Monopoly Power and Distribution in Fragmented Markets: The Case of Groundwater

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Abstract

This paper uses data from Pakistan's Punjab to examine monopoly power in the market for groundwater--irrigation water extracted using private tubewells--a market characterized by barriers to entry and spatial fragmentation. Our analysis of individual groundwater transactions over an 18 month period shows that tubewell owners price discriminate in favor of their own share-tenants, as a simple optimal contracting model would predict. Consequently, tubewell owners and their tenants use considerably more groundwater than do other farmers. We also find evidence that monopoly pricing of groundwater leads to compensating, albeit small, reallocations of canal water, which farmers exchange in a separate informal market. Despite the substantial misallocation of groundwater, a welfare analysis shows that efforts to counteract monopoly pricing would have only modest effects on efficiency and equity.

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I. Introduction

Markets in less developed economies often appear to deviate considerably from the competitive ideal. Two features of rural markets, in particular, underlie this observation: “fragmentation” due to high transportation or information costs, and entry barriers due to the interaction of credit constraints and indivisibilities in investment. Under such conditions, local monopoly can be widespread and persistent, with potentially large efficiency and distributional implications.[1] Yet, evidence of such monopoly power and especially of its welfare consequences is surprisingly sparse.[2]

This paper uses data from Pakistan's Punjab to examine monopoly power in the market for irrigation water, specifically groundwater extracted by tubewells. Groundwater markets have flourished throughout South Asia, emerging over the past few decades along with the rapid development of private tubewells.[3] These markets are characterized by barriers to entry and extreme spatial fragmentation. Barriers to entry arise from the fact that one must own land above an aquifer before boring a tubewell and because of high installation costs.[4] Tubewell ownership in South Asia is, therefore, limited mostly to large landowners.[5] Heavy seepage losses involved in conveying groundwater through unlined field channels also severely restrict competition. These technological features of groundwater extraction and distribution have led several commentators to express concern over local monopolies, more colorfully termed “water-lords” (see Meinzen-Dick, 1996, and Shah, 1993, for an overview of the debate and evidence).

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[1] The leading example is rural credit markets themselves, which are typically fragmented because of weak legal institutions that put a premium on trust and personal relationships. Basu and Bell (1991) formalize a notion of market fragmentation in the context of rural credit. Basu (1987) considers the implications of a lender’s monopoly power over his informationally isolated borrowers.

[2] Banerjee et al. (2000) examine price and capacity determination by local sugar processing *monopsonies* in India, but do not focus on welfare implications.

[3] There are now nearly half a million private tubewells in Pakistan's Punjab province alone, supplying about a third of total irrigation at the farmgate (Shah, et al, 2000).

[4] Typical installation costs are about $500, or roughly a year’s income for the average rural household in Pakistan. Moreover, land ownership by itself is not a guarantee of access to groundwater, since some bore-holes fail to find adequate groundwater and must be abandoned. Indeed, since the existence and quality of groundwater vary considerably over a small area, it may often not be economical for even a large landowner to bore a well.

[5] In 1991, 88 percent of tubewells in Pakistan were owned by large farmers (with at least 12.5 acres) who comprised just 19 percent of all farms (Meinzen-Dick, 1996; Government of Pakistan, 1994).

Two features of groundwater markets in the Punjab provide unique and complementary tests for monopoly power. First, groundwater markets and tenancy contracts are interlinked. A monopolistic tubewell owner who sells groundwater both to his own share-tenants and to other cultivators would be expected to price discriminate between the two groups, charging a lower price to his own tenants for the simple reason that he shares their output. We use detailed data on daily groundwater transactions over an 18 month period to compare prices that the *same* tubewell owner charges to different customers, including his own tenants. Second, irrigation water is a production input not only for buyers but also for the tubewell owner himself, who typically cultivates adjacent land. Since the shadow price of groundwater to the owner is just the marginal extraction cost, he should use more of it per acre than a groundwater buyer facing a monopoly price. Comparing groundwater use across buyers, tubewell owners, and their tenants, at the plot level, therefore, provides a test for monopoly distortion that does not require estimates of shadow prices.. The unique combination of price information and farm level quantity data allows an analysis of both the efficiency and equity implications of monopoly power; i.e., the deadweight loss and the transfer of surplus from buyers to sellers.

We also look for repercussions of monopoly pricing of groundwater in a closely related "market", that in which farmers exchange entitlements to canal water. The question we address is whether, given monopoly power, informal exchange of canal water fosters allocative efficiency. Since canal water is free at the margin, whereas groundwater is expensive to extract, farmers resort to tubewells mainly during periods of peak water demand. Thus, farmers may be able to alleviate the impact of monopoly pricing of groundwater by “borrowing” canal water during critical periods from tubewell owners and their tenants. We explore this possibility using weekly panel data on canal water endowments and use over three agricultural seasons.

This paper brings together three disparate literatures. First, a large body of work has sought to measure market power in different industries using a variety of empirical strategies (see Bresnahan, 1989, for a survey). Our approach to inferring monopoly mark-ups is distinct, however, in that it does not rely upon measuring marginal cost or structurally estimating demand, both of which often require auxiliary restrictive assumptions. Second, this paper contributes to the voluminous literature on agricultural tenancy, specifically on the interlinkage of rural factor markets. Despite some theoretical analyses of interlinked sharecropping contracts (see Braverman and Stiglitz, 1982 and the survey by Bell, 1988), there is virtually no empirical work exploring the implications for factor market efficiency. Third, in examining the intertemporal exchange of canal water, this paper touches upon the role and functioning of *informal* markets. These markets, characterized principally by the prominence of commitment problems and therefore by the reliance on self-enforcing contracts (see Greif, 1993, and Coate and Ravallion, 1993, and Ligon, Thomas, Worrall, 1996, in the context of risk-sharing), have also received scant empirical attention.

Our findings strongly support the existence of monopolistic price discrimination and a corroborating pattern of water misallocation within one watercourse in Pakistan. Evidence from canal water transactions, however, indicates that the impact of this misallocation on crop yields may be blunted somewhat by reallocations within the season. In any case, our welfare analysis shows that efforts to counteract monopoly power in the groundwater market would have only modest effects on efficiency and equity.

The rest of this paper is organized as follows. Section II describes the setting for this study and the data set in detail. We develop our theoretical predictions on pricing and use of groundwater in Section III, while Section IV models the institution of canal water trading in a general equilibrium framework. Section V presents the empirical analysis. We conclude in Section VI with the welfare analysis and the broader implications of our findings.

II. Institutional Setting and Data

The data for this study come from a survey of irrigation practices collected by the International Water Management Institute (IWMI) in the Fordwah-Eastern Sadiqia irrigation system of southern Punjab, Pakistan from 1993-95. In this agroclimatic zone, cotton and fodder are the main *kharif* (summer) season crops, with cotton by far the more important in terms of cultivated area. Wheat is the main crop in the *rabi* (winter) season, while sugarcane is cultivated year-round. The region receives low and erratic rainfall averaging 100-200 mm per year, mainly concentrated during the monsoon period from July to September. Farmers, therefore, rely heavily upon canal water and groundwater for agriculture.

In this paper, we focus on a single, but fairly typical, Punjabi watercourse, Fordwah-14R (Fd14R). A watercourse, or tertiary irrigation canal, is a natural unit of analysis for the study of water markets because, aside from its connection to the secondary canal, it is largely closed to import or export of water.[6] The eight watercourses covered by IWMI surveys were purposefully selected from the tail-end of the Fordwah-Eastern Sadiqia irrigation system, and hence have particularly unreliable canal supplies. We chose Fd14R because it has the most complete data. Most of our empirical analysis covers three seasons: *kharif* 1994 (mid-April through October), *rabi* 1994-95 (November through mid-April), and *kharif* 1995.

In the Punjab, as in much of Pakistan and Northern India, canal water is distributed to each plot within a watercourse according to a rotational system, or *warabandi*. Fd14R is no exception. Each farmer is allotted a turn to use the entire water flow in the canal at a pre-specified time each week. Access to water is limited to farmers with land in the watercourse command area, and the length of the water turn is proportional to landholding (though not necessarily cropped area), irrespective of the crops grown by the farmer. In Fd14R, the canal water entitlement is about 20 minutes per acre of landholding per week, viewed by farmers as about half of irrigation "requirements", although farmers in the tail-reach of the watercourse can lose much of their water to seepage (there is no allowance for this). Leasing or sharecropping in a plot of land entitles the cultivator to full use of the canal water allocation for that plot. In response to this rigid allocation scheme and the unreliability of actual water deliveries,[7] farmers have developed an informal system of canal water trading, discussed below.

The IWMI surveys cover every cultivator and plot of land in the watercourse command area; thus, we have a "census" rather than a “sample”, though we use the latter term for convenience. Since canal water turns are assigned to plots rather than to individuals, farmers who operate more than one plot (or set of contiguous plots) have more than one canal water turn. Moreover, since the holdings of such farmers are often dispersed throughout the watercourse command, and hence may lie in different local groundwater “markets”, it makes sense to conduct

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[6] This is not strictly true, as there are occasionally groundwater transactions between farmers in neighboring watercourse commands. In the case of Fd14R, only 3 percent of the sales were to farmers outside the watercourse. There were no cases of purchases from outside the command area during the survey period.

[7] The rivers of the Punjab never supply enough water to consistently meet irrigation needs. Under the canal irrigation system established by the British in colonial times, water flow is rotated to different canals at different times depending on availability. Consequently, the amount of water entering the secondary canals is highly unpredictable, a problem compounded by silting and illegal breaching of canals (Bandaragoda and Rehman, 1995).

the analysis at the plot-level. As a result, while there are around 71 cultivators in Fd14R, there are up to 93 canal water turns (identified by '*warabandi* id'), depending on the season.[8]

A unique feature of this data set is that it includes information on every groundwater and canal water transaction between all *warabandi* ids in the watercourse command during a season. A daily log was kept of canal water operations, including discharges and the exact timings of each turn at the canal, the amount of irrigation time exchanged, and the identity of the trading partners. A similar log was kept of the operations of each tubewell in the watercourse command, including hours of operation, and if water was sold, cash prices, any special transaction terms, and the identity of the buyer (these are described in more detail in section V). These data, along with daily rainfall measurements, provide a complete accounting of water availability and use throughout the survey period.

In addition, an exhaustive mapping and crop survey of the watercourse command area identifies the location of each plot, what was grown on the plot, and the location of each tubewell. Figure 1 shows a diagram of FD14R pinpointing all 18 tubewells as of the end of the survey period. Most of the tubewells sit along the main watercourse channel to facilitate mixing of canal water and groundwater and to avoid using field channels with higher conveyance losses. There are no tubewells in the tail-reach of the watercourse, at the far left of the map, because of the lack of adequate groundwater in this area.

All farmers in Fd14R trade canal turns. We present more detailed evidence on trading frequency in Section V. Typically, transfers of canal time involve one or two partners on closely neighboring plots; the greater the distance between farmers, the greater the number of intervening farmers whose turns must be shifted to accommodate the new timing. These transactions do not involve cash, at least not explicitly, nor is the receipt of water in one week necessarily followed by a reciprocal transfer of water the following week. Field interviews indicate an informal system of borrowing and lending depending on the relative irrigation demands of the participants. Over the long-term, there is a rough balance between the amounts given to and received from any one partner.

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[8] The number of *warabandi* ids vary across seasons primarily due to changes in tenancy arrangements between the *rabi* and *kharif* seasons. Most of the changes arise because plots that were rented out in the previous season are subsequently cultivated by the owner. There are a few cases in which a landowner rents out the plot to a different tenant.

At the end of the survey period, there were 18 diesel-powered tubewells in the watercourse command of Fd14R, 3 of which were installed during the 3 seasons covered in the survey. 17 of these sold water at least once during the survey period. Most (90%) of the *warabandi* ids used water from these wells, either as owners (23%), share tenants of tubewell owners (14%), or buyers (53%).[9] Because of conveyance losses, most farmers use water from the nearest one or two tubewells. Farmers in the tail-reaches of the watercourse, where the closest tubewell is more than 650 meters away, may be excluded from groundwater use altogether; 6 of the 11 *warabandi* ids who never used groundwater are located in this area.

Figure 2 shows the overall weekly pattern of irrigation supply from groundwater, canal water, and rainfall in Fd14R during the survey period (April 1994-October 1995). Notice that much more irrigation water is applied during *kharif* season than during *rabi*, even after controlling for rainfall which peaks during the July-August monsoon. Groundwater use is most intensive shortly after the monsoon, with the competing demands of cotton and sugarcane in the *kharif*, but there is also a brief flurry of tubewell activity in May coincident with cotton sowing. Canal water supplies have no regular pattern, as diversions can occur at any time. An exception is the scheduled canal closure beginning in January for desiltation and maintenance. During these five weeks of the *rabi* season, wheat must be irrigated mainly with groundwater. Lastly, note that canal water supplies were relatively plentiful in *kharif* 1994 compared to *kharif* 1995, whereas the situation with rainfall was the reverse.

III. Groundwater Monopoly, Tubewell Tenancy, and Price Discrimination

Environment

Our analysis of market power focuses on the ability of tubewell owners to price discriminate across two types of water buyers: their own tenants and everyone else in their market territory. Understanding why such price discrimination is profitable and what form it takes requires modeling the behavior of:

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[9] Owners typically use water from their own well, and share tenants typically purchase water from their landlords' wells. Occasionally, however, both sets of farmers also purchase water from other tubewell owners.

- Tubewell owners (*O*), who may cultivate some of their own plots adjacent to the tubewell and rent or sharecrop out others;
- Tubewell tenants (*T*), i.e., share-tenants of tubewell owners;[10]
- Other groundwater buyers (*B*), who may be share-tenants of other landlords, owner-cultivators of nearby land, or renters.

We assume that groundwater is extracted at constant marginal cost, c, and that capacity constraints on groundwater pumping are never binding. The latter assumption is explored in Section V. There we also show that groundwater prices are essentially fixed over the course of the season. Given constant marginal cost and non-binding capacity constraints, the absence of peak-load pricing is perhaps unsurprising. Whatever the reason, this institutional feature is taken as given in our analysis. The model below is therefore static, with water prices, p, agreed upon at the beginning of each season.

Each farmer cultivates one unit of land with the same technology, given by a neoclassical production function, f. For the moment, f is assumed to depend only on the water input w and we ignore other sources of water (canal irrigation and rainfall), so that w refers only to groundwater. We also abstract from production risk. Note that we do not specify a separate technology for each crop cultivated, so that a farmer may reduce his water use, not only by using less water on a given crop, but also by substituting away from water sensitive crops. After normalizing the price of output to unity, profit from farming is given by $\pi = f(w) - pw$.

Pricing groundwater to non-tenants

The pricing decision of the tubewell owner with respect to buyers who do not have a tenancy contract with him is straightforward. The owner's problem is

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[10] We ignore the case of farmers who rent (as opposed to sharecrop) land of the tubewell owner. In the simplest model outlined below, the tubewell owner should charge the same price for groundwater to these farmers as he does to his share-tenants because he can extract all the surplus through the fixed rent. There are, however, no cases of such farmers in Fd14R.

$$\underset{p}{Max}(p-c)w^*(p) \quad s.t. \quad w^*(p)=\underset{w}{\arg\max}\{\pi\} \tag{1}$$

which yields the standard single-price monopoly (interior) solution

$$p_B - c = \frac{-w^*(p_B)}{w^*_p(p_B)} \tag{2}$$

where the *p* subscript denotes partial derivative and $w^*_p < 0$. In this case, there is no price discrimination across other buyers by tenancy status; share-tenants and renters (of other landlords), as well as owner-cultivators all have the same demand curve for groundwater and hence face the same price p_B (we ignore incentive problems for now).

Pricing groundwater to tubewell tenants

Pricing to tenants of tubewell owners is complicated by the fact that the owner, as a landlord, receives a share of the tenant's output and also pays a share of the input costs, both of which depends on how much water the tenant uses. Denote the tenant's share of output by *s*, and assume that groundwater costs are also shared in this same proportion between tenant and landlord. This assumption is trivial in this single input model, but also happens to be consistent with the information in our production survey. We assume that *s* is a choice variable, even though in reality it rarely deviates from 0.5.[11] This is not necessarily a shortcoming of the theory, since there may be other, unobserved, ways that the landlord extracts his tenant's surplus, which can be modeled equivalently as through the choice of *s*.

A contract between tubewell owner and his tenant is, therefore, a pair (*p,s*) that solves

$$\begin{aligned}
&\underset{p,s}{Max}(1-s)f(w^*(p))+(sp-c)w^*(p) \quad s.t.\\
&ICC: \quad w^*(p)=\underset{w}{\arg\max}\{s\pi\}\\
&PC: \quad s\pi \geq \mu
\end{aligned} \tag{3}$$

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[11] Although only one well owner in Fd14R sets a quarter tenant share for output and for input costs, shares below 0.5 are more common in the broader study area.

In other words, the optimal contract maximizes the owner's income net of groundwater extraction costs, where income includes the owner's share of output as well as the tenant's share of the water cost. The owner also faces the tenant's incentive compatibility constraint, *ICC*, and the tenant's participation constraint, *PC*, where μ is the value of the tenant's outside option.[12] Note that $w^*(p)$ does not depend on *s*, because the tenant shares both its cost and benefit with the owner at the same rate.

The (interior) solution to (3) implies

Proposition 1: (a) $p_B > p_T = p_O = c$; (b) $w^*(p_B) < w^*(p_T) = w^*(p_O)$

Proof: see Appendix for part (a); part (b) trivial.

Part (a) just says that the tubewell tenant faces a two-part tariff (cf. Basu, 1987). The owner uses marginal cost pricing to generate maximal surplus and extracts the surplus, to the extent permitted by the *PC*, by adjusting the tenant's share. Since the tenant pays only *c*, by virtue of equation (2), we have that $p_B > p_T$ and $w^*(p_B) < w^*(p_T)$. In addition, if the owner cultivates land adjacent to his tubewell, his shadow price of groundwater is $p_O = c$, so that $w^*(p_O) = w^*(p_T)$.

Pricing groundwater with non-contractible inputs

The model presented thus far does not incorporate incentive problems that arise from the fact that some inputs, such as tenant effort, are prohibitively costly to observe and therefore cannot be specified in the tenancy contract. As we show next, accounting for non-contractible inputs (as in Braverman and Stiglitz, 1982) modifies some of the above conclusions.

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[12] The outside option may be to sharecrop land of someone who does not own a tubewell and earn $s\pi(p_B)$. In this case, which we do not pursue here, the groundwater pricing decision of each tubewell owner might impose an externality on all the other tubewell owners in the area. Namely, by setting a high p_B a given owner lowers μ and allows some other owner to reduce his tenant's share.

Let output be now given by $f(w,e)$, where *e* is tenant effort. Assume that effort and water are complements in production so that $f_{we} > 0$,[13] and that tenant utility is $u_T = s(f(w,e) - pw) - v(e)$, where $v' > 0$ and $v'' > 0$. Making the appropriate substitutions in (3) and solving for the optimal contract we obtain

Lemma 1: $p_T - c < \dfrac{-sw^*(p_T,s)}{w_p^*(p_T,s)}$

Proof: see Appendix.

The optimal contract, in general, no longer involves marginal cost pricing of groundwater. In the presence of the unobserved input, extracting the tenant's surplus solely by reducing his share, as above, exacerbates the incentive problem. On the other hand, raising the price of groundwater to extract surplus is costly because it reduces water use and effort, and hence output. The owner trades off the use of these two instruments. It is even possible that the tenant is charged *below* marginal cost for groundwater; that is, if water and effort are sufficiently complementary.

It would seem that tenants should still pay less for groundwater than other buyers because the owner has another method to extract surplus from the tenant besides raising *p*. However, lemma 1 does not allow a direct comparison between p_T and p_B without further restrictions on the technology. We therefore assume that $f(w,e) = \sum_{i=0}^{2}\sum_{j=0}^{2-i}\gamma_{ij}w^i e^j$, which is simply a second-order approximation to the underlying production function, and that $v(e) = \frac{\delta}{2}e^2$, where $\delta > 0$. These assumptions lead to a linear (in *p*) demand for water and deliver

Proposition 2: (a) $p_T < p_B$; (b) $w^*(p_B) < w^*(p_O)$

Proof: see Appendix for part (a).[14] Part (b) follows from the fact that $p_O = c$ and the owner faces no incentive problem when cultivating his own land, whereas $p_B > c$ and the buyer may also face an incentive problem if he is a share-tenant.

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[13] This assumption is difficult to test empirically, but it is hard to imagine that effort could be *substitute* for irrigation, in which case farmers could maintain their output in a drought by working harder.

Note that although the tubewell tenant is charged a lower price he does not necessarily use more groundwater than other buyers; it depends on the amount of effort supplied by the other buyers. If other buyers are on fixed rent contracts or cultivate their own land, they will supply more effort than the tenant of the tubewell owner and, if effort and water are strong enough complements, they could even demand more water.[15]

The model also implies that a tubewell owner may price discriminate among buyers who are not his tenants. As just pointed out, renters and owner-cultivators have a higher demand for water than sharecroppers because they do not face an incentive problem (assuming complementarity of water use and effort). Therefore, among his other buyers, the tubewell owner should charge share-tenants less.[16] Recall that in the absence of non-contractible inputs there should be no price discrimination across these other buyers.

We would still expect the tubewell owner to charge share-tenants of other landlords a higher price than he charges his *own* tenants. Intuitively, the sole reason for giving a tenant of another landlord a discount is the complementarity between water and effort, which reduces water demanded by the tenant. But this complementarity cuts both ways: The higher the complementarity, the greater the incentive to price groundwater cheaply to one's own tenant to extract greater effort from him.[17]

To sum up, both the model with and without non-contractible inputs imply price discrimination by the tubewell owner in favor of his tenant. Discrimination in favor of other

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[14] The proof assumes that the solution for p_B is interior in the presence of the unobserved input, which means that $c < f_w(0, e^*)$, where e^* is the chosen effort level when *w*=0 and *s*=1.

[15] Shaban (1987) finds that rented and owned plots in rural India are cultivated equally intensively, suggesting the incentives of owners and renters are similar.

[16] An alternative to the moral hazard model of tenancy is one of adverse selection, in which low productivity (i.e., ability) farmers are selected into sharecropping contracts (Hallagan, 1978). If ability and water use are complements, this model also delivers the implication that sharecroppers have a lower demand for water, and thereby face a lower price.

[17] Unfortunately, this proposition is difficult to demonstrate formally since it requires explicit solutions for price in the two types of tenancy contracts, one with groundwater market interlinkage and one without interlinkage. There is also the complication that in setting their respective contract terms the landlord of the non-interlinked tenant and the tubewell owner may take into account each other's actions.

share-tenants is also possible. In any case, owners of tubewells are predicted to use more water on their own land than any of their customers, with the possible exception of their own tenants.

IV. General Equilibrium: The Role of Canal Water Transactions

In the setting outlined thus far, unequal groundwater prices across users translate directly into allocative inefficiency. But groundwater is not the only source of irrigation; there is also surface water from irrigation canals and rainfall. In comparing total water use across farmers, these alternative irrigation sources must be taken into account. There are two complications, however. First, the timing of irrigation matters. Because tubewells are expensive to operate, groundwater is used mainly as a supplement during periods of peak water demand and of surface water shortage. Second, through the intertemporal exchange of irrigation turns described in Section II, canal water use is endogenous. While over the course of a season a farmer may end up giving as much canal water as he receives, the institution of canal water trading may affect the timing of irrigation within a season. In this section, we explore the implications of canal water trading for overall allocative efficiency.

The basic intuition comes from imagining the social planner's problem of allocating canal water within a watercourse, taking the allocation of *groundwater* as given. Suppose that the social planner is working under the constraint that each farmer must receive the same total canal water volume over the course of the season. During peak periods of water demand, when tubewell owners and their tenants obtain more groundwater than other buyers, the social planner will want to reallocate canal water from the former group to the latter group of farmers. During periods of slack water demand, when groundwater is seldom used, other buyers must repay this "loan" of canal water. Although all farmers use the same amount of canal water during the season, those farmers facing high groundwater prices are still able to meet much of their irrigation needs during the critical periods and thereby differences in crop yields across farmers are attenuated.

To formalize this argument, consider a simple two-period model of irrigation decisions within a season. Denote groundwater by x and canal water by z, and let $w = x + \gamma z$, where $\gamma > 1$ reflects the better quality of canal water. Since canal water is free at the margin, we assume that farmers decide how much groundwater to purchase only after receiving their canal water allocation. In each of the two periods, $t = H, L$, irrigation contributes to crop growth according the period-specific production functions $f_t(w)$, which are identical across farmers. We assume the productivity of water is higher in period *H* than in period *L*; i.e., $f'_H(w) > f'_L(w)$ for all *w*.

Consider two farmers, *i* and *j*, each of whom receives with certainty a canal water allocation each period, z^e_{kt}, $k = i, j \;\; t = H, L$.[18] Without loss of generality, assume that these allocations are the same across time and farmers so that $z^e \equiv z^e_{iH} = z^e_{iL} = z^e_{jH} = z^e_{jL}$. Note that canal water cannot be stored (i.e., in reservoirs). In this setup, farmers first agree on an actual canal water allocation $\{z_{iH}, z_{iL}, z_{jH}, z_{jL}\}$, and then, conditional on this allocation, each farmer makes his groundwater purchase decisions $\{x_{kH}, x_{kL}\}$ to maximize total seasonal profit $\pi_k = f_H(w_{kH}) + f_L(w_{kL}) - p_k x_{kH} - p_k x_{kL}$ (adapting our earlier notation). In assuming additive separability, we ignore any intertemporal link between productivity in the two periods; i.e. $f_H(w_H)$ does not depend on w_L, or vice-versa.[19] Given the choices of $\{x_{kH}, x_{kL}\}$, maximal profit conditional on the canal water allocation can be written as $\pi^*_k = \pi^*(p_k, z_{kH}, z_{kL})$.

We can now trace out the marginal value curves for canal water, $\partial\pi^*_k / \partial z_{kt}$. In each period, there is a critical value, $\bar{z}_t(p_k)$, below which a farmer will resort to purchasing groundwater (i.e., $x_{kt} > 0 \Leftrightarrow z_{kt} < \bar{z}_t(p_k)$). Moreover, $\bar{z}_t(p_k)$ is decreasing in p_k; the higher the price of groundwater the lower the supply of canal water must be to induce a farmer to purchase groundwater. At low canal volumes, farmers set $f'_t(w_{tk}) = p_k$ (recall that p_k is contractually fixed over the season), so that the marginal value curve is flat at p_k, until canal volume exceeds

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[18] As mentioned in Section II, daily canal water supplies are actually quite uncertain and part of the motivation for canal water trading could be risk-sharing, although the scope for risk sharing is severely limited by coordination problems and high covariance of shocks across neighboring farmers. For the purposes of our investigation here, risk is an inessential complication.

[19] Such dependence is certainly not implausible in the case of irrigation, but it would greatly complicate the theoretical analysis. Since the return to current groundwater and canal water use would in this case depend on all future irrigation decisions, the model would have to be solved backwards from the end of the season. Incorporating dynamics aspects of irrigation is a topic for future research.

$\bar{z}_t(p_k)$. From that point onwards, $x_{tk} = 0$, and the marginal value of canal water declines, since $f_t'' < 0$ (the decline is linear in the case of a quadratic production function).

So far, there is no gain from intertemporal canal water exchange between the farmers, since they have identical endowments and technology. However, suppose that farmer *i* faces a lower groundwater price than farmer *j* ($p_i < p_j$). It follows that $\bar{z}_t(p_i) > \bar{z}_t(p_j)$. Prior to any canal water trading, there are now two scenarios to consider: (1) neither farmer would use groundwater given their endowment ($\bar{z}_t(p_j) < \bar{z}_t(p_i) < z^e$); (2) farmer *i* would use groundwater, but not farmer *j* (($\bar{z}_t(p_j) < z^e < \bar{z}_t(p_i)$)).[20] Suppose that technology and water endowments are such that scenario (1) holds in period *L* and scenario (2) holds in period *H*. The marginal value curves corresponding to this situation are illustrated in Figure 3. During the low productivity period, the two farmer's marginal values of canal water are equated at the endowment. But when productivity is high, farmer *j*'s marginal value exceeds that of farmer *i* because, unlike farmer *i*, he does not use groundwater.

The equilibrium canal water allocation depends on the social norms or "rules" governing canal water transactions. As mentioned earlier, interviews with farmers in Fd14R reveal that these transactions are strictly exchanges of turns at the canal; no cash payments are involved.[21] If borrowing of canal water must balance lending over the course of a season, we have the constraint $z_{iH} + z_{iL} = z_{jH} + z_{jL}$. A different interpretation of the trading convention is that, though only in-kind transactions are permissible, the rate of intertemporal exchange is not necessarily one. In other words, there may exist an implicit "price" κ such that $\kappa z_{iH} + z_{iL} = \kappa z_{jH} + z_{jL}$. Indeed, one might expect that canal water is considered more valuable in period *H* so that $\kappa > 1$. Another possibility is that, field reports notwithstanding, there is in fact

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[20] A third possible scenario is that both farmers would use groundwater ($z^e < \bar{z}_t(p_j) < \bar{z}_t(p_i)$), but this leads to the same outcome as scenario (2).

[21] While cash payments for canal water turns are occasionally observed in the region—typically when tail farmers sell all their turns for a season to upstream farmers because canal discharge is too low to reach the tail (see Strosser, 1997)—there were no instances of cash transactions in Fd14R.

an informal cash market for canal water. We discuss the implications of these alternative rules momentarily, but for now we focus on the strictest interpretation of canal turn exchange.[22]

Figure 3 illustrates the Pareto optimal allocation, i.e., the one which maximizes $\pi_i^* + \pi_j^*$ subject to the constraint imposed by the trading rule (see the Appendix). In period *H*, farmer *i* provides canal water to farmer *j*, but not enough to equate the two farmer's marginal values. In period *L*, farmer *j* returns the amount he borrowed, which drives farmer *i*'s marginal value below that of farmer *j*. These "wedges" between marginal values in each period arise from the constraint that all transactions must be in-kind.

We can contrast the equilibrium depicted in Figure 3, with one in which the intertemporal exchange rate is not one. If $\kappa > 1$, then the marginal value curves will be farther apart in period *H* than in period *L* and less water will be lent to farmer *j* than in the case where $\kappa = 1$. The case of an unfettered cash market in canal water is even simpler. Farmer *j* would purchase canal water from farmer *i* in period *H* until the marginal values of the two farmers are equated. There would be no trade at all in period *L*.[23]

In sum, regardless of the specific rules governing canal water transactions, the presence of this adjacent market mitigates the misallocation of irrigation water due to groundwater monopoly. In peak demand periods, more canal water is always directed to the farmers facing higher groundwater prices. As a result, differences in crop yield across tubewell owners/tenants and other buyers should not be as large as they otherwise would be. Of course, unless we know the parameters of the technology, we cannot directly quantify the efficiency enhancing role of canal water trading. The objective of the empirical work reported in the next section is therefore more modest: to assess whether such trading follows the pattern suggested by the theory and how much water is actually involved.

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[22] Our analysis assumes that the intertemporal constraint holds with equality, so that there is no "default". A more complete model of self-enforcing contracts with lack of commitment would not necessarily lead to a Pareto optimal allocation of canal water (see, e.g., Kletzer and Wright, 2000). It is unclear, however, that such a model would yield different empirical implications than the ones derived below.

[23] Empirically, these three cases are distinguishable by their implications for overall seasonal water use. In-kind exchange of canal water obviously implies that canal water use should be equal across farmers over the course of the season. In-kind exchange with $\kappa > 1$ implies that farmers facing higher groundwater prices would use *less* canal water over the season, because every hour of canal water that they borrow in peak periods must be repaid "with interest" in slack periods. A cash market for canal water would imply that those farmers facing higher groundwater prices would use *more* canal water.

V. Empirical Results

Groundwater pricing

Data are available on all 886 groundwater transactions that occurred in Fd14R over the 18 month period from the beginning of *kharif* 1994 to the end of *kharif* 1995. As mentioned earlier, this is primarily a cash market, and the price per hour of water pumped is recorded for each transaction along with any special terms.[24] While most transactions are straightforward purchases, the following special terms appear: (1) Only fuel costs charged to buyer (81 cases); (2) Buyer used own engine (54 cases); (3) Water given free of charge (9 cases); (4) Buyer used own fuel (7 cases). In the first three cases, the buyer is in effect getting a price discount. In case (2), the buyer--typically, an owner of another tubewell--brings his own diesel engine (and fuel) to the owner's bore hole and is allowed to extract water for free to use on his nearby plot. Tubewell tenants never receive these concessions and a given buyer may only get a discount occasionally, paying the full cash price most of the time. We include a dummy variable in the regressions for cases (2) and (4) to control for the element of "self-service". Finally, the transaction prices recorded for tubewell tenants already reflect the tenant's cost share (i.e., it is sp_T rather than p_T). Therefore, we double the prices of half-share tenants and quadruple those of quarter-share tenants to get comparable prices for all buyers.

Each of the price regressions reported in Table 1 includes tubewell fixed effects to control for, among other things, variation in water quality and hourly volume (due to differences in pipe width), as well as season of transaction dummies. Specification (1) shows that tenants of tubewell owners pay significantly less for groundwater coming from their landlord's tubewell. A crucial question is whether this price discount is specific to tubewell tenants or rather applies to sharecroppers in general. Specification (2), therefore, controls for both the proportion of cultivated land sharecropped in and owned by the buyer (rented in land is the omitted category). Evidently, only tubewell tenants, and not other tenants, receive lower prices, since the proportion of sharecropped land is not significant. The estimates also show that tubewell owners do not price discriminate among their other buyers according to tenancy status. Sharecroppers, owner-

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[24] Payments are not necessarily immediate. In the case of tubewell tenants, the owner usually keeps track of what his tenant owes him and only asks for payment at the end of the season. Thus, there is a minor credit element in the price to tenants, meaning that their effective price is slightly lower than what is recorded in the data.

cultivators, and renters all pay about the same for groundwater, and each pays more than tubewell tenants. The absence of price discrimination among these other buyers casts doubt on the importance of non-contractible inputs in explaining groundwater pricing.

Only eight of the tubewells in Fd14R (comprising 602 transactions) sell to both tenants and nontenants and thus contribute to the estimation of the price differential in the tubewell fixed effects specifications. Allowing for different degrees of price discrimination across these eight tubewells, as in specification (3), uncovers considerable heterogeneity. In particular, five of the tubewells have highly significant tenant price differentials of between 9 and 22 Rupees/hour, while the other three tubewells do not seem to price discriminate at all. Unfortunately, there are not enough tubewells to allow us to understand why pricing behavior differs; the watercourse map in Figure 1 reveals no obvious spatial characteristic of the nondiscriminating wells.

Spatial characteristics are potentially important though in explaining groundwater prices, and ignoring them could bias our results. First of all, because they farm the land of the tubewell owner, tubewell tenants tend to be closer to their source of groundwater than other buyers. In the simplest model of section III, without non-contractible inputs and with linear demand, the price to other buyers falls with distance, because the elasticity of demand rises with transport costs, whereas the price to tubewell tenants is fixed at c and hence should be independent of distance (the implications of the model with non-contractible inputs are less clear-cut). A second spatial consideration is position in the watercourse. Since farmers in the tail-end of the watercourse receive less canal water due to conveyance losses than farmers at the head, they should have a higher demand for groundwater and be willing to pay a higher price. Again, in the simple model, distance to the head of the watercourse should only affect the price charged to nontenant buyers.

Specification (4) investigates these spatial issues by including distance between the plots of the buyer and the tubewell he purchases from, as well as distance to the head of the watercourse. Both distance variables are also interacted with tubewell tenancy status. Since distance between buyer and seller may be endogenous with respect to price--i.e., buyers choose which tubewell to purchase from (and hence distance) based on unobservable buyer-seller match characteristics that may be correlated with price--we estimate specification (4) by 2SLS, using the distance to the *nearest* tubewell as an instrument. None of the distance variables are statistically significant in Table 1 (neither are the unreported OLS estimates). This is not to say that distance is unimportant, as farmers clearly tend to buy from nearby tubewells. Rather, distance is evidently not an important determinant of groundwater demand conditional on the choice of tubewell.[25] We provide more evidence on this point in our analysis of quantity.

Returning to some of the other explanatory variables, the season of transaction dummies are insignificant in all specifications, indicating that prices were fairly stable over the sample period. We also check for peak-load pricing *within* seasons by including a measure of aggregate groundwater demand; namely, the total operating hours of all tubewells in the watercourse on the day of each transaction (much of which goes to the fields of tubewell owners). This variable has no significant impact on the price paid that day, which confirms the point made earlier that prices are fixed throughout the season. This finding is also consistent with the view that capacity constraints in groundwater extraction are inconsequential; sellers do not need to use price to ration quantity in periods of high demand. However, given the importance of this issue for our interpretation of the evidence, we explore tubewell capacity constraints in more detail next.

To sum up, we find strong evidence of price discrimination in favor of tubewell tenants, a finding that persists even after controlling for distance between buyer and seller. Although there is considerable heterogeneity across tubewells, a given owner charges an average of about 9 Rupees/hour more to other buyers than he does to his own tenant, which is quite a lot given that other buyers pay an average hourly price (adjusted for contract terms) of 32 Rupees/hour. It remains to be seen whether and by how much this price distortion affects resource allocation.

Do higher prices reflect greater 'reliability'?

Our interpretation of the price differentials in Table 1 as evidence of monopolistic behavior is based on the premise that the groundwater is a homogeneous commodity. While it is true that water is water regardless of who uses it, the timing of water delivery may matter. If it is important to a farmer that he receives water on certain days *and* capacity constraints are at least occasionally binding, then he would be willing to pay to avoid the possibility of being rationed out on those days.[26] Thus, a buyer may contract with a tubewell owner to be near the top of the

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[25] Another possibility is that the distance variables are picking up the density of neighboring tubewells and hence the degree of local competition. Thus, buyers farther away from their source of groundwater face less competition and a higher price, rather than a lower price as argued above. Unfortunately, the limited spatial variation in the data and the high correlations among spatial characteristics make it difficult to distinguish the impact of local competition.

[26] One reason for wanting groundwater on certain days is that farmers often mix it with canal water during their scheduled turn. During *kharif* 1994, nearly one-third of the days on which groundwater was used coincided with the farmer's canal turn.

water "queue" on full capacity days, in exchange for which privilege the buyer agrees to pay a higher fixed price. If tubewell tenants care less about reliability,[27] then they will pay lower prices than other buyers, which might explain the observed price differential.

To assess the relevance of this reliability hypothesis, we examine data on daily tubewell use for the same 18 month period used in our price analysis. If other buyers are favored in the daily queue over the tenants of tubewell owners, then we should see that the fraction of groundwater pumped by a given tubewell on a given day that goes to other buyers is higher when that tubewell is being operated at or near capacity, and the fraction going to tubewell tenants is lower. There are only a handful of days in our sample on which a tubewell operates at maximum capacity of 24 hours. However, on about five percent of the 1,069 tubewell operating days over this period, a tubewell was running for a total of 16 hours or more.

Table 2 presents OLS regressions for both the proportion of daily pumping hours going to tubewell tenants and to other buyers (note that 44 percent of groundwater goes to tubewell owners themselves). The regressions include tubewell fixed effects. We use a three-piece linear spline in total daily hours with knots at 8 and 16 to capture nonlinearities (a four-piece spline yields identical conclusions). Also included in the regressions is the total number of users at the tubewell that day. This variable corrects for the possibility that the proportion of tenant (other buyer) hours might diminish (increase) in total hours merely because most tubewell owners in Fd14R have only one or two tenants, so that high output days tend to have more non-tenant users.

The evidence is not favorable to the reliability hypothesis. Although the point estimate indicates that the proportion of tenant hours is diminishing in total hours on days when the tubewell is operating at 16 or more hours, this coefficient is not nearly significant. Moreover, the corresponding coefficient in the regression for the proportion of other buyer hours is *also* negative (and also insignificant). If the reliability hypothesis were true, we should observe that other buyers receive relatively *more* groundwater on near full capacity days. Similarly, there is no significant relationship between total hours and distribution across the two groups at the

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[27] It is not clear why this might be. Tubewell tenants actually grew more sugarcane in *kharif* 1994 than other buyers, and sugarcane has particularly high water requirements (more on this later), which might argue for tubewell tenants caring *more* about reliability.

intermediate level of tubewell use, 8-16 hours (42 percent of operating days).[28] In sum, it does not appear that price differentials between tubewell tenants and other buyers can be explained by differences in service reliability.

Use of groundwater

We analyze groundwater use per acre separately for the three seasons covered in our data, including all plots in the watercourse, even those that relied solely on canal water or were left entirely fallow (as these may be irrigated in preparation for sowing of the next season's crop). Each regression includes indicators for whether the cultivator of that plot is a tubewell owner or a tenant of one during that season, the omitted category being a (non-tenant) buyer. Since farmers, particularly those with large plots, often use more than one tubewell to irrigate a single plot to minimize conveyance losses, we calculate volume share-weighted averages of the tubewell owner and tubewell tenant variables across all the tubewells used on that plot over the season. As in the price regressions, we also control for tenancy *per se*; i.e., the proportion of land sharecropped and owner-cultivated.

It is also important to control for canal water used during the season (rainfall does not vary across farmers). Since canal turns are actively traded in Fd14R, seasonal canal water use is not necessarily exogenous; unobserved water productivity shocks that influence groundwater demand may also influence canal water use. A natural excluded instrument in this case is the canal water endowment, since it is clearly uncorrelated with the productivity shock yet highly correlated with canal water use, given imperfect insurance of idiosyncratic canal water supply risk. Lastly, we include two potentially important spatial characteristics in the regressions: distance to the nearest tubewell and distance to the head of the watercourse. Although these two variables are highly correlated (*rho* is about 0.7), the latter should capture the extent of conveyance losses in the delivery of canal water, and possibly local tubewell density as well.

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[28] The fact that total daily hours appears in the denominator of the dependent variable and as a regressor may create a division bias if total hours are measured with error. As a result, the coefficients on total hours may be biased downward. However, this bias would be present both in the tenant and other buyer regression and, for this reason, would not explain our findings. That is, if the reliability hypothesis were true, we should find a significantly negative coefficient on total hours for tenants and a positive coefficient for other buyers. Division bias might make the latter coefficient insignificantly different from zero (though hardly negative given the general accuracy of the data), but then it should make the former coefficient even more negative, which is not what we observe.

Table 3 presents the groundwater use regression results. The main finding is that tubewell owners and their tenants use significantly more groundwater per acre than other buyers in all three seasons. The result for tubewell tenants is consistent with our earlier evidence that these tenants face lower prices than other buyers. Moreover, there is never a significant difference in groundwater use between tubewell owners and tenants. This implies that the two groups face roughly the same shadow price of groundwater, a key result that we use later. It is also important to note that sharecroppers who are not tubewell tenants and owner-cultivators who are not tubewell owners do not use significantly more groundwater than other farmers. This finding is again consistent with the results from the price regressions showing no price discrimination by tenancy status for buyers who are not tenants of the tubewell owner.

A Smith-Blundell test for the exogeneity of canal water only rejects for *kharif* 1995, so we report the two-stage tobit estimates only in this case. In fact, canal water only has a significant impact on groundwater use for *kharif* 1995, and it is negative as should be expected. Evidently, there is not as much variation across plots in the amount of canal water received over the entire course of the other two seasons. However, as Figure 2 suggests, the situation is likely to be very different at the weekly frequency. We explore intraseasonal patterns of canal water trading in more detail below.

The two distance variables have negative coefficients in Table 3, but are rarely significant. Again, these variables are highly correlated and the sample sizes are not large, which is why we do not also include interactions with the tenant and owner variables as in the price regressions. If distance to the head of the watercourse captures only conveyance losses in canal water delivery, then its coefficient should be positive, since farmers in the tail-end should have a higher demand for groundwater. Apparently, though, this variable is also picking up the absence of tubewells in the tail of the watercourse (see Figure 1), which is not fully captured by distance to the nearest tubewell.

Finally, note that we do not control for crop composition in Table 3, since crop substitution is just one of the ways farmers may respond to higher groundwater prices. As mentioned earlier, cotton and fodder are the main *kharif* crops, wheat and *rabi* fodder are grown during the *rabi* season, and sugarcane spans both seasons with a growing period from February through December. Of these crops, sugarcane is by far the most water intensive, with the bulk of its irrigation applied in the *kharif* season. The water "requirement" for cotton is almost twice as high as that for wheat (Strosser, 1997). We find some evidence that tubewell owners and their tenants devote a higher proportion of their land to sugarcane than do other groundwater buyers, while the evidence for cotton is less conclusive. In any case, it turns out that controlling for crop composition has little effect on the results in Table 3 (see Appendix Table A.1), except for a modest diminution of the tubewell tenant coefficients in both of the *kharif* seasons.[29] This result suggests that most of the response to monopoly pricing of groundwater occurs at the intensive margin; i.e., less water for a given crop.

Summing up this analysis, we find a large and significant difference between the groundwater use of tubewell owners and their tenants, taken together, and that of other buyers. In *kharif* 1994, for example, the predicted effect of converting a pure nontenant buyer into a pure tubewell tenant is to augment his groundwater use by 623 m^3/acre, which is about a one and a half fold increase. Given that other sources of irrigation do not substitute for this discrepancy, there appears to be a substantial resource misallocation; whether the associated deadweight loss is also large is a question we address in the next section.

Canal water trading

For the analysis of canal water transactions, the natural unit of time is the week since each plot (i.e., *warabandi* id) is assigned one turn at the canal every week. Virtually all transactions take place around the time of the farmer's turn. For example, if a farmer wishes to augment his weekly allocation, he usually does so by extending his turn either earlier or later than scheduled, typically by asking the farmer who goes before or after him, as the case may be, for some extra time. More complicated trades occur, but rarely, between farmers separated by some distance, requiring each of the intervening farmers to shift the times of their canal turns.

Each week, in each of the three seasons, we have the minutes of canal water actually used by each *warabandi* id as well as the minutes entitled to under the official *warabandi* schedule.[30] Though recorded exchanges involve as little as one minute of irrigation time, farmers frequently trade away their entire weekly endowment. We convert canal time into water volume using

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[29] The crop portfolio variables are not entirely accurate in *rabi* because the proportion of land devoted to sugarcane is not accounted for in that season; sugarcane may be irrigated in the *rabi*.

[30] Since each turn at the canal begins at a different point in the calendar week, we start counting the week at the start of each turn. Therefore, any given "week" starts seven days later for the last *warabandi* id in the watercourse than it does for the first.

information on the daily discharge at the head of the watercourse, and normalize by cropped area for each *warabandi* id. Canal water transactions occur in 47 percent of the weekly observations during *kharif* 1994, involving about 11 percent of total water volume in the watercourse in the average week; during *rabi* 1994-95, transactions occur in 46 percent of the id-weeks (12 percent of total water volume); and during *kharif* 1995 this number rises to 54 percent (16 percent of total volume).

The general equilibrium analysis of the previous section implies that farmers facing higher groundwater prices should be net recipients of canal water in peak periods of water demand, whereas tubewell owners and their tenants should be net givers in these periods. In the context of our model, "peak" periods are precisely those with high aggregate groundwater use. Thus, within each season, we rank weeks according to the total amount of groundwater used in Fd14R based on the data that underlie Figure 2. Our first indicator, **peak I**, comprises 6 of the 22 weeks in *kharif* 1994, 5 of 25 weeks for *rabi* 1994-95 (excluding the canal closure period), and 7 of the 22 weeks in *kharif* 1995. A variable threshold insures the maximum contrast between peak and non-peak weeks. **Peak II** uses a much more stringent definition, consisting of only the two weeks of highest groundwater use each season.

Table 4 reports OLS regressions for the net volume of canal water per acre received on each plot or *warabandi* id in each week (i.e., use minus endowment). Included in the regressions are *warabandi* id fixed effects, the peak period dummy, and the tubewell ownership and tenancy indicators (volume share-weighted averages across all the tubewells used on the plot over the season) interacted with the peak period dummy. Standard errors are problematic because of cross-sectional dependence. Since farmers mostly trade with their nearest neighbors, there is negative contemporaneous correlation in the residuals of adjacent *warabandi* ids, but not necessarily across ids some distance apart. Driscoll and Kraay (1998) propose a standard error correction suitable for panel data that allows arbitrary spatial dependence across all cross-sectional units as well as serial correlation within units. We report t-values based on these standard errors along with the usual robust t-values in Table 4; both sets are similar.

The results in Table 4 generally support the implications of the theory, though statistical significance is not overwhelming. Relative to other groundwater buyers, tubewell owners and their tenants trade away more of their canal water in peak periods than they do in non-peak periods, hence the negative coefficients on the interaction terms in all seasons. **Peak I** appears to be more relevant than **peak II** in *kharif* 1994 and *rabi* 1994-95, but not so in *kharif* 1995. We discuss the economic significance of these findings in the next section.[31]

VI. Implications and Conclusions

Rural institutions and resource allocation

This paper explores the role of two distinctive institutions, tenancy and informal markets, in the allocation of irrigation water. Sharecropping is often viewed as inefficient because of the moral hazard problem. Indeed, Shaban (1987) finds persuasive evidence from India that input use is less intensive on sharecropped land than it is on owned land. By constrast, our findings suggests that in a monopolized input market, such as that for groundwater, interlinked tenancy contracts actually enhance efficiency. Tubewell tenants use about as much groundwater per acre as their landlords do, and both sets of farmers use more than do other groundwater buyers. Since the shadow price of groundwater to the tubewell owner is presumably the marginal extraction cost, we conclude that the tubewell tenant is essentially being charged marginal cost, whereas other buyers are being charged above marginal cost.

We also find that incentive problems do not influence groundwater pricing and use decisions. In a model with noncontractible effort, in which irrigation water and effort are complementary in production, tubewell owners should charge lower prices not only to their own tenants, but to the tenants of other landlords as well. However, we find neither groundwater price nor use differentials among other buyers according to their tenancy status. This result does not necessarily imply that moral hazard is absent; rather, it may only mean that the complementarity between irrigation water and effort is weak or nonexistent.

The second rural institution investigated in this paper is the informal market for canal water. The "informality" of this market derives from the fact that canal turns are borrowed without an explicit commitment to repay. Our empirical analysis is limited to the question of whether, given the observed groundwater price differentials between tenant and nontenant

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[31] To address the question of which trading rule governs canal water transactions, we also regress the net volume of canal water received per acre over the whole season on the tubewell tenant and tubewell owner indicators. In none of the seasons is either coefficient significant, which implies that $\kappa = 1$ --i.e., there is no premium on peak period water. Given the standard errors, however, it would be difficult to detect a small premium if one existed.

buyers, canal water transactions bring the allocation of irrigation closer to Pareto optimality. The answer appears to be "yes"; canal water is transferred from tubewell owners and their tenants to other buyers during peak periods of high water productivity and repaid in periods of low productivity. But, as discussed below, the practical impact of canal water trading is small. Future work using these data will focus on the broader implications of lack of commitment for the intertemporal allocation of canal water.

Efficiency and equity implications of groundwater monopoly

Is the deadweight loss from groundwater monopoly large enough to warrant concern? Our conclusion that tubewell tenants are being charged marginal cost for groundwater is consistent with a model without non-contractible inputs in which the monopolist uses a two-part tariff (cf., proposition 1). In this case, there is no deadweight loss involved in the allocation of groundwater to the tubewell tenant, only in the allocation to other buyers. We wish to compare the current situation in Fd14R with a scenario in which all groundwater is purchased at marginal cost, keeping in mind that some plots receive groundwater from multiple tubewells under different arrangements. This counterfactual would correspond to a policy of taxing each tubewell owner at the rate of $p_B - c$ for every hour of groundwater sold to other buyers and distributing the proceeds to the other buyers on a *pro rata* basis.

Assuming a linear demand for groundwater and using $p_T = c$, deadweight loss is given by $\frac{1}{2}(p_B - p_T)[w^*(p_T) - w^*(p_B)]$, where w^* refers strictly to groundwater use. Table 1 provides an estimate of the average $p_B - p_T$, namely 9.3 Rupees/hour, which we then convert into volumetric terms. To get $w^*(p_T) - w^*(p_B)$ for each plot, we take the groundwater use differentials estimated in Table 3 for *kharif* 1994 and *rabi* 1994-95 and multiply them by the change in (volume share-weighted) tenancy status required to produce the counterfactual scenario. The result is an annual deadweight loss of about 13,000 Rupees for the whole watercourse. This is a relatively small number, amounting to less than one percent of annual watercourse income (based on 71 cultivating farmers and using the figure for average household expenditures discussed below).

Our calculation ignores canal water trading, which the evidence suggests ameliorates deadweight loss. However, the estimates in Table 4 most favorable to this hypothesis, those for *kharif* 1994, imply that during six "peak" weeks only about 16 cubic meters per acre per week more of canal water are supplied to other buyers than on non-peak weeks, or about 100 cubic meters per acre for the whole season. This latter number is less than five percent of total irrigation water volume during *kharif* 1994 in Fd14R. The same calculation for *kharif* 1995 shows that trading reallocates less than two percent of seasonal irrigation. While this may be a very valuable two percent, it is still hard to imagine that canal water trading appreciably reduces the deadweight loss from groundwater monopoly, such as it is.

To assess the distributional implications of monopoly power, again consider the policy of marginal cost pricing. We calculate the implied surplus gain on each plot and then aggregate to the farm level for the *kharif* 1994 and *rabi* 1994-95 seasons. Also, using information on total groundwater sales by each tubewell owner over this period, we calculate the surplus loss to groundwater monopolists. Figure 4 plots each farmer's annual net surplus gain as a proportion of his imputed household expenditures against his imputed expenditures.[32] Since expenditures are imputed solely on the basis of household landholdings, and more than a quarter of the households in Fd14R are landless, there is a large cluster of observations at the minimum expenditure level.

The story that emerges from Figure 4 is not consistent with the "water-lord" stereotype, in which a move to marginal cost pricing would benefit many poor farmers at the expense of a handful of wealthy tubewell owners. To be sure, net benefits decline relative to wealth and become negative as wealth increases, but the rate of decline is not dramatic. There are three factors militating against the water-lord scenario, at least in Fd14R. First, tubwell tenants do not gain at all from marginal cost pricing, and they tend to be small landowners or landless. Second, there are a few cases of tubewells jointly owned by two farmers, each with modest landholdings, and these farmers are net losers from the policy. Third, several tubewell owners with large landholdings are also buyers of groundwater on plots they rent or sharecrop in elsewhere in the watercourse, and so may even gain on net from marginal cost pricing.[33]

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[32] The imputation is done as follows: We use four years (1988-91) of household panel data from IFPRI's survey of rural Pakistan. The sample is restricted to 373 households in two districts in the Punjab. We regress median (over time) real household consumption expenditures on a quadratic in median total land ownership ($R^2 = 0.22$). Household expenditures are then imputed for our sample using data on household land ownership. Average imputed expenditures for the 71 farmers is about $500.

[33] One caveat is that in the long run the price of land and the terms of tenancy contracts will adjust to the policy. Rents on plots near monopolistic tubewells will increase so as to just compensate the cultivator for the surplus gain

We conclude that, even if it were feasible to achieve the first-best allocation of groundwater, the impact on both efficiency and distribution would be limited. Nonetheless, it is still worth considering alternative approaches to ameliorating the effects of monopoly power.

Natural monopoly

Local groundwater markets resemble natural monopolies. Tubewell installation cost are high relative to the financial resources of the typical farmer and marginal extraction costs for groundwater are essentially constant up to the capacity constraint of a tubewell. Therefore, given a sufficiently low density of tubewells, average costs are falling over the range of local market demand. Under these conditions, a policy of marginal cost pricing would result in too "few" tubewells unless installation costs are also subsidized (ignoring possible overexploitation of groundwater).[34] Increasing competition in the groundwater market through subsidization of tubewells, without the impractical price regulation, may be a more sensible solution to the monopoly problem. Since at least a third of the costs of installing a tubewell are sunk, groundwater markets are not fully "contestable". A subsidy equivalent to the cost of boring the well would eliminate the inherent advantage of extant tubewell owners. To reach poorer farmers, such a subsidy could be combined with a credit to cover the remaining fixed costs (mainly the diesel pump).

Other solutions to the monopoly problem involve changes in the ownership structure of either land or tubewells. For example, if a tubewell owner could be encouraged to purchase all the land in the "command area" of his tubewell, then he would perfectly internalize the deadweight loss associated with monopoly pricing. Whether he then sharecrops out some of this land to tubewell tenants (as is common in Fd14R), or rents it out, he should charge only marginal cost for groundwater. Indeed, the puzzle is why trade in land does not entirely eliminate monopoly pricing of groundwater through buy-outs of landowners who do not also own tubewells. One answer might be that the land market has been slow to adjust to the relatively new technology of groundwater extraction spurred by the availability of inexpensive diesel

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due to marginal cost pricing. Thus, it is the surrounding landowners, not necessarily the actual cultivators, who ultimately stand to gain from the elimination of their neighbors' monopoly power.

[34] In the Punjab, where water tables are falling, an additional tubewell or more intensive use of an existing tubewell raises the marginal cost of groundwater extraction for everyone else. In this context, groundwater monopolies, by restricting use, may actually be socially desirable, albeit inequitable.

engines in the 1980's; in fact, none of the tubewells in Fd14R were installed prior to 1987. Another answer may be that the situation is complicated by the fact that tubewell command areas often overlap and so the efficient distribution of land ownership is unclear.

The alternative to consolidating land ownership around a given tubewell is to divide tubewell ownership among several neighboring landowners (see Meinzen-Dick, 1996). Here, again, the question is why joint ownership has not happened already--only 3 of the 18 tubewells in Fd14R are jointly owned by two farmers. Evidently, there are significant costs to joint ownership, perhaps due to coordination problems or moral hazard. Interestingly, all three cases of joint ownership in Fd14R involve two brothers or father and son, between whom such costs are presumably low. In any case, before promoting joint ownership of tubewells (e.g., by targeting credit or subsidies to groups of farmers), more research is needed to understand the costs of sharing large capital investments.

All of this discussion may be obviated by the pace of recent developments. There were 15 tubewells in Fd14R at the start *kharif* 1994, and three more were installed during *kharif* 1995. A field visit in early 2000 revealed an additional 9 tubewells, thus nearly doubling the existing number in about five years. It would be surprising if such a dramatic increase in the supply of groundwater does not alleviate the misallocation of 1994-95, but this remains to be seen. If so, monopoly power in the groundwater market would only be an ephemeral problem, a "growing pain" in the transition to a new technology.

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Appendix

Since proposition 1 is a special case with $f_{we} = 0$ and $v \equiv 0$, we first prove Lemma 1.

Proof of Lemma 1: The Lagrangian for the problem is

$$L = (1-s) f(w^*(p,s), e^*(p,s)) + (sp - c) w^*(p,s) + \lambda\{s[f(w^*(p,s), e^*(p,s)) - p w^*(p,s)] - v(e^*(p,s)) - \mu\}$$

where the multiplier $\lambda \geq 0$. The first-order conditions imply

$$(p_T - c) w_p^*(p_T, s) = -(1-\lambda) s w^*(p_T, s) - \frac{(1-s)}{s} v'(e^*(p_T, s)) e_p^*(p_T, s) \qquad \text{(A.1)}$$

$$\begin{aligned} &(p_T - c) w_s^*(p_T, s) = \\ &(1-\lambda)[f(w^*(p_T, s), e^*(p_T, s)) - p_T w^*(p_T, s)] - \frac{(1-s)}{s} v'(e^*(p_T, s)) e_s^*(p_T, s) \end{aligned} \qquad \text{(A.2)}$$

From the tenant's maximization problem we have that $f_w(w^*(p_T, s), e^*(p_T, s)) = p_T$ and $s f_e(w^*(p_T, s), e^*(p_T, s)) = v'(e^*(p_T, s))$, which together imply that $e_p^*(p_T, s) < 0$ and $w_s^*(p_T, s) > 0$ given that $f_{we} > 0$.

From (A.1), we have (simplifying notation) that $p_T - c < -(1-\lambda) \frac{s w^*}{w_p^*}$. Thus, it is sufficient to show that $\lambda < 1$ at the optimum. (A.1) and (A.2) together imply

$$(1-\lambda) g(p_T, s) + h(p_T, s) = 0 \qquad \text{(A.3)}$$

where $g(p_T, s) = \frac{s w^*}{w_p^*} + \frac{f(w^*, e^*) - p_T w^*}{w_s^*}$ and $h(p_T, s) = \frac{(1-s)}{s} v'(e^*) \left[\frac{e_p^* w_s^* - e_s^* w_p^*}{w_s^* w_p^*} \right]$. Note that $h(p_T, s) < 0$, given an interior maximum for the tenant. (A.3) holds at any point on the contract curve, but the tubewell owner can always push his tenant to where the *PC* is binding by choosing the contract (p_T^*, s^*). At this point $\lambda^* > 0$. Now consider the contract $(\tilde{p}_T, \tilde{s})$ satisfying (A.1) and (A.2), where $0 < \tilde{s} - s^* < \varepsilon_1$, $0 < p_T^* - \tilde{p}_T < \varepsilon_2$, and with $\varepsilon_1, \varepsilon_2 > 0$ chosen arbitrarily small. Since this contract is strictly preferred by the tenant, the *PC* is non-binding and $\tilde{\lambda} = 0$. It then follows from (A.3) that $g(\tilde{p}_T, \tilde{s}) > 0$. Now since g is a continuous function and the two contracts are arbitrarily close, it must also be true that $g(p_T^*, s^*) > 0$. Hence, by (A.3), $\lambda^* < 1$. ||

Proof of proposition 1(a): The second term on the RHS of (A.1) and (A.2) vanishes and $f_{we} = 0$ $\Rightarrow$ $w_s^*(p_T, s) = 0$ $\Rightarrow$ $\lambda = 1$ by (A.2) $\Rightarrow$ $p_T = c$ from (A.1). ||

Proof of Proposition 2(a): The assumed technology allows us to write $w^*(p,s) = a(s) - b(s)p$, where $a(s)$ and $b(s)$ are functions of the γ_{ij} 's and of s. Let $\eta(s) = a(s)/b(s)$, which is the price at which water demand is zero. It is straightforward to show that $\eta(s) < \eta(1)$. From equation (2) $p_B - c = \eta(1) - p_B$, and from Lemma 1 $p_T - c < s\eta(s) - sp_T$. Therefore, to prove that $p_B > p_T$ it is sufficient to show that

$$c < \frac{1+s}{1-s}\eta(1) - \frac{2s}{1-s}\eta(s) = \eta(1) + \frac{2s}{1-s}[\eta(1) - \eta(s)]$$

This inequality holds by the assumption of an interior solution for p_B, which implies that $c < \eta(1)$. ||

Pareto optimal allocation of canal water:

Consider the general case $\kappa z_{iH} + z_{iL} = \kappa z_{jH} + z_{jL}$. The Lagrangian for the social planner's problem is

$$L = \pi^*(p_i, z_{iH}, z_{iL}) + \pi^*(p_j, 2z^e - z_{iH}, 2z^e - z_{iL}) + \omega[\kappa z_{iH} + z_{iL} - (2\kappa z^e - \kappa z_{iH} + 2z^e - z_{iL})].$$

Where ω is the multiplier. The first-order conditions are

$$\frac{\partial \pi^*(p_i, z_{iH}, z_{iL})}{\partial z_{iH}} - \frac{\partial \pi^*(p_i, z_{jH}, z_{jL})}{\partial z_{jH}} = 2\omega\kappa$$

$$\frac{\partial \pi^*(p_i, z_{iH}, z_{iL})}{\partial z_{iL}} - \frac{\partial \pi^*(p_i, z_{jH}, z_{jL})}{\partial z_{jL}} = 2\omega$$

With $\kappa = 1$, we have the case depicted in Figure 3.

In the case of a cash market, the social planner maximizes

$$L = \pi^*(p_i, z_{iH}, z_{iL}) - p_{cH}(z_{iH} - z^e) - p_{cL}(z_{iL} - z^e) + \\ \pi^*(p_j, 2z^e - z_{iH}, 2z^e - z_{iL}) - p_{cH}(z^e - z_{iH}) - p_{cL}(z^e - z_{iL})$$

where p_{ct} is the period-specific cash price of canal water. The first-order conditions are

$$\frac{\partial \pi^*(p_i, z_{iH}, z_{iL})}{\partial z_{it}} = \frac{\partial \pi^*(p_i, z_{jH}, z_{jL})}{\partial z_{jt}} \qquad t = H, L.$$

Note that *j*'s purchase decision maximizes $\pi^{*}(p_{j}, z_{jH}, z_{jL}) - p_{cH}(z_{jH} - z^{e}) - p_{cL}(z_{jL} - z^{e})$, which implies that $\frac{\partial \pi^{*}(p_{i}, z_{iH}, z_{iL})}{\partial z_{jH}} = p_{cH}$. Since $\frac{\partial \pi^{*}(p_{i}, z_{iH}, z_{iL})}{\partial z_{iH}} = p_{i}$, it follows that $p_{cH} = p_{i}$.

Table 1
Determinants of Groundwater Prices

	(1)	(2)	(3)	(4)
Tenant of tubewell owner	-8.45 (3.27)	-9.29 (2.83)	---	---
Tenant of tubewell #65	---	---	-11.7 (6.59)	-11.9 (2.52)
Tenant of tubewell #66	---	---	-1.79 (0.66)	-0.64 (0.10)
Tenant of tubewell #67	---	---	-0.66 (0.17)	0.40 (0.08)
Tenant of tubewell #73	---	---	-17.0 (8.87)	-18.1 (9.34)
Tenant of tubewell #74	---	---	-18.0 (11.9)	-17.7 (5.07)
Tenant of tubewell #75	---	---	-21.9 (12.7)	-19.7 (5.12)
Tenant of tubewell #77	---	---	1.30 (0.85)	0.58 (0.26)
Tenant of tubewell #133	---	---	-9.21 (5.68)	-9.57 (4.99)
Sharecropped (% cultivated area)	---	0.358 (0.12)	0.247 (0.09)	0.226 (0.08)
Owner-cultivated (% cultivated area)	---	-1.04 (0.38)	-2.66 (0.99)	-2.63 (0.97)
Buyer provided fuel	-15.5 (6.90)	-15.1 (6.36)	-13.0 (4.40)	-13.6 (4.88)
Buyer provided engine & fuel	-30.9 (19.4)	-30.6 (19.2)	-28.8 (15.1)	-29.4 (14.2)
Aggregate tubewell operating hours	-0.002 (0.17)	-0.003 (0.22)	-0.006 (0.53)	-0.006 (0.51)
Kharif 1994	-0.038 (0.05)	-0.113 (0.15)	-0.252 (0.38)	-0.187 (0.25)
Rabi 1994-95	0.147 (0.16)	0.129 (0.14)	0.330 (0.35)	0.382 (0.41)

Table 1 -- *continued*

Distance to tubewell [a]	---	---	---	0.146 (0.33)
Tenant × distance [a]	---	---	---	0.089 (0.18)
Distance to head of watercourse	---	---	---	-0.138 (0.44)
Tenant × distance to head	---	---	---	-0.033 (0.09)
R^2	0.615	0.617	0.662	0.660

Notes.-- Absolute t-values in parentheses, adjusted for clustering on individual buyer. Estimation by OLS unless otherwise noted. Dependent variable is price of groundwater in Rupees/hour. All regressions include a constant and tubewell fixed effects. Sample size is 886 transactions.

[a] Endogenous variable. Identifying instruments for 2SLS: distance to nearest tubewell and interaction of this distance variable with tenant.

Table 2
Reliability of Groundwater Supply

	Proportion of total daily hours received by:	
	Tubewell tenants	**Other buyers**
Spline:		
$0 <$ total daily hours < 8	0.0059	-0.0174
	(1.35)	(2.77)
$8 \leq$ total daily hours < 16	0.0024	0.0057
	(0.05)	(0.89)
$16 \leq$ total daily hours ≤ 24	-0.0148	-0.0114
	(1.06)	(0.57)
Number of users on day	-0.0126	0.1011
	(1.05)	(5.85)
Tubewell dummies: $F_{(17,1016)}$	78.5	15.1
R^2	0.581	0.266
Mean of dependent variable	0.226	0.338

Notes.-- Absolute t-values of OLS estimates in parentheses. Sample size is 1,069 operating days for 18 tubewells. Regressions include a constant and tubewell fixed effects.

Table 3
Determinants of Plot-level Groundwater Use

	Kharif 1994	*Rabi 1994-95*	*Kharif 1995*
Tubewell owner	759	392	948
	(3.57)	(2.87)	(7.15)
Tubewell tenant	802	686	732
	(2.49)	(3.13)	(3.47)
Sharecropped	-92	-99	-67
(% cultivated area)	(0.37)	(0.60)	(0.38)
Owner-cultivated	143	218	121
(% cultivated area)	(0.68)	(1.60)	(0.81)
Canal water use (m^3/acre)	0.049	-0.149	-1.09 [a]
	(0.45)	(1.16)	(2.02)
Distance to nearest	-35.4	-24.0	-11.0
tubewell	(1.27)	(1.29)	(0.66)
Distance to head of	-8.0	-14.8	-11.3
watercourse	(0.77)	(2.12)	(1.46)
H_0: equality of owner and tenant variables (p-value)	0.90	0.21	0.37
Log-likelihood	-651.9	-557.5	-532.8
No. censored observations	12	19	21
No. observations	93	92	91

Notes.-- Absolute t-values of ML tobit estimates in parentheses. Dependent variable is total groundwater use during season on plot (m^3/acre). All regressions include a constant. Owner and tenant variables are volume share-weighted averages across all tubewells used on that plot over the season.

[a] Two-stage tobit estimate. Excluded instrument is seasonal canal water endowment per acre.

Table 4
Analysis of Weekly Canal Water Transactions

	Kharif 1994		***Rabi 1994-95***[a]		***Kharif 1995***	
Peak period definition:[b]	**I**	**II**	**I**	**II**	**I**	**II**
Peak period	10.5	3.9	2.7	1.3	5.4	6.7
	(2.07)[c]	(0.54)	(0.85)	(0.21)	(2.40)	(2.21)
	[2.27][d]	[1.08]	[0.96]	[0.32]	[3.17]	[2.66]
Peak × tubewell tenant	-16.7	-6.2	-8.4	-5.9	-5.5	-10.3
	(2.05)	(0.63)	(1.68)	(0.80)	(1.10)	(2.38)
	[1.92]	[0.86]	[1.85]	[1.22]	[1.13]	[1.89]
Peak × tubewell owner	-14.7	-2.3	-5.7	-2.2	-4.0	-7.8
	(1.83)	(0.22)	(1.27)	(0.27)	(1.11)	(1.97)
	[2.03]	[0.44]	[1.17]	[0.29]	[1.72]	[1.78]
R^2	0.155	0.154	0.188	0.188	0.294	0.293
Observations	2046		2300		2002	
(ids/weeks)	(93/22)		(92/25)		(91/22)	

Notes.-- Dependent variable is net volume of canal water received in week per acre. All regressions include *warabandi* id fixed effects.

[a] Excludes period of canal closure (five weeks).

[b] Definition I: 6 weeks with highest overall groundwater use for *kharif* '94, five weeks for *rabi* '94-95, and seven weeks for *kharif* '95. Definition II: 2 weeks with highest groundwater use in each season.

[c] Robust (Huber-White) absolute t-values.

[d] Absolute t-values adjusted for spatial dependence and serial correlation (lag window = 2).

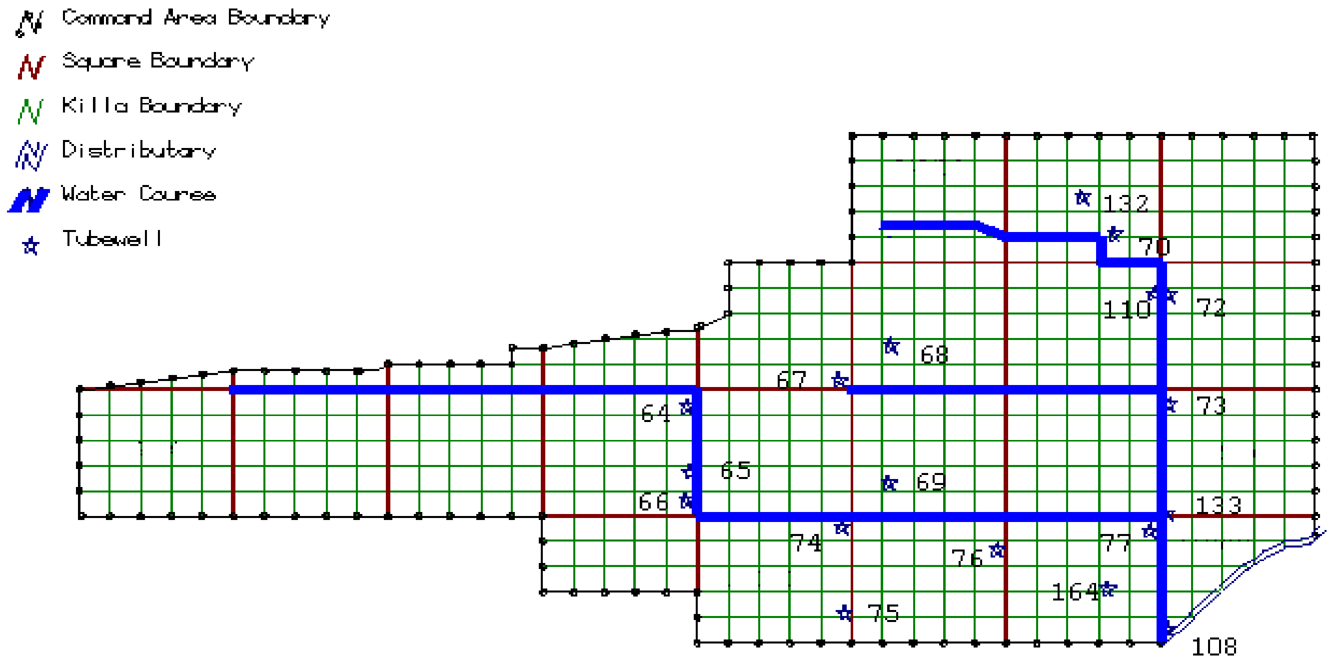
Table A.1
Determinants of Plot-level Groundwater Use Conditional on Crop Mix

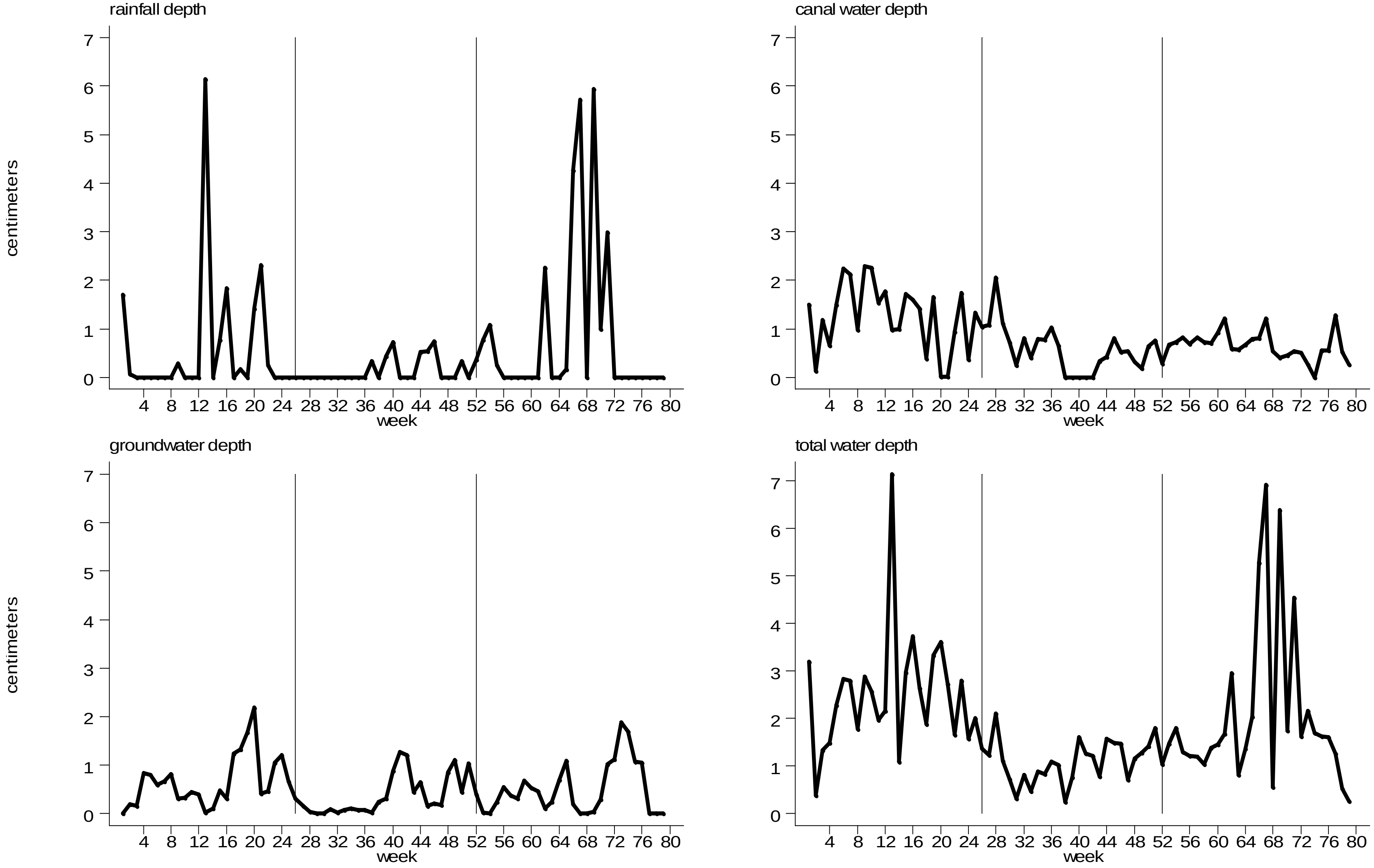
	Kharif 1994	*Rabi 1994-95*	*Kharif 1995*
Tubewell owner	685	404	938
	(3.22)	(3.00)	(7.02)
Tubewell tenant	556	714	532
	(1.60)	(3.31)	(2.60)
Sharecropped	76	-82	66
(% cultivated area)	(0.78)	(0.50)	(0.38)
Owner-cultivated	219	202	122
(% cultivated area)	(1.03)	(1.48)	(0.82)
Canal water use (m^3/acre)	0.043	-0.176	-0.85
	(0.36)	(1.32)	(1.70)
Distance to nearest	-40.7	-21.4	-1.42
tubewell	(1.44)	(1.15)	(0.08)
Distance to head of	0.3	-16.6	-5.4
watercourse	(0.03)	(2.38)	(0.78)
% area in cotton/wheat[a]	-309	275	181
	(0.36)	(1.15)	(0.47)
% area in sugarcane	333	---	499
	(0.36)		(0.91)
% area in fodder	-267	22	227
	(0.30)	(0.04)	(0.47)
% area left fallow	-886	-141	-719
	(0.87)	(0.47)	(1.52)
H_0: equality of owner and tenant variables (p-value)	0.72	0.18	0.08
Log-likelihood	-649.5	-555.4	-531.0
No. censored observations	12	19	21
No. observations	93	92	91

Notes.-- See notes to Table 3.

[a] Refers to cotton in the *kharif* seasons and wheat in the *rabi* season.

Figure 1. Fd-14R Watercourse Map





(vertical lines = season boundaries)

Figure 2. Weekly Irrigation Supply in Fd14R: Apr. 94-Oct. 95

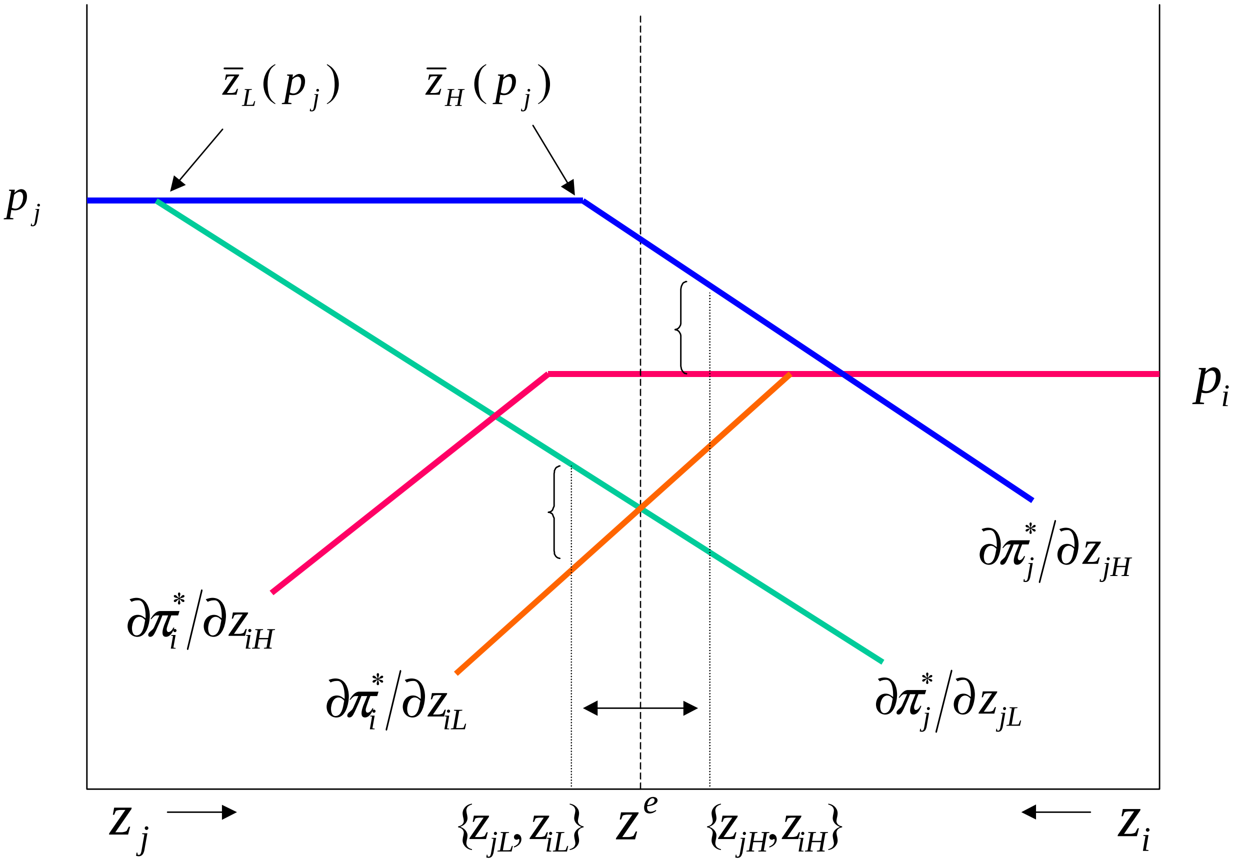


Figure 3. General Equilibrium in Canal Water Market

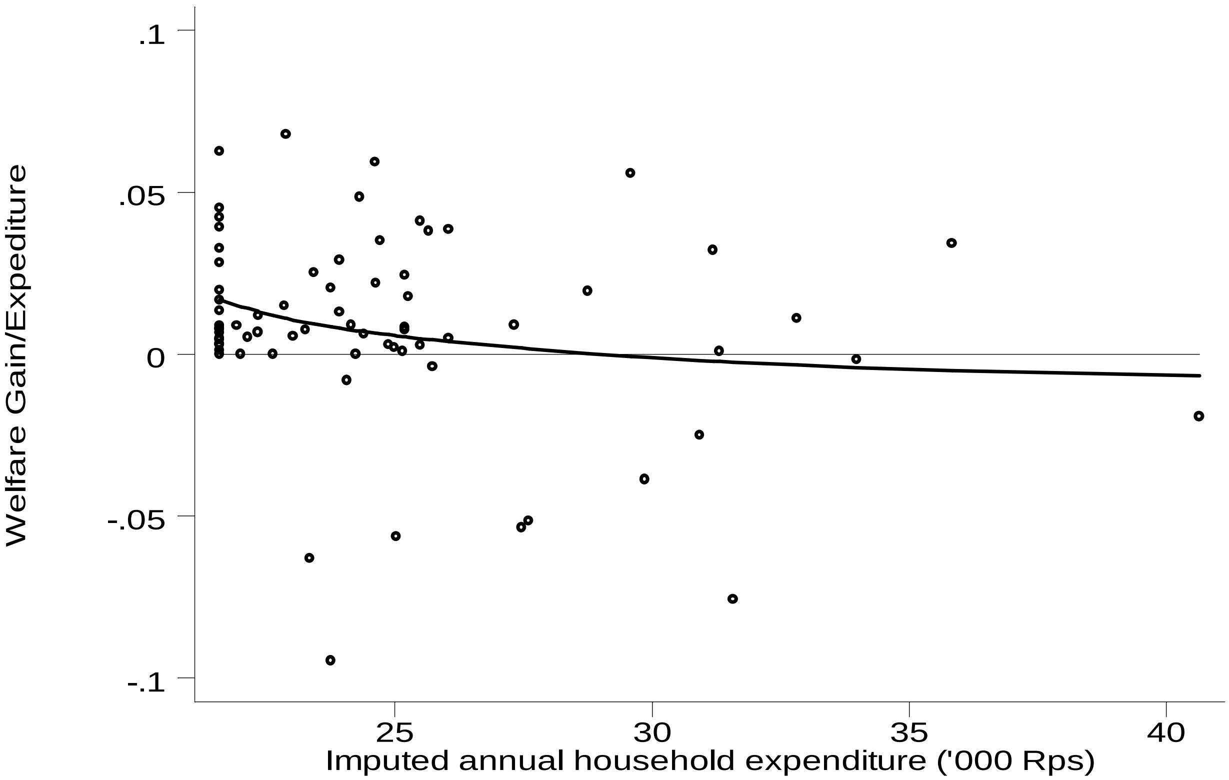


Figure 4. Distribution of welfare gains