Markets, Contracts, and Uncertainty in a Groundwater Economy

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Abstract

Groundwater is a vital yet threatened resource in much of South Asia. This paper develops a model of groundwater transactions under payoff uncertainty arising from unpredictable fluctuations in groundwater availability during the agricultural dry season. The model highlights the trade-off between the ex post inefficiency of long-term contracts and the ex ante inefficiency of spot contracts. The structural parameters are estimated using detailed micro-data on the area irrigated under each contract type combined with subjective probability distributions of borewell discharge elicited from a large sample of well-owners in southern India. The findings show that, while the contracting distortion leads to an average welfare loss of less than 2 percent and accounts for less than 50 percent of all transactions costs in groundwater markets, it has a sizeable impact on irrigated area, especially for small farmers. Uncertainty coupled with land fragmentation also attenuates the benefits of the water-saving technologies now being heavily promoted in India.
Markets, Contracts, and Uncertainty in a Groundwater Economy

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1 Introduction

Water scarcity is one of the fundamental challenges facing developing country agriculture, one that is only expected to be exacerbated by climate change. In India, by far the world’s largest user of groundwater, millions of borewells have sprung up in recent decades (Shah, 2010). While groundwater exploitation has allowed increased agricultural intensification, a boon to the rural poor (Sekhri, 2014), unregulated drilling has also raised concern about the sustainability of this vital resource (e.g., World Bank, 2005). India’s main policy related to groundwater has been its effort to promote water-saving technologies such as drip and sprinkler irrigation, targeted particularly at small farmers.\(^1\) For such farmers, however, the benefit of water-saving technology depends on their ability to expand water sales to neighboring cultivators, in other words on the efficiency of groundwater markets.\(^2\)

To explore the implications of water-saving technology in a setting where there are contracting distortions, we build and structurally estimate a model of south India’s groundwater economy incorporating three salient features: First, given high irrigation conveyance losses, groundwater transactions tend to be highly localized, typically involving bilateral-monopolistic contracts between a well-owner and a water-buyer on adjacent land (see Jacoby et al., 2004). Second, during the dry (\textit{rabi}) season, agricultural production relies almost exclusively on borewell irrigation, the supply of which is, at least in part, unpredictable.\(^3\) Third, planting requires upfront and irreversible outlays. Insofar as a water-buyer has a single borewell from which to purchase irrigation, his standing crop effectively becomes an investment specific to that trading relationship.

In our setting, bilateral transactions between well-owners and neighboring farmers take one of two forms: spot contracts, in which groundwater is sold on a per-irrigation basis throughout the season, and long-term (i.e., seasonal) contracts, which specify ex-ante the price and area irrigated over the entire season. We develop a model in which spot contracts are fully state contingent and thus ex-post efficient, but, due to the classic hold-up problem, ex-ante inefficient. In particular, planting incentives of water-buyers are distorted. Long-term contracts, by contrast, are assumed immune from hold-up, but lead to ex-post

\(^1\)The National Mission on Micro Irrigation, initiated in 2006, is perhaps the largest subsidy program of its kind in the world. When combined with complementary subsidies recently offered by several states, including Andhra Pradesh, smallholders may be eligible to defray up to 90% of a system’s cost.

\(^2\)Due to the high degree of land fragmentation, groundwater markets are pervasive in India. The 2011-12 India Human Development Survey (Desai and Vanneman, 2011) indicates that, of the 83% of agricultural households nationwide that do not own a borewell, 37% purchase irrigation (groundwater).

\(^3\)During the wet (\textit{kharif}) season, groundwater is typically used as a buffer against insufficient rainfall or shortfalls in surface water flows rather than as the sole source of irrigation.
inefficiency inasmuch as a fixed transfer of groundwater necessarily leads to a misallocation across farms once the state of nature is revealed. Our model yields the sharp prediction that as groundwater supply uncertainty increases, long-term contracts become unattractive relative to spot arrangements.

The assumption that long-term (ex-ante) contracts deter holdup appeals to the reference-point insight of Hart and Moore (2008) and Hart (2009) wherein a contract establishes what each party in the transaction is entitled to; opportunism thus leads to deadweight losses (see also Herweg and Schmidt, 2014, for a related model). \(^4\) In the earlier property rights theory of the firm associated with Grossman and Hart (1986) and Hart and Moore (1990), renegotiation is efficient so that hold-up is virtually inevitable (Hart, 1995). Since there is, consequently, no functional difference between contracts agreed upon ex-ante and those agreed upon ex-post, payoff uncertainty, in Hart’s (2009) terminology, can play no role.

A key contribution of this paper lies in quantifying the contracting distortion, as well as its impact on the return to water-saving technology, using a structural econometric model. A rather unique feature of a groundwater economy that allows us to do this is that buyers and sellers are both agricultural producers, cultivating side-by-side with the same technology. Our model of agricultural production under stochastic groundwater supply accounts for the choice between seasonal contracts and per-irrigation sales, for water transfers through leasing, as well as for the area irrigated under each such arrangement. We use data from a large sample of borewell owners across six districts of Andhra Pradesh and Telangana states. The specially-designed survey instrument takes particular care to elicit from each well owner a subjective probability distribution of their borewell’s discharge near the end of the season conditional on its initial discharge. The structural parameters of the model are identified principally from the variation across borewells in this conditional probability distribution.

To assess external validity of the structural model, we retain two nonrandom holdout samples corresponding to two of the six surveyed districts; borewells from the remaining four districts constitute the estimation sample on which we fit the model. Keane and Wolpin (2007) argue for choosing “a [holdout] sample that differs significantly from the estimation sample along the policy dimension that the model is meant to forecast (p. 1352).” The analogue, in our setting, to a policy regime “well outside the support of the data” are the large differences in first and second moments of groundwater supply between estimation and holdout districts.

\(^4\)Fehr et al. (2011), Hoppe and Schmitz (2011), and Bartling and Schmidt (2014) corroborate the reference-point idea experimentally.
Structural estimation provides a threefold benefit: First, it enables us to assess the performance of actual contractual arrangements against the benchmark of Pareto-efficiency. Relative to this first-best counterfactual, we find that observed contracts induce a substantial reduction in irrigated area but only a modest welfare distortion. Second, structural estimation allows us to compare the contracting distortion against another groundwater market friction. In particular, once neighboring farmers all have borewells of their own, there is limited scope for groundwater trade. A social planner, in this case, would want to drill fewer wells (thus economizing on fixed costs) and share more water among neighbors. To capture the extent of this coordination failure, our empirical model incorporates a cost of arranging groundwater transactions, which we find to be of about the same magnitude as the contracting distortion. Third, our structural estimates allow us to simulate irrigation choices and returns to cultivation under a counterfactual water-saving technology, specifically drip irrigation. Here we find that switching from traditional to drip irrigation would greatly stimulate groundwater market activity. We also show that, as a result, the farm-level benefits of drip adoption depend in a nuanced way on local patterns of land fragmentation.

This paper contributes to the empirical contracts literature in three ways. Early writings in the transactions costs tradition (Williamson, 1971; Klein et al., 1978) recognize that long-term contracts protect investments specific to a trading relationship but do so at a cost; in an uncertain environment, contractual rigidity inevitably leads to resource misallocation, which is obviated by ex-post or spot contracting. While the ensuing empirical literature investigates the nature of long-term contracts, it has been largely silent on the choice of long-term over spot contract, and, in particular, on how this choice is driven by the fundamental tradeoff between ex-ante and ex-post inefficiency. Second, structural estimation and quantitative welfare analysis has been rare in the empirical contracts literature. Gagnepain et al. (2013) is a notable exception. However, in their context of French public-sector contracts the tradeoff between ex-post renegotiation and ex-ante incentives is driven by asymmetric information rather than, in our case, by payoff uncertainty. Moreover, in the setting we consider, agents have the option not to contract or trade at all (and many do not), which allows us to investigate how payoff uncertainty affects overall market activity. Third, this paper is the first contract-theoretical application we are aware of incorporating subjective probabilities 

Lafontaine and Slade (2012) review empirical studies of inter-firm contracting from various theoretical perspectives. See Joskow (1987) on asset specificity and contract duration and Goldberg and Ericson (1987), Masten and Crocker (1985), and Crocker and Masten (1988) on the structure of long-term contracts in uncertain environments. Carlton (1979), Polinsky, (1987), and Hubbard and Weiner (1992) consider the choice between long-term contracts and spot markets, but in these models there is no relationship-specific investment; firms incur the transactions costs of long-term contracts to insure against cash-flow variability.
(see Attanasio 2009, Delvande et al. 2011, and Mahajan et al. 2012 for reviews of related work in other areas of economics).

Finally, there is burgeoning interest in the industrial organization of groundwater (e.g., Jacoby et al. 2004, Aggarwal 2007, Foster and Sekhri 2008, Anderson 2011, Banerji et al. 2012, Chakravorty and Somanathan 2014, and Michler and Wu 2014). None of this work, however, focuses on groundwater supply uncertainty as a source of market failure nor on how groundwater markets interact with water-saving technology adoption.footnote{6}

The next section of the paper lays out the formal theoretical arguments. Section 3 describes our survey data and the groundwater economy of southern India in greater detail. Section 4 adapts the theoretical model for the purposes of structural estimation and derives the likelihood function. Estimation results and counterfactual simulations are reported in Section 5. Section 6 concludes.

2 Theory

2.1 Preliminaries

We begin by briefly enumerating the assumptions, leaving the more extended justifications for Section 3.

A.1) Fragmentation: Agricultural production occurs on discrete plots of land of area $a$, each owned by a distinct individual.

A.2) Borewells and groundwater: A reference plot has a borewell drawing a stochastic quantity of groundwater $w$ over the growing season, where $w$ has p.d.f. $\psi(w)$ on support $[w_L, w_H]$.

As noted, groundwater is the sole (dry-season) irrigation source in our setting. Since property rights to groundwater are not clearly delineated in India, there is no legal limit to withdrawals. Upon striking an underground spring, farmers install the widest feasible pipe consistent with the expected outflow. Likewise, because electricity is provided free at the margin, farmers run their pumps for the maximum number of hours that power is available on any given day. Aside from pipe-width and electricity constraints, $w$ depends on the availability of groundwater in the aquifer at any given time and on the local hydro-geology.

footnote{6}Cary and Zilberman (2002) and Dridi and Khanna (2005) consider theoretically how spot markets in surface water affect water-saving technology adoption decisions in the developed country context. Pfeiffer and Lin (2014) provide empirical evidence that the switch to water-efficient center pivot irrigation in Kansas led to an increase in groundwater use. Groundwater markets, however, are not relevant in this setting.
A.3) **Agricultural technology:** The common crop output production function, \( y = F(l, w, x) \), depends on three inputs: land \( l \), seed \( x \), and water \( w \), with land and seed used in fixed proportions. For any level of \( x \), \( y/l = f(w/l) \equiv f(\omega) \), where \( \omega \) is irrigation intensity and the intensive production function, \( f \), is increasing, concave, with \( f(0) = 0 \).\(^7\)

Given A.3, we may write net revenue as \( l\{f(\omega) - c\} \), where \( c \) is the cost of the required seed per acre cultivated.

A.4) **Risk preferences:** Farmers are risk neutral.

Risk neutrality, a core assumption of transactions cost economics, is justified by evidence presented below showing little, if any, role for risk preferences in irrigation decisions.

A.5) **Land availability:** A well-owner is not limited in the area of adjacent land that his borewell can irrigate.

In invoking A.5, we abstract from any demand-side constraints that may arise when most or all adjacent landowners also have their own borewells. While this assumption simplifies the theoretical analysis, it is unrealistic and will therefore be relaxed in the empirical implementation.

Consider, first, a well-owner’s choice of area cultivated (irrigated) when his own plot size is not a constraint. Let \( \ell_U = \text{arg max}_l \{ Ef(w/l) - c \} \) and define the marginal return as

**Definition 1** \( g(\omega) = f(\omega) - \omega f'(\omega) \).

The necessary condition for optimal planting

\[ Eg(\omega) = c \]

(1)

equates the expected marginal return to the marginal cost of cultivation.

Now, letting \( r \) index mean preserving increases in groundwater supply uncertainty, we have

**Proposition 1 (Precautionary planting)** If \( g \) is strictly concave, then \( \partial \ell_U / \partial r < 0 \).\(^8\)

\(^7\)Constant returns to scale is both technically convenient and empirically sensible. Diminishing returns is unlikely to set in over the range of cultivated areas that we are considering. Moreover, under diminishing returns, well-owners might simultaneously leave their own plot partially fallow while selling water to a neighboring plot, a scenario virtually never observed in practice.

\(^8\)Proof: Follows directly from Theorem 1 of Diamond and Stiglitz (1974).
In other words, well-owners may exhibit a precautionary motive analogous to that in the savings literature (e.g., Kimball, 1990), in this case limiting their exposure to increases in supply uncertainty by committing less area to irrigate.

The surplus generated by a borewell under unconstrained self-cultivation is

\[ V_U = \ell_U E \left[ f\left(\frac{w}{\ell_U}\right) - c \right]. \]

In case \( \ell_U > a \), we may think of \( V_U \) as the surplus derived by the well-owner if he could sell an unlimited amount of groundwater in a competitive spot market.\(^9\) As mentioned, however, groundwater transactions do not resemble this competitive, arm’s-length, ideal.

The next two subsections discuss each of the two observed forms of bilateral contracting in turn, using Table 1 as an organizing framework.

### 2.2 Long-term contracts

The canonical long-term contract commits the well-owner to irrigate a buyer’s field, or some portion thereof, for the whole season at a pre-determined price. Following Hart and Moore (2008), we think of such (ex-ante) contracts as establishing entitlements. Ex-post renegotiation of the terms, or hold-up, will therefore lead to deadweight losses due to aggrievement by one or both parties.\(^{10}\) To bring the tradeoff between ex-ante and ex-post inefficiency into

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\(^{9}\) To see why, let subscripts \( b \) and \( s \) denote water-buyer and seller, respectively. Further, let \( p \) be the spot price and \( \ell_b \) the buyer’s cultivated area such that \( \ell_U = a + \ell_b \). It is easy to see that \( f'(\omega_b) = f'(\omega_s) = p \) which implies that \( \omega_b = \omega_s \). Thus, \( V_U = E\left[a(f(\omega_s) - c) + p\omega_b\ell_b\right] = E\left[a(f(\omega_s) - c) + f'(\omega_b)\omega_b\ell_b\right] = E\left[a(f(\omega_s) - c) + \ell_b(f(\omega_b) - c)\right] = E\left[(a + \ell_b)(f(\omega_s) - c)\right] \), where the penultimate expression follows from \( E\ell_b(\omega_b) = c \), the necessary condition for the buyer’s optimal area cultivated.

\(^{10}\) More precisely, there are noncontractible actions that either party can take ex-post to add value to the transaction. As long as a party feels he is getting what he is entitled to in the contract, he will undertake such helpful actions, but if he feels shortchanged he will withhold them, generating a loss in surplus. In the
stark relief, we assume that these deadweight losses make hold-up prohibitively costly. Our evidence, in fact, indicates that renegotiation of seasonal contracts is extremely rare.11

Summarizing, the seasonal contract has two salient features: First, by serving as reference point in, and hence as a deterrent to, renegotiation, it protects relationship-specific investment (in our context, planting inputs); second, water allocations under the contract are unresponsive to the state of the world.

Let $\tau$ denote the total transfer of groundwater at per unit price $p$ to irrigate a field of size $l$. The optimal simple (i.e. single-price) contract solves

$$
\max_{p,l} a \left\{ E f\left( \frac{w - \tau}{a} \right) - c \right\} + p\tau \quad \text{s.t.}
$$

$$
PC : l \left\{ f\left( \frac{\tau}{l} \right) - c \right\} - p\tau \geq 0
$$

$$
IC : \tau = \arg \max_{\tau \in [0,w_L)} l \left\{ f\left( \frac{\tau}{l} \right) - c \right\} - p\tau
$$

The first term in the well-owner’s objective function (top line) is the expected revenue from crop production on his own plot net of cultivation costs, which is diminished when he sells water to a neighbor;12 the second term is his total revenue from the sale. The participation constraint ($PC$) stipulates that the crop revenue of the buyer net of both cultivation and water costs cannot be negative. Finally, the incentive constraint ($IC$) says that the transfer is maximizing the buyer’s net revenue, subject to the constraint that the promised amount cannot exceed the available supply of water in the lowest state of the world, $w_L$. Note that expectations are dropped in both the $PC$ and $IC$ because, under the contract, $l$ and $\tau$ are fixed ex-ante. Thus, the seasonal contract offers an assured supply of irrigation to the buyer; the direct cost of production variability is borne fully by the seller on his plot.

words of Hart (2009): “Although our theory is static, it incorporates something akin to the notion of trust or good will; this is what is destroyed if hold-up occurs.” (p. 270). Alternatively, Herweg and Schmidt (2014) motivate the inefficiency of contract renegotiation using the notion of loss aversion.

11For each of the 873 well-buyer-crop combinations in which a seasonal contract was undertaken in rabi 2011-12, our survey asks the borewell owner “Was the arrangement carried out as originally agreed?” with possible responses: “(1) Yes; (2) No, price increased; (3) No, price decreased; (4) No, contract terminated.” In all but one of these cases, the response was (1).

12Without loss of generality, we assume that the constraint that the water-seller’s cultivated area $l_s$ cannot exceed his plot area $a$ is binding; i.e., the well-owner always fully cultivates his land before selling any groundwater. Proof: Suppose not, then the optimal choice of $l_s$ requires $E g\left( \frac{w - \tau}{l_s} \right) = c$. However, equation (1) implies $E g\left( \frac{w}{l_s} \right) = c \Rightarrow \tau = w(1 - l_s/l_U)$, which is a contradiction because $\tau$ cannot be state-contingent.
Given a binding PC, the necessary conditions for the optimal contract are as follows:

\[ Ef' \left( \frac{w - \tau}{a} \right) = p \]
\[ g \left( \frac{\tau}{\ell} \right) = c \]
\[ f' \left( \frac{\tau}{\ell} \right) = p, \tag{3} \]

the solution to which is the water transfer-area pair \((\tau_C, \ell_C)\). Divergence of supply and demand for irrigation ex-post creates a distortion. Since (3) implies \( Ef' \left( \frac{w - \tau_C}{a} \right) = f' \left( \frac{\tau_C}{\ell_C} \right) \), it is not true, in general, that \( f' \left( \frac{w - \tau_C}{a} \right) = f' \left( \frac{\tau_C}{\ell_C} \right) \) \( \forall \) \( w \), which would obtain if \( \tau \) were state-contingent, as in a competitive spot market (see fn. [9]). It follows as a corollary that the distortion vanishes as uncertainty goes to zero, in which case \( g \left( \frac{\tau_C}{\ell_C} \right) = g \left( \frac{w}{\ell_C + a} \right) = c = g \left( \frac{w}{\ell_U} \right) \) which implies that \( \ell_C = \ell_U - a \). Thus, in the absence of uncertainty, the amount of land irrigated and the economic surplus generated by the borewell would be the same under the seasonal contract as under a competitive spot market; i.e., the long-term contract would achieve the first-best.

As usual, the roles of principal and agent here are entirely arbitrary; i.e., the constrained Pareto efficient allocation would be identical if the buyer were the monopsonist and it was the seller whose PC was saturated. In other words, the division of ex-ante joint surplus is both indeterminate and irrelevant for our purposes.

### 2.3 Spot contracts

Groundwater may also be sold on a per-irrigation basis. Once the season is underway, however, commitments have been made. The potential seller has retained (i.e., refrained from contracting out) the rights to some excess water from his well during the season whereas the potential buyer has planted a crop in an adjacent plot. Since each party has some degree of ex-post bargaining power, we use a Nash bargaining framework. To be clear, in a per-irrigation arrangement there is a self-enforcing agreement to trade during the season, even though the terms of these trades are not fully delineated ex-ante. Indeed, side-payments may be made (or favors rendered) to secure an exclusive trading relationship. In other words, as with the long-term contract, there is a division of ex-ante joint surplus (see Table 1) and, just as in the long-term case, this division is irrelevant for allocations. We only assume that
any negotiations over this surplus are efficient, leaving no money on the table.\textsuperscript{13}

Turning to the ex-post stage, let $\bar{\tau}$ be the amount of water already transferred to the buyer and suppose that buyer and seller negotiate the price $p$ of incremental transfer $\Delta$. The buyer’s net payoff from consummating the trade is given by $u = lf((\bar{\tau} + \Delta)/l) - p\Delta$, whereas that of the seller is $v = af((w - \bar{\tau} - \Delta)/a) + p\Delta$. The no-trade payoffs are given by $u = lf(\bar{\tau}/l)$ and $v = af((w - \bar{\tau})/a)$, respectively. The absence of $c$ in these payoff functions reflects the fact that all cultivation costs have already been incurred.

Given Nash bargaining, $p^* = \arg \max (u - \bar{u})\eta(v - \bar{v})^{1-\eta}$, where $\eta$ is the buyer’s bargaining weight.\textsuperscript{14} Therefore, $p^*$ solves

\begin{equation}
\eta(v - \bar{v}) - (1 - \eta)(u - \bar{u}) = 0
\end{equation}

where the last line takes the limit of the second line as $\Delta \to 0$. Thus, we obtain the standard surplus-splitting rule\textsuperscript{15}

\begin{equation}
p^*(\bar{\tau}) = (1 - \eta)f'(\bar{\tau}/l) + \eta f'(w - \bar{\tau}/a).
\end{equation}

Furthermore, once $f'(\bar{\tau}) - p^*(\tau) = \eta [f'(\bar{\tau}) - f'(w - \bar{\tau}/a)] = 0$, the buyer’s demand for irrigation is sated. Thus, the total transfer $\tau$ must satisfy $f'(\bar{\tau}/l) = f'(w - \bar{\tau}/a)$, which is the condition for an ex-post efficient allocation of groundwater conditional on area cultivated.

Now consider the buyer’s ex-ante problem of choosing area cultivated to maximize ex-
pected returns given price function $p^*$ and the total transfer $\tau$. In particular,

$$\ell_P = \arg \max_l E \left\{ \frac{r}{l} - \int_0^\tau p^*(t) dt \right\} - cl. \quad (6)$$

Observe that the per unit price of water is now state-dependent and, in particular, is no longer constant as in the seasonal contract; each small increment of irrigation now has a different cost. From (5),

$$\int_0^\tau p^*(t) dt = (1 - \eta)lf(\frac{\tau}{l}) + \eta a \left[ f(\frac{w-\tau}{a}) - f(\frac{w}{a}) \right],$$

so only the first term on the right-hand side depends on $l$. The necessary condition for the buyer’s cultivation choice is, therefore, simply

$$\eta E_g(\tau/l) = c. \quad (7)$$

Comparing equations (7) and (1), we see that they differ by the factor $\eta$. Surplus extraction on the part of the water seller effectively taxes the marginal benefits of cultivation, with the tax rate decreasing in the buyer’s bargaining power.\(^{16}\)

To summarize, spot contracts lead to an ex-post efficient allocation but distort ex-ante incentives. The latter inefficiency is due to the hold-up problem first formalized by Grout (1984); the buyer under-invests (indeed, $\ell_P < \ell_U - a$) in anticipation of ex-post rent appropriation.

2.4 Other contracts

Our approach, following in the tradition of the empirical contracts literature (e.g., Gagnepain et al., 2013), has been to model only the principal arrangements observed in the data. Nevertheless, it is worth a digression to discuss contracts that, although largely hypothetical, are potentially more efficient than those considered above.

2.4.1 First-best

It is clear from equation (7) that the first-best contract has the seller committing to $\eta = 1$. This contract is tantamount to one in which the price of groundwater is indexed (cf. Hart, 2009) to the seller’s post-transfer marginal product $f'\left(\frac{w-\tau}{a}\right)$. Perhaps the complexity of this pricing scheme, the lack of observability (e.g., well flow may be manipulable by the seller),

\(^{16}\)As before, the borewell owner fully cultivates his own plot before selling any groundwater (i.e., $l_s = a$).

Proof: Suppose not, then $E_g \left( \frac{w-\tau_P}{l_s} \right) = c$ is necessary. However, equation (7) and $f'\left(\frac{\tau_P}{l_s}\right) = f'\left(\frac{w-\tau_P}{l_s}\right) \Rightarrow E_g \left( \frac{w-\tau_P}{l_s} \right) = c/\eta$, which is a contradiction.
or lack of third-party state verification, explains why we do not observe it in practice.\textsuperscript{17}

Alternatively, a well-owner could achieve the first-best allocation by subsidizing the buyer’s planting cost at a rate of $1 - \eta$; obviously, allowing the planting investment to be contractible obviates the hold-up problem. As a practical matter, however, it may be quite difficult for the seller to ensure the optimal ex-post demand for his water through such an incentive scheme if the buyer is free to adjust the intensity of cultivation. While this type of moral hazard problem, strictly speaking, lies outside of our model (because we have assumed that land and inputs like seed are always used in fixed proportions), it may explain the absence of such planting subsidies in our setting.

2.4.2 Mixed

Thus far, we have analyzed each type of contract in isolation, not allowing borewell owners to engage in both simultaneously. Our main reason for doing so is empirical; groundwater sales to multiple buyers under different contracts are rare in our data. The analysis of a mixed contract, however, is straightforward. Given his residual water $w - \tau_C$ available ex-post, the borewell owner sells an amount $\tau_P(\tau_C)$ on a per-irrigation basis to buyer B. Working backwards, the amount sold to buyer A on a seasonal contract is the $\tau_C$ that maximizes

\[
\tau \left\{ Ef\left(\frac{w-\tau_C-\tau_P(\tau_C)}{a} - c\right) + p\tau_C\right\},
\]

subject to the participation and incentive constraints.

Clearly, the mixed contract does not achieve the first-best. While the allocation of water between the seller’s plot and that of buyer B is ex-post efficient, this is not the case for buyer A. Indeed, neither the ex-post nor the ex-ante distortion is entirely eliminated.\textsuperscript{18}

2.5 Characterizing the tradeoff

Returning to the main argument, we have already seen that the distortion induced by the long-term contract disappears when groundwater supply becomes perfectly certain, whereas the distortion induced by the spot contract does not. Next, we establish a general result about the dominance of long-term over spot contracts in our environment.

Recall that increases in $r$ correspond to mean preserving increases in uncertainty, with $r = 0$ indicating perfect certainty. Let $V_j(r)$ be the surplus derived from contract of type

\textsuperscript{17}A share-contract by which groundwater is paid for out of the buyer’s crop partially mimics an indexed price, though creates other incentive problems. Aggarwal (2007) finds that share-contracts for groundwater are prevalent in parts of western India, but we have less than a handful of such cases in our data.

\textsuperscript{18}In the spirit of contracts as reference points, a buyer under a seasonal contract is precluded from selling back water to the borewell owner, or to anyone else, on a per-irrigation basis as this would presumably aggrieve the borewell owner.
\( j = C, P, \)\(^{19}\) and note that \( V_P(r, \eta) \) also depends on the bargaining weight \( \eta \).

**Proposition 2 (Dominance)** If \( g \) is strictly concave and \( \tau_C(0) < w_L \),\(^{20}\) then (a) for some \( \eta \), \( \exists \) a unique \( r^*(\eta) \) such that \( V_C(r^*) = V_P(r^*, \eta) \); (b) \( [V_C(r) - V_P(r, \eta)](r^* - r) > 0 \).\(^{21}\)

Simply put, under the conditions of proposition 2, there can be a level of uncertainty at which the parties are indifferent between seasonal and per irrigation arrangements. If so, then the seasonal contract must dominate at low levels of uncertainty and per-irrigation sales at high levels of uncertainty.

Figure 1 illustrates the intuition underlying proposition 2, showing how the economic surplus generated by a borewell varies with uncertainty level \( r \) under alternative water transfer arrangements. Regardless of arrangement, surplus always decreases with \( r \) (see Appendix). In the case of autarky (\( A \)), in which the borewell irrigates exactly plot area \( a \), surplus is \( V_A = aE[f(w/a) - c] \). \( V_A \) must lie strictly below first-best surplus \( V_U \) except at \( r = r_U \); at this level of uncertainty, \( \ell_U = a \) and autarky is the optimal unconstrained choice. When the borewell owner sells water under a seasonal contract, surplus \( V_C \) is also less than first-best (except under perfect certainty), coinciding with \( V_A \) at some positive level of uncertainty \( r_C < r_U \). Note that \( V_C \) declines relatively rapidly with \( r \) because higher uncertainty operates upon two margins under a seasonal contract: It leads to greater ex-post misallocation of groundwater across plots as well as to a contraction of overall area irrigated by the borewell (precautionary planting). Only the latter effect is operative under the per-irrigation arrangement. In this case, surplus \( V_P \) approaches \( V_U \) as \( \eta \) approaches one. Moreover, at some low level of bargaining power \( \eta = \eta_2 \), \( \ell_P = 0 \) and \( V_P \) coincides with \( V_A \). So, for some range of \( \eta \in (\eta_1, 1) \), \( V_P \) and \( V_C \) must cross. Given such a crossing (at \( r^* \), \( V_P \) coincides with \( V_A \) at a level of uncertainty \( r_P \) between \( r_C \) and \( r_U \). This shows that the spot contract can only dominate the long-term contract at higher levels of uncertainty.

\(^{19}\)For the seasonal contract, surplus is given by the private returns to the well-owner; since the \( PC \) is binding, the water-seller gets all the surplus. By contrast, in the per-irrigation case, we must consider the joint surplus of well-owner and water-buyer. It might be argued that the choice of per-irrigation over alternative arrangements should be governed by the water seller’s private returns as well. This, however, runs counter to our assumption that all ex-ante negotiations are efficient. In other words, situations in which the per irrigation arrangement yields the highest joint surplus but fails to maximize the well-owner’s private return would be resolved through side-payments.

\(^{20}\)In words, this latter condition states that the water transfer under perfect certainty is less than total water available in the worst state of the world. Otherwise, \( V_C \) has a discontinuity at \( r = 0 \); i.e., at \( r = \epsilon \), the optimal transfer must be discretely less than \( \tau_C(0) \). In this case, \( r^*(\eta) \) still exists for some \( \eta \) but it is not necessarily unique. Part (b) of the proposition continues to hold, however, with respect to the largest \( r^* \).

\(^{21}\)Proof: See Appendix A.
Figure 1: **Long-term versus spot contracts and uncertainty**

![Diagram showing surplus, mean preserving spread, and regions C, P, A, U]

*Notes:* C, P, A, and U denote regions where dominant arrangement is, respectively, long term contract, spot contract, autarky, and unconstrained cultivation. Dashed portion of $V_U$ curve is unattainable given absence of competitive spot markets.

## 3 Context

### 3.1 Groundwater markets survey

Our data come from a randomly selected survey of about 2300 borewell owners undertaken in 2012-13 in six districts of Andhra Pradesh (AP) and Telangana (until 2014, also part of AP). The districts were selected to cover a broad range of groundwater availability, conditions for which generally improve as one moves from the relatively arid interior of the state toward the lusher coast. Drought-prone Anantapur and Mahbubnagar districts were originally selected as part of a weather-index insurance experiment (Cole et al., 2013); all 710 borewell owners were followed up from that study’s 2010 household survey. Guntur and Kadapa districts, which fall in the intermediate range of rainfall scarcity, and the water-abundant coastal districts of East and West Godavari, each contribute around 400 borewell owners. All in all, our survey obtained information on 2,411 borewells in 144 villages (21-25 per district). At the time of the survey, none of the plots on which these borewells were situated

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22 Our sample is broadly representative of areas where groundwater is sufficient for *rabi* cultivation and where it is the sole source of irrigation for that season (canal command areas were avoided).
was equipped with drip irrigation systems.

To capture transfers of groundwater, which typically occur between adjacent plots so as to minimize conveyance losses,\textsuperscript{23} we departed from the usual household-based sampling strategy. Instead, each respondent (borewell owner) was also asked to report on all the plots adjacent to the one containing the reference borewell, including characteristics of the landowner, details on how the plot was irrigated during the \textit{rabi}, if not left fallow, and on the transfer arrangement if one occurred. The number of adjacent plots varies from 1 to 7, with a mode of 3. Not only does this \textit{adjacency} approach provide information about transfers that did happen but also about those that could have happened but did not.

\subsection*{3.2 Recharge and uncertainty}

As in much of India, farmers in AP rely almost exclusively on groundwater during the \textit{rabi} (winter or dry) season, when rainfall is minimal and surface irrigation typically unavailable. Indeed, recent years have seen an explosion of borewell investment as the costs of drilling and of submersible electric pumpsets have fallen, raising concern about groundwater over-exploitation (e.g., World Bank, 2005). Nonetheless, the time-series of depth to watertable across AP in the last decade and a half is dominated by \textit{intra}-annual variability (see Appendix Figure \textsuperscript{B.1}). This is explained by the limited storage capacity of the shallow hard rock aquifers that characterize the region. Most of the recharge from monsoon rains occurring over the summer months is depleted through groundwater extraction in the ensuing \textit{rabi} season. In contrast to the deep alluvial aquifers of Northwest India, there are no deep groundwater reserves to mine (see Fishman et al., 2011).

This annual cycle of aquifer replenishment and draw-down throughout AP is central to our analysis of groundwater markets. Although farmers can observe monsoon rainfall along with their own borewell’s discharge prior to \textit{rabi} planting, they cannot perfectly forecast groundwater availability over the entire season. To measure the degree of uncertainty, as part of the borewell owner’s survey we fielded a well-flow expectations module, which was structured as follows: First, we asked owners to assess the probability distribution of flow on a typical day at the \textit{start} of (any) \textit{rabi} season, the metric for discharge being fullness of the outlet pipe (i.e., full, $\frac{3}{4}$ full, $\frac{1}{2}$ full, $\frac{1}{4}$ full, empty).\textsuperscript{24} Next, using the same format,

\footnotesize
\begin{itemize}
  \item[\textsuperscript{23}]Most irrigation water is transferred through unlined field channels with high seepage rates. While our survey also picked up a number of transfers to non-adjacent plots using PVC pipe, usually these cases involved sharing of groundwater between well co-owners or between multiple plots of the same owner.
  \item[\textsuperscript{24}]To appreciate how discharge can be fractional for an extended period, the metaphor for the aquifer to keep in mind is that of a sponge rather than of a bathtub.
\end{itemize}

\normalsize

14
we asked about the probability distribution of end-of-season flow conditional on the most probable start-of-season flow. Thus, the question was designed to elicit residual uncertainty about groundwater availability.

The bottom left panel of Figure 2 shows substantial variability in groundwater uncertainty (well-specific coefficients of variation of end-of-season flow) in the overall sample. Notice that virtually no borewell owner (save five) report having a perfectly certain supply of groundwater. Next, we consider the salience of groundwater supply uncertainty for dry season production decisions.

3.3 Precautionary planting and risk aversion

Proposition 1 shows that uncertainty in groundwater availability can lead to precautionary planting. This result, however, hinges on the properties of $g$, the marginal return to planting, which is not directly observable. To motivate our theoretical assumptions, we now present a reduced-form analysis of planting decisions. Ultimately, of course, it is only by estimating the full structural model that we can distinguish precautionary planting per se from the effects of contracting distortions and other transactions costs.

*Rabi* season cultivation in southern India falls into two broad categories: wet crops (in
Table 2: Precautionary Planting and Risk Aversion

|                      | (1)          | (2)          | (3)          | (4)          | (5)          |
|----------------------|--------------|--------------|--------------|--------------|--------------|
| log(borewell plot area) | 0.573***    | 0.560***    | 0.544***    | 0.545***    | 0.545***    |
|                      | (0.0155)     | (0.0149)     | (0.0146)     | (0.0144)     | (0.0145)     |
| log(mean well flow)  | 0.692***    | 0.763***    | 0.770***    | 0.762***    |
|                      | (0.110)      | (0.110)      | (0.111)      | (0.110)      |
| log(pipe width)      | 0.463***    | 0.441***    | 0.439***    | 0.440***    |
|                      | (0.0366)     | (0.0405)     | (0.0406)     | (0.0405)     |
| log(CV)              | -0.709***   | -0.311***   | -0.249***   | -0.226***   |
|                      | (0.0256)     | (0.0459)     | (0.0468)     | (0.0882)     |
| log(CV) × RISK1      | 0.0146      | 0.00309     |
|                      | (0.0231)     | (0.0118)     |
| RISK2                | -0.144      |
|                      | (0.176)      |
| log(CV) × RISK2      | -0.0537     |
|                      | (0.0925)     |
| R²                    | 0.599        | 0.634        | 0.645        | 0.645        | 0.645        |
| Controls             | No           | No           | Yes          | Yes          | Yes          |

Notes: Robust standard errors in parentheses adjusted for clustering on borewell (*** p < 0.01, ** p < 0.05, * p < 0.1). Sample size is 2,411 borewells. Dependent variable in all regressions is log(total irrigated area by borewell); CV is the coefficient of variation of end-of-season well flow; RISK1 is a self-assessed ranking of risk tolerance; RISK2 is an index of marginal willingness-to-pay for risk based on Binswanger lotteries. Unreported controls are as follows: pump horse-power, log of well depth, number of other borewells within 100 meters, dummy for presence of recharge source.

our six districts, principally paddy, banana, sugarcane, and mulberry) and irrigated-dry or ID crops (e.g., groundnut, maize, cotton, chillies), distinguished by the much greater water requirements of the former. Since a field that, planted to ID crops, would take 3 days to irrigate would take a week to irrigate under wet crops, we use the equivalence 1 acre wet = \( \frac{7}{3} \) acre ID to compute total area irrigated by a borewell.\(^{25}\)

We investigate the effect of uncertainty on \textit{rabi} area irrigated by a borewell conditional on the plot area of that borewell. For 27\% of the borewells, irrigated area is less than reference plot area (also expressed in dry-equivalent acres), indicating that part of the borewell’s plot...
was left fallow in the past *rabi* season, whereas for 46% of borewells, the opposite is true; groundwater was either sold (irrigating the land of another farmer in the adjacency) or was transferred to a leased plot. Thus, we regress log irrigated area on log of reference plot area and the log($CV_i$) of end-of-season flow (see figure 2). The negative coefficient on the latter variable in column 1 of Table 2 means that that as groundwater uncertainty increases area planted/irrigated declines. The impact of uncertainty is diminished, but not eliminated, after controlling for mean end-of-season well flow (based on the five-point scale) and outlet pipe-width (col. 2). The result is also robust to controls for additional borewell characteristics (pump horse-power, well depth, number of nearby wells, presence of groundwater recharge) as seen in column 3.

While this evidence supports a precautionary planting motive, as well as the salience of our uncertainty measure, we have not yet established the theoretical mechanism. To the extent that variability in irrigation supply induces fluctuations in household income, simple risk aversion may explain why farmers limit their *rabi* planting in the face of uncertainty.

To assess this, we use two measures of preferences towards risk collected from well owners in the survey. The first measure, $RISK_1^i$, is a self-assessed ranking of risk tolerance, with 1 indicating “I am fully prepared to take risks” and 10 indicating “I always try to avoid taking risk.” The second measure is based on a Binswanger (1980) lottery played by each respondent for real money. Following Cole et al. (2013), $RISK_2^i$ is an index of marginal willingness-to-pay for risk constructed from the characteristics of the preferred lottery. Ranging from 0 to 1, higher values of $RISK_2^i$ indicate greater risk aversion. In columns 4 and 5 of Table 2, we report results of adding, respectively, $RISK_1^i$ and $RISK_2^i$, and, most importantly, their interactions with log($CV_i$), in the corresponding baseline regression of column 3. The estimated coefficients on these interactions, and particularly their lack of significance, betrays no indication that highly risk averse borewell owners are especially responsive to groundwater uncertainty. Precautionary planting, therefore, does not appear driven by risk preference. For this reason, as noted in A.4, we assume risk neutrality throughout the paper.

### 3.4 Land fragmentation, fixed costs, and groundwater markets

Aside from uncertainty, our environment is characterized by considerable land fragmentation coupled with a high fixed cost of borewell installation, on the order of US$1000 (excluding the pump-set). Fragmentation is driven by the pervasive inheritance norm dictating equal division of land among sons and the prohibitive transaction costs entailed in consolidating spatially dispersed plots through the land market. In our data, nearly 80 percent of plots...
were acquired through inheritance.

Land fragmentation would be irrelevant, of course, were groundwater markets frictionless. In this case, Coasian reasoning suggests that allocations should be independent of asset ownership. Thus, borewells would be just as likely on small plots as on large plots; the owner of a small plot could simply sell any excess groundwater to a neighbor. Obversely, small plots would be just as likely cultivated in the dry season as large plots; any plot owner without a borewell of his own could purchase groundwater from that of a neighbor. In Appendix B, however, we use plot-level data from our sample to strongly reject both implications of frictionless groundwater markets. Thus, in practice, land fragmentation does predict the distribution of borewells and fellowed area.

When we aggregate these data from around 9600 plots to the adjacency level in Figure 3, two key facts emerge: First, borewell density—measured as the ratio of borewell irrigated area to total area in the adjacency—is increasing in average adjacency plot area. Put another way, in more fragmented adjacencies, borewell density is lower; this simply reflects the finding in Appendix B that borewells are much less likely to be installed on small plots. Second, the proportion of plots in the adjacency receiving any groundwater transfer from the reference well (aside from transfers between its co-owners) is decreasing in average adjacency plot area. So, borewell density and groundwater market activity are substitutes, both driven by the degree of land fragmentation. We return to this feature in the econometric model.
3.5 Sub-samples and characteristics of adjacent plots

Our subsequent analysis will rely on three subsamples of borewells: First, we have the estimation sample, consisting of 1646 observations from the districts of Mahbubnagar, Guntur, Kadapa, and West Godavari. As the name implies, this sample will be used to estimate the structural econometric model as described in the next section. Borewells from the remaining districts shall comprise two distinct holdout samples reserved for model validation. Following Keane and Wolpin (2007), the choice of holdout districts is dictated by their outlier status with respect to the first and second moments of groundwater supply. The top two panels of Figure 2 show that the coefficients of variation of end-of-season flow (second moment) and pipe-widths (first moment) in the holdout districts are indeed well beyond the median values for the sample as a whole. In the case of Anantapur, the most arid district, groundwater uncertainty is extremely high and borewells have median pipe-width of only two inches. By contrast, in the much wetter and groundwater abundant East Godavari, median pipe-width is 4 inches, far above that of the other five districts, and CVs are also among the lowest.

### Table 3: Characteristics of Adjacent Plots by Subsample

| Holdout Samples | Estimation | Anantapur | E. Godavari | Total |
|-----------------|------------|-----------|-------------|-------|
| Mean number per adjacency | 3.46 | 3.64 | 3.25 | 3.45 |
| Mean area (acres) | 3.16 | 2.59 | 3.20 | 3.04 |
| % left fallow in rabi | 11 | 40 | 2 | 14 |
| % irrigated in rabi by | | | | |
| • reference borewell | 34 | 16 | 46 | 33 |
| of which, % irrigated under | | | | |
| • joint ownership | 31 | 96 | 17 | 33 |
| • land lease | 7 | 2 | 4 | 6 |
| • water sale | 62 | 2 | 80 | 62 |
| • own borewell | 48 | 43 | 41 | 46 |
| • other borewell | 12 | 1 | 13 | 10 |
| % owned by | | | | |
| • brother | 12 | 24 | 5 | 12 |
| • other relative | 11 | 11 | 4 | 10 |
| • unrelated/same caste | 45 | 31 | 57 | 45 |
| • unrelated/different caste | 32 | 34 | 34 | 33 |
| Number of plots | 4992 | 1106 | 1195 | 7293 |

Descriptive statistics on the nearly 7300 adjacent plots, shown in Table 3 provide insights into the nature of groundwater transfers and how they vary across subsamples. Overall, a
third of adjacent plots are irrigated in whole or in part by the reference borewell. However, this figure falls to just 16% of adjacent plots in Anantapur, even though the proportion owned by brothers, who are more likely to be co-owners of the reference borewell, is comparatively high in this holdout district. A similarly wide disparity exists in the percentages of plots accessing other borewells, which may or may not be in the adjacency. Thus, transfers of groundwater outside of joint ownership arrangements, and especially sales, are extremely limited in Anantapur and commensurate with this is a relatively high fraction of adjacent plots left fallow in *rabi* season. The situation is reversed for the holdout district of East Godavari, which has more groundwater sales than average and much less fallow.

4 Estimation framework

4.1 Preliminary analysis

Table 4 provides descriptive statistics for the estimation and holdout samples according to the groundwater transfer choices made by the borewell owner. Half of the owners in the estimation sample transferred groundwater to other plots in the adjacency during the past *rabi* season, slightly favoring the seasonal contract over the per-irrigation sale, with leasing trailing far behind in terms of popularity. Conditional on making a transfer, mean area irrigated is highest for the seasonal contract, followed by leasing and the per-irrigation arrangement.

As noted above, there are stark differences between the two holdout samples. Groundwater transactions are virtually nonexistent in Anantapur and more than half of the borewells are unconstrained (*U*) in the sense that they are irrigating less than their plot area. In East Godavari, on the other hand, unconstrained cultivation is comparatively rare. And, while the fraction of borewells with groundwater sales is certainly higher than in the estimation sample, what is particularly striking is the large proportion of seasonal contracts among sales in this holdout district.

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Our theory suggests that spot contracts are more attractive than long-term contracts

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26 As most sales transactions (86%) are between non-relatives, hold-up concerns are not *prima facie* misplaced. Among these non-relative transactions, 60% are between members of the same caste. However, 57% of non-related adjacent plot owners are of the same caste as the owner of the reference borewell. Hence, Anderson’s (2011) suggestion of caste-based barriers to groundwater trade does not find support in our data.

27 In the 116 cases where the reference plot has multiple borewells, we allocate the total area of the adjacency equally among wells, treating each well as an independent decision unit within its own (pro-rated) adjacency. Also, in case of joint ownership of the reference borewell, we merge the plots of all co-owners found in the adjacency.
### Table 4: Descriptive Statistics by Subsample

| Choice $j$         | Estimation | Anantapur | E. Godavari |
|-------------------|------------|-----------|-------------|
|                   | $N$        | $\ell_j$  | $N$         | $\ell_j$  | $N$        | $\ell_j$  |
| $U = \text{unconstrained}$ | 436        | 5.10      | 184         | 3.20      | 31         | 10.23    |
|                   | [0.26]     | (3.89)    | [0.51]      | (2.55)    | [0.08]     | (7.21)   |
| $A = \text{autarky}$  | 381        | 6.29      | 170         | 3.82      | 104        | 13.00    |
|                   | [0.23]     | (4.11)    | [0.47]      | (2.40)    | [0.26]     | (26.94)  |
| $L = \text{leasing}$ | 91         | 2.45      | 5           | 0.90      | 12         | 6.78     |
|                   | [0.06]     | (2.43)    | [0.01]      | (0.60)    | [0.03]     | (7.56)   |
| $C = \text{seasonal contract}$ | 400        | 2.80      | 1           | 1         | 238        | 3.61     |
|                   | [0.24]     | (2.45)    | [0.00]      | –         | [0.59]     | (3.07)   |
| $P = \text{per-irrigation sale}$ | 338        | 1.77      | 2           | 1.87      | 21         | 3.42     |
|                   | [0.21]     | (1.48)    | [0.01]      | (1.23)    | [0.05]     | (2.29)   |
| **Total**         | 1646       | –         | 362         | –         | 406        | –        |

*Notes:* Sample means (standard deviations). Proportions in square brackets.

### Figure 4: Prevalence of spot contracts and uncertainty

![Graph showing prevalence of spot contracts and uncertainty](image)

*Notes:* Nonparametric regression of per-irrigation arrangement indicator ($P$) on $CV$ using sample of 1000 borewells engaged in any groundwater sale (either $P = 1$ or $C = 1$). Endpoints of confidence interval approximated by logit transformation.
when uncertainty is high. Figure 4 bears out this key implication. Conditional on engaging in one of the two transactions, the probability of choosing the short-term per-irrigation arrangement \( P \) is increasing in the coefficient of variation of well flow (the arc-elasticity of the probability between the 1st and 99th percentile of \( CV \) is 0.41).\(^{28}\) While this finding supports the theoretical model, there are compelling reasons to press forward with structural estimation. First, the structural model fully accounts for selection into who transacts in the groundwater market. Second, and most importantly, the theoretical model has quantitative implications for the contracting distortion that cannot be captured in a reduced-form analysis.

4.2 Leasing

To account for leasing, we allow that this arrangement may entail an efficiency cost making it less attractive than irrigating one’s own land. A rationalization for such costs, corroborated by Jacoby and Mansuri (2009), is that underprovision of non-contractible investment (e.g., soil improvement) lowers the productivity of leased land. At any rate, without invoking some sort of leasing cost, the existence of a market for groundwater and, indeed, the predominance of groundwater sales over land leasing would be problematic (in the next subsection, we also introduce a fixed cost of leasing).

Thus, let \( \gamma > 0 \) be the proportional increment to cultivation costs that applies only to leased land. Optimal leased area is then given by

\[
\ell_L = \arg \max (a + l) \{ Ef(w/(a + l)) - c \} - \gamma cl. \tag{8}
\]

4.3 Functional form

We next assume that the intensive production function, \( f \), takes the form

\[
f(\omega) = \zeta \omega^\alpha, \tag{9}
\]

where \( 0 < \alpha < 1 \). That is, \( F \) is Cobb-Douglas in land and water. For reasons that will become clear shortly, we normalize the parameter \( \zeta = 1 \). With these assumptions, the implied \( g \) (marginal return to planting) is globally concave and, thus, by proposition 1

\(^{28}\)Based on a simple probit regression, the null hypothesis of no uncertainty effect on contract choice can be strongly rejected \( (p = 0.004) \); likewise \( (p = 0.003) \), if we condition on \( Ew/a \), a measure of per acre groundwater availability.
Table 5: Theoretical Solutions for Irrigated Area and Economic Surplus

| Choice $j$       | Area ($\ell_j$)                                      | Surplus ($V_j$)                                      |
|------------------|------------------------------------------------------|-----------------------------------------------------|
| $U$ = unconstrained | $(1 - \alpha)Ew^\alpha)^{1/\alpha}$                   | $\frac{\alpha c}{1 - \alpha} \ell_U$               |
| $A$ = autarky    | $a$                                                  | $a^{1-\alpha}Ew^\alpha - ca$                        |
| $L$ = leasing    | $(1 + \gamma)^{-1/\alpha} \ell_U - a$                | $(1 + \gamma)^{1-1/\alpha} V_U + \gamma ca$        |
| $C$ = seasonal contract | $\ell_C$ solves $E\Omega^\alpha - 1 = 0$               | $\frac{\alpha c}{1 - \alpha} [E\Omega^\alpha + \alpha \ell_C/a - (1 - \alpha)]$ |
| $P$ = per-irrigation sale | $\eta^{1/\alpha} \ell_U - a$                          | $\delta V_U$                                       |

Notes: $\Omega = \frac{1}{a} \left[ w \left( \frac{1 - \alpha}{w} \right)^{1/\alpha} - \ell_C \right]$, where $\ell_C \leq \left( \frac{1 - \alpha}{w} \right)^{1/\alpha} w_L$, and $\delta = \frac{1 - \eta(1 - \alpha)}{\alpha} \eta^{1/\alpha - 1}$.

and consistent with the empirical evidence presented in Section 3, there is a precautionary planting motive.

Combining equations (9) and (1) along with definition 2 yields expressions for $\ell_U$ and $V_U$ as reported in the first row of Table 5. As seen in the remainder of the table, a closed form for area irrigated is lacking only for the seasonal contract. In the case of per-irrigation sales, we find that the ratio of economic surplus to unconstrained or first-best surplus, $V_P/V_U$, is simply equal to a constant $\delta < 1$ (see note to Table 5). Thus, $1 - \delta$ represents the relative distortion of the per-irrigation arrangement, which vanishes as the buyer’s bargaining weight $\eta$ approaches unity.

### 4.4 Borewell discharge

As noted in Section 3, well-owners report conditional probabilities for five water flow states, corresponding to “full”, 3/4, 1/2, 1/4, and zero flow. For empirical purposes, therefore, the groundwater distribution $\psi(w)$ is discrete, consisting of five points of support $k = 0, 1, 2, 3, 4$ and corresponding borewell-specific probabilities, $\pi_{ki}$.

Since water discharge is proportional to the square of pipe radius $R_i$, we have

$$w_{ki} = \lambda R_i^2 k.$$  \hspace{1cm} (10)

Note that the parameter $\lambda$ in equation (10) and $\zeta$ in equation (9) always enter the model together in the form $\zeta \lambda^\alpha$, which is why we normalize $\zeta$ to one. Since expected groundwater supply is $\bar{w}_i \equiv Ew_i = \lambda R_i^2 \sum_k \pi_{ki} k$, we think of $\lambda$ as reflecting factors that shift the first
moment of total effective discharge, such as soil moisture retention capacity and, importantly for later, the water-efficiency of the irrigation technology.

4.5 Cost disturbance

To explain why different water transfer arrangements (including no transfers at all) are chosen across observationally equivalent borewells, and also why different areas are cultivated conditional on the transfer arrangement, we introduce a cost disturbance \( \varepsilon_i \sim N(0, \sigma^2_{\varepsilon}) \) such that \( c_i = \varepsilon_i \). We assume that cost heterogeneity reflects variation in local (adjacency-level) conditions, such as soil texture and depth, or in the shadow price of inputs like seed and fertilizer, rather than in cultivator characteristics.

Inserting \( c_i \) into the expressions given in the first column of Table 5 and inverting the resulting functions \( \ell_{ji} = \ell_j(\varepsilon_{ji}) \) yields choice-specific residuals \( \varepsilon_{ji} \) for \( j = U, L, C, P \), where \( \ell_{ji} \) is the area under that arrangement for borewell \( i \).

4.6 Fixed transactions costs

Given the contracting distortions built into our model, a well-owner would want to remain in autarky (choice \( A \)) over a range of \( \varepsilon \). As it stands, however, the model implies that the minimum groundwater market transaction would involve an infinitesimal quantity of water (area).\(^{29}\) To allow for a discontinuity in irrigated area as one exits autarky, we introduce a fixed transactions cost \( \kappa \).

We also allow \( \kappa \) to vary across adjacencies to account for the availability of neighboring land to irrigate. A lease or water sale is difficult, if not impossible, to arrange if all nearby plots are already irrigated by their own borewells. In this sense, there is strategic substitutability among borewells. Indeed, there may be greater incentives for farmers to drill wells of their own in areas less conducive to groundwater markets in the first place. In other words, the density of borewells within an adjacency may be endogenous with respect to groundwater market activity.

To capture heterogeneity in \( \kappa \) across adjacencies, therefore, we require, in effect, an instrument for borewell density. As Figure 3 suggests, we do have such an instrument: average plot size in borewell \( i \)'s adjacency, \( a_i \), which is plausibly unrelated to groundwater markets except through borewell density. Thus, we incorporate heterogeneity in irrigable

\(^{29}\) At least for choices \( L \) and \( P \). For the seasonal contract, choice \( C \), the minimum transaction is the area that can be irrigated by \( w_L \), the available groundwater supply in the lowest state.
land availability by introducing $\pi_i$ into $\kappa$ as follows:

$$\kappa_{ji} = \pi_j + \beta \log \pi_i$$

(11)

for water transfer type $j = L, P, C$. Note that $\beta$ is assumed to be the same across transaction types, which is consistent with its interpretation as the effect of availability of adjacent land to irrigate. As for the constant term $\pi_j$, we allow for a separate $\pi_L$, but restrict $\pi_C = \pi_P \equiv \pi_T$. Whereas we expect that $\pi_L > \pi_T$, since a land lease is likely to be more costly to arrange than a water sale, our presumption is that the cost of arranging a water sale is independent of its specific contractual terms.

4.7 Likelihood function

The mixed continuous/discrete choice likelihood function involves the probabilities of the different water arrangements (choices) $j = U, A, L, C, P$ and the densities of irrigated areas, $\ell_{ji}$, conditional on these choices. Choice probabilities are determined by the set of thresholds, $\bar{\varepsilon}_{jj'i}$, that solve the following crossing conditions for arrangement-specific value functions:

$$V_A(\varepsilon_{j'i}) = V_U(\varepsilon_{j'i})$$

$$V_A(\varepsilon_{ji}) = V_j(\varepsilon_{ji}) - \kappa_{ji} \quad j = L, C, P$$

$$V_j(\varepsilon_{jj'i}) - \kappa_{ji} = V_{j'}(\varepsilon_{jj'i}) - \kappa_{j'i} \quad (j, j') = \{(C, L), (P, L), (C, P)\} \quad (12)$$

The solution to the first of these equations yields $\bar{\varepsilon}_{j'i}$, the upper limit of integration for the autarky probability, which has a simple closed form. The second set of equalities in (12) yield the cultivation costs at which the well-owner is just indifferent between autarky and transferring water under arrangement $L, C$ and $P$, respectively. Given nonzero fixed costs, these thresholds do not have closed-form solutions and, hence, must be solved for numerically given data and parameters. The third set of equalities give the cost thresholds between alternative transfer arrangements and also do not have closed form solutions in general.

Letting $\Pr(j|\Theta, Z_i)$ denote the probability of choice $j$ conditional on parameters $\Theta = (\alpha, \eta, \gamma, \pi_L, \pi_T, \beta, \lambda, \pi, \sigma_\varepsilon)$ and data $Z_i = (\pi_{ki}, R_i^2, a_i, \pi_i)$, we have

$$\Pr(j|\Theta, Z_i) = \int_{R^2_{ji}} \frac{1}{\sigma_\varepsilon \phi(\frac{\varepsilon}{\sigma_\varepsilon})} d\varepsilon$$

(13)
where $\phi$ is the standard normal pdf, and $\mathcal{R}_j$ is the relevant region of integration for choice $j$. The simplest choice probability is for unconstrained cultivation, which is $\Pr(U|\Theta, Z_i) = 1 - \Phi(\bar{\varepsilon}_{AUi}/\sigma_\varepsilon)$, where $\Phi$ is the standard normal cdf and the dependence of $\bar{\varepsilon}_{AUi}$ on parameters and data is implicit. For autarky,

$$\Pr(A|\Theta, Z_i) = \Phi(\bar{\varepsilon}_{Ai}/\sigma_\varepsilon) - \Phi(\bar{\varepsilon}_{Ai}/\sigma_\varepsilon),$$

(14)

where $\bar{\varepsilon}_{Ai} = \max \{\bar{\varepsilon}_{LAi}, \bar{\varepsilon}_{CAi}, \bar{\varepsilon}_{PAi}\}$ represents the highest $\varepsilon_i$ that would induce any kind of water transfer. For the probabilities of arrangements $j = L, C, P$, the regions of integration are not easy to write out as there are many possible configurations of the relevant thresholds, including cases where $\mathcal{R}_j$ has two disjoint segments. Appendix Table D1 enumerates all 38 possible configurations and their associated integration limits.

Now, let $d_{ji}$ take a value of 1 when well-owner $i$ chooses water arrangement $j = U, A, L, C, P$ and zero otherwise. The likelihood contribution of borewell $i$ is

$$L_i(\Theta|d_{ji}, \ell_{ji}, Z_i) = H_U(\ell_{Ui})^{d_{Ui}} \Pr(A|\Theta, Z_i)^{d_{Ai}} \prod_{j=L, P, C} \left[ \frac{\Pr(j|\Theta, Z_i)}{\Phi(\bar{\varepsilon}_{Ai})} \right]^{d_{ji}},$$

(15)

where $H_j = |\partial \varepsilon_{ji}/\partial \ell_{ji}| \phi(\varepsilon_{ji}/\sigma_\varepsilon)/\sigma_\varepsilon$ is the density of irrigated area under arrangement $j$, the product of the absolute value of the Jacobian of inverse transformation $\varepsilon_{ji}(\ell_{ji})$ and the density of the cost disturbance for the given $j$.

The first two terms of the likelihood essentially form a tobit model, with $H_U$ accounting for the uncensored observations, $\ell_{Ui} < a_i$; and $\Pr(A|\Theta, Z_i)$, as given by equation (14), accounting for the censored observations. The third term of the likelihood can be understood using Figure 5, which illustrates two possible configurations for a well-owner selling water on a per-irrigation ($P$) basis ($V_L$ is not relevant for these cases and hence does not appear in the figure). In panel (a), $P$ is optimal only for $\varepsilon_i$ in the left tail. Thus, to observe $\ell_P > 0$, not only must we have $\varepsilon_i < \bar{\varepsilon}_{Ai}$, but also $\varepsilon_i < \bar{\varepsilon}_{CPi}$. To account for this additional right truncation, $\Pr(P|\Theta, Z_i)$ multiplies the truncated density $H_P(\ell_{Pi})/\Phi(\bar{\varepsilon}_{Ai})$ in the third likelihood term. In panel (b), $P$ is optimal for moderate $\varepsilon_i$ with $C$ dominating in the left tail. As in the previous scenario, the third term of the likelihood must include $\Pr(P|\Theta, Z_i)$ to account for this left truncation.32

30This is, of course, why $\Pr(U|\Theta, Z_i)$ drops out of the likelihood.

31The presence of $\Pr(j|\Theta, Z_i)/\Phi(\bar{\varepsilon}_{Ai})$ is reminiscent of Cragg’s (1971) hurdle model. In our model, however, there is one error term; i.e., the hurdle is not determined by a second independent error. Note as well that the fixed transactions cost ($\kappa_{ji}$) guarantees a discontinuity in the irrigated area schedule.

32With only a single transaction type, say $P$, the third term would collapse to $H_P(\ell_{Pi})$ and the likelihood
Figure 5: **Surplus and area irrigated under two possible model configurations**

(a) **PCAU Configuration**

(b) **CPAU Configuration**

*Notes:* Solid line segments in bottom graphs show irrigated area schedule relevant for the optimal contractual arrangement given $\varepsilon$.

### 4.8 Identification

Although, in practice, identification is secured through the full set of nonlinear cross-equation restrictions embedded in the thresholds defined by (12) and in the choice-specific residuals, heuristically, it is helpful to think of particular moments of the data identifying particular parameters. Thus, for example, the $\pi_j$ of equation (11) are identified from the fractions of well-owners selling water and leasing in land whereas $\beta$ is identified by the extent to which these fractions vary with average plot size in the adjacency.

Note that, for $j = L, P, U$, log area irrigated is

$$
\log I_{ji} = \frac{1}{\alpha} \left[ K + \log \eta d_i - \log(1 + \gamma) d_i + \log \left( \sum_k \pi_{ki} w_{ki}^\alpha \right) - \varepsilon_i \right]
$$

(16)

where $I_{ji} = \ell_{ji} + a_i$ for $j = L, P$ and $I_{ji} = \ell_{ji}$ for $j = U$ and the constant term $K = \log(1 - \alpha) - \log \sigma + \alpha \log \lambda$. It is evident from (16) that $\eta$ and $\gamma$ are identified off of mean differences in irrigated area across arrangements (controlling for selection), $\alpha$ by the rate at which irrigated area falls with variability in water supply, $K$ by average area in unconstrained cultivation, and $\sigma$ by the residual variance of irrigated area. Although $\lambda$ and $\overline{\sigma}$ are conflated would be identical to that of models with piecewise-linear budget constraints (see, e.g., Moffitt, 1986).
in the constant term $K$ and hence are not identified from irrigated areas alone, $\lambda$ enters
the choice probabilities distinctly, both through the value of autarky $V_A$ (see Table 5) and
through $w_L$, water availability in the lowest state.

Equation (16) also makes clear that a nondegenerate groundwater supply distribution
$\psi(w)$ is critical for model identification even with substantial variation in $w_{ki}$ (which is to
say, in pipe width) across borewells. In particular, if $\forall i \pi_{ki} = 1$ for some $k$, then $\alpha$
drops out of the fourth term of that equation (i.e., $\frac{1}{n} \log (\sum_k \pi_{ki} w_{ki}^\alpha) = \log w_{ki}$)
and is thus identified solely off of nonlinearities. Finally, note that had we only had data on
choices, rather than on both choices and areas irrigated, the likelihood would involve only
the $\Pr(j|\Theta, Z_i)$. While predicted choice probabilities based on estimates of such a
likelihood would obviously match the empirical choice probabilities extremely closely,
identification of the full set of model parameters would be tenuous (e.g., $\gamma$ and $\bar{\kappa}_L$
could not be distinguished).

5 Results

5.1 Parameter estimates

Table 6 reports parameter estimates along with asymptotic standard errors. The estimates
appear reasonable. In particular, the curvature parameter $\alpha$ is considerably less than one,
whereas a value close to one would have implied little role for groundwater uncertainty. Our
estimate of buyer bargaining-power $\eta$ translates (cf., definition of $\delta$ in Table 5) into a 3.7%
efficiency loss due to holdup in the per-irrigation arrangement, which is an upper bound
on the overall contracting distortion. The incremental cost of cultivating leased land versus
own land, $\gamma$, is precisely estimated at less than 1%. So, evidently, the paucity of land-
lease activity in the data is driven by the high fixed transactions cost, $\kappa_L$, both in absolute
terms and relative to $\kappa_T$. Finally, as expected, we estimate $\beta > 0$, which says that fixed
transactions costs are higher in adjacencies with greater borewell density (i.e., those with
larger plot sizes). Thus, owners of borewells surrounded by plots with borewells of their own
have greater difficulty arranging water sales.

5.2 Within-sample fit

Table 7, column (2), reports mean predictions for the estimation sample, which can be
compared to the corresponding means of the data in column (1). As seen in the first row, on
average, the model predicts (log) total area irrigated by a borewell extremely well. Figure
Table 6: Parameter Estimates

| Parameter | Interpretation                                      | Estimate | Std. Error |
|-----------|-----------------------------------------------------|----------|------------|
| $\alpha$  | production function curvature                      | 0.218    | 0.003      |
| $\eta$    | buyer’s bargaining weight                          | 0.929    | 0.001      |
| $\gamma$  | leasing inefficiency                               | 0.008    | 0.0004     |
| $\kappa_L$| leasing transaction cost - intercept               | 0.105    | 0.009      |
| $\kappa_T$| selling transaction cost - intercept               | 0.012    | 0.0095     |
| $\beta$   | transaction cost - slope                            | 0.043    | 0.006      |
| $\lambda$ | effective borewell discharge                       | 0.367    | 0.034      |
| $\bar{c}$ | mean cultivation cost                              | 0.607    | 0.013      |
| $\sigma_c$| standard deviation cultivation cost                | 0.264    | 0.006      |

Notes: The maximized log-likelihood is -5599.7 on a sample of 1646 observations.

Figure 6: Irrigated area and groundwater supply uncertainty

Notes: Nonparametric regressions of actual and predicted log irrigated area on coefficient of variation of end-of-season flow.
Table 7: Model Predictions

|                      | Holdout Samples | Anantapur | E. Godavari | E. Godavari |
|----------------------|-----------------|-----------|-------------|-------------|
|                      | Est. sample     |           | Data        | Model       | Data        | Model       | ∆π         | ∆π, ∆R     |
|                      | (1)             | (2)       | (3)         | (4)         | (5)         | (6)         | (7)         | (8)         |
| log(I)               | 1.67            | 1.68      | 1.06        | 1.01        | 2.32        | 2.60        | 1.47        | 2.56        |
| Pr(U)                | 0.26            | 0.46      | 0.51        | 0.59        | 0.08        | 0.29        | 0.47        | 0.21        |
| Pr(A)                | 0.23            | 0.15      | 0.47        | 0.16        | 0.26        | 0.10        | 0.15        | 0.10        |
| Pr(L)                | 0.06            | 0.02      | 0.01        | 0.00        | 0.03        | 0.12        | 0.01        | 0.12        |
| Pr(P)                | 0.21            | 0.15      | 0.01        | 0.20        | 0.05        | 0.19        | 0.13        | 0.25        |
| Pr(C)                | 0.24            | 0.22      | 0.00        | 0.05        | 0.59        | 0.30        | 0.24        | 0.32        |

Notes: All figures are sample means. Log irrigated area, log(I), and choice probabilities, Pr(j), are simulated by drawing multiple values of ε for each borewell and then averaging optimal choices. Column (7) reports mean predictions when each borewell in the E. Godavari sample is assigned well-flow state probabilities (π_κ) drawn at random from the Anantapur sample. Column (8) is the same as column (7) except that the E. Godavari sample is also assigned pipe widths (R_i) drawn at random from the Anantapur sample.

shows that the model also reproduces, more or less faithfully, the bivariate relationship between area irrigated (relative to borewell plot area) and the coefficient of variation of groundwater supply.

Comparing the remainder of columns (1) and (2) of Table shows that the model is quite successful at predicting choices of transfer arrangements (L, C, and P), but far less so when it comes to unconstrained self-cultivation (U) versus autarky (A). While the latter result may not seem encouraging, it must be emphasized that our model is extremely parsimonious. Moreover, as alluded to earlier, we are not only estimating choice probabilities. Indeed, it is remarkable that our likelihood, which recruits parameters such as ̄c, λ, and α to fit the mean (and variance) of irrigated area without the benefit of any free constant terms (or fixed effects), ends up fitting choices as well as it does. That said, our model is, of course, not an exact description of reality.
5.3 Out-of-sample fit

Also in Table 7, we report predictions based on estimation sample parameters for borewells in the holdout districts of Anantapur (column 4) and East Godavari (column 6). In Anantapur, the gap between mean irrigated area predicted by the model and that found in the data is an astonishingly narrow 5%, whereas the corresponding deviation in E. Godavari is 28%. Similarly, the model does somewhat better in capturing choices in Anantapur than in E. Godavari, especially with respect to unconstrained cultivation ($U$). In both districts, however, the model greatly over-predicts the prevalence of the per-irrigation arrangement and, in E. Godavari, the prevalence of leasing. Thus, as was the case within sample, the model seems to predict irrigated area better than it predicts choices out of sample.

Importantly, the model nicely captures the contraction of area irrigated per borewell and the concomitant collapse of the seasonal contract as we move from E. Godavari to Anantapur and both groundwater scarcity and supply uncertainty increase. To disentangle which of these changes—i.e., that of the first or second moment—is driving the result, we perform two comparative statics exercises reported, respectively, in columns (7) and (8) of Table 7. In the first, for each borewell in Anantapur, we replace the vector of subjective probabilities ($\pi_{0i},...,\pi_{4i}$) with a corresponding vector drawn at random (with replacement) from the E. Godavari sample. This change alone raises the predicted prevalence of seasonal contracts by 19 percentage points (from 0.05 to 0.24) and predicted area irrigated by 46% ($= 1.47 - 1.01$). In the second exercise, we draw pipe-widths in addition to the $\pi_{ki}$ vector from the E. Godavari sample. Endowing borewells in Anantapur with the first moments of E. Godavari increases predicted area irrigated by an additional 109% ($= 2.56 - 1.47$), while the prevalence of seasonal contracts rises by just 8 percentage points. In sum, regional variation in contract type, as seen through the lens of the model, is driven primarily by variation in uncertainty, which is to say by the second moment of groundwater supply, whereas variation in irrigated area is largely due to variation in the first moment.

6 Implications

6.1 Welfare

The structural model allows us to compare welfare and area irrigated under different counterfactuals. We first simulate baseline expected surplus $E[V_{j^*} - \kappa_{j^*}]$ for each borewell owner, where $j^*$ is the optimal water transfer arrangement chosen given a particular draw of $\varepsilon_i$. 
Next, to assess the respective magnitudes of the contracting distortion, the fixed transaction cost, and the cost of precautionary planting, we perform three counterfactual experiments in sequence: (1) Rebate the transaction cost associated with the optimal choice $\kappa_j^*$ back to the borewell owner; (2) Consolidate fragmented landholdings, which leads to the Pareto-efficient allocation with each borewell owner earning (expected) first-best surplus $E[V_U]$; (3) Consolidate land as in (2) while eliminating groundwater supply uncertainty, holding expected borewell discharge constant.\footnote{In this case, surplus is given by $E[V_U^0] = \alpha \bar{w}_i (\bar{c}/(1 - \alpha))^{1-1/\alpha} E^{(1-1/\alpha)\epsilon_i}$ (cf. Table 5).} We also simulate irrigated area under scenarios (2) and (3); irrigated area under (1) is identical to that of the baseline scenario because we are not allowing choices to adjust.

Figure 7 plots the percentage changes (relative to baseline) in surplus (left panel) and in area irrigated (right panel) of each counterfactual against borewell plot area. Beginning with scenario (1), borewell owners with smaller plots, ceteris paribus, are more likely to sell groundwater and hence incur proportionally greater transaction cost than those with large plots. The difference between the dashed consolidation line and the transaction cost rebate line indicates the size of the uncertainty-induced contracting distortion; it averages about

Notes: Nonparametric regressions of predicted log changes in welfare (left panel) and irrigated area (right panel) on borewell plot area.
1.5% of the total *rabi* surplus generated by the borewell, similar in magnitude to the average fixed transaction cost of 1.8%. For the same reason as before, the contracting distortion is greater for borewell owners with smaller plots. Interestingly, comparing the right and left panels of the figure, the impact of groundwater market frictions on area irrigated is, in percentage terms, roughly triple its impact on welfare.

Finally, shutting down uncertainty altogether by means of counterfactual scenario (3) results in modest gains in both welfare (in this case, more so for larger plots) and in area irrigated.\(^{34}\) Thus, in reference to the reduced form regressions in Table 2, our model suggests that groundwater market distortions are far more important than the precautionary planting motive in explaining the variation in irrigated area due to groundwater supply uncertainty.

### 6.2 Drip irrigation and land fragmentation

Based on agricultural experiments in India, water use efficiency is 2-3 times greater under drip than under flood irrigation (Narayananamoorthy 2006). Taking the conservative estimate of a doubling of irrigation efficiency, we use the model, through a doubling of the effective discharge parameter \(\lambda\), to simulate the gross return to drip adoption\(^{35}\)

\[
\Delta V^* = E[V_j^* - \kappa_j^* | 2\lambda] - E[V_j^* - \kappa_j^* | \lambda].
\]

Based on the four-district estimation sample, the average borewell owner would realize a 53% surplus gain by converting his plot to drip irrigation, with an interquartile range of 44-65%.

The interesting question, however, is how these gains are achieved, since the gross return reflects the full range of endogenous responses to increased irrigation efficiency, including more intensive cultivation of the borewell plot, increased water sales, and switches between alternative transfer arrangements. To gauge the nature and extent of these responses, Table 8 reports the predicted transition probabilities pre- to post-drip adoption. Thus, we see that of those starting in unconstrained self cultivation (\(U\)), 62% remain unconstrained post-drip, 13% move to autarky (\(A\)), meaning that they now fully cultivate their own plot, and 25% start selling water, virtually all under the seasonal contract (\(C\)). The most dramatic transition is, of course, from autarky, where virtually no one remains post-drip, to \(P\) and \(C\) (mostly the latter). Overall, the model predicts that the proportion of borewell owners

\(^{34}\) Indeed, since \(\log(V_j^0/U_j) = \log(\ell_j^0/\ell_U)\), the percentage gains are mathematically equivalent.

\(^{35}\) Equation (17) is a simplification for purposes of exposition. In practice, through suitable adjustments to \(\lambda\), we only allow for an increase in irrigation efficiency on the borewell plot area, not on the area of other plots that may be (or could be) irrigated by the borewell.
Table 8: PREDICTED CHOICE TRANSITION PROBABILITIES

| Pre-drip | Post-drip |  |  |  |  | All |
|---|---|---|---|---|---|---|
|  | U | A | L | P | C |  |
| U | 0.622 | 0.126 | 0.000 | 0.003 | 0.249 | 0.462 |
| A | 0.000 | 0.011 | 0.004 | 0.234 | 0.751 | 0.153 |
| L | 0.000 | 0.000 | 1.000 | 0.000 | 0.000 | 0.023 |
| P | 0.000 | 0.000 | 0.031 | 0.968 | 0.000 | 0.146 |
| C | 0.000 | 0.000 | 0.014 | 0.166 | 0.820 | 0.216 |
| All | 0.287 | 0.060 | 0.031 | 0.215 | 0.407 | 1.000 |

Notes: Computed using estimation sample.

selling water would rise from 36% to 62% upon adoption of drip irrigation.36

Given the evident importance of groundwater markets in farmers’ exploitation of drip irrigation, we next explore how land fragmentation, the driving force behind these markets, affects the benefits of drip adoption. To isolate the role of groundwater market frictions, we use the analog of equation (17) to compute $\Delta V_U$, the gross return to drip under the first-best (unconstrained) counterfactual. The ratio $\rho = \Delta V^*/\Delta V_U$ thus represents the surplus gain from drip adoption given frictions relative to the surplus gain absent frictions. The mean of $\rho$ in the estimation sample is 0.94; so, the distortions uncovered in this paper reduce the gross return to drip adoption by an average of 6% relative to first-best.

Looking beyond averages, Figure 8 shows that $\rho$ increases (toward unity) with borewell plot size. In other words, consistent with what we have already seen in Figure 7, groundwater market frictions are more salient on smaller plots. However, $\rho$ decreases with average adjacency plot size. Recall that adjacencies with larger plots have a higher borewell density (cf. Figure 3) and, in our model, have a higher fixed cost of groundwater transactions (because $\beta > 0$). As a result, farmers surrounded by larger plots (i.e., more borewells) would profit less, ceteris paribus, by switching to drip irrigation, and this is especially true when they themselves have a small plot. Paradoxically, fragmentation of neighboring land is conducive to drip adoption even as fragmentation of own land is detrimental to it.

36One caveat is that, as the effective supply of groundwater expands, the fixed cost of arranging a sale (difficulty of finding a buyer) may increase. Since this type of general equilibrium consideration lies outside of our model, we should think of the results in Table 8 as an upper bound on extensification via the market.
Notes: Average values of \( \rho \) (gross return to drip adoption normalized by first-best gross return) by quintiles of plot area \((a)\) and average adjacency plot area \((\bar{a})\).

7 Conclusion

We have developed a model of contracting under Hartian payoff uncertainty, which, in the spirit of transactions cost economics, features a tradeoff between ex-post and ex-ante inefficiency. Since long-term contracts are more protective of relationship-specific investment but less flexible than spot contracts, they are preferred in low uncertainty environments.

Structural estimation of the model against the backdrop of south India’s groundwater economy allows us to quantitatively evaluate the contracting distortion in a real-world setting. We find that contractual form is sensitive to the extent of payoff uncertainty in the direction implied by the theory. Indeed, cross-sectional variation in uncertainty accounts for most of the predicted (out-of-sample) regional difference in prevalence of long-term contracts. However, the welfare cost of constrained-efficient contracting turns out to be rather modest, even though the impact on irrigated area is substantial.

Our analysis also points to another significant source of inefficiency in groundwater markets. Due to uncoordinated borewell drilling, those with water to sell invariably have too few willing buyers. This coordination failure combined with the contracting distortion attenuates the return to drip irrigation. Thus, land fragmentation and groundwater supply uncertainty, together, may constrain adoption of water-saving technology in India.
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Appendix (not for publication)

A Proof of Proposition 2

We begin by proving that under any water-transfer arrangement economic surplus, $V_j(r)$ for $j = U, A, C, P$, strictly diminishes with mean-preserving increases in uncertainty $r$. But first, we paraphrase a result from Diamond and Stiglitz (1974, p. 340, fn. 8). For any twice continuously differentiable function $h(w)$

$$
\int h(w)\psi_r dw = \int h_{\omega w}(w)T(w, r)dw,
$$

(A.1)

where $\psi$ is a p.d.f., $\psi_r$ is its partial derivative with respect to $r$, and $T(w, r)$ is a nonnegative function defined in equation (5) of Diamond and Stiglitz (1974).

Lemma 1 If $g$ is strictly concave, then $V'_j(r) < 0$ for $j = U, A, C, P$.

Proof. (i) $V_U$: Differentiating definition 2 and using the envelope theorem yields

$$
V'_U(r) = \ell_U \int f(w/\ell_U)\psi_r dw < 0
$$

(A.2)

by (A.1) and the concavity of $f$.

(ii) $V_A$: Follows from (A.2) with $\ell_U$ replaced by $a$.

(iii) $V_C$: As noted in fn. 19, $V_C = aE \left[ f\left(\frac{w-\tau C}{a}\right) - c \right] + \ell_C \left[ f\left(\frac{\tau C}{\ell C}\right) - c \right]$. Differentiating with respect to $r$ and using the envelope theorem leads to an expression analogous to (A.2).

(iv) $V_P$: Given the discussion in fn. 19,

$$
V_P = aE \left[ f\left(\frac{w-\tau P}{a}\right) - c \right] + \ell_P \left[ f\left(\frac{\tau P}{\ell P}\right) - c \right]
$$

(A.3)

$$
= (a + \ell_P)E \left[ f\left(\frac{w}{a + \ell P}\right) - c \right],
$$

where the second line follows from the ex-post efficiency condition $f'(\frac{\tau P}{\ell P}) = f'(\frac{w-\tau P}{a})$. Dif-
ferentiating with respect to \( r \) in this case yields
\[
V'_P(r) = E \left[ g \left( \frac{w}{a + \ell_P} \right) - c \right] \frac{\partial \ell_P}{\partial r} + (a + \ell_P) \int f \left( \frac{w}{a + \ell_P} \right) \psi_r dw
\]
\[= c \left( \frac{1}{\eta} - 1 \right) \frac{\partial \ell_P}{\partial r} + (a + \ell_P) \int f \left( \frac{w}{a + \ell_P} \right) \psi_r dw,
\]
where the second line uses equation (A.1). In the case of the per-irrigation arrangement, a precise analog to Proposition 1 applies. Thus, given that \( g \) is concave, \( \partial \ell_P / \partial r < 0 \). The first term of (A.4) must, therefore, be negative and, using (A.1) again, the second term must also be negative.

**Proof of proposition 2:** (a) Proposition 1 implies that for sufficiently large \( r \), say \( r_U, \ell_U = a \) and, hence, \( V_U(r_U) = V_A(r_U) \). Recall that under perfect certainty, \( V_C(0) = V_U(0) > V_A(0) \). Given \( \tau_C(0) < w_L \) (see fn. [20] and lemma 1, \( V_C \) is continuously decreasing in \( r \) until it equals \( V_A \) at some \( r = r_C \). Now use equation (A.1) under perfect certainty to define \( \eta = c / g(w/a) \). For \( \eta \leq \eta_C, \ell_P = 0 \forall r \) and, consequently, \( V_P(r, \eta) = V_A(r) \forall r \) and, in particular, for \( r = 0 \). Define \( r_P(\eta) \) as the solution to
\[
V_P(r_P(\eta), \eta) = V_A(r_P(\eta)).
\]

Thus, clearly, \( r_P(\eta) = 0 \). Recall, also, that \( V_P(r, 1) = V_U(r) \forall r \), so \( r_P(1) = r_U \). To prove part (a), it is sufficient to show that \( r_P(\eta) \in (r_C, r_U) \) for some \( \eta \). This is so because \( V_P(0, \eta) < V_C(0) \) for all \( \eta < 1 \) and, therefore, by continuity, the functions \( V_C(r) \) and \( V_P(r, \eta) \) must cross at \( r^* < r_C \) if indeed \( r_P(\eta) > r_C \) (see figure 3).

Thus, it is sufficient to show that \( r'_P(\eta) > 0 \) so that as \( \eta \) is increased from \( \eta \) to \( 1 \) \( r_P(\eta) \) eventually exceeds \( r_C \). Differentiating equation (A.5) with respect to \( \eta \), substituting from equation (A.1), and rearranging gives
\[
c \left( \frac{1}{\eta} - 1 \right) \frac{\partial \ell_P}{\partial \eta} + \left[ \int h(w) \psi_r dw \right] r'_P(\eta) = 0 \tag{A.6}
\]
where \( h(w) = (a + \ell_P)f \left( \frac{w}{a + \ell_P} \right) - af \left( \frac{w}{a} \right) \). Since \( \partial \ell_P / \partial \eta < 0 \), and given (A.1), we have that \( \text{sign}(r'_P(\eta)) = -\text{sign}(h_{ww}(w)) \). Differentiating \( h(w) \) twice, we get
\[
h_{ww}(w) = \frac{1}{a + \ell_P} \left[ f'' \left( \frac{w}{a + \ell_P} \right) - \frac{a + \ell_P}{a} f'' \left( \frac{w}{a} \right) \right] \tag{A.7}
\]
A Taylor expansion around $\ell_P = 0$ gives $f''\left(\frac{w}{a+\ell_P}\right) \approx f''\left(\frac{w}{a}\right) - \frac{w\ell_P}{a^2} f'''\left(\frac{w}{a}\right)$. Substituting into equation $\text{(A.7)}$ and rearranging yields

$$h_{ww}(w) \approx \frac{-\ell_P}{a(a + \ell_P)} \left[f''\left(\frac{w}{a}\right) + \frac{w}{a} f'''\left(\frac{w}{a}\right)\right].$$ \hspace{1cm} \text{(A.8)}$$

Since the term in square brackets is just $-g''(w/a)$, the concavity of $g$ ensures that $h_{ww} < 0$ and hence that $r'_P(\eta) > 0$.

(b) Having just established that $r_P(\eta) > r_C$ for some $\eta \in (\eta, 1)$, it must be true that $V_P(r, \eta) > V_C(r)$ over the interval $(r^*(\eta), r_P(\eta))$. ■

### B  Groundwater in Andhra Pradesh

**Figure B.1: Water table fluctuations: 1998-2014**

**Notes:** Average depth to water table (meters below ground-level) from all state observation wells and rainfall (millimeters) by month (Source: Government of Andhra Pradesh, Groundwater Department, 2014, http://apsgwd.gov.in/swfFiles/reports/state/monitoring.pdf).
C Tests of frictionless groundwater markets

Here we test the two hypotheses implied by frictionless groundwater markets: that borewells are just as likely to be sunk on small plots as on large plots and that small plots are just as likely to be cultivated in the dry season as are large plots.

Our survey covers nearly 9600 plots, each of which either has a borewell itself or is adjacent to a plot that does and, thus, could in principle receive a transfer of groundwater. Panel (a) of Figure C.2 shows that borewells are actually much less likely on small plots than on large ones. One might think that a random allocation of borewells across space could generate such a pattern mechanically; larger plots would be more likely to have borewells insofar as they constitute the majority of farmland area. But this ignores the fact that well placement is determined by individual decision-makers at the plot-level. If we suppose, not unreasonably, that the probability of finding a viable groundwater source (i.e., an underground spring) is uniform across space and that each plot-owner makes the same number of drilling attempts, then the likelihood of observing a borewell under the null hypothesis should be equal across plots of different size.

To be sure, owners of small plots may also be less wealthy and thus unable to afford multiple drilling attempts, or any attempts at all for that matter (see, e.g., Fafchamps and Pender, 1997), so we need to control for wealth. To do so, we next focus only on the subset of plots whose owners possess at least one other plot; otherwise, plot area and total owned area are perfectly correlated. We then partial out the effect of wealth (as proxied by total landholdings) using dummies for each of the deciles of total landownership. The result, shown in panel (b) of Figure C.2 confirms that borewells are more likely on larger plots.

Returning to the full sample of plots, Figure C.3 also indicates that small plots are much more likely to be left fallow in the dry season than large plots. Taken together with the pattern of borewell placement, this evidence points strongly to frictions in groundwater markets.
Figure C.2: Presence of a borewell and area of plot

(a) Unconditional (all plots)

(b) Partialing out wealth (multi-plot farmers)

Notes: Nonparametric regression of borewell indicator on plot area. Panel (a) uses sample of 9584 plots that either have a borewell or are adjacent to a borewell plot. Panel (b) uses a subsample of 4544 plots whose owners possess at least one other plot. The solid curve replicates that of panel (a) on the smaller sample, whereas the short-dashed curve partials out 9 dummies for the deciles of total land area owned.
Figure C.3: Dry-season fallow and area of plot

Notes: Nonparametric regression of dry-season fallow indicator on plot area using sample of 9584 plots that either have a borewell or are adjacent to a borewell plot.

D Choice configurations
Table D1: Choice probability integration limits by configuration

| Configuration | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| CAU           | $(\infty, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU}]$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |     |
| CLAU          | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |
| CLCAU         | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |
| CLCPAU        | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| CLPCAU        | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| CPLAU         | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| CPLCAU        | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| CPAU          | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{PA})$ | $[\varepsilon_{PA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |
| CPCAU         | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |
| CPCLAU        | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| CPLAU         | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| CPLCAU        | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| LAU           | $(\infty, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |     |
| LCAU          | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |
| LCLAU         | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| LCPAU         | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |
| LPCAU         | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| LPCPLAU       | $(\infty, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| LPLAU         | $(\infty, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| LPLCAU        | $(\infty, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| PAU           | $(\infty, \varepsilon_{PA})$ | $[\varepsilon_{PA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |     |
| PCAU          | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CA})$ | $[\varepsilon_{CA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |
| PCLAU         | $(\infty, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{CL})$ | $[\varepsilon_{CL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |
| PCPAU         | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |
| PCPLAU        | $(\infty, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{CP})$ | $[\varepsilon_{CP}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |
| PLAU          | $(\infty, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |     |     |
| PLCAU         | $(\infty, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ |     |     |
| PLCLAU        | $(\infty, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{PL})$ | $[\varepsilon_{PL}, \varepsilon_{LA})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{LA}, \varepsilon_{AU})$ | $[\varepsilon_{AU}, \infty)$ |     |

Notes: See text for definitions of the $\varepsilon_{ij}$ (i subscript suppressed for convenience). Numerical superscripts refer to cases of a double value function crossing over the range of $\varepsilon_i$, with 1 being the threshold for the leftmost crossing and 2 being the threshold for the rightmost.