmental stress overcomes the transaction frictions by raising the opportunity cost of holding land in agricultural use sufficiently high to motivate sale. Formal land-use reclassification is a distinct margin: converting agricultural land to non-agricultural use in India requires regulatory permits and zoning approvals that operate independently of market transactions, and may constrain the extent to which ownership transfers translate into productive reallocation.

Who transacts further reveals the underlying mechanism. Two distinct processes operate across the depth distribution. First, ownership consolidates as small farmers exit and land flows to larger individual landowners, consistent with the model's prediction that the credit advantage of large, high-capacity farmers widens as depth increases (Proposition 3), echoing broader findings on credit and land in agricultural organization (Eswaran and Kotwal, 1986). Second, and separately, institutional buyers progressively enter the formal market as depth increases, with their share rising from roughly 3 percent at shallow depths to 14 percent at extreme depths. This institutional entry accumulates gradually across the depth distribution rather than jumping at the pump-failure threshold, and is absent in the non-market channel: land flows to institutional holders through formal market sales, not through near-zero-price transfers.

Urban proximity shapes who participates in this reallocation. Institutional market activity is concentrated near urban centres, where conversion value is highest; in remote villages, non-market family transfers are the primary adjustment channel, without institutional involvement.

The financial channel runs through these land transactions. Rising groundwater depth increases borrowing, but raises loan-backed sales sharply in the most stressed locations, with debt burdens transmitted intergenerationally through encumbered inheritance and rising family partition. Burlig et al. (2021) and Badiani-Magnusson and Jessoe (2018) trace how subsidized electricity shapes extraction behavior and pump adoption; this paper extends that analysis to the asset side. The same households who cannot afford to upgrade technology are also the ones who lose land when revenues fall short of debt obligations.

Downstream, land market stress connects to household welfare through two margins. Agricultural income shares fall sharply at the district level, consistent with production contracting and income diversifying away from farming. The asset channel compounds this: forced sales, encumbered inheritance, and partition strip households of land wealth during the transition, removing the collateral base needed to sustain investment. This contrasts with Nath (2025), who identifies subsistence constraints as a potential brake on labour reallocation out of agriculture; here, exit occurs but is accompanied by asset loss rather than a clean move to higher-value work. Whether exit is ultimately welfare-reducing cannot be determined from the available data, but the evidence that credit stress and land loss concentrate in the reorganization phase suggests the welfare cost begins to accumulate before adjustment is complete.

7 Conclusion

This paper uses newly digitized administrative land records, groundwater monitoring data, and household surveys from Haryana, India, to trace how persistent groundwater depletion propagates from agricultural production through land markets and collateralized credit to labour and welfare outcomes. Three sets of findings stand out.

First, the production response to groundwater depletion is nonlinear and sequential. Dry-season water-intensive crop production contracts while wet-season output expands, and costlier extraction technologies are adopted subject to credit constraints. These within-agriculture adjustments are well-documented margins, but they are insufficient as depletion persists.

Second, land markets are the central transmission channel. As groundwater stress intensifies, land exits agriculture through both market sales and non-market transfers. Market exits concentrate in irrigated and tube-well-operated plots. Two distinct reallocation processes operate: ownership consolidates as small, low-credit farmers exit to larger individual landowners, and institutional buyers progressively enter the formal market, with their share rising from roughly 3 percent at shallow depths to 14 percent at extreme depths; institutional participation in non-market transfers shows no depth gradient. Non-market transfers (family partitions, encumbered inheritance, near-zero-price transfers) rise alongside market exits. Credit amplifies these effects: rising groundwater depth increases loan take-up broadly but concentrates default and forced sales in the most water-stressed locations, with debt passed across generations through encumbered inheritance and rising partition.

Third, land market stress connects to downstream household outcomes through the asset channel. Agricultural income shares fall as households shift away from farming. Forced sales, encumbered inheritance, and partition erode land wealth during the transition, removing the collateral base that would allow households to invest in alternatives. Credit stress and land loss concentrate during the reorganization phase before the full exit.

The results identify three interconnected channels through which environmental risk propagates: production, credit, and land markets. Because these channels interact, policies targeting only one margin are likely to be incomplete. Interventions focused solely on water extraction overlook the role of financial and land markets in amplifying extraction, while credit relief without complementary limits on extraction may inadvertently accelerate resource depletion.

Groundwater depletion reshapes who owns land and who can remain in farming, with distributional consequences that run through credit and land markets rather than production alone. These mechanisms are likely operative wherever groundwater depletion is advancing, including much of South Asia and other irrigated agricultural regions with weak or unregulated water resources.

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A Additional Figures and Tables

A.1 Tables

Table A1: First-Stage

	Groundwater Depth (m)	
	(1)	(2)
Median Rainfall (5 Years, m)	-0.45***	0.014***
	(0.049)	(0.0026)
Porosity × Rainfall	0.70***	
	(0.077)	
Permeability × Rainfall	-0.021***	
	(0.0023)	
% Clay × Rainfall		0.00043***
		(0.00013)
% Silt × Rainfall		-0.00071***
		(0.000038)
Outcome mean:	16.96	16.91
N	169141	168344
Village FE	✓	✓
Year FE	✓	✓
Cluster	Village	Village
F-stat	50.7	204.4
R^2	0.74	0.75

Notes: This table reports estimates from the first-stage regression of soil characteristics on groundwater depth at the village-year level. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is indicated by * p<0.10, ** p<0.05, *** p<0.01.

Table A2: Impact of Groundwater Depth on Crop Composition, 2010-2020

	Maize (1)	Wheat (2)	Rice (3)	Maize (4)	Wheat (5)	Rice (6)
D_{vt}	-37.9***	-310.8**	489.0***	-0.00091***	-0.0024***	0.0034***
	(7.12)	(152.5)	(103.5)	(0.00015)	(0.00058)	(0.00056)
Outcome mean:	469.63	35860.41	15206.28	.02	.71	.27
Obs.	43655	43655	43655	43655	43655	43655
Village FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village
R^2	0.96	0.97	0.97	0.98	0.97	0.97

Notes: This table reports estimates of the relationship between groundwater depth and crop composition at the village–year level in Haryana over the period 2010–2020. The dependent variables are village-level total production (Columns 1–3) and production shares (Columns 4–6) of maize, wheat, and rice. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A3: Impact of Groundwater Depth on Land Use, 2000-2020

	Cropland (1)	Builtup (2)	Natural (3)
D_{vt}	-0.0066***	0.00090	0.0070***
	(0.0016)	(0.0014)	(0.0012)
Outcome mean:	.66	.22	.09
Obs.	18899	18899	18899
Village FE	✓	✓	✓
Year FE	✓	✓	✓
Cluster	Village	Village	Village
R^2	0.89	0.89	0.88

Notes: This table reports estimates of the relationship between groundwater depth and land use composition at the village–year level in Haryana from 2000 to 2020. The dependent variables are village-level shares of land allocated to cropland, built-up areas and natural (fallow) land. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is indicated by * p<0.10, ** p<0.05, *** p<0.01.

Table A4: Impact of Water Depletion on Land Use in South Asia, 2005-2020

	Surface Water	Cropland	Builtup	Wetlands	Natural Land
	(1)	(2)	(3)	(4)	(5)
Water Storage Depth (m)	-0.0067***	-0.16***	0.024***	0.0018	0.14***
	(0.0017)	(0.035)	(0.0080)	(0.0024)	(0.042)
Outcome mean:	.02	.41	.08	.02	.47
Ind. mean:	.29	.29	.29	.29	.29
N (District × Year)	1558	1558	1558	1558	1558
District FE	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓
Cluster	District	District	District	District	District
R^2	0.94	0.84	0.94	0.82	0.81

Notes: This table shows how changes in water storage (meters), measured using a three-year rolling window from GRACE data, affect land use across South Asia over the period 2005–2020. All specifications include district and year fixed effects, and standard errors are clustered at the district level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A5: Impact of Groundwater Depth on Land Market Activity

	Prop. Sold (M)	Prop. Sold (N)	# Transactions (M)	# Transactions (N)	Log(Price)	Log(Price per ha)
	(1)	(2)	(3)	(4)	(5)	(6)
D_{vt}	-0.0094	-0.0019	0.38	0.86***	-0.12***	-0.10***
	(0.0078)	(0.0040)	(0.26)	(0.092)	(0.024)	(0.025)
Outcome mean:	.4	.48	3.77	1.93	13.95	16.06
Obs.	24871	20961	24871	24871	13433	13433
Village FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village
R^2	0.74	0.80	0.39	0.62	0.71	0.62

Notes: This table reports village–year estimates of the effect of groundwater depth on land market outcomes in Haryana. Columns (1)-(2) measures the cumulative share of land sold in market and non-market, Column (3)-(4) the number of transactions at market and non-market, Column (5) the log transaction price (all plots), and Column (6) the log transaction price per hectare, where hectares are computed as the total area (in ha) across all plots sold in cadastral records. Controls include contemporaneous and lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A6: Impact of Groundwater Depth on Land Market Activity by Land Type (M)

	Agri	NonAgri	Irrigated	Rainfed	Tubewell	Dugwell
	(1)	(2)	(3)	(4)	(5)	(6)
D_{vt}	-0.011	-0.068***	-0.0094	-0.068***	-0.0082	-0.031***
	(0.0078)	(0.0067)	(0.0078)	(0.0067)	(0.0078)	(0.0074)
Outcome mean:	.31	.17	.31	.17	.31	.23
Obs.	24871	24871	24871	24871	24871	24871
Village FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village
R^2	0.74	0.64	0.74	0.64	0.74	0.69

Notes: This table reports village–year estimates of the effect of groundwater depth on cumulative share of land sold in Haryana by land type: agricultural, non-agricultural, irrigated, rainfed, land with tubewell, and land with dugwell. Controls include contemporaneous and lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A7: Impact of Groundwater Depth on Land Market Activity by Land Type (N)

	Agri	NonAgri	Irrigated	Rainfed	Tubewell	Dugwell
	(1)	(2)	(3)	(4)	(5)	(6)
D_{vt}	-0.0023	-0.035***	-0.0021	-0.035***	-0.00091	-0.0054
	(0.0040)	(0.0044)	(0.0040)	(0.0044)	(0.0040)	(0.0044)
Outcome mean:	.13	.08	.13	.08	.13	.1
Obs.	20961	20961	20961	20961	20961	20961
Village FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village
R^2	0.80	0.63	0.80	0.63	0.81	0.71

Notes: This table reports village–year estimates of the effect of groundwater depth on cumulative share of land sold in Haryana by land type: agricultural, non-agricultural, irrigated, rainfed, land with tubewell, and land with dugwell. Controls include contemporaneous and lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A8: Impact of Groundwater Depth on Farm Size Distribution

	HHI	Small (0-2]ha	Medium (2-7.5]ha	Large (7.5+) ha
	(1)	(2)	(3)	(4)
D_{vt}	0.0083	-0.011**	0.00051	0.011***
	(0.0086)	(0.0054)	(0.0045)	(0.0034)
Outcome mean:	.26	.78	.15	.07
Obs.	4402	4402	4402	4402
Village FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Cluster	Village	Village	Village	Village
R^2	0.47	0.77	0.62	0.74

Notes: This table reports village–year estimates of the effect of groundwater depth on land concentration and the farm size distribution in Haryana, using an instrumental variables specification in which groundwater depth is instrumented with soil texture instruments. The dependent variables are the Herfindahl–Hirschman Index (HHI) and the village–year shares of farms that are small (0–2] ha), medium (2–7.5] ha), and large (7.5+) ha. Controls include contemporaneous and lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A9: Impact of Groundwater Depth on Buyer and Seller Types

	Institution Buyer (M)	Institution Seller (M)	Institution Buyer (N)	Institution Seller (N)
	(1)	(2)	(3)	(4)
D_{vt}	0.013	-0.000075	0.0031	0.0022
	(0.011)	(0.00099)	(0.0046)	(0.0017)
Outcome mean:	.4	0	.01	0
N	4224	4314	2551	2552
Village FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Cluster	Village	Village	Village	Village
R^2	0.87	0.70	0.66	0.53

Notes: This table reports village–year estimates of the effect of groundwater depth on the type of buyer and seller. Columns (1) and (2) report indicators for an institutional buyer and an institutional seller, respectively, for market transactions, defined as sales with a recorded price exceeding INR 101. Columns (3) and (4) report the corresponding outcomes for non-market transactions, defined as sales with a recorded price less than or equal to INR 101. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is indicated by * p<0.10, ** p<0.05, *** p<0.01.

Table A10: Impact of Groundwater Depth on Land Market Activity

	I2I(M) (1)	I2I(N) (2)	I2B(M) (3)	I2B(N) (4)	B2B(M) (5)	B2B(N) (6)	B2I(M) (7)	B2I(N) (8)
D_{vt}	0.026***	-0.0045	0.021***	0.0051*	-0.000092	0.00028	0.00021	-0.0012
	(0.0063)	(0.0031)	(0.0074)	(0.0027)	(0.00047)	(0.00020)	(0.00055)	(0.0013)
Outcome mean:	.53	.99	.42	.01	0	0	0	0
Obs.	13764	8044	13764	8044	13764	8044	13764	8044
Village FE	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village	Village	Village
R^2	0.82	0.59	0.78	0.58	0.50	0.52	0.60	0.58

Notes: This table reports village–year estimates of the effect of groundwater depth on the type of land market transactions by market (M) and non-market (N): individual-to-individual (I2I), individual-to-institute (I2B), institute-to-institute (B2B), and institute-to-individual (B2I). Controls include contemporaneous and lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A11: Impact of Groundwater Depth on Land Market Activity by Urban Proximity

	Transactions (M) (1)	Transactions (N) (2)	Log(Price per ha) (3)	Institutional Buyer (4)	Institutional Seller (5)
D_{vt}	0.41	0.46**	-0.048	0.023	0.0040**
	(0.65)	(0.21)	(0.054)	(0.015)	(0.0019)
D_{vt} × Urban (km)	-0.0026	0.029*	-0.0043	-0.0025**	-0.00030***
	(0.040)	(0.015)	(0.0037)	(0.00098)	(0.00011)
Outcome mean:	3.77	1.93	16.06	.44	.01
N	24871	24871	13433	13377	13755
Village FE	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village
R^2	0.39	0.62	0.62	0.82	0.60

Notes: This table reports village–year estimates of the effect of groundwater depth on land market activity and buyer/seller composition in Haryana. Outcomes include the number of transactions disaggregated by market and non-market, the average transaction price per ha for market sales (INR; excluding INR < 101 transactions), and indicators for institutional buyers and institutional sellers in market transactions. Groundwater depth indicators are interacted with distance to the nearest urban center (km). Controls include contemporaneous lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A12: Impact of Groundwater Depth on Land Market Activity by Urban Proximity

	I2I(M) (1)	I2I(N) (2)	I2B(M) (3)	I2B(N) (4)	B2B(M) (5)	B2B(N) (6)	B2I(M) (7)	B2I(N) (8)
D_{vt}	-0.40	1.15***	0.14	0.0046	0.0060	0.0028*	0.0050	0.018**
	(0.83)	(0.33)	(0.21)	(0.0041)	(0.0048)	(0.0015)	(0.028)	(0.0078)
D_{vt} × Urban (km)	0.074	0.015	-0.042**	-0.00038	-0.00056*	-0.00018**	-0.0015	-0.0013**
	(0.053)	(0.024)	(0.017)	(0.00030)	(0.00029)	(0.000082)	(0.0016)	(0.00052)
Outcome mean:	5.09	3.67	2.58	.01	.01	0	.06	.01
N	13906	13906	13906	13906	13906	13906	13906	13906
Village FE	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village	Village	Village
R^2	0.57	0.68	0.61	0.37	0.53	0.47	0.59	0.27

Notes: This table reports village–year estimates of the effect of groundwater depth on types of land market transactions disaggregated by market and non-market (INR < 101 transactions): indvidual-to-individual (I2I), individual-to-institue(I2B), institute-to-institute(B2B), and institute-to-individual(B2I). Groundwater depth indicators are interacted with distance to the nearest urban center (km). Controls include contemporaneous lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A13: Impact of Groundwater Depth on Mortgage, Defaults, and Inheritance

	Loan (1)	Default (2)	Loan + Sale (3)	Loan + Inherit (4)	Partition (5)	Inheritance (6)
D_{vt}	0.013**	-0.000028	0.0097***	0.0050	0.011***	0.0019
	(0.0054)	(0.00055)	(0.0032)	(0.0037)	(0.0027)	(0.0048)
Outcome mean:	.41	0	.11	.14	.05	.24
Obs.	7698	7698	7698	7698	7698	7698
Village FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Cluster	Village	Village	Village	Village	Village	Village
R^2	0.79	0.52	0.68	0.72	0.54	0.71

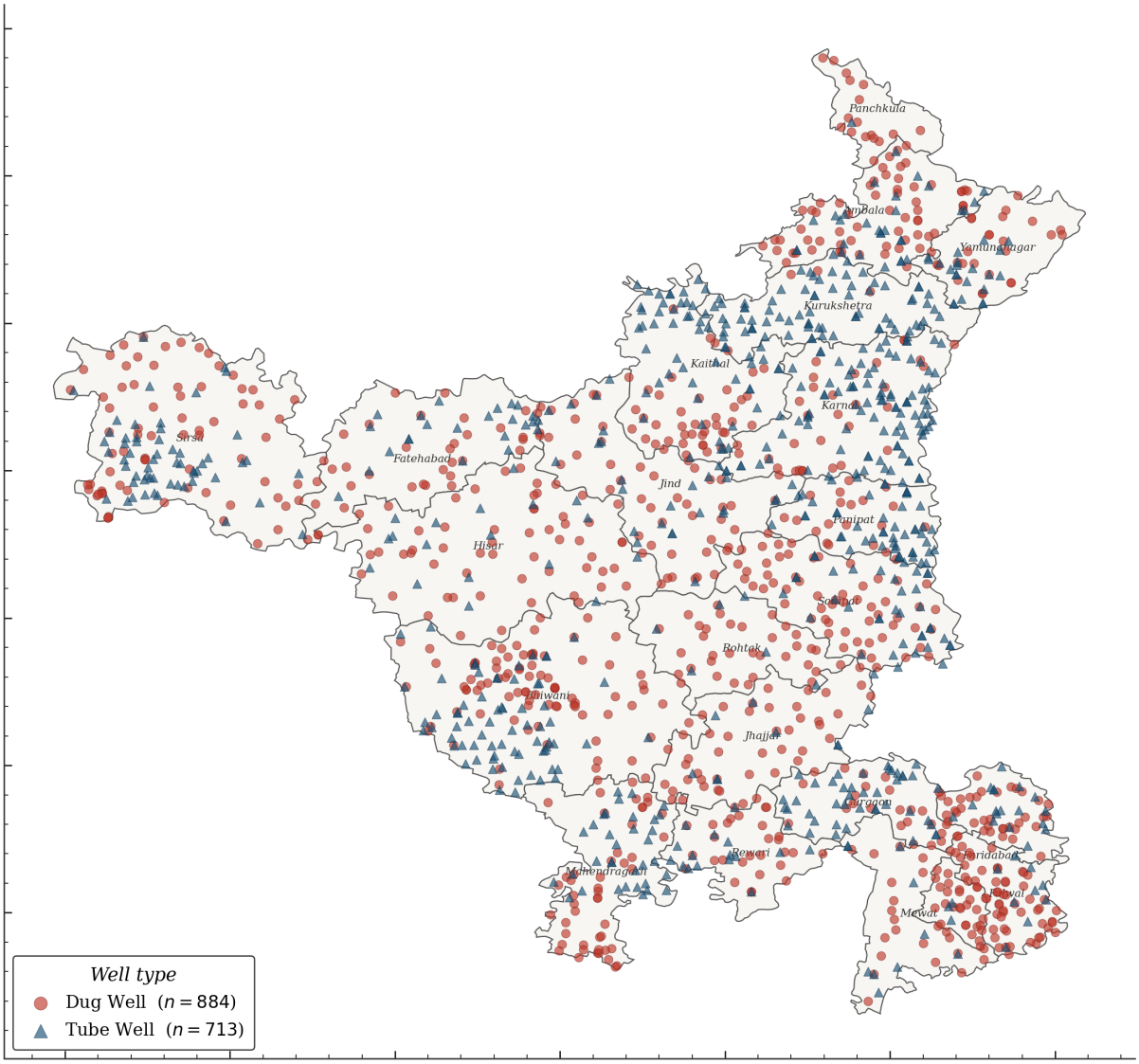
Notes: This table reports village–year estimates of the effect of groundwater depth on mortgage borrowing, default, and inheritance outcomes. Controls include lagged rainfall. All specifications include village and year fixed effects. Standard errors are clustered at the village level. Statistical significance is denoted by * p<0.10, ** p<0.05, *** p<0.01.

Table A14: Impact of Groundwater Depth on Agriculture, Labor, and Consumption

	Wheat(1/0) (1)	Agriculture (1/0) (2)	AgShare (3)	AgLabW (4)	Consumption (5)
D_{dt}	-0.087***	-0.048	-11.9***	0.11	-8876.4
	(0.025)	(0.035)	(4.42)	(0.11)	(5374.5)
Outcome mean:	.25	.5600000000000001	31.56	.5600000000000001	3.34
N	15216	15216	15216	15216	15216
State FE	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓
Cluster	District	District	District	District	District
R^2	0.13	0.13	0.010	0.22	0.31

Notes: This table reports OLS estimates of the effect of groundwater depletion on agricultural organization among households in water-stressed states: Punjab, Haryana, Rajasthan, Gujarat, Maharashtra, and western UP, using the India Human Development Survey (IHDS) across two waves (2005–06 and 2011–12). D_{dt} equals one if mean groundwater depth in district d exceeds 8 metres in survey year t. Controls include years resident at current location, total household assets measured in the first survey round (2005–06), and household size. All regressions include state and survey-year fixed effects and are estimated with IHDS sampling probability weights. Standard errors are clustered at the district level. Statistical significance is indicated indicated by * p<0.10, ** p<0.05, *** p<0.01.

A.2 Figures



Notes: Dug Cum Bore Wells excluded. Source: CGWB.

Figure A1: Monitoring Units in Haryana

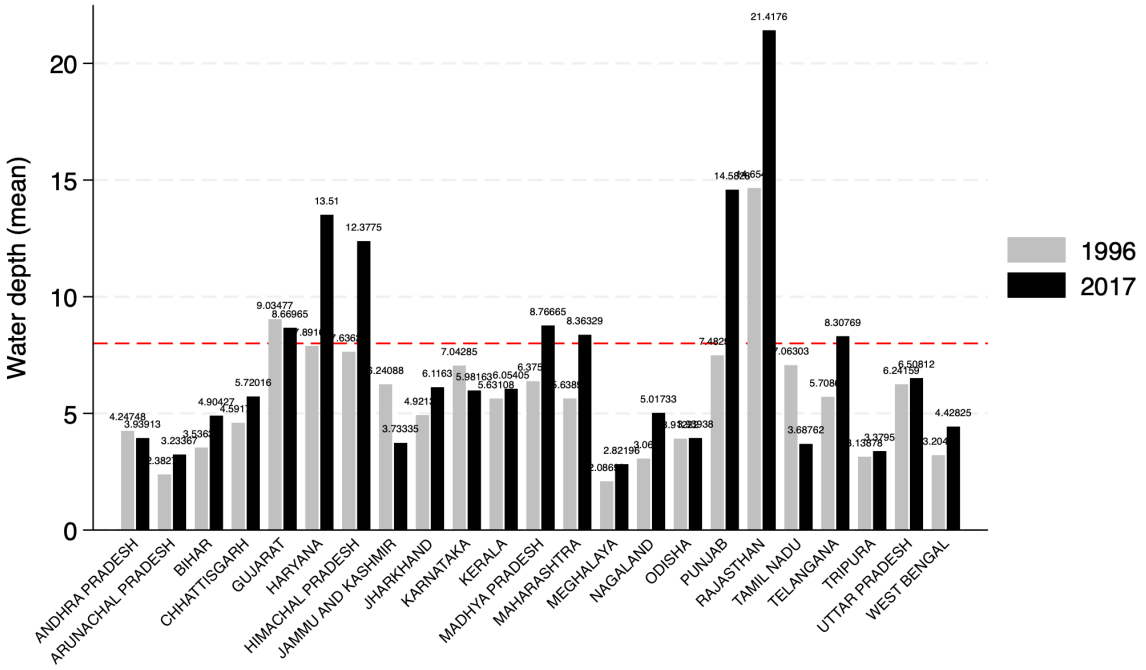


Figure A2: Groundwater Depth Change in Indian States (1996-2016)

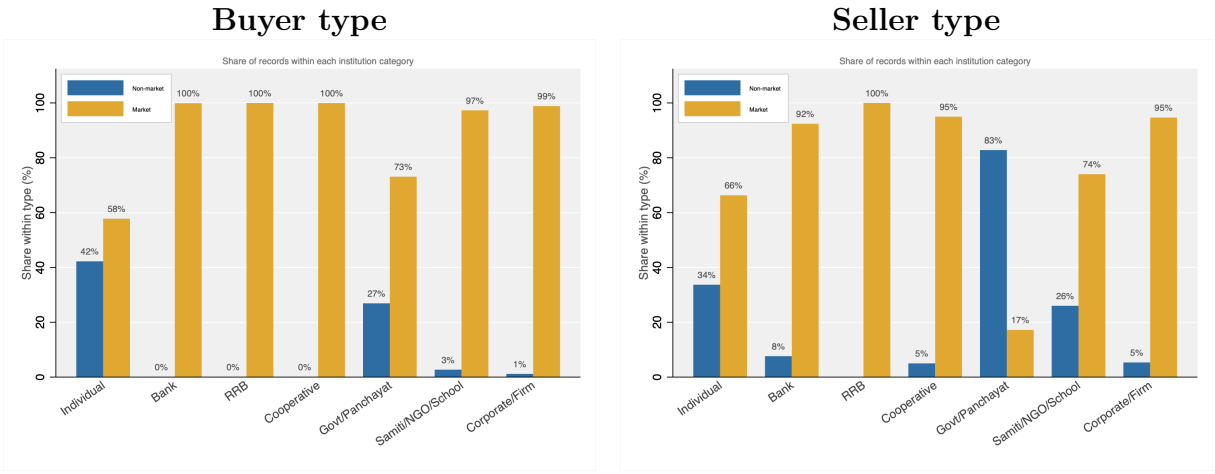


Figure A3: Market vs. Non-Market Transactions by Participant Type

Notes: Each panel shows the share of transactions classified as market (price above INR 101) versus non-market (price at or below INR 101) for each buyer type (left) and seller type (right). Individual smallholders account for the majority of both market and non-market transactions. Institutional participants—banks, regional rural banks, and state agencies—conduct almost all of their transactions at market prices.

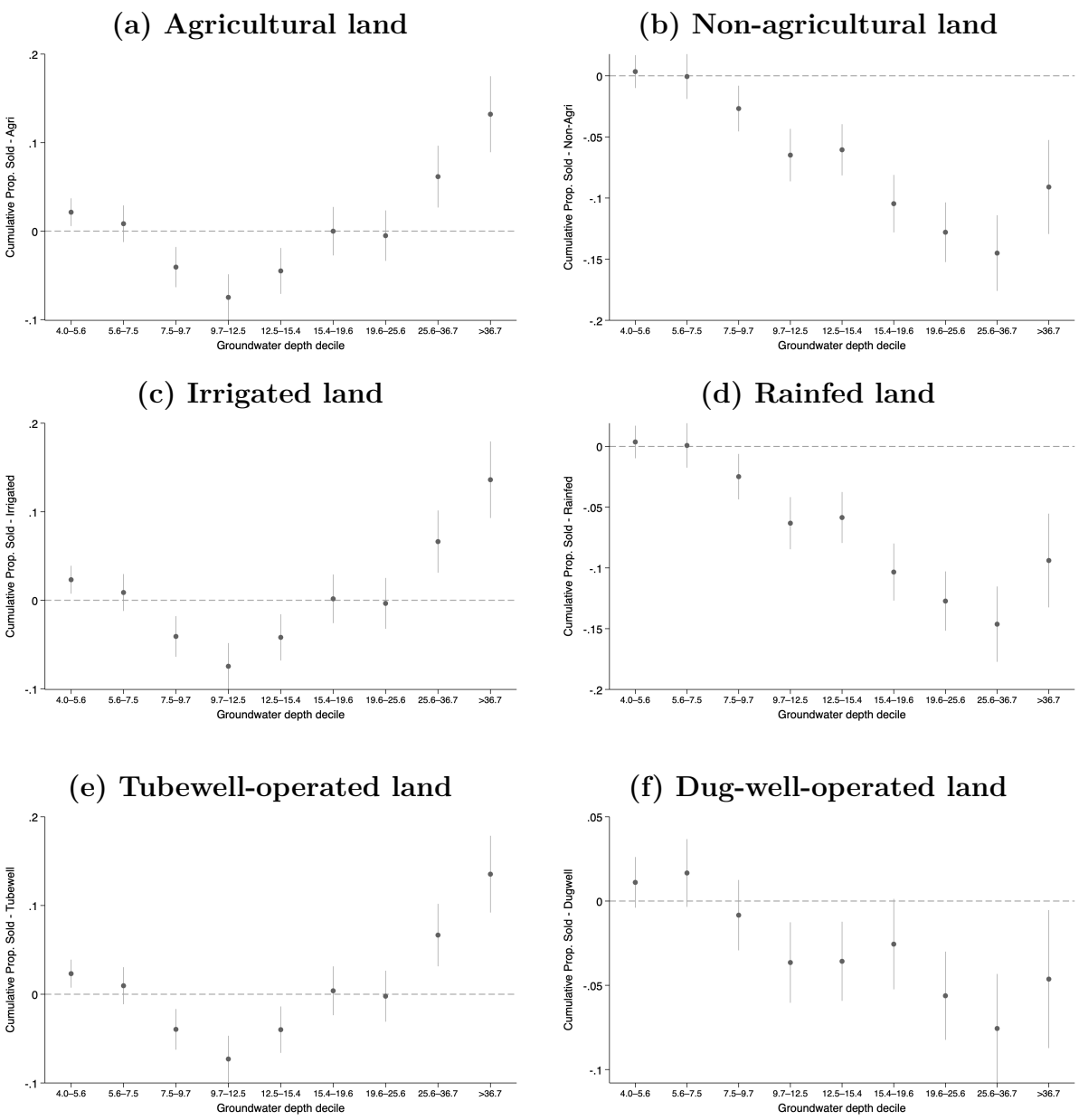


Figure A4: Cumulative market sales by land type (market)

Notes: The figure reports control-function instrumental variables estimates of the effect of groundwater depth on the cumulative share of village plots transacted at a market price (recorded price above INR 101), estimated separately by land classification. Panels (a) and (b) show agricultural and non-agricultural land; panels (c) and (d) show irrigated and rainfed land; panels (e) and (f) show tubewell-operated and dug-well-operated land. Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and year fixed effects. Standard errors are clustered at the village level.

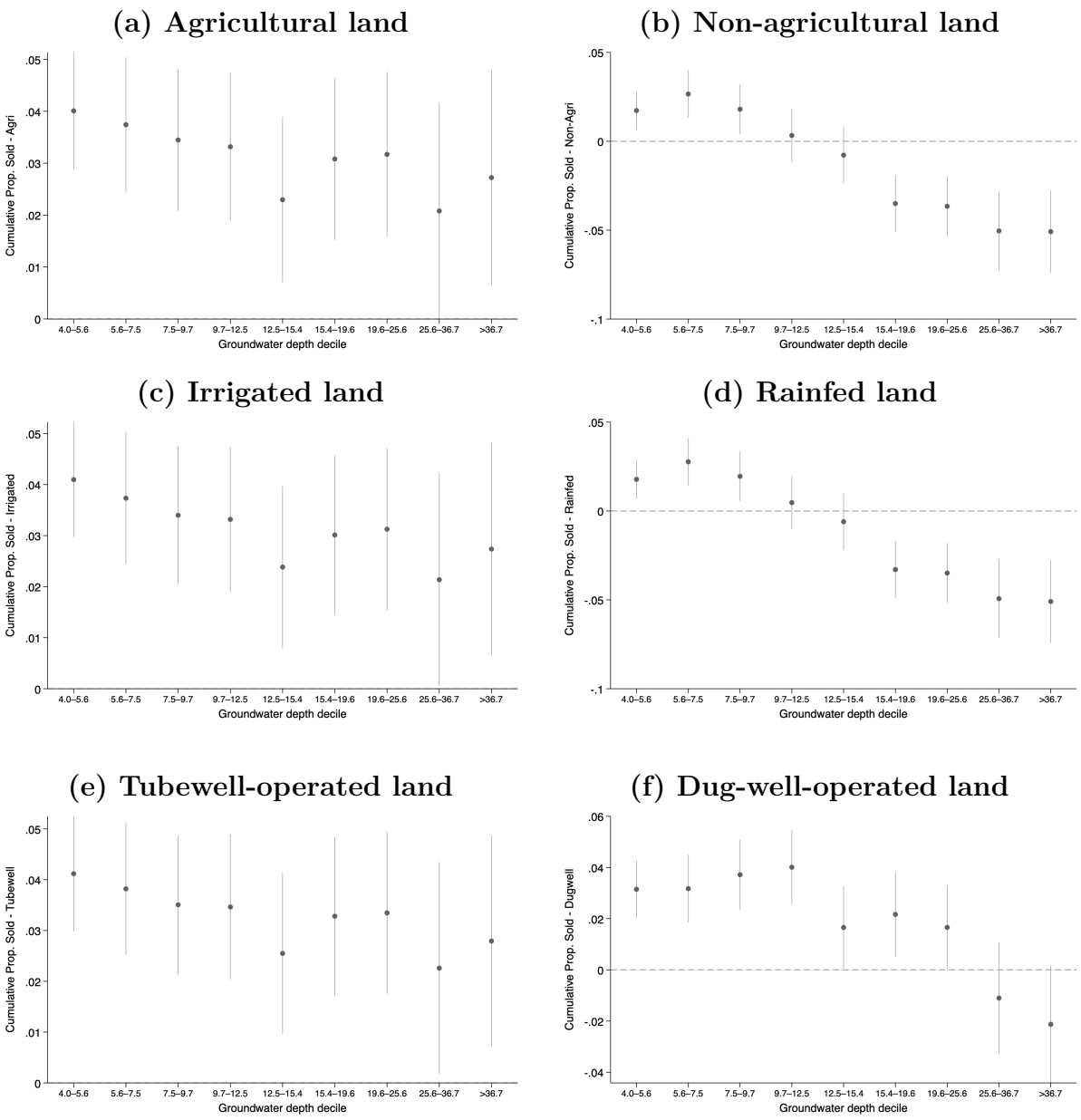


Figure A5: Cumulative non-market transfers by land type (non-market)

Notes: The figure reports control-function instrumental variables estimates of the effect of groundwater depth on the cumulative share of village plots transferred at a non-market price (recorded price at or below INR 101, covering inheritance, partition, and family transfers), estimated separately by land classification. Panels (a) and (b) show agricultural and non-agricultural land; panels (c) and (d) show irrigated and rainfed land; panels (e) and (f) show tubewell-operated and dug-well-operated land. Groundwater depth is instrumented using the porosity–permeability instrument. All specifications include village and year fixed effects. Standard errors are clustered at the village level.

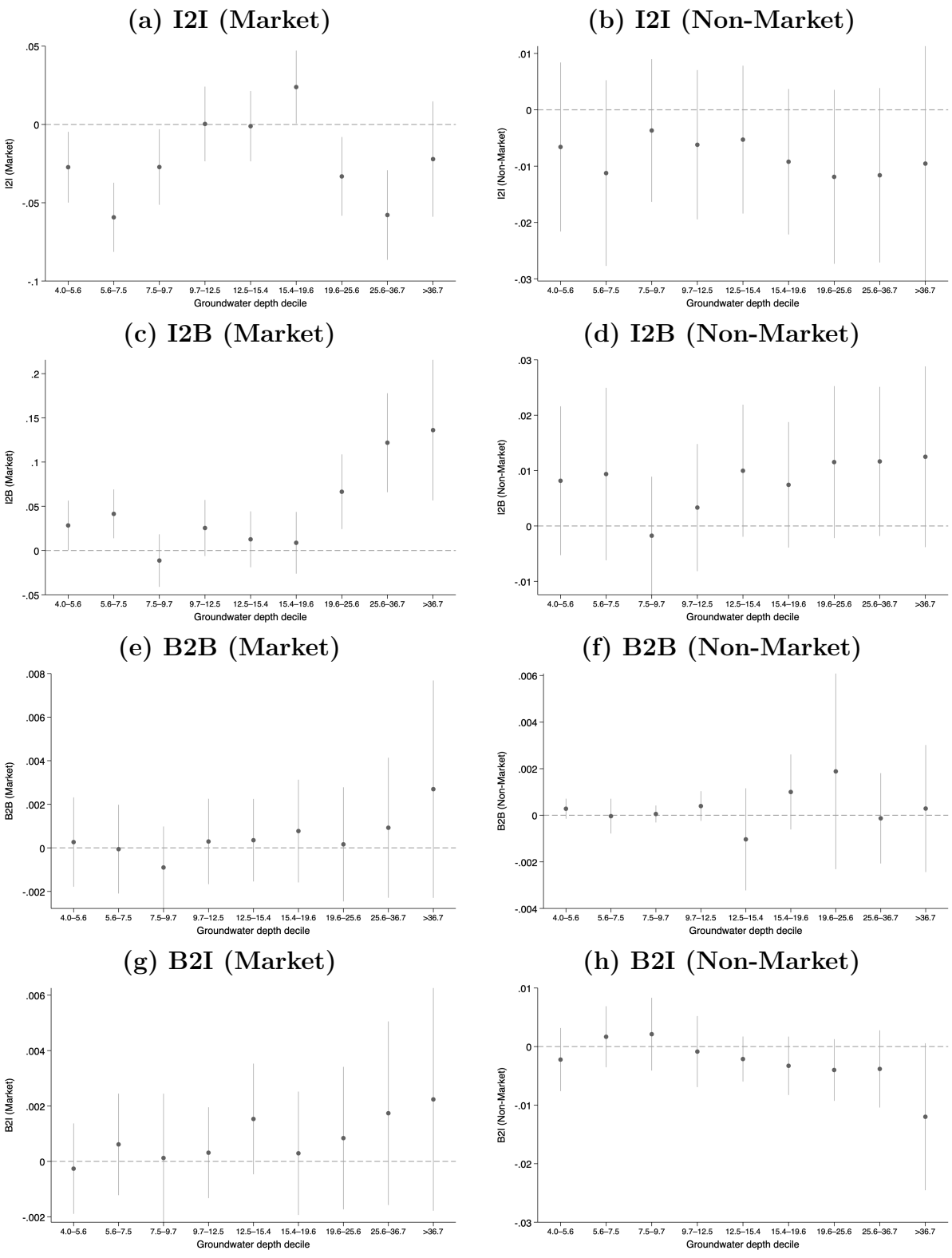


Figure A6: Land transactions by buyer and seller type

Notes: The figure reports control-function instrumental variables (porosity–permeability) estimates of the effect of groundwater depth on the composition of land transactions by participant type at the village–year level in Haryana. Each outcome is the share of transactions of a given type (individual-to-individual (I2I), individual-to-business/institution (I2B), business-to-business (B2B), business-to-individual (B2I)) within the relevant channel (market transactions on the left, and non-market transfers on the right). All specifications include village and year fixed effects. Standard errors are clustered at the village level.

B Model Proofs and Derivations

B.1 Proof of Lemma 1

Part (i): π is weakly decreasing in g. For any fixed (λ, w) and any $g' > g$, the feasible technology set satisfies $\mathcal{T}(g') \subseteq \mathcal{T}(g)$ (deeper groundwater does not expand the set of feasible technologies) and the variable pumping cost satisfies $\kappa_T(g') \geq \kappa_T(g)$ for each T. Therefore, the maximum in (2) is taken over a weakly smaller set of technologies at weakly higher variable costs: $\pi(g', \lambda; w) \leq \pi(g, \lambda; w)$.

Part (ii): π is weakly increasing in λ. For any fixed (g, w) and any $\lambda' > \lambda$, the credit constraint $F_T \leq \lambda'$ admits all technologies available to a farmer with credit λ and potentially additional technologies with $\lambda < F_T \leq \lambda'$. Since the feasible technology set at λ' weakly contains the feasible set at λ, the maximum is weakly higher: $\pi(g, \lambda'; w) \geq \pi(g, \lambda; w)$.

Part (iii): The return differential is increasing in g. Let $T^*(g, \lambda)$ denote the optimal technology for a farmer with credit λ at depth g. At shallow depths, both high- and low-credit farmers may operate the same (low-cost centrifugal) technology, so the differential $\pi(g, H; w) - \pi(g, L; w)$ may be zero. As depth g increases past the centrifugal-pump threshold, centrifugal pumps become infeasible. Low-credit farmers ($\lambda = L$) who cannot afford the fixed cost F_{T_D} of the next available technology are forced to use a more expensive or less effective alternative (or exit), while high-credit farmers ($\lambda = H$) can adopt the deeper technology. The profitability gap therefore weakly widens at each technological threshold. More formally, for g above any threshold $\bar{g}$ at which a technology becomes feasible for high-credit but not low-credit farmers:

$$\frac{\partial}{\partial g}\left[\pi(g, H; w) - \pi(g, L; w)\right] = \frac{\partial \pi(g, H; w)}{\partial g} - \frac{\partial \pi(g, L; w)}{\partial g} \geq 0,$$

since low-credit farmers face a more binding constraint set as depth increases, implying their marginal costs rise faster than high-credit farmers'. □

B.2 Proofs of Propositions

Proof of Proposition 1. The proof follows directly from π being decreasing in g through variable pumping costs $\kappa_T(g)$. For water-intensive crops c, the crop-specific return $p_c A_c f_c(\ell, x) - \kappa_T(g)x$ is decreasing in g faster than for low-water-intensity crops c', because the optimal x^* is larger for water-intensive crops. Thus, as g rises, the relative profitability of

water-intensive crops declines. □

Proof of Proposition 2. From the value functions (4)–(5), farmer willingness to pay $W_t^F(g, q, \lambda) = V_t^1(g, q, \lambda, 0) - V_t^0(g, \lambda, 0)$ is decreasing in g through π. Non-agricultural willingness to pay $W_t^N(q) = z_t q$ is independent of g. Therefore, the competitive price $P_t(g, q) = \max\{W_t^N(q), \sup_\lambda W_t^F(g, q, \lambda)\}$ transitions from agricultural-buyer-determined to non-agricultural-buyer-determined as g increases. Market activity increases because (i) more farmers find that selling generates higher utility than holding (the sell option in (4) becomes preferred), and (ii) non-agricultural buyers find prices attractive at falling agricultural values. □

Proof of Proposition 3. For $g > \bar{g}$ (the threshold above which expensive technology is required), Lemma 1(iii) implies $\pi(g, H; w) > \pi(g, L; w)$. Thus, $W_t^F(g, q, H) > W_t^F(g, q, L)$: high-credit farmers are willing to pay more for land, so within-agricultural trades flow from low-credit to high-credit farmers. Additionally, the distress constraint (3) binds at lower thresholds for low-credit farmers, who have smaller $B(L)$ and lower $\pi(g, L; w)$, forcing sales at higher rates as g increases. Together, these forces generate consolidation toward high-credit (typically larger) landholders. □

Propositions 4 and 5 follow directly from the competitive price formula (6) and the distress constraint (3), respectively, by monotone comparative statics in g. □

B.3 Groundwater Law of Motion and Common Pool Externality

The law of motion (1) captures the negative externality in extraction. Individual farmer i's extraction x_{it} enters aggregate $X_t = \int x_{it}\, di$, which raises the depth for all future periods. Because farmer i takes X_t as given, private extraction exceeds the social optimum—the classic common pool result. The social planner would internalize $\partial g_{t+1}/\partial x_{it} = \kappa > 0$, choosing lower aggregate extraction. The equilibrium trajectory of g_t is therefore faster-rising than the socially optimal trajectory, accelerating the distress dynamics in Proposition 5.

C Data Appendix

C.1 Land Records Data Collection

C.1.1 Background

Land records in Haryana are maintained under the North Indian revenue administration system, whose institutional foundations were established during the colonial period and have remained largely intact in their legal structure (Banerjee and Iyer, 2005). The central document in this system is the Jamabandi (Record of Rights), which provides a legally binding account of land ownership, cultivator identity, tenancy arrangements, land classification, and revenue liabilities at the village–parcel level. The Jamabandi serves as the authoritative record for land taxation, inheritance, registration of transactions, and adjudication of land disputes (Government of Haryana, Revenue Department, n.d.).

Historically, Jamabandi records were compiled through a system of quinquennial revisions. Each village underwent a comprehensive revision once every five years, during which the Patwari (the village-level revenue official) verified ownership and cultivation details through field visits and administrative checks. These revisions consolidated all legal changes that had occurred since the previous cycle, including sales, inheritances, partitions, and consolidations. Draft records were subjected to public inspection, after which they were formally attested by supervisory revenue officials, including the Kanungo and Tehsildar. This process produced a legally certified snapshot of land rights for each village at fixed points in time.

Between quinquennial revisions, land-related changes were recorded through the mutation system. Mutations documented specific legal events, such as registered sales, inheritance following death, or court orders, and were entered contemporaneously rather than waiting for the next Jamabandi revision. These mutation entries were subsequently incorporated into the next Jamabandi, ensuring continuity between high-frequency legal updates and the periodic consolidation of the Record of Rights. As a result, Jamabandi records reflect legally recognized ownership rather than self-reported land claims.

Beginning in the mid-2000s, Haryana transitioned from paper-based land records to a digitized system under the Haryana Land Records Information System (HALRIS), now operated through Web-HALRIS. Historical Jamabandis and mutation registers were digitized, and current updates are entered electronically by revenue officials. While the five-year Jamabandi cycle remains a formal administrative feature, revisions today primarily involve reconciliation and validation of digital records rather than universal physical ver-

ification through village visits (Government of Haryana, n.d.).

C.1.2 Land data collection process

Web-HALRIS is Haryana's integrated land records and registration system. It integrates deed registration and core land record modules—including Jamabandi (record of rights and ownership), mutation (title transfers), and khasra girdawari (crop inspection)—and has been implemented across all tehsils and sub-tehsils in Haryana. I retrieve these records through the web portal, which publishes administrative land records publicly at the plot level.

The data collection process involves three steps. First, I identify village-level identifiers (Hadbast numbers) from cadastral map metadata. Second, for each village–year cell, I download the relevant Jamabandi (ownership ledger) and mutation records. Third, I parse the raw administrative records into structured data, linking each plot (identified by its unique Khasra number) to its owners, transaction history, land use classification, and irrigation source. For transaction records, village selection follows a stratified random design: for each of Haryana's 22 districts, tehsils are drawn at random, villages within sampled tehsils are drawn at random, and plots within sampled villages are drawn at random. This design ensures that the transaction records sample is geographically representative across the state.

For ownership records, the sampling proceeds similarly at the village level: for each of the 22 districts, a tehsil is drawn at random, a village within that tehsil is drawn at random, a year is drawn at random, and a household identifier within that village–year cell is drawn at random. The ownership records sample covers ### villages across ### years.

The final dataset covers 6,841 villages in Haryana, spanning 2002–2025, with a total of approximately 18 million plot–year observations for ownership records and 4.2 million registered land transactions.

C.2 Land Classification and Zoning

Land in Haryana is administratively classified into several categories. *Agricultural land* includes irrigated (Chahi: well-irrigated; Nahri: canal-irrigated), rainfed (Barani), and fallow (Banjar Jadid: recently fallow; Banjar Kadim: long-fallow) land. *Non-agricultural land* includes residential (Abadi Deh) and non-cultivable (Gair Mumkin) land.

Conversion of agricultural land to non-agricultural use requires approval from district

authorities under Haryana's land use regulation framework. This creates an institutional friction that slows the transition from agricultural to built-up uses: parcels cannot be reclassified from agricultural to non-agricultural without formal approval, even if they have effectively ceased to be farmed. This implies that land-use data from administrative records may understate the extent of effective conversion, a potential source of measurement error that biases estimates toward zero.