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Contracting under uncertainty: Groundwater in South India

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To quantify contracting distortions in a real-world market, we develop and structurally estimate a model of contracting under payoff uncertainty in the south Indian groundwater economy. Uncertainty arises from unpredictable fluctuations in groundwater supply during the agricultural dry season. Our model highlights the tradeoff between the ex post inefficiency of long-term contracts and the ex ante inefficiency of spot contracts. We use unique data on both payoff uncertainty and relationship-specific investment collected from a large sample of well-owners in Andhra Pradesh to estimate the model's parameters. Our estimates imply that spot contracts entail a 3% efficiency loss due to hold-up. Counterfactual simulations also reveal that the equilibrium contracting distortion reduces the overall gains from trade by about 4% and the seasonal income of the median borewell owner by 2%, with proportionally greater costs borne by smaller landowners.

Keywords. Hold-up, relationship-specific investment, subjective probabilities, structural estimation.

JEL classification. L14, Q15.

1. Introduction

Transactions cost economics (Williamson (1979) and Klein, Crawford, and Alchian (1978)) views the choice among alternative contractual forms as a trade-off between different types of distortions. Long-term contracts protect quasi-rents generated by relationship specific investments, but do so at a cost; in an uncertain environment, contractual rigidity results in resource misallocation. Short-term or spot contracts provide the flexibility to adjust to changing conditions, but lead to under-investment due to the lack of quasi-rent protection. Despite the centrality of such ex post and ex ante inefficiencies to contract theory, there is little evidence on their magnitude or impact on real-world

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markets.[1] Underlying this lacuna are the difficulties in quantifying the relevant uncertainty on the one hand and relationship-specific investments on the other. This paper uses unique data on both uncertainty and investments to structurally estimate the magnitude of contracting distortions.

Four salient features of the groundwater economy of south India make it an ideal laboratory for studying contracting costs. First, given high irrigation conveyance losses, groundwater sales transactions tend to be highly localized, typically involving bilateral-monopolistic contracts between, on the one side, the owner of a borewell—a machine-drilled, deep and narrow well, usually equipped with a submersible electric pump—and, on the other side, a cultivator of an adjacent plot of land (see Jacoby, Murgai, and Rehman (2004)). Second, during the dry season, agricultural production relies almost exclusively on borewell irrigation, the supply of which is, at least in part, unpredictable.[2] Third, planting involves an upfront and irreversible investment. 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. Fourth, bilateral transactions between well-owners and neighboring farmers take one of two simple forms: spot contracts, in which groundwater is sold on a per-irrigation basis throughout the season, and long-term contracts, in which the area irrigated (quantity) and price for the entire season are fixed ex ante.

In specifying the contracting environment, we draw together different strands of contract theory. In our model, spot contracts are fully state contingent, and thus ex post efficient, but, due to the classic hold-up problem emphasized in property rights theory (Grossman and Hart (1986) and Hart and Moore (1990)), they are ex ante inefficient. In particular, planting incentives of water-buyers are distorted; hold-up acts like a tax on irrigated area whose rate depends on ex post bargaining power (as in Grout (1984)). Long-term contracts are presumed to be immune from hold-up but lead to ex post inefficiency inasmuch as rigid adherence to prespecified quantities necessarily misallocates groundwater across farms once the state of nature is revealed. The assumption that long-term contracts deter hold-up 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.[3]

Our model yields the sharp prediction that as groundwater supply uncertainty increases, long-term contracts become more distorting, and hence more unattractive relative to spot arrangements. While we test this implication informally using data from a large sample of borewell owners across six districts of Andhra Pradesh and Telangana

[1]Property rights theory (Grossman and Hart (1986), Hart and Moore (1990)) focuses on ex ante inefficiency (hold-up) and has seen a resurgence in recent theories of trade (Antràs (2005) and Antrààs and Helpman (2004)) and technology adoption (Acemoglu et al. (2007)). Reference point contract theory (Hart and Moore (2008) and Hart (2009)) eschews relationship-specific investment to focus on ex post inefficiency. Transactions cost economics, as noted, considers both quasi-rent appropriation and uncertainty.

[2]During the wet (*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.

[3]In property rights theory, by contrast, 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.

states, the key contribution of the paper lies rather in quantifying the equilibrium contracting distortion. A 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. Moreover, we observe area planted by each party and the portion of the buyer's area irrigated by the seller's borewell. Last but not least, we have collected a direct measure of payoff uncertainty, eliciting from each borewell owner a subjective probability distribution of their well's discharge near the end of the season conditional on its initial discharge. Using these data, we construct and maximize a likelihood function 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 that incorporates all of the restrictions of our theoretical model. The structural parameters are identified principally from the variation across borewells in the conditional probability distribution of groundwater supply.[4]

Our estimates allow us to compare actual contractual arrangements against the first-best counterfactual to determine the size of the distortion in terms of foregone gains from trade in the groundwater market. In doing so, we distinguish between the contracting distortion and other market frictions. In particular, once all neighboring farmers have borewells of their own, there will be limited scope for groundwater trade. A social planner, in this case, would rather 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 making groundwater transactions independent of the type of contract chosen. Our counterfactual analysis then allows us to decompose the total distortion into the part due to contracting per se and the part due to such transactions costs.

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 deliberately choosing "a [holdout] sample that differs significantly from the estimation sample along the policy dimension that the model is meant to forecast (p. 1352)." In our setting, the policy regime "well outside the support of the data" is the large difference in first and second moments of groundwater supply between estimation and holdout districts.

No existing study, to our knowledge, has quantified the welfare cost of hold-up in an actual market. There is, however, a considerable empirical literature within the transactions cost economics tradition investigating how contractual terms adapt to particular economic environments (see Lafontaine and Slade (2012) for a comprehensive review). Closest in spirit to the present paper is Crocker and Masten's (1988) study of US natural gas contracts under demand uncertainty. In their model (as in ours), greater uncertainty raises the cost of long-term contracting relative to spot contracting or "bargaining"; but, spot-contracting is not an actual choice in their data nor in their model (as it is in ours), and the inefficiency associated with it is exogenous rather than arising endogenously

[4]This paper is the first contract-theoretical application that we are aware of incorporating subjective probabilities (see Attanasio (2009) and Delavande, Giné, and McKenzie (2011) for reviews of related work in other areas of economics).

from underinvestment. Last and most crucial, Crocker and Masten tested the qualitative implications of their model in "reduced form" specifications using proxy variables to measure uncertainty (similarly, see Crocker and Reynolds (1993)). Thus, in contrast to our structural estimation, their approach does not deliver the *magnitude* of the contracting distortion.

The next section of the paper describes the setting and data for the study. Section 3 then lays out the formal theoretical arguments. Section 4 adapts the theoretical model for the purposes of structural estimation and derives the likelihood function. Estimation results are reported in Section 5 along with within and out-of-sample fit diagnostics. Section 6 presents the welfare analysis of contracting distortions and Section 7 concludes the paper.

2. Context and data

India is by far the world's largest user of groundwater, the vast majority of it for agriculture (World Bank (2005)). As the costs of drilling and of submersible electric pumpsets have fallen in recent decades, there has been an explosion of borewell investment (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 (Jacoby (2017)). Due to the high degree of land fragmentation, groundwater markets are pervasive in India. The 2011–2012 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). This figure undoubtedly underestimates the extent of the groundwater market in India, as even borewell owners may buy irrigation for some of their plots.

2.1 *Groundwater markets survey*

Our data come from a survey of 2304 randomly chosen borewell owners undertaken in 2012 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.[5] Drought-prone Anantapur and Mahbubnagar districts were originally selected as part of a weather-index insurance experiment (Cole, Giné, Tobacman, Topalova, Townsend, and Vickery (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 2414 borewells (108 owners had multiple borewells on their reference plot) in 144 villages (21–25 per district).

[5]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).

To capture transfers of groundwater, which typically occur between neighboring plots so as to minimize conveyance losses,[6] each respondent (borewell owner) was 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, 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.

2.2 *Borewells, recharge and uncertainty*

As in much of India, farmers in AP rely almost exclusively on groundwater during the *rabi* (winter or dry) season, when rainfall is minimal and surface irrigation is typically unavailable. Since property rights to groundwater are not clearly delineated in India, there is no legal limit on withdrawals. Upon striking an underground spring, farmers install the widest feasible pipe consistent with the expected outflow. Likewise, because electricity is provided for free at the margin, farmers run their pumps for the maximum number of hours that power is available on any given day (about 5.5 hours at the time of our survey). Aside from pipe-width and electricity constraints, the yield of the well depends on the availability of groundwater in the aquifer at any given time and on the local hydrogeology.

Despite a massive increase in borewell numbers, the time-series of depth to watertable across AP in the last decade and a half is dominated by *intra*-annual variability (see Figure 1). This pattern 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 *rabi* season. In contrast to the alluvial aquifers of northwest India, there are no deep groundwater reserves to mine (see Fishman, Siegfried, Raj, Modi, and Lall (2011)).

This annual cycle of aquifer replenishment and draw-down is central to our contracting environment. Although farmers can observe monsoon rainfall along with their own borewell's discharge prior to *rabi* planting, the precise amount of groundwater stored beneath them is unknowable; in other words, while they can form a forecast of groundwater availability over the course of the season, the forecast is necessarily imperfect. 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 *start* of (any) *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).[7] Next, using the same format, we asked about the probability distribution of end-of-season flow *conditional* on the

[6]Most irrigation water is transferred through unlined field channels with high seepage rates. While our survey also picked up a number of transfers to nonadjacent plots using PVC pipe, usually these cases involved sharing of groundwater between well co-owners or between multiple plots of the same owner.

[7]The flow assessment is based solely on the amount of water that comes out of the ground when the farmer turns on the pump at that point in the season, regardless of whose land or how much land the borewell irrigates. 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. Farmers appear to understand

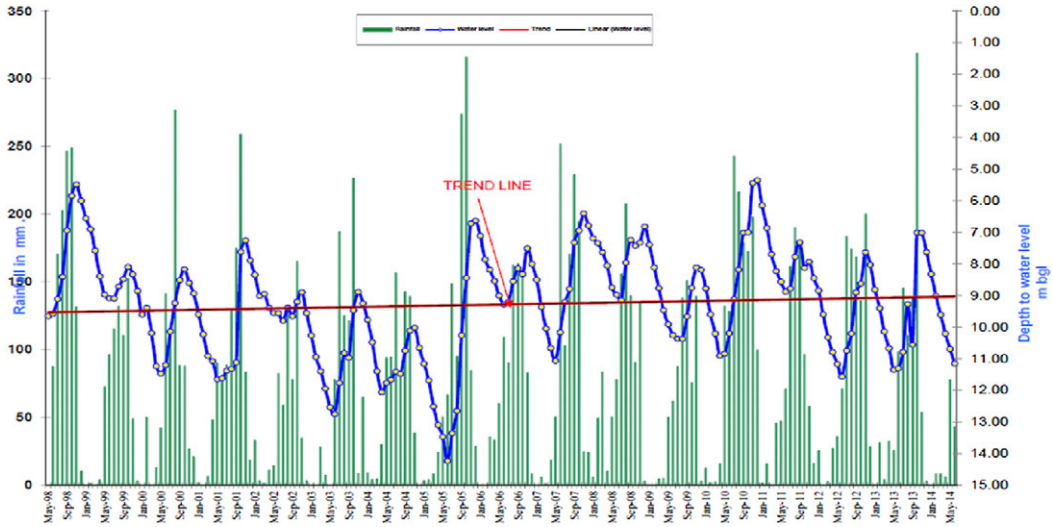


FIGURE 1. Water table fluctuations: 1998–2014. *Notes*: Average depth to water table (meters below ground-level) from all state observation wells and rainfall (millimeters) by month (Source: Government of Andhra Pradesh, Groundwater Department, 2014, http://apsgwd.gov.in/swfFiles/reports/state/monitoring.pdf).

most probable start-of-season flow. Thus, the question was designed to elicit *residual* uncertainty (i.e., conditional on monsoon rainfall, etc.) about groundwater availability.

Using these data, with $\pi_{si} = \Pr(\text{late flow of borewell } i = s/4 | \text{typical early flow})$, where $s = 0, \ldots, 4$, we compute borewell-specific coefficients of variation as follows:

$$\mathrm{CV}_i = \frac{\sqrt{\sum_s \pi_{si}(s/4)^2 - \left(\sum_s \pi_{si} s/4\right)^2}}{\sum_s \pi_{si} s/4}. \tag{1}$$

The bottom left panel of Figure 2 shows substantial variability in late-season groundwater uncertainty in the overall sample. Notice that virtually no borewell owner (save five) report having a perfectly certain supply of groundwater.

2.3 *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

how fractional discharge translates into irrigation capacity without a problem. When asked to estimate how much area could be irrigated in a day with a typical borewell (3-inch pipe width) with full flow, 3/4 flow, and half-flow, focus groups gave median responses of 3.5, 2.5, and 1.5 acres, respectively. The ratios of these acreages closely corresponds to the ratios of discharges.

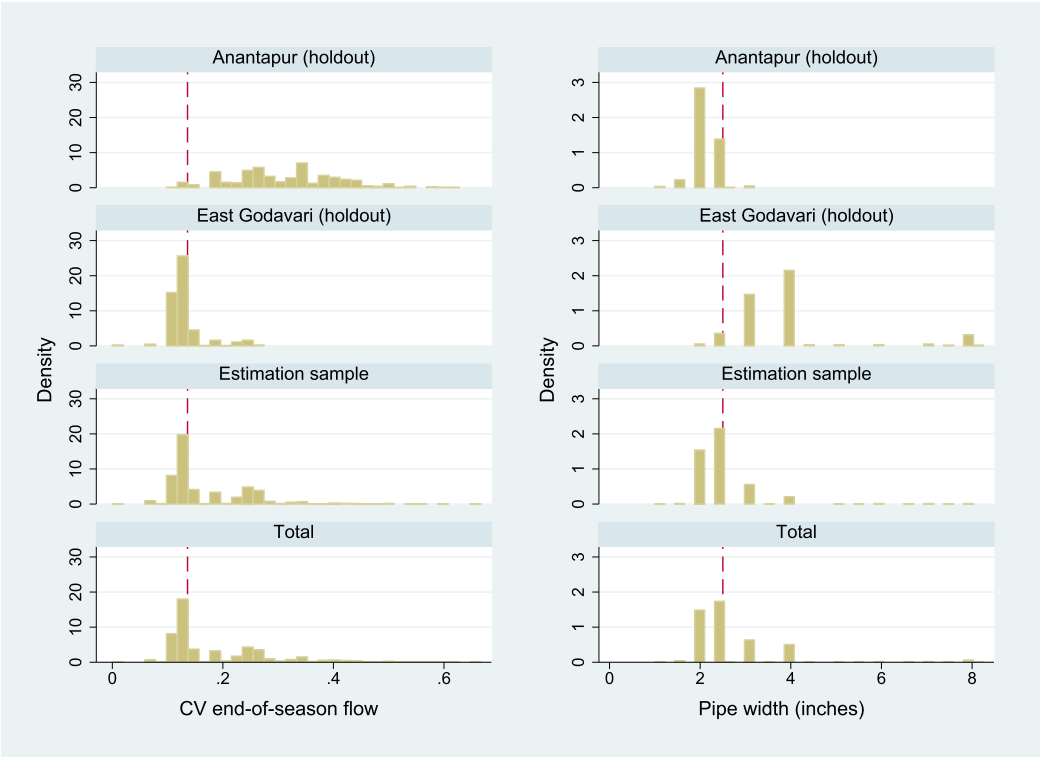


FIGURE 2. Distribution of groundwater supply uncertainty and pipe width. *Notes*: Histograms in the left column are for the coefficient of variation of end-of-season flow (see equation (1)) for four different samples of borewells: Anantapur district, East Godavari district, the four-district estimation sample, and the full sample. Histograms in the right column are for borewell pipe-width in inches for the same four samples. Dashed vertical lines represent medians for the full sample.

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% of plots were acquired through inheritance.

When we aggregate 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, which reflects the fact that borewells are much less likely to be installed on small plots (see the Online Supplementary Material, Giné and Jacoby (2020), Appendix B). 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 finding in our discussion of the econometric model.

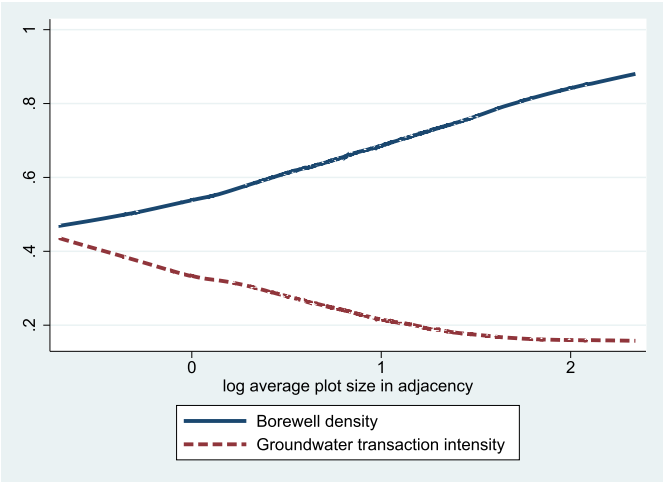


FIGURE 3. Effects of average plot size in adjacency. *Notes*: Nonparametric regressions of borewell density and groundwater transactions per plot, respectively, on log average plot size for all 2306 reference borewell plot adjacencies.

2.4 *Groundwater sales contracts*

Extensive fieldwork in the study areas prior to drafting the Groundwater Markets Survey revealed two dominant contractual arrangements for selling groundwater: A "seasonal" or long-term contract, characterized by a lump-sum sale of irrigation for an entire crop-season—that is, a fixed number of complete waterings—and a spot contract or "per-irrigation" sale. Table 1 summarizes the contracts data, collected by reference borewell (seller), adjacent plot (buyer), and crop. Roughly two-thirds of the 1509 contracts are seasonal (979 contracts) versus 530 contracts that are per-irrigation. In *rabi* season, south Indian farmers grow so-called "wet" crops (in our six districts, principally paddy, banana, sugarcane, and mulberry) and irrigated-dry or ID crops (e.g., groundnut, maize, cotton, chilies), distinguished by the much greater water requirements per unit area of the former. Nearly 70% of seasonal and virtually all per-irrigation contracts are

TABLE 1. Characteristics of groundwater sales contracts.

	Seasonal	Per-irrigation
Number of contracts	979	530
% Irrigated dry crop (vs. wet crop)	69.8	97.4
% Output share as payment in lieu of cash	0.3	–
% Arrangement carried out as agreed	99.9	–
% Same borewell w/multiple buyers	49.5	34.7
% Same borewell used other contract type	3.7	5.7
% Same borewell used other contract w/same buyer	0.6	0.8

Note: Based on 1509 groundwater sales contracts at level of borewell (seller), adjacent plot (buyer), and crop.

for ID crops; in other words, most groundwater sales for wet crops are under seasonal contracts.

While per-irrigation contracts are, by definition, cash sales, for seasonal contracts, we asked whether payment was in the form of a crop output share. Crop-sharing is interesting because it effectively makes the price of groundwater contingent on the available supply. Nevertheless, it is virtually nonexistent in our data. Table 1 also shows that reneging on the agreed price or terminating the seasonal contract ex post is exceedingly rare, a feature that we emphasize in the next section. Not uncommon is for the same borewell owner to sell water to multiple neighbors. To retain tractability of the structural model, we aggregate the area irrigated by a selling borewell across the corresponding buyers. Seldomly, the same borewell owner offers both types of contracts, but nearly always to different buyers. Although we could extend the model to handle such mixed contracts, they are sufficiently rare in the data that we instead simply assign one contract type to each borewell according to which arrangement accounts for the most cropped area.

Aside from groundwater selling, an alternative avenue for an owner to exploit his borewell is to lease, or even ultimately purchase, adjacent land. While seasonal leasing contracts do occur in our sample, as discussed below, they are not common. Evidently, arranging adjacent leases, let alone land purchases (which are generally rare in south India), involves significant transactions costs.

3. Theory

3.1 *Preliminaries*

The environment described in the last section motivates the following assumptions:

(A.1) *Fragmentation:* Agricultural production occurs on discrete plots of land of area a, each owned by a distinct individual and some having borewells.

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

We make three additional assumptions for the sake of tractability:

(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 ω is irrigation intensity and the intensive production function, f, is increasing, concave, with $f(0) = 0$.

Aside from its technical convenience, constant returns to scale (CRS) is consistent with the observation that well-owners virtually never simultaneously sell water and leave their own plot partially fallow. The CRS hypothesis can also not be rejected in a production function estimation detailed in the Online Supplemental Material in Appendix C of Giné and Jacoby (2020). 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.

While (A.4) is a standard modeling assumption in the contracts literature, here the concavity of the production function in (A.3) provides a rationale, independent of risk aversion, for why uncertainty is undesirable.

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

Thus, for example, if all the land that the well-owner could *potentially* irrigate—that is, all the adjacent plots—already have borewells of their own providing adequate irrigation, then there may be little or no *demand* for purchased groundwater. Assumption (A.5) rules out such a scenario of constrained demand. While this assumption simplifies the theoretical analysis, in the empirical implementation, we do allow the borewell density in the adjacency to influence the likelihood of a groundwater transaction.

Now consider a well-owner's choice of area cultivated (irrigated) when his own plot size is not a constraint. Let $\ell_U = \arg\max l\{Ef(w/l) - c\}$ be the unconstrained (U) irrigated area and define the marginal return as the following.

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

The necessary condition for optimal planting

$$\mathrm{E}g(\omega) = c \tag{2}$$

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

Let r index mean preserving increases in groundwater supply uncertainty. We have the following.

Proposition 1. *If g is strictly concave, then $\partial \ell_U / \partial r < 0$.*[8]

Note that g is concave if and only if the production function analog to Kimball's (1990) coefficient of relative prudence, $-\omega f'''/f''$, is greater than unity. Under this condition, which does *not* characterize the quadratic production function, for example, well-owners exhibit a precautionary planting motive, limiting their exposure to increases in supply uncertainty by committing less area to irrigation.

The surplus generated by a borewell under unconstrained self-cultivation (U) is the following.

Definition 2. $V_U = \ell_U E[f(w/\ell_U) - c]$.

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 2 as an organizing framework.

[8] *Proof*: Follows directly from Theorem 1 of Diamond and Stiglitz (1974).

[9] To see why, let subscripts b and s denote water-buyer and seller, respectively. Further, let p be the spot price and ℓ_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

TABLE 2. Model decisions.

Contract type	Moniker	Timing: Ex ante	Timing: Ex post
Long term	Seasonal (C)	p, τ, ℓ surplus divided	–
Spot	Per-irrigation (P)	ℓ surplus divided	p, τ

Note: p is the price per unit of irrigation, τ is the total transfer of groundwater, and ℓ is area irrigated by the buyer.

3.2 *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 stark relief, we assume that these deadweight losses make hold-up prohibitively costly. The evidence presented in Table 1 indicates that renegotiation of seasonal contracts is indeed 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 such as planting inputs in our context; second, water allocations under the contract are unresponsive to the state of the world.

Let τ 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

$$\begin{aligned}
&\max_{p,l} a\left\{Ef\left(\frac{w-\tau}{a}\right)-c\right\}+p\tau \quad \text{s.t.}\\
&PC: l\left\{f\left(\frac{\tau}{l}\right)-c\right\}-p\tau \geq 0,\\
&IC: \tau = \underset{\tau\in[0,w_L)}{\arg\max} l\left\{f\left(\frac{\tau}{l}\right)-c\right\}-p\tau. \qquad (3)
\end{aligned}$$

implies that $\omega_b = \omega_s$. Thus, $V_U = E[a(f(\omega_s)-c)+p\omega_b\ell_b] = E[a(f(\omega_s)-c)+f'(\omega_b)\omega_b\ell_b] = E[a(f(\omega_s)-c)+\ell_b(f(\omega_b)-c)] = E[(a+\ell_b)(f(\omega_s)-c)]$, where the penultimate expression follows from $\mathrm{E}g(\omega_b)=c$, 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 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) motivated the inefficiency of contract renegotiation using the notion of loss aversion.

[11]While there may exist states of the world in which the seller would renege, our argument here is that such states occur with sufficiently low probability that they can be safely ignored.

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 τ 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.

Given a binding *PC*, the necessary conditions for the optimal contract are as follows:

$$\begin{aligned} Ef'\left(\frac{w-\tau}{a}\right) &= p, \\ g\left(\frac{\tau}{l}\right) &= c, \\ f'\left(\frac{\tau}{l}\right) &= p, \end{aligned} \tag{4}$$

the solution to which is the water transfer-area pair (τ_C, ℓ_C). Divergence of supply and demand for irrigation ex post creates a distortion. Since (3) implies $Ef'(\frac{w-\tau_C}{a}) = f'(\frac{\tau_C}{\ell_C})$, it is *not* true, in general, that $f'(\frac{w-\tau_C}{a}) = f'(\frac{\tau_C}{\ell_C})\ \forall w$, which would obtain if τ were state-contingent, as in a competitive spot market (see footnote 9). It follows as a corollary that the distortion vanishes as uncertainty goes to zero, in which case $g(\frac{\tau_C}{\ell_C}) = g(\frac{w}{\ell_C+a}) = c = g(\frac{w}{\ell_U})$ 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; that is, the long-term contract would achieve the first-best.

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

3.3 *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

[12]Without 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; that is, the well-owner always fully cultivates his land before selling any groundwater. *Proof*: Suppose not, then the optimal choice of l_s requires $\mathrm{E}g(\frac{w-\tau}{l_s}) = c$. However, equation (2) $\Rightarrow \mathrm{E}g(\frac{w}{l_U}) = c \Rightarrow \tau = w(1 - l_s/l_U)$, which is a contradiction because τ cannot be state-contingent.

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 2) 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.

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

Invoking the Nash algorithm, so that $p^* = \arg\max(u-\underline{u})^{\eta}(v-\underline{v})^{1-\eta}$, where η is the buyer's bargaining weight,[13] p^* solves

$$\begin{aligned} \eta(v-\underline{v}) - (1-\eta)(u-\underline{u}) &= 0, \\ \eta a\left[\frac{f\left(\dfrac{w-\widehat{\tau}-\Delta}{a}\right) - f\left(\dfrac{w-\widehat{\tau}}{a}\right)}{\Delta}\right] - (1-\eta)l\left[\frac{f\left(\dfrac{\widehat{\tau}+\Delta}{l}\right) - f\left(\dfrac{\widehat{\tau}}{l}\right)}{\Delta}\right] + p &= 0, \\ -\eta f'\left(\frac{w-\tau}{a}\right) - (1-\eta)f'\left(\frac{\tau}{l}\right) + p &= 0, \end{aligned} \tag{5}$$

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

$$p^*(\widehat{\tau}) = (1-\eta)f'\left(\frac{\widehat{\tau}}{l}\right) + \eta f'\left(\frac{w-\widehat{\tau}}{a}\right). \tag{6}$$

Furthermore, once $f'(\frac{\tau}{l}) - p^*(\tau) = \eta[f'(\frac{\tau}{l}) - f'(\frac{w-\tau}{a})] = 0$, the buyer's demand for irrigation is sated. Thus, the total transfer τ must satisfy $f'(\frac{\tau}{l}) = f'(\frac{w-\tau}{a})$, 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 expected returns given price function p^* and the total transfer τ. In particular,

$$\ell_P = \arg\max_{l} E\left\{lf\left(\frac{\tau}{l}\right) - \int_0^{\tau} p^*(t)\,dt\right\} - cl. \tag{7}$$

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

[13]As a referee rightly points out, the Nash product, with or without exponents, is a shortcut meant to approximate in a static framework the solution to a dynamic bargaining game. In this context, Binmore, Rubinstein, and Wolinsky (1986) discussed alternative interpretations of the exponents or "bargaining weights."

a different cost. From (6), $\int_0^\tau p^*(t)\,dt = (1-\eta)lf(\frac{\tau}{l}) + \eta a[f(\frac{w-\tau}{a}) - f(\frac{w}{a})]$, 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

$$\eta Eg(\tau/l) = c. \tag{8}$$

Comparing equations (8) and (2), we see that they differ by the factor η. 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.[14] Thus, a 50–50 ex post surplus split in the spot arrangement, for instance, would imply a halving of the water buyer's marginal returns to planting. In sum, 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): anticipating ex post rent appropriation, the buyer underinvests ($\ell_P < \ell_U - a$).

We close our discussion of spot contracts with three remarks about the bargaining power parameter η. First, ex post surplus, to which this parameter refers, is distinct from ex ante surplus in that the former does not account for (sunk) cultivation costs. Having some degree of ex post bargaining power ($\eta > 0$) is, therefore, consistent with the assumption that the water buyer is held to his *PC* in the long-term contract. Second, bargaining power may vary with the number of local borewells that could potentially offer groundwater for sale on a spot basis; but note that merely having other borewells nearby does not guarantee competition once the season is underway. Moreover, in a multiborewell scenario, η would depend, not only on the relative number of buyers and sellers, but also, critically, on the link structure of the trading network (see Corominas-Bosch (2004) and Charness, Corominas-Bosch, and Frechette (2007) on bilateral bargaining in networks).[15] Third, to the extent that competition between sellers does raise η, this same force may also raise buyers' share of *ex ante* surplus in the seasonal contract. Be that as it may, water allocations, and hence, distortion under the seasonal contract would not be affected because these are independent of surplus division.

3.4 *Characterizing the tradeoff*

We have 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 (see the Appendix for a formal statement and proof) regarding the desirability of long-term over spot contracts as uncertainty, indexed by mean preserving spread r, increases.

[14]As before, the borewell owner fully cultivates his own plot before selling any groundwater (i.e., $l_s = a$). *Proof*: Suppose not, then $\mathrm{Eg}(\frac{w-\tau_P}{l_s}) = c$ is necessary. However, equation (8) and $f'(\frac{\tau_P}{l_P}) = f'(\frac{w-\tau_P}{l_s}) \Rightarrow \mathrm{Eg}(\frac{\tau_P}{\ell_P}) = \mathrm{Eg}(\frac{w-\tau_P}{l_s}) = c/\eta$, which is a contradiction.

[15]Observing these networks in practice would involve mapping essentially every plot and borewell in a village, which we could not feasibly do in a sample survey. Our data suggest, however, that local groundwater markets are thin; the median number of *other* (aside from reference) borewells within an adjacency is 1 and the mean is 1.5.

Proposition 2. *If g is strictly concave, then there can be a level of uncertainty r^* at which the parties are indifferent between long-term and spot contracts. If so, then the long-term contract dominates for $r < r^*$ and the spot contract dominates for $r > r^*$.*

Thus, all else equal, in environments of higher groundwater uncertainty, we should see a higher prevalence of the per-irrigation arrangement relative to the seasonal contract.

4. Empirical framework

4.1 *Samples and descriptive statistics*

Our subsequent analysis uses 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 is used to estimate the parameters of the structural econometric model as described below. Borewells from the remaining districts 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 wettest and most 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.

Descriptive statistics on 7293 adjacent plots by subsample, shown in Table 3, provide insights into the nature of groundwater transfers. Overall, a third of adjacent plots are irrigated in whole or in part by the reference borewell. However, this figure falls to just 16% in the holdout district of Anantapur, where the limited groundwater transfers that do occur are mostly through well co-ownership, especially common among brothers.[16] Commensurately, *rabi* season fallow is pervasive in Anantapur. In the other holdout district, East Godavari, the situation is reversed, with more groundwater sales activity and much less fallow. Finally, while nearly half of adjacent plots rely in whole or in part on own wells, this is true for only 10% of plots using purchased groundwater (most of which are in the estimation sample).

Table 4 provides descriptive statistics for the estimation and holdout samples according to the groundwater transfer choices made by the borewell owner.[17] 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 being far less prevalent. The two holdout samples show

[16]Since 86% of groundwater sales are to nonrelatives, hold-up concerns are not *prima facie* misplaced.

[17]In the 108 cases of the reference plot having multiple borewells, we allocate total adjacency area 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 3. Characteristics of adjacent plots by subsample.

		Holdout Samples		
	Estimation	Anantapur	E. Godavari	Total
Mean no. of plots per *adjacency*	3.46	3.64	3.25	3.45
Mean plot area (acres)	3.16	2.59	3.20	3.04
% plots left fallow in *rabi*	11	40	2	14
% plots irrigated in *rabi* by				
• own borewell	48	43	41	46
• reference borewell	34	16	46	33
of which, % irrigated under				
–joint ownership	31	96	17	33
–land lease	7	2	4	6
–groundwater sale	62	2	80	62
of which, % also irrigated by own borewell	14	0	1	10
• other borewell	12	1	13	10
% plots 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

TABLE 4. Descriptive statistics by subsample.

				Holdout Samples					
	Estimation			Anantapur			E. Godavari		
Choice j	N	ℓ_j	a	N	ℓ_j	a	N	ℓ_j	a
U = unconstrained	436	5.10	10.93	184	3.20	6.75	31	10.25	17.02
	[0.26]	(3.89)	(8.10)	[0.51]	(2.55)	(4.78)	[0.08]	(7.19)	(10.39)
A = autarky	382	–	6.27	170	–	3.82	101	–	13.11
	[0.23]		(4.07)	[0.47]		(2.40)	[0.25]		(27.34)
L = leasing	91	2.45	4.43	5	0.90	3.31	12	6.78	6.56
	[0.06]	(2.43)	(3.07)	[0.01]	(0.60)	(2.09)	[0.03]	(7.56)	(3.19)
C = seasonal contract	400	2.80	5.33	1	1	2.00	242	3.60	7.28
	[0.24]	(2.47)	(3.95)	[0.00]	–	–	[0.60]	(3.06)	(10.18)
P = per-irrigation sale	337	1.77	4.25	2	1.87	2.00	20	3.25	4.53
	[0.20]	(1.48)	(2.65)	[0.01]	(1.23)	(1.41)	[0.05]	(2.21)	(3.82)
Total borewells	1646			362			406		
Groundwater market area ÷ total irrigated area	0.18			0.01			0.22		

Note: Sample means (standard deviations) [proportions]. Note that $\ell_U < a$, by definition, where ℓ_U is equivalent to total area irrigated by the borewell and a in this case is borewell plot area that is potentially irrigable. For $j = L, C, P$, total area irrigated by the borewell is $\ell_j + a$, where a is area irrigated and cultivated by the borewell owner (seller), ℓ_L, is area leased and cultivated by the borewell owner, and ℓ_j for $j = C, P$ is area irrigated by the borewell but owned and cultivated by the buyer. All areas are in ID equivalent acres. Final row reports sample-level fraction of irrigated area involving market transactions (inclusive of leasing).

starkly different patterns. 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 there than in the estimation sample districts, what is particularly striking is the large proportion of seasonal contracts among sales in East Godavari.

Regarding irrigated areas (ℓ_j and a), we must account for differences in the water-intensity of wet and ID crops. 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 1 acre wet = $\frac{7}{3}$ acre ID to compute area irrigated by a borewell in ID equivalent acres.[18] In the estimation sample, Table 4 shows that, conditional on making a transfer, mean area irrigated is highest for the seasonal contract, followed by leasing and the per-irrigation arrangement. Lastly, note that groundwater market activity accounts for 18% of irrigated area in the estimation sample compared to 22% in East Godavari and only 1% in Anantapur.

4.2 *Evidence from contract choice*

The main implication of the theory is that spot contracts are more attractive than long-term contracts when uncertainty is high. In Table 5, we provide evidence on this hypothesis using data from the 1002 borewell owners (737 in the estimation sample) that sell groundwater. 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. This result is robust to controlling for characteristics of the borewell, of the reference plot containing the borewell, of the owner of the borewell, and of the adjacency surrounding the borewell, as well as to including *mandal* dummies.[19] Findings in the full sample (columns 1–4) are similar to those in the estimation sample (columns 5–8), which is not surprising inasmuch as there are only 22 P contracts in the two holdout districts combined.[20]

Other research emphasizes moral hazard and risk aversion as driving the form of agrarian contracts (see, e.g., Pandey (2004)) whereas here, as noted, we assume risk neutrality. Could the results in Table 5 also be consistent with a risk-sharing motive? Note that, from the water seller's perspective, it is not clear whether total income—the sum of

[18]The conversion from wet to ID crops was provided by K. P. C. Rao, an expert in semi-arid tropical agriculture and confirmed by farmers during data collection. To appreciate the simplification achieved by this efficiency units assumption, consider the implications of separate wet and ID crop technologies. In the first place, conditional on area choices of each crop type, farmers would presumably allocate groundwater ex post across crops in response to the realized w. This gives rise to one additional optimality condition *for each state of nature*. Second, there would be two cultivated area choices, and farmers are observed opting for mixed wet-ID cropping as well as for monoculture of either type. To rationalize the data, our empirical model would need two structural error terms (instead of just the one ultimately assumed) and would have to account for the two types of corner solutions in cropped area. Third, for any form of groundwater transfer, each cell of the 3×3 matrix of wet-ID-mixed cropping decisions of borewell owner and groundwater recipient would have to be compared to determine the optimal arrangement and the bivariate distribution of the structural error terms partitioned accordingly. As the composite-crop model already captures

TABLE 5. Logit estimates of contract choice.

	Full Sample				Estimation Sample			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
CV (marginal effect)	0.0642	0.0575	0.0588	0.0657	0.0798	0.0687	0.0702	0.0882
	(0.0260)	(0.0258)	(0.0256)	(0.0309)	(0.0329)	(0.0333)	(0.0332)	(0.0356)
Pseudo-R^2	0.079	0.104	0.121	0.111	0.038	0.058	0.072	0.078
Observations	1002	1002	1002	757	737	737	737	646
Controls:								
Borewell	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reference plot	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Owner/adjacency	No	No	Yes	Yes	No	No	Yes	Yes
Mandal dummies	No	No	No	Yes	No	No	No	Yes

Note: Standard errors of logit marginal effects in parentheses. Binary dependent variable is one if per-irrigation (spot) contract is chosen and zero otherwise. CV is the coefficient of variation of end-of-season well flow (normalized by the standard deviation of CV in the respective sample). Borewell controls: mean end-of-season well flow, mean start-of-season well flow, pump horse-power, log of well depth, dummy for presence of recharge source. Reference plot controls: log plot area, dummies for soil type, color, and degree of salinity. Borewell-owner/adjacency controls: age, education level dummies, forward caste dummy, log total land owned, number of plots in adjacency, log average adjacency plot area. Since logit estimation with *mandal* dummies drops *mandals* without variation in contract type, only 20 *mandals* contribute observations in the full sample and 16 in the estimation sample.

net crop revenue and groundwater sales revenue—is more or less variable under short-term or long-term contracts because variability in the two components of income move in *opposite* directions. Thus, a risk averse borewell owner facing higher uncertainty may or may not want to switch out of the seasonal contract and into the spot arrangement. By contrast, from the water buyer's perspective, the seasonal contract provides sure income—crop revenue net of cultivation and groundwater costs is constant—whereas income under the spot contract is uncertain. So, a risk averse water buyer facing higher uncertainty *would*, at the margin, want to switch out of the spot arrangement into a seasonal contract. A risk-sharing motive, therefore, implies that CV should have a *negative* coefficient in Table 5, which is the opposite of what we find.

While the results in Table 5 thus lend support to our theoretical mechanism, they do not account for selection into groundwater selling; in particular, our model suggests that when uncertainty is high groundwater sales are less likely.[21] Structural estimation, by contrast, fully accounts for selection into the alternative irrigation regimes and allows

the fundamental trade-off between ex ante and ex post efficiency, we believe that a dual-crop model offers little in the way of additional insight relative to this enormous increase in computational burden.

[19]Overall, there are 37 *mandals* (clusters of several villages) in our dataset. Only about 40% of the variation in CV is within *mandals*.

[20]In the Online Supplemental Material in Table D1 of Giné and Jacoby (2020), we show that the effect of CV on contract type is not driven by crop choice (which is arguably endogenous to contract choice). Controlling for the fraction of borewell irrigated area under wet crops slightly *increases* the magnitude and precision of the estimated marginal effects for CV.

[21]This conjecture is confirmed in logit regressions analogous to those in Table 5, but with an indicator of groundwater transfer (either through sales or land leasing) as the dependent variable. As reported in the Online Supplemental Material, Giné and Jacoby (2020), Table D2, higher CV significantly decreases the probability that such transfers are made, except when *mandal* dummies are included.

us to exploit the quantitative implications of the theory to make welfare statements. After laying out the details of the structural model next, we conclude this section with a discussion of how data on irrigated areas under each contract type help us nail down particular model parameters.

4.3 *Structural estimation*

4.3.1 *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 (2008), is that underprovision of noncontractible 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

$$\ell_L = \arg\max(a+l)\big\{Ef\big(w/(a+l)\big) - c\big\} - \gamma cl. \tag{9}$$

4.3.2 *Functional form* We next assume that the intensive production function, f, takes the form

$$f(\omega) = \omega^{\alpha}, \tag{10}$$

where $\alpha \in (0,1)$; that is, F is Cobb–Douglas in land and water (see Giné and Jacoby (2020), in the Online Supplmental Material, Appendix C, for empirical support for this form). Note that, because the output scale parameter is not separately identified from the groundwater supply scale parameter λ (defined below), we normalize the former to unity. With these assumptions, the implied g—marginal return to planting—is globally concave, and thus, by Proposition 1 there is a universal precautionary planting motive. Combining equations (10) and (2) along with Definition 2 yields expressions for ℓ_U and V_U as reported in the first row of Table 6. As seen in the remainder of the table, a closed form for area irrigated is lacking only for the seasonal contract.

Table 6. Theoretical solutions.

Choice j	Area (ℓ_j)	Surplus (V_j)
U = unconstrained	$(\frac{1-\alpha}{c}Ew^{\alpha})^{1/\alpha}$	$\frac{\alpha c}{1-\alpha}\ell_U$
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	ℓ_C solves $E\Omega^{\alpha-1} = 1$	$\frac{\alpha c}{1-\alpha}[E\Omega^{\alpha} + \alpha\ell_C/a - (1-\alpha)]$
P = per-irrigation sale	$\eta^{1/\alpha}\ell_U - a$	δV_U

Note: $\Omega = \frac{1}{a}[w(\frac{1-\alpha}{c})^{1/\alpha} - \ell_C]$, where $\ell_C \le (\frac{1-\alpha}{c})^{1/\alpha}w_L$, and $\delta = \frac{1-\eta(1-\alpha)}{\alpha}\eta^{1/\alpha-1}$.

4.3.3 *Borewell discharge* Recall that 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 $s/4 \in \{0, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1\}$ and the corresponding borewell-specific probabilities, π_{si}, defined in Section 2. Since water discharge is proportional to the square of pipe radius R_i, we have

$$w_{si} = \lambda R_i^2 s/4. \tag{11}$$

Expected groundwater supply is thus $\bar{w}_i \equiv Ew_i = \lambda R_i^2 \sum_s \pi_{si} s/4$. We may think of λ as reflecting factors that shift the first moment of total *effective* discharge, such as soil moisture retention capacity.

4.3.4 *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 $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ such that $c_i = \overline{c}e^{\varepsilon_i}$. We assume that this cost shock is realized by the borewell owner before deciding on area irrigated and the water transfer arrangement (if any). We also think of ε_i as reflecting variation in local (adjacency-level) conditions—that is, in the shadow price of inputs like seed and fertilizer—not in *cultivator* characteristics.

Inserting c_i into the expressions given in the first column of Table 6 and inverting the resulting functions $\ell_{ji} = \ell_j(\varepsilon_{ji})$ yields expressions for choice-specific residuals ε_{ji} $j = U, L, C, P$, where ℓ_{ji} is the area under that arrangement for borewell i.

4.3.5 *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 ε. As it stands, however, the model implies that the minimum groundwater market transaction would involve an infinitesimal quantity of water (area).[22] To allow for a discontinuity in an irrigated area, as one exits autarky, we introduce a fixed transactions cost κ_j, which varies by type of water transfer arrangement. Let the cost of participating in the groundwater market (i.e., choosing $j = P$ or C) be κ_T and the cost of leasing a plot of land be κ_L. In our setting, a land lease is likely to be more costly to arrange than a water sale so that $\kappa_L > \kappa_T$, although we do not impose this constraint in estimation.

We also allow transactions costs to vary across adjacencies so as 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 κ across adjacencies, therefore, we use average plot size in borewell i's adjacency, $\overline{a}_i$, which is plausibly exogenous. Thus, let

$$\kappa_{ji} = \overline{\kappa}_j + \beta \log \overline{a}_i \tag{12}$$

[22]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.

for $j = L, T$. Note that β 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.

4.3.6 *Bargaining weight* We also allow for heterogeneity in the buyer's bargaining weight or surplus share, η, to account for potential competition among sellers; that is, bargaining power could vary with borewell density in the adjacency (see discussion in Section 3.3). As in the case of fixed transactions costs, we proxy borewell density with average plot size $\overline{a}_i$. We also allow bargaining power to depend on an index of social "cohesion" in the adjacency, SC_i, which is a plot area weighted average of an indicator for whether the adjacent plot owner is of the same caste as the reference plot owner. So, we have

$$\log\big[(1-\eta_i)/\eta_i\big] = \eta_0 + \eta_1 \log \overline{a}_i + \eta_2 SC_i \tag{13}$$

with η_i thus restricted to $(0, 1)$. We expect $\eta_1 < 0$ so that a seller facing more competition would yield a higher surplus share to the buyer, and perhaps $\eta_2 < 0$ as well.

4.3.7 *Likelihood function* The mixed continuous/discrete choice likelihood function involves the probabilities of the different water arrangements (choices)—unconstrained (U), autarky (A), leasing (L), seasonal contract (C), and per-irrigation contract (P)—and the densities of irrigated areas, ℓ_{ji}, conditional on choice $j = U, A, L, C, P$. Choice probabilities are determined by the set of thresholds, $\tilde{\varepsilon}_{jj'i}$, that solve the following crossing conditions for arrangement-specific value functions:

$$\begin{aligned}
&V_A(\varepsilon_{AUi}) = V_U(\varepsilon_{AUi}),\\
&V_A(\varepsilon_{jAi}) = V_j(\varepsilon_{jAi}) - \kappa_{ji}, \quad j = L, C, P,\\
&V_j(\varepsilon_{jj'i}) - \kappa_{ji} = V_{j'}(\varepsilon_{jj'i}) - \kappa_{j'i}, \quad \big(j, j'\big) = \big\{(C, L), (P, L), (C, P)\big\}.
\end{aligned} \tag{14}$$

The solution to the first of these equations yields $\tilde{\varepsilon}_{AUi}$, the upper limit of integration for the autarky probability, which has a simple closed form. The second set of equalities in (14) determine 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; they 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.

Letting $\Pr(j|\Theta, Z_i)$ denote the probability of choice j conditional on parameters $\Theta = (\alpha, \eta_0, \eta_1, \eta_2, \gamma, \overline{\kappa}_L, \overline{\kappa}_T, \beta, \lambda, \overline{c}, \sigma_\varepsilon)$ and data $Z_i = (\pi_{ki}, R_i^2, a_i, \overline{a}_i, SC_i)$, we have

$$\Pr(j|\Theta, Z_i) = \int_{\Re_{ji}^{\varepsilon}} \frac{1}{\sigma_\varepsilon} \phi\left(\frac{\varepsilon}{\sigma_\varepsilon}\right) d\varepsilon, \tag{15}$$

where ϕ is the standard normal pdf, and $\Re_{ji}^{\varepsilon}$ is the relevant region of integration for choice j. The simplest choice probability is for unconstrained cultivation, which is

$\Pr(U|\Theta, Z_i) = 1 - \Phi(\tilde{\varepsilon}_{AUi}/\sigma_\varepsilon)$, where Φ is the standard normal cdf and the dependence of $\tilde{\varepsilon}_{AUi}$ on parameters and data is implicit. For autarky,

$$\Pr(A|\Theta, Z_i) = \Phi(\tilde{\varepsilon}_{AUi}/\sigma_\varepsilon) - \Phi(\tilde{\varepsilon}_{Ai}/\sigma_\varepsilon), \tag{16}$$

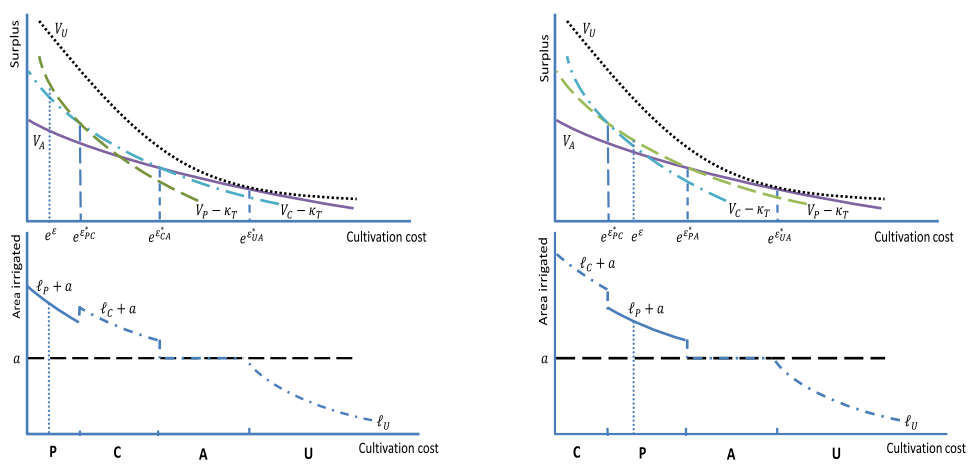
where $\tilde{\varepsilon}_{Ai} = \max\{\tilde{\varepsilon}_{LAi}, \tilde{\varepsilon}_{CAi}, \tilde{\varepsilon}_{PAi}\}$ represents the highest ε_i that would induce any kind of water transfer. For the probabilities of arrangements $j = L, C, P$, the regions of integration are not easy to write out as there are many possible configurations of the relevant thresholds, including cases where $\Re_{ji}^{\varepsilon}$ has two disjoint segments. Table D3 of Giné and Jacoby (2020) in the Online Supplemental Material 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

$$\mathcal{L}_i(\Theta|d_{ji}, \ell_{ji}, Z_i) = H_U(\ell_{Ui})^{d_{Ui}} \Pr(A|\Theta, Z_i)^{d_{Ai}} \prod_{j=L,P,C} \left[\frac{\Pr(j|\Theta, Z_i)}{\Phi(\tilde{\varepsilon}_{Ai})} H_j(\ell_{ji})\right]^{d_{ji}}, \tag{17}$$

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 intuition for equation (15) is provided by Figure 4, which illustrates how surplus and irrigated area vary with the cost disturbance ε_i (ignoring leasing choice L throughout to avoid clutter). At very high ε_i, $V_U > V_A$ and $\ell_{Ui} < a_i$ so that irrigated area is not censored by plot size (unconstrained cultivation U). The first two terms of the likelihood thus take a familiar tobit-like form, with the density H_U accounting for the uncensored observations and $\Pr(A|\Theta, Z_i)$, as given by equation (16), accounting for the



(a) PCAU Configuration (b) CPAU Configuration

FIGURE 4. Surplus and area irrigated under two possible model configurations. *Notes*: Solid line segments in bottom graphs show irrigated area schedule relevant for the optimal contractual arrangement given ε.

censored (autarky A) observations $\ell_{Ui} = a_i$. To understand the third term of (15), panels (a) and (b) of Figure 4 show two possible parameter configurations consistent with a well-owner selling water on a per-irrigation (P) basis. In panel (a), P is optimal only for ε_i in the left tail; in other words, at very low unobserved cultivation cost, given parameters, $V_P - \kappa_T > V_C - \kappa_T > V_A$. In particular, to observe $\ell_P > 0$, not only must we have $\varepsilon_i < \tilde{\varepsilon}_{Ai}$, but also $\varepsilon_i < \tilde{\varepsilon}_{CPi}$. To account for this additional right truncation, $\Pr(P|\Theta, Z_i)$ multiplies the truncated density $H_P(\ell_{Pi})/\Phi(\tilde{\varepsilon}_{Ai})$ in the third likelihood term.[23] In panel (b), P is optimal for moderate ε_i with the seasonal contract 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.[24] An analogous argument applies for parameter configurations in which C (or L) is the optimal choice of transfer arrangement given ε_i.

4.3.8 *Identification* Although, in practice, identification is secured through the full set of nonlinear cross-equation restrictions embedded in the thresholds defined by (14) 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 $\overline{\kappa}_j$ of equation (12) are identified from the fractions of well-owners selling water and leasing in land whereas β 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

$$\log I_{ji} = \frac{1}{\alpha}\left[K + \log \eta_i d_{Pi} - \log(1+\gamma) d_{Li} + \log\left(\sum_s \pi_{si} w_{si}^{\alpha}\right) - \varepsilon_i\right], \tag{18}$$

where $I_{ji} = \ell_{ji} + a_i$ for $j = L, P$ and $I_{ji} = \ell_{ji}$ for $j = U$ and the constant term $K = \log(1-\alpha) - \log \overline{c} + \alpha \log \lambda$. It is evident from (18) that η_i (or, rather, η_0) and γ are identified off of mean differences in irrigated area across arrangements (controlling for selection), α by the rate at which irrigated area falls with variability in water supply, K by average area in unconstrained cultivation, and σ_ε by the residual variance of irrigated area. Although λ and $\overline{c}$ (mean cost) are conflated in the constant term K, and hence are not identified from irrigated areas alone, λ enters the choice probabilities distinctly, both through the value of autarky V_A (see Table 6) and through w_L, water availability in the lowest state.

Equation (18) also highlights the importance of a nondegenerate groundwater supply distribution $\psi(w)$ for model identification, even with substantial variation in w_{si} (i.e., pipe width) across borewells. In particular, if $\forall i\ \pi_{si} = 1$ for some s, then α drops out of the fourth term of that equation (i.e., $\frac{1}{\alpha}\log(\sum_s \pi_{si} w_{si}^{\alpha}) = \log w_{si}$) and is thus identified solely off of nonlinearites.[25] Finally, equation (18) allows us to state more explicitly our one

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

[24]With only a *single* transaction type, say P, the third term would collapse to $H_P(\ell_{Pi})$ and the likelihood would be identical to that of models with piecewise-linear budget constraints (see, e.g., Moffitt (1986)).

[25]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., γ and $\bar{\kappa}_L$ could not be distinguished).

identifying assumption outside the structural model itself, which is that unobserved cost shocks ε_i are uncorrelated with groundwater supply as summarized by $\log(\sum_s \pi_{si} w_{si}^{\alpha})$. This assumption could be violated if, for instance, both costs and groundwater supply vary systematically across districts or across some finer geographic strata. We will thus consider a less restrictive model in the next section to address this concern.

5. Results

5.1 *Parameter estimates*

Table 7 reports baseline parameter estimates under the corresponding column heading, along with bootstrapped standard errors that account for clustering on well-owner (in case of multiple wells on a reference plot).[26] The estimates appear reasonable. The curvature parameter α is considerably less than one, whereas a value close to one would have implied little role for groundwater uncertainty. This structural estimate of α is also remarkably close to that obtained from a production function estimation (see Table C1, row 3, in Giné and Jacoby (2020) in the Online Supplemental Material).

Table 7. Maximum likelihood parameter estimates.

		Baseline		Expanded	
Parameter	Description	Coeff.	S.e.	Coeff.	S.e.
α	production function curvature	0.265	(0.014)	–	–
α_M	Mahbubnagar	–	–	0.273	(0.010)
α_G	Guntur	–	–	0.264	(0.012)
α_K	Kadapa	–	–	0.266	(0.006)
α_W	West Godavari	–	–	0.277	(0.009)
η_0	bargaining weight – intercept	−2.30	(0.030)	−2.324	(0.017)
η_1	bargaining weight – slope ($\bar{a}_i$)	−0.114	(0.036)	−0.114	(0.021)
η_2	bargaining weight – slope (SC_i)	0.001	(0.037)	0.001	(0.043)
γ	leasing inefficiency	0.0008	(0.0033)	0.0004	(0.0011)
κ_L	leasing transaction cost – intercept	0.216	(0.010)	0.210	(0.007)
κ_T	selling transaction cost – intercept	0.005	(0.000)	0.008	(0.000)
β	transaction cost – slope ($\bar{a}_i$)	0.051	(0.005)	0.047	(0.003)
λ	effective borewell discharge	0.942	(0.010)	0.949	(0.025)
$\bar{c}$	cultivation cost (overall mean)	0.672	(0.022)	–	–
$\bar{c}_M$	Mahbubnagar	–	–	0.629	(0.012)
$\bar{c}_G$	Guntur	–	–	0.680	(0.015)
$\bar{c}_K$	Kadapa	–	–	0.682	(0.008)
$\bar{c}_W$	West Godavari	–	–	0.679	(0.010)
σ_ε	standard deviation cultivation cost	0.239	(0.023)	0.238	(0.012)
$\bar{\eta}$	Sample mean of bargaining weight	0.927		0.928	
log-likelihood		−5332.1		−5308.4	

Note: Bootstrapped standard errors clustered on borewell owner in parentheses. Total estimation sample is 1646.

[26]Bootstrapping is necessary because the likelihood function is not smooth in the neighborhood of the optimum, leading to gradients that are not close enough to zero. We checked that we indeed had found the global optimum by also using the simulated annealing algorithm from different starting values.

The mean of 0.93 for buyer bargaining-power η_i translates into a 7% average tax-rate on the return to planting under the per-irrigation arrangement. We also find, as expected, that buyer bargaining power is increasing in average adjacency plot size (i.e., borewell density), but that social cohesion (SC_i) in the adjacency has no significant impact on bargaining power. The incremental cost of cultivating leased land versus own land, γ, is a precisely estimated zero. Evidently, the paucity of land-lease activity in the data is driven by the high fixed transactions cost, κ_L. Note that κ_L is much greater than κ_T, so it is indeed much more difficult to find a leasing than a water-selling opportunity. Finally, as we also expected, $\beta > 0$, implying that fixed transactions costs are higher in adjacencies with greater borewell density. Thus, owners of borewells surrounded by plots with borewells of their own have greater difficulty arranging water sales.

Next, we relax our identifying assumption that variation is cultivation cost is orthogonal to groundwater supply, by allowing each of the four districts in the estimation sample to have a separate (mean) cultivation cost. In addition, we allow each district to have its own curvature parameter, α, in case the technology differs across regions with broadly different cropping patterns.[27] Although these two parameters turn out to vary little across districts (see Table 7), a likelihood ratio test rejects the more restrictive baseline model. Otherwise, the estimated parameters of the expanded model are quite close to their counterparts in the baseline model.

5.2 *Within-sample fit*

Table 8, column (2), reports mean model predictions for the estimation sample, which can be compared to the corresponding actual data means in column (1). We use the baseline model estimates; predictions for the expanded model are very similar and are

TABLE 8. Baseline model predictions.

			Holdout Samples				Anantapur→	
	Est. sample		Anantapur		E. Godavari		E. Godavari	
	Data	Model	Data	Model	Data	Model	$\Delta\pi$	$\Delta\pi$, ΔR
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Pr(U)$	0.26	0.42	0.51	0.57	0.08	0.24	0.42	0.14
$\Pr(A)$	0.23	0.16	0.47	0.20	0.25	0.10	0.18	0.09
$\Pr(L)$	0.06	0.03	0.01	0.00	0.03	0.19	0.01	0.17
$\Pr(P)$	0.20	0.15	0.01	0.18	0.05	0.17	0.11	0.26
$\Pr(C)$	0.24	0.24	0.00	0.05	0.60	0.31	0.29	0.35
$E\log I$	1.67	1.82	1.06	1.12	2.33	2.73	1.58	2.68

Note: Expected log irrigated area, $E\log I$, and choice probabilities, $\Pr(j)$, are simulated by drawing 50 values of ε for each borewell and then averaging optimal choices (i.e., indicator functions for choice j in the case of the probabilities) based on parameters of baseline model in Table 7. Table reports sample averages of these calculations. Column (7) reports mean predictions when each borewell in the E. Godavari sample is assigned well-flow state probabilities (π_{ki}) 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.

[27]The proportion of irrigated area devoted to wet crops ranges from just 7% in Kadapa to 43% in Mahbubnagar (despite the latter being one of the most arid of the six study districts).

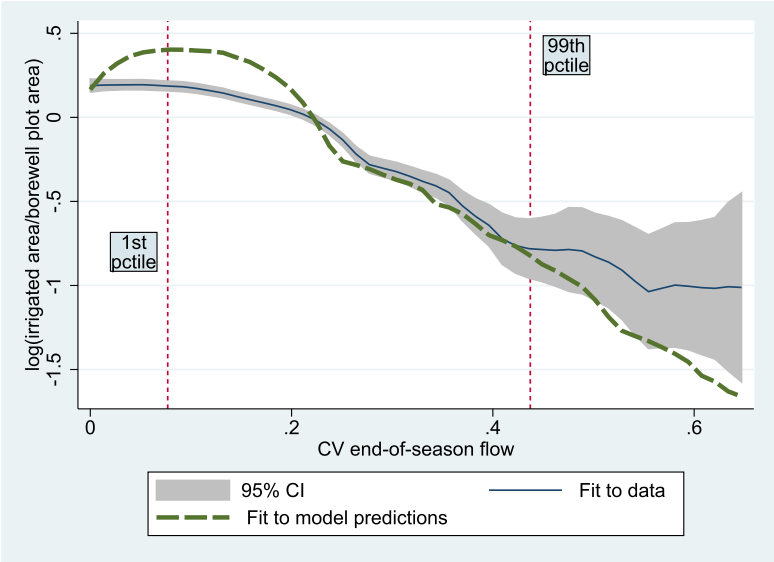


FIGURE 5. Irrigated area and groundwater supply uncertainty. *Notes*: Nonparametric regressions of actual and predicted (from baseline model) log irrigated area on coefficient of variation of end-of-season flow.

relegated to Giné and Jacoby (2020), Table D4 in the Online Supplemental Material.[28] The top panel of the table reveals that the model successfully predicts choices of transfer arrangements (L, P, and especially C) in the estimation sample, but over-predicts the proportion of borewell owners in unconstrained self-cultivation (U).

Turning to (log) areas, in the bottom panel of Table 8, we find that the model modestly overpredicts total borewell irrigated area by roughly 15 log points,[29] and the correlation between predicted and actual log irrigated area is 0.45. Figure 5 shows that the model also reproduces, more or less faithfully, the bivariate relationship between log area irrigated (relative to borewell plot area) and the coefficient of variation of groundwater supply, with the overprediction problem occurring at low CVs.

Despite this overall goodness of fit, the model does not accurately predict the contractual choices of borewell owners conditional on their actual choices. Table 9 reports the average predicted choice probabilites by the actual choice of the borewell owner. Probability mass concentrated along the table's diagonal would indicate a strong fit to the data, as the model would attribute a high probability of making choice j to borewell owners who actually made choice j. As it turns out, the diagonal term is maximal only for choices U and C. The model does a very poor job, for example, predicting who leases (choice L), given plot area and borewell characteristics. Similarly, for those choosing the

[28]The advantage of the baseline model is that we do not have to make any assumption about the curvature parameter or about cultivation costs to predict out of sample. By contrast, in the case of the expanded model, each district has its own value of these two parameters. Therefore, we have to make a somewhat arbitrary assignment of α and $\bar{c}$ to each out-of-sample district.

[29]This is only an approximation because in simulating log irrigated area from the model we take the average of log area over draws of ε_i.

TABLE 9. Conditional predictions.

	Choice probability					$E \log I$	
Actual	U	A	L	P	C	Data	Model
U	0.716	0.121	0.009	0.067	0.086	1.42	1.83
A	0.413	0.178	0.029	0.150	0.230	1.65	1.95
L	0.271	0.184	0.023	0.222	0.300	1.78	2.76
P	0.259	0.168	0.032	0.225	0.316	1.68	0.76
C	0.264	0.154	0.049	0.181	0.352	1.93	1.41

Note: Choice probabilities given actual choices (left panel) are simulated by drawing 50 values of ε (based on parameters of baseline model in Table 7) for each borewell and then averaging choice indicator functions over borewell owners/replications whose actual choice is j. Rows of left panel sum to 1.0. Expected log irrigated area, $E \log I$, conditional on choices (right panel) are simulated in the same way, averaging predicted areas over all borewell owners/replications that the model assigns to choice j.

per-irrigation contract (P), the model puts more probability mass on them choosing U or C.

These prediction failures can be attributed to the structural model's partitioning of the single, normally distributed, disturbance into ordered segments corresponding to the different choices (see Figure 4). In the case of the baseline model, 92% of the sample observations are associated with configuration LPCAU (see the Online Supplemental Material, Giné and Jacoby (2020), Table C3). This explains why, for instance, the model assigns a borewell doing A a large probability mass on adjacent choices C and U, and why the model assigns similar probabilities for all choices to borewell owners that actually chose L, P or C. Plot area and the groundwater supply distribution are not powerful enough predictors of individual choices (given that they simultaneously have to predict irrigated areas). In particular, the observable characteristics do little to shift the thresholds defining a choice given a configuration or to assign the borewell owner to the configuration that would maximize his actual choice. In light of this misclassification, it is not surprising that the model also fails to accurately predict (log) irrigated area *conditional* on particular choices, especially in the case of L and P (see the right panel of Table 9).

In sum, while the within sample fit of our structural model of contract choice and area irrigated is encouraging, *on average*, its predictive performance conditional on choices is poor. The latter result limits the model's usefulness in evaluating how a counterfactual scenario shifts *particular* individuals across contractual arrangements or how it changes the area irrigated under a specific arrangement. However, in evaluating the market-level contracting distortions, as we do in Section 6, we rely on averages across all borewell owners, which our model matches reasonably well, both within and (as we show next) out of sample.

5.3 *Out-of-sample fit*

To assess external validity, we also report in Table 8 predictions based on estimation sample parameters for borewells in the holdout districts of Anantapur (column 4) and

East Godavari (column 6). In Anantapur, there is only a 6 log point gap between mean irrigated area predicted by the model and that found in the data, lower than even in the estimation sample, whereas the corresponding deviation in E. Godavari is 40 log points. This latter result is no doubt due to the previously noted tendency of our model to over-predict irrigated area for low-CV borewells, which happen to predominate in E. Godavari. The model also does somewhat better at capturing choices in Anantapur than in E. Godavari, especially with respect to unconstrained cultivation (U). In both districts, however, the model greatly over-states the prevalence of per-irrigation sales and, in E. Godavari, the prevalence of leasing.

The key out-of-sample success of our model lies in capturing the contraction of irrigated area per borewell and the collapse of the seasonal contract as one moves from E. Godavari to Anantapur and both groundwater scarcity and supply uncertainty increase. To disentangle which of these changes—that is, 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 8. In the first, for each borewell in Anantapur, we replace the vector of subjective probabilities $(\pi_{1i}, \ldots, \pi_{5i})$ 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 24 percentage points (from 0.05 to 0.29) and predicted area irrigated by 46 log points. In the second exercise, we draw pipe-widths in addition to the π_{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* 110 log points, while the prevalence of seasonal contracts rises by just 6 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. Contracting distortion

6.1 *Deadweight loss from hold-up*

Our model delivers a simple expression for the efficiency loss due to the classic hold-up problem in the per-irrigation contract. Recall that the inefficiency arises from too little area under irrigation (the buyer underinvests), a cost which is only partly offset by the concomitant benefit of having more water per acre planted, including on the seller's own plot. Noting that V_U is first-best total surplus generated by the borewell and using the expression for V_P shown in Table 6, the proportionate deadweight loss is $1 - V_P/V_U = 1 - \delta$, where $\delta = \frac{1-\eta(1-\alpha)}{\alpha}\eta^{1/\alpha-1}$. Given our baseline estimate of $\alpha = 0.265$ and $\bar{\eta}_i = 0.927$, we obtain a deadweight loss of 2.6%. Since only a fraction of borewell owners choose to sell under the spot contract, this figure is an upper bound on the equilibrium contracting distortion. In other words, those who would incur the highest deadweight loss from per-irrigation sales instead choose a less distortionary arrangement.

6.2 *Distortions and gains from trade*

Viewing V_U as the surplus from a hypothetical perfect market, the theoretical maximum market-wide gains from trade are given by

$$\begin{aligned} G_{\max} &= \sum_i E\big\{\big[V_U(\varepsilon_i) - V_A(\varepsilon_i)\big]\mathbb{1}_{\ell_U(\varepsilon_i)>a_i}\big\} \\ &= \sum_i E\big\{\big[V_U(\varepsilon_i) - V_A(\varepsilon_i)\big]\mathbb{1}_{\varepsilon_i<\tilde{\varepsilon}_{AUi}}\big\}, \end{aligned} \tag{19}$$

the sum across borewell owners of the expected counterfactual surplus deviation from autarky for those induced to trade in the perfect market.[30] Likewise, the *actual* gains from trade are

$$\begin{aligned} G_{\text{actual}} &= \sum_i E\big\{\big[V_{j^*}(\varepsilon_i) - \kappa_{j^*} - V_A(\varepsilon_i)\big]\mathbb{1}_{V_{j^*}(\varepsilon_i)-\kappa_{j^*}>V_A(\varepsilon_i)}\big\} \\ &= \sum_i E\big\{\big[V_{j^*}(\varepsilon_i) - \kappa_{j^*} - V_A(\varepsilon_i)\big]\mathbb{1}_{\varepsilon_i<\tilde{\varepsilon}_{j^*Ai}}\big\}, \end{aligned} \tag{20}$$

where j^* is the optimal transfer arrangement (P, C, or L). Thus, G_{actual} is the sum across borewell owners of the expected actual surplus deviation from autarky for those induced to trade in the distorted market. Figure 6 illustrates G_{actual} and $G_{\max}$ for a market consisting of a single borewell. The ratio of these two numbers, $G_{\text{actual}}/G_{\max}$, represents the fraction of potential gains from trade achieved in the distorted market. Thus, the relative size of the total market distortion is given by $\hat{G} = 1 - G_{\text{actual}}/G_{\max}$.

As noted, part of the total market distortion is attributable to the fixed cost of selling water, κ_T, and part is attributable to contracting under uncertainty. To distinguish the two components, we consider a counterfactual in which $\kappa_T = 0$ and construct the analog to (20), namely $G_{\kappa_T=0}$. We may thus write

$$\hat{G} = \underbrace{1 - \frac{G_{\kappa_T=0}}{G_{\max}}}_{\text{contracting}} + \underbrace{\frac{G_{\kappa_T=0} - G_{\text{actual}}}{G_{\max}}}_{\text{transactions costs}}. \tag{21}$$

Figure 6 illustrates the decomposition of the total distortion in terms of surplus. Results of this calculation, reported in Table 10, reveal that actual (or, rather, predicted) contractual arrangements lead to 3.3% lower gains from trade than would prevail in a hypothetical perfect groundwater market. A bit less than half of the total surplus loss is attributable to contracting under uncertainty.

[30]That is,

$$G_{\max} = \sum_i \int_{-\infty}^{\tilde{\varepsilon}_{AUi}} \big[V_U(\varepsilon) - V_A(\varepsilon)\big]\phi_i(\varepsilon/\sigma)/\sigma\, d\varepsilon,$$

where the density ϕ_i and the threshold ε_{AUi} both depend on the data Z_i. We use Monte Carlo integration, generating draws of ε from a Halton sequence.

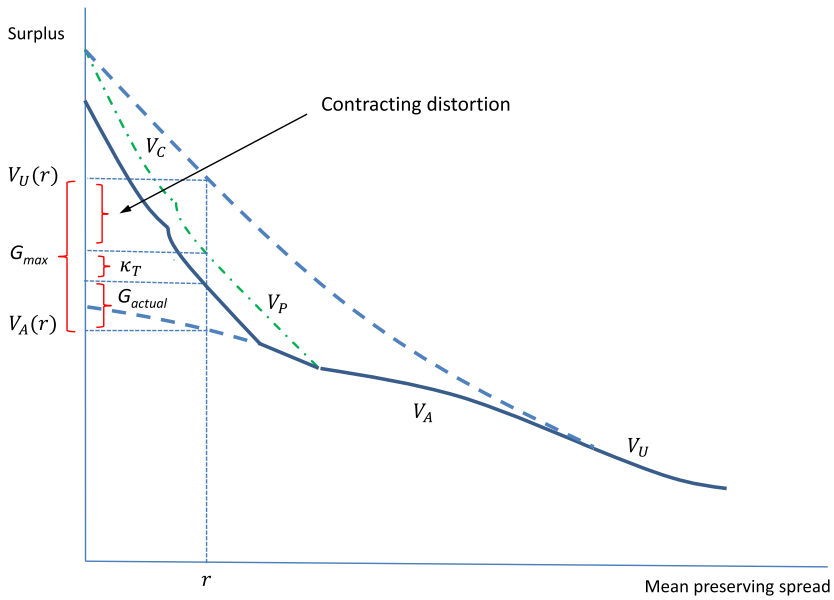


FIGURE 6. Contracting Envelope and Magnitude of Distortion. *Notes*: Solid curve represents optimal contracting envelope (i.e., second-best surplus at each level of uncertainty r); dashed-dotted curve represents optimal contracting envelope before deducting fixed transactions cost κ_T; dashed curves represent counterfactuals (autarky or perfect market).

6.3 *Distortions and farm income*

How costly is the contracting distortion in terms of foregone income to the individual borewell owner? To answer this question, we monetize borewell surplus using data on *rabi* season (irrigated) land rents collected from village informants as part of our borewell owners survey. Thus, let actual borewell surplus $\tilde{V}_{j^*} = \rho_m I_i$, where ρ_m is median rent per acre in the *mandal* and I_i is total area irrigated by borewell i.

Next, we compute for each borewell $\Pi_i^{\text{total}} = E[V_U - V_{j^*}]/EV_{j^*}$, the total distortion as a fraction of actual surplus, and (as above) $\Pi_i^{\text{contract}} = E[V_U - V_{\kappa_T=0}]/EV_{j^*}$, the contracting distortion as a fraction of actual surplus; the median values of these constructs in the estimation sample are 3.5% and 1.3%, respectively.[31] Figure 7 illustrates the re-

TABLE 10. Market-level distortion.

	Total	Contracting	$\kappa_T > 0$
Distortions as % of max gains from trade	3.3	1.4	2.0

Note: Based on estimation sample of 1646 borewell owners.

[31]These numbers are comparable to the corresponding entries in Table 10. Also, as alluded to earlier, since $(V_U - V_P)/V_P = (1-\delta)/\delta = 0.026$, 2.6% is an upper bound on the average contracting distortion as a proportion of total (actual) surplus.

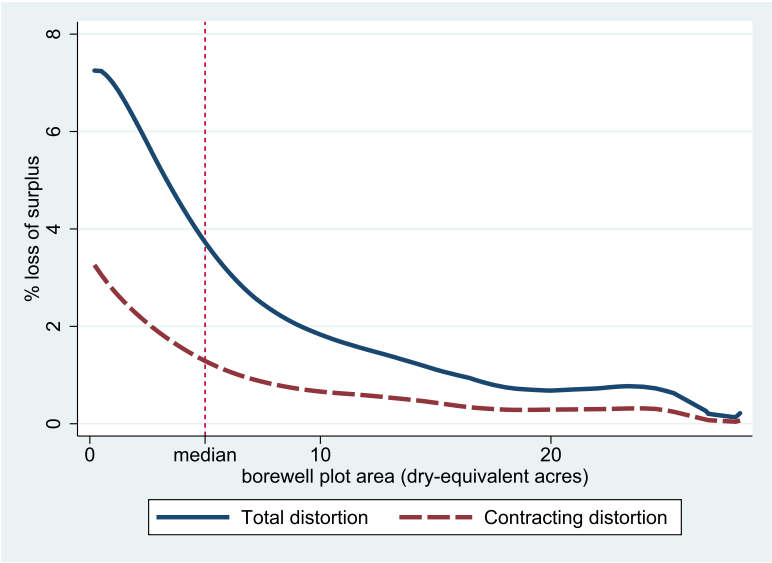


FIGURE 7. Distortions and Plot Area. *Notes*: Solid curve is nonparametric fit of total distortion as a fraction of surplus (Π_i^{total}) and the dashed curve is the nonparametric fit of the contracting distortion as a fraction of surplus (Π_i^{contract}) against borewell plot area.

gressive nature of these distortions: Borewells on the smallest plots, which tend to be owned by the poorest farmers (among borewell owners) and being the most reliant on groundwater markets, incur the greatest proportionate surplus loss.

Multiplying Π_i^{total} and Π_i^{contract} by $\tilde{V}_{j*}$, and summing across borewells for owners with multiple wells on the reference plot, we find that groundwater market distortions overall cost the median borewell owner in our estimation sample \$39 per dry season, whereas the contracting distortion alone costs \$13. These costs amount to, respectively, 5.9% and 1.9% of seasonal income.[32] However, it is worth observing that in districts with relatively active groundwater markets, namely Guntur and West Godavari, the median burden of the contracting distortion alone is 3.6% and 3.4% of seasonal income, respectively.

7. Conclusion

We have developed a model of contracting under 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, we believe for the first time, the cost of opportunism, on the one hand, and the cost of uncertainty, on the other, in a real-world market setting.

[32]We use median rural household expenditures over 6 months (length of season) by district taken from the 68th round of India's National Sample Survey (2011–2012).

We find that the welfare loss attributable to constrained-efficient contracting, both in terms of forgone gains from trade and in terms of foregone farmer income, is modest on average but nontrivial for certain subgroups. Borewell owners with small plots in areas with already active groundwater markets, in particular, bear a substantial burden.

Our empirical findings are well in line with the broader development literature. While households in small village economies are adept at mitigating market failure because of relatively low information costs and through repeated interactions with their neighbors, often across multiple markets, distortions remain. Townsend (1994), for example, famously demonstrated only partial risk-sharing in south Indian villages, a result attributable, at least in part, to limited commitment (Ligon, Thomas, and Worrall (2002)), a form of hold-up.[33] In this context, our finding that contracting distortions are significant, but not too large, is plausible. Of course, in settings where trading relationships are more impersonal and ephemeral, hold-up may well be more costly.

Appendix A: Proof of Proposition 2

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 $j = C, P$ and note that $V_P(r, \eta)$ also depends on the bargaining weight η.[34] We now restate Proposition 2 formally.

Proposition 2. *If g is strictly concave and $\tau_C(0) < w_L$,*[35] *then* (a) *for some η, $\exists$ a unique $r^*(\eta)$ such that $V_C(r^*) = V_P(r^*, \eta)$;* (b) $[V_C(r) - V_P(r, \eta)](r^* - r) > 0$.

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

$$\int h(w)\psi_r \, dw = \int h_{ww}(w)T(w, r) \, dw, \tag{A.1}$$

[33]Also in the context of groundwater markets, Bubb, Kaur, and Mullainathan (2018) used a subsidy experiment in North India to uncover evidence that farmers fail to undertake mutually beneficial contracts, presumably because payment cannot be enforced. Though not about hold-up per se, their paper also points to considerable barriers to efficient contracting within village economies.

[34]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.

[35]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 $r = 0$; that is, at $r = \epsilon$, the optimal transfer must be discretely less than $\tau_C(0)$. In this case, $r^*(\eta)$ still exists for some η but it is not necessarily unique. Part (b) of the proposition continues to hold, however, with respect to the largest r^*.

where ψ is a p.d.f., ψ_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

$$V_U'(r) = \ell_U \int f(w/\ell_U)\psi_r \, dw < 0 \tag{A.2}$$

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

(ii) V_A: Follows from (A.2) with ℓ_U replaced by a.

(iii) V_C: As noted in footnote 34, $V_C = aE[f(\frac{w-\tau_C}{a}) - c] + \ell_C[f(\frac{\tau_C}{\ell_C}) - c]$. 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 footnote 34,

$$\begin{aligned} V_P &= aE\left[f\left(\frac{w-\tau_P}{a}\right) - c\right] + \ell_P\left[f\left(\frac{\tau_P}{\ell_P}\right) - c\right] \\ &= (a+\ell_P)E\left[f\left(\frac{w}{a+\ell_P}\right) - c\right], \end{aligned} \tag{A.3}$$

where the second line follows from the ex post efficiency condition $f'(\frac{\tau_P}{\ell_P}) = f'(\frac{w-\tau_P}{a})$. Differentiating with respect to r in this case yields

$$\begin{aligned} V_P'(r) &= E\left[g\left(\frac{w}{a+\ell_P}\right) - c\right]\frac{\partial \ell_P}{\partial r} + (a+\ell_p)\int f\left(\frac{w}{a+\ell_P}\right)\psi_r \, dw \\ &= c\left(\frac{1}{\eta} - 1\right)\frac{\partial \ell_P}{\partial r} + (a+\ell_p)\int f\left(\frac{w}{a+\ell_P}\right)\psi_r \, dw, \end{aligned} \tag{A.4}$$

where the second line uses equation (8). 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 footnote 35) and Lemma 1, V_C is continuously decreasing in r until it equals V_A at some $r = r_C$. Now use equation (8) under perfect certainty to define $\underline{\eta} = c/g(w/a)$. For $\eta \le \underline{\eta}$, $\ell_P = 0$ $\forall r$ and, consequently, $V_P(r, \underline{\eta}) = V_A(r)$ $\forall r$ and, in particular, for $r = 0$. Define $r_P(\eta)$ as the solution to

$$V_P\big(r_P(\eta), \eta\big) = V_A\big(r_P(\eta)\big). \tag{A.5}$$

Thus, clearly, $r_P(\underline{\eta}) = 0$. 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 η. 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 A.1).

Thus, it is sufficient to show that $r_P'(\eta) > 0$ so that as η is increased from $\underline{\eta}$ to 1 $r_P(\eta)$ eventually exceeds r_C. Differentiating equation (A.5) with respect to η, substituting from equation (8), 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 $h(w) = (a + \ell_P) f(\frac{w}{a+\ell_P}) - af(\frac{w}{a})$. Since $\partial \ell_P / \partial \eta < 0$, and given (A.1), we have that $\operatorname{sign}(r_P'(\eta)) = -\operatorname{sign}(h_{ww}(w))$. 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 $f''(\frac{w}{a+\ell_P}) \approx f''(\frac{w}{a}) - \frac{w\ell_P}{a^2} f'''(\frac{w}{a})$. Substituting into equation (A.7) and rearranging yields

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

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 $\eta \in (\underline{\eta}, 1)$, it must be true that $V_P(r, \eta) > V_C(r)$ over the interval $(r^*(\eta), r_P(\eta))$. □

Figure A.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. 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 η approaches one. Moreover, at some low level of bargaining power $\eta = \underline{\eta}$, $\ell_P = 0$ and V_P coincides with V_A. So, for some range of $\eta \in (\underline{\eta}, 1)$, 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.

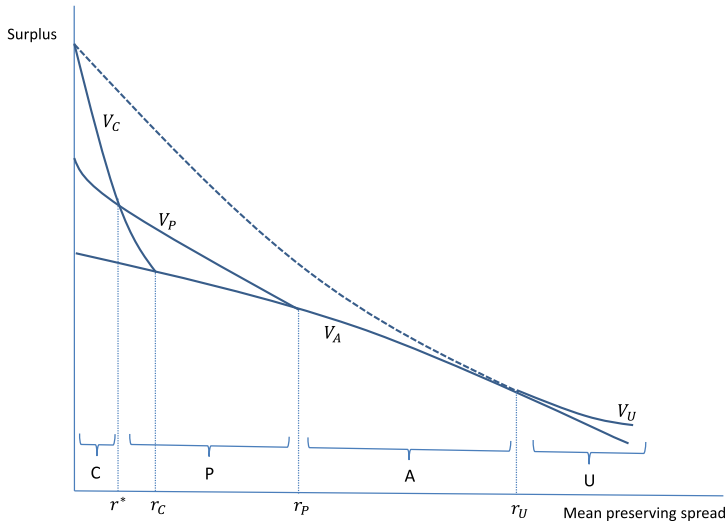


FIGURE A.1. Long-term versus spot contracts and uncertainty. *Notes*: The regions C (long term contract), P (spot contract), A (autarky), and U (unconstrained cultivation) denote the range of mean preserving spread r over which the arrangement is dominant. The dashed portion of the V_U curve is unattainable given the absence of competitive spot markets.

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