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Inequality and the Sustainability of Agricultural Productivity Growth:
Groundwater and the Green Revolution in Rural India

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Although analysis of the extent and nature of the tradeoffs between economic growth, equity, and environmental sustainability might be considered to be at the core of economic development as a field, there have been few attempts to assess the relative magnitudes of these tradeoffs in a particular setting or context. This is perhaps not surprising. The difficulty of monitoring and regulating use that hampers effective market or non-market management of many natural resources also makes it difficult to efficiently collect data on a sufficiently large geographical and temporal scale to capture important differences in rates of productivity growth.

The case of groundwater (that is water pumped from below ground) use in the context of India seems a particularly relevant one in which to examine this set of issues. Although surface water has traditionally been the major supplier of water for India's crops, groundwater use has been the major source of growth in irrigated area in recent years, particularly in the those areas most impacted by the growth of high-yielding variety crops. In 1970, for example, surface water was responsible for more than 3 times as much wealth generation in agriculture than groundwater (Rs 77 billion versus Rs 21). By 1993, however, the ranking had reversed with 132 billion being generated by groundwater as opposed to Rs 115 billion for surface water. Groundwater now sustains 27 million hectares of farmland or almost 60% of irrigated area. Indeed it has been suggested that the primary value of much of the current surface infrastructure is in terms of its actual and potential value as a source for recharging underground aquifers. (IWMI 2002).

It is also clear that groundwater use has played a particularly important role as a vehicle for private investment in irrigation by small farmers. This is because in contrast to surface water, which typically involves significant public or community expense to build and maintain, the

extraction of groundwater can and typically is undertaken by an individual farmer by sinking a tubewell on his own land. The provision of the key inputs to well production - labor, pipes and pump sets - can in principle be provided by an efficient market-based system at the local level, encouraging innovation and cost minimization in this dimension. Indeed, such subsidies in the form of loans for private groundwater irrigation are argued to be a major tool for poverty reduction in some areas (IWMI 2002).

The enhanced potential for individual investment in groundwater irrigation clearly has benefits in terms of the extent to which it allows individual farmers to respond flexibly to changing economic opportunities and incentives. On the other hand it has a downside. The possibility of individual investment coupled with the fact that the underlying aquifer is effectively a public resource means that coordination problems are particularly acute. The public and visible nature of surface water distribution provides at least in principle a basis for monitoring individual resource use, even though this may not always be done in an efficient or equitable way (Bardhan and Dayton-Johnson, 2002; Bardhan 2000). However, public monitoring of private tubewell use would seem to present extraordinary challenges even in the best of circumstances.

It is not surprising, therefore, that over-exploitation of groundwater is potentially a major public policy issue that threatens to significantly constrain future growth in agricultural productivity. Bose et al (1998) report that only about 32% of annual utilizable groundwater potential in India is currently being used. However they also note that in some states due to the demands of the green revolution water tables have been over-exploited and water tables are declining. It is estimated that in Harayana average water table depth falls by 1-33 cm annually.

Because, as will be modeled below, well depth is affected by the rate at which extracted water is replenished from the local aquifer, time series data on well depth are a sensitive measure of the stress placed on local groundwater resources. Figure 1 plots tubewell depth by the year the well was built from a nationally representative sample of rural areas that will provide the basis of our analysis below. It is clear that over time tubewells have become significantly deeper.

Despite the emerging importance of groundwater as a public policy issue, there has been very little research by economists on the subject in general and, in particular, on how inequality in landholding impacts and is impacted by groundwater conditions and extraction. There has, however, been some interesting and important recent work on the issue on the efficacy of community management of surface water. Bardhan and Dayton-Johnson (2002) is particularly notable for its scope and detailed assessment of rules in a relatively large number of communities in two areas of Mexico and South India. They find evidence that these groups are most effective when they involve relatively homogenous groups in terms of landholding. Perceptions about for and by whom the rules were designed were also found to play an important role in determining compliance—compliance was low when it was perceived that rules were designed by the local elite and particularly low when they were designed by government officials.

One detailed study on groundwater management seems to highlight the particular difficulties in maintaining effective group ownership in the context of groundwater. In a study of two villages, Aggarwal (2000) found that existing water sharing arrangements tended to be the result of pre-existing single wells that had subsequently been shared among kin as a result of household division. However, new investments in tubewells by the individuals involved in these groups were individually rather than collectively exploited despite the obvious inefficiencies

involved with sinking a single wells on adjacent land. In explaining this choice, villagers reported the great uncertainty associated will with well digging and water supply and hold-up problems that arose when additional investment was needed but one individual was unwilling or unable to contribute. The importance of geographic proximity also limited the scope for efficient selection of group members as might occur, for example, in group-based lending.

There is also clearly not an effective water market in these regions. Aggawal attributes the ineffectiveness of water market as a result in part of a perception of the immorality of charging for a natural resource that in principle belongs to the community. Anderson's (2006) argues that caste-barriers play an important role in limiting access to purchased water across caste lines, a result that may help explain the especially low yields received by low-caste farmers in villages where high-caste farmers are the dominant landholders. Neither of these papers, however, explores the physical properties of groundwater extraction and how these properties may influence decisions about groundwater extraction by neighboring farmers. .

In this paper we develop a simple economic model of groundwater extraction that captures the relationships between growth in agricultural productivity, the distribution of land ownership, water table depth, and tubewell failure. The model highlights the role of well interference as a potential source of coordination failure among neighboring farmers. The model shows that the problem of the "tragedy of the commons" in the context of groundwater is unusual in the sense that, in addition to generating negative spillovers (farm profitability is decreasing in neighbors' groundwater usage), groundwater extraction exhibits strategic complementarity (groundwater use of an irrigating farmer is increasing in the groundwater use of his neighbors). The basic features of the model are then tested using a 30-year nationally-

representative panel of rural India that contains detailed data on household irrigation assets including, from the 1999 round, a history of tubewell construction and depth.

The results indicate that expansion in crop-productivity on irrigated land, for a given distribution of landholdings, leads to both a greater number of and deeper tubewells. We also find, consistent with the model, that large landowners are more likely to construct tubewells, that input use per irrigated area is declining in farmer total area, and that the largest farmers have disproportionately shallow wells given the level of their irrigated area. The results also indicate the presence of a “concavity effect” whereby a redistribution of land toward the center of the distribution leads to greater overall extraction of water resources—larger farmers use less water per irrigated area while smaller farmers do not find it profitable to sink wells. These results are indicative of a free-riding effect in the sense that large farmers are less able to effectively poach the water from neighboring farmers by lowering the water-table under their own lands. We also find evidence of land consolidation as might be expected given the incentives associated with groundwater extraction. We conclude by noting the evident tradeoffs that emerge between inequality, productivity growth, and environmental sustainability.

II. Theory

In order to capture the technological and strategic aspects of water consumption in the absence of a market for water as well to assess the implications for water consumption under different circumstances we develop a simple model of water extraction by neighboring farmers. The model integrates farmer behavior into a stylized model of well-interference that builds on a basic insight from mathematical hydrogeology known as the Thiem Solution. This latter solution describes, in the context of a stylized environment, how water extraction at one point affects

water levels in surrounding areas and thus can be used to characterize how the costs of water extraction on the part of one farmer are affected by the water extraction of other farmers. We show in particular that water flow from one farmer in the context of a Nash equilibrium is increasing in the water flow of a neighboring farmer and that the extent of coordination can be tested by relating distance between wells to well depth.

A key aspect of the model is that it emphasizes the short-term (hours) steady-state equilibria arising from well-interference but is set in the context of medium-term (multiple years) decision making about well construction and largely ignores the long-term (a decade or more) declines in regional aquifer levels. This approach, we believe, appropriately balances concerns of tractability, theoretical insight, empirical inference, and policy relevance. While the long-term declines in regional aquifers obviously play a critical role in terms of the long-term sustainability of groundwater resources, the decision making of individual farmers over such issues as what crops to plant and how much area to irrigate is primarily governed by the amount of groundwater that can be extracted during peak irrigation periods, when irrigation wells may be running more or less continuously during daylight hours. Over this time-frame the steady-state equilibrium in terms of water extraction by neighbors who are competing for local water resources, as emphasized in the model, is likely to be the key constraint. The availability of groundwater, in turn, is importantly governed by decisions about own well depth and how this relates to the well depth of neighboring farmers. But, given the fixed cost elements of drilling or extending a well, decisions about well depth must be made with concern for access to water resources over a number of seasons but without full knowledge of future trends in terms of the level of the aquifer or the behavior of farmers from other villages accessing the same watershed. Thus it is at least a

reasonable approximation to assume that farmers take the level of the regional aquifer as given in making well depth decisions. Moreover, it is precisely the individual farmer decisions about well-depth and pumping that in the long term will determine the state of the regional aquifer by influencing overall levels of water extraction. Thus while our analysis says little about optimal levels of water extraction from a regional perspective, it can help provide insight into the source of the problem and help in the design of policy to help protect regional aquifers.

II.a Well interference

The starting point of the analysis is to recognize that unlike water flowing through a river or over a waterfall, groundwater does not flow quickly from high to low areas. Because it is moving through a relatively dense but porous material (e.g., soil or sand) it moves slowly, with the rate being determined by a simple relationship known as Darcy's Law (1865). This law relates flow Q between points \mathbf{z} and $\mathbf{z}+\Delta$ (located on a plane) in units of volume per time

$$(1) \quad Q = AK (h_{\mathbf{z}+\Delta} - h_{\mathbf{z}}) / \|\Delta\|$$

where K is a constant of hydraulic conductivity (in units of volume per unit area), A is the cross-sectional area through which the water can flow, $\|\Delta\|$ denotes the distance between these points, and $h_{\mathbf{z}+\Delta}$ and $h_{\mathbf{z}}$ denote the hydraulic head at each point, that is the height at that point above some fixed reference the water would achieve in a non-pumping well.

We now turn to a description of the hydraulic head that arises around a well that is pumping at a constant rate. The basic insight here is that the hydraulic head will form a kind of cone centered on the well. Consider a simple world which a farmer i who sinks a well of radius b in the center of a circular island of radius R in the middle of a large lake (Figure 2). At a distance

of h_f units below the surface of the land is a flat impermeable (to water) barrier to water that constitutes the bottom of the aquifer and serves as the reference point. The lake is h_0 units deep, with the bottom of the lake coinciding with the bottom of the aquifer. The aquifer is assumed to be confined in the sense that lateral flow in the aquifer only is possible in the bottom h_q units of the aquifer.

It is assumed that water is pumped from the well at a constant rate w_i and that a steady-state is achieved. The symmetry of the problem ensures that steady state may be characterized by a function $h(x)$ that describes the hydraulic head at a distance x from the center of the island. The hydraulic head at the boundary of the island is fixed by the level of the lake at h_0 . To characterize the steady state at interior points, we use the fact that the conservation of mass dictates that for any cylinder of radius $x < R$ that extends between the ground and the bottom of the aquifer and is centered on the well, the amount flowing into that cylinder must equal the amount flowing out at each point of time in steady state. In particular, water flows into the cylinder through the boundary of the cylinder at a rate that is governed by Darcy's Law. As water is only flowing in the part of the aquifer below h_q the area A through which water is flowing into the cylinder is $2\pi x h_q$. The rate of flow over this boundary at any point in time is uniform and in the direction of the well. In particular, considering two points z and $z + \Delta$ that lie along a line extended outward from the center of the well with z at radius and $\|\Delta\|$ arbitrarily small, the rate of flow along that line toward the origin is

$$(2) \quad K(h_{z+\Delta} - h_z) / \|\Delta\| = K \frac{\partial h(x)}{\partial x}$$

per unit area. Thus the mass balance equation is at each point in space within the radius R is

$$(3) \quad w_1 = K \frac{\partial h(x)}{\partial x} 2\pi x h_q$$

Solving (3) subject to the boundary condition that $h(R)=h_0$ yields the Theim result for an confined aquifer:

$$(4) \quad h_0 - h(x) = \frac{1}{2\pi K h_q} w_1 \ln(R/x).$$

Note that, as illustrated in Figure 2, the hydraulic head forms a kind of cone centered around the point of the well.

In the case of multiple active wells that are in close proximity there will be well interference. That is the hydraulic head in the neighborhood of a given well will be affected not only by the extraction of water from that well but also by the extraction of water from neighboring wells. Exact solutions to this process are not available, and hydrogeologists have generally relied instead on numerical methods that discretize space. However, for the purpose of constructing a testable model of strategic interaction it is useful to have analytic expression that approximates well-interference.

We consider first the case of two wells and then extend this result to the N-well case. Figure 3 presents a numerically constructed contour map of the steady-state hydraulic head for two wells that are located over a circular aquifer surrounded by a circular constant head (the equivalent of the island presented above). As is evident from this graph, the hydraulic head consists of a large set of contours that encircle both wells and two sets of smaller contours surrounding the original well. The approximate model replicates this pattern by constructing three separate cones based on the Theim result that are smoothly linked along one dimension. Figure 4

provides a diagrammatic representation of this system. Assume that farmer 1 and 2 are located along a line P that passes through the origin with farmer 1 located t_1 units to the left of the center and farmer 2 t_2 units to the right of the center. The hydraulic head for each farmer i may then be approximated over the range $x^i \in [0, m_{ai}]$ for some m_{ai} in terms of the distance x^i from the respective well by a function $h^i(x^i)$ that solves the equivalent of (3)

$$(5) \quad w_i = K \frac{\partial h^i(x^i)}{\partial x^i} 2\pi x^i h_q^i$$

Assume, in addition, that everywhere else (e.g., outside of the two smaller cylinders around the wells) the hydraulic head is well approximated in terms of the distance x^c from the center of the island by a cylinder that solves the following differential equation.

$$(6) \quad w_1 + w_2 = K \frac{\partial h^c(x^c)}{\partial x^c} 2\pi x^c h_q^c$$

and that the joint between the upper and each of the lower cylinders must be continuous and differentiable along the line P. We show in the appendix that $m_{a1} = w_1 t_1 / w_2$ and $m_{a2} = w_2 t_2 / w_1$ and derive an expression for the hydraulic head at the location of a well. In terms of multiple wells, as long as all other wells on the island are located outside of the radius m_{ai} from well i and within a radius $m_{ai} + t_i$ of the center of the island, the same analytical structure can be justified with w_{-i}

¹The issue of overlap in the domain of the two well-specific cones will be addressed below but is, in any case, of secondary importance from the standpoint of deriving predictions about well depth.

representing total water extraction on all other farms.² In particular, the hydraulic head at well i may be approximated by

$$(7) \quad \delta_i = h_f - h_0 + \frac{1}{2\pi K h_q} (w_i \ln(Rw_i / ((w_i + w_{-i})b)) + w_{-i} \ln(Rw_{-i} / ((w_i + w_{-i})t_i)))$$

Note that in the limit as w_{-i} approaches zero the expression for (7) equals the well depth that would be obtained by evaluating the Thiem solution (4).

To establish how well this formula works in practice we applied standard numerical procedures to generate hydraulic head depths that could then be compared to the predictions of the analytic model. In particular, we randomly selected locations and depths for eight wells in a given “village”, which is assumed to be situated over a circular aquifer that is surrounded by a constant head.³ The resulting contour maps for two villages, including information on well locations, are presented in Figures 5a and 5b. It is evident that the basic structure consists of an overall bowl shape centered around the middle of the village with individual cones isolated around each of the individual wells. The simulated hydraulic head depths using the numerical and analytic procedures are presented for two villages in Figure 6. Although a linear fit line has a slope greater than 1 (slope=1.6, constant=8.22) the linear fit is very good (R-squared=.71).

The largest outlier is a case in which a well is located very close to the center of the village and

²Because the other wells are outside of m_{a1} they do not influence the shape of the lower cone associated with well 1 net of distance and total well pumped. Because they are inside of $m_{a1} + t_1 d$ they do not affect the shape of the upper cone net of these measures.

³Simulation parameters are as follows: $R=300$, $b=.1$, $h_a=20$, $K=3$, location is constructed by selecting distance and angle in radians from a uniform distributions over $[0,200]$ and $[0,2\pi]$, respectively and water extraction is selected from a uniform distribution $[500,1500]$.

in which the analytic model predicts too deep a head.⁴

II.b Farmer behavior

With these structures determined we now turn to an analysis of farmer behavior. We assume that there are N farmers in a particular watershed area and order these farmers by landsize from largest to smallest. Land for each farmer is assumed differentially suitable to being irrigated with the distribution of irrigatability being uniformly distributed over each farmer's total acreage. Profits per unit of land on unirrigated land are normalized to 1 while profits gross of the cost of water provision on the k^{th} unit of irrigated land on a farm with total land size a_i depends on the amount of water and inputs used per unit of irrigated land and the suitability of the land for irrigation

$$(8) \quad 1 + \theta f(w, z) - 2\varphi \frac{k}{a_i} - p_z z,$$

where θ denotes agricultural productivity on irrigated lands and φ the difference between the most profitable and least profitable land on a given farmer if irrigated and given the same level of inputs w and z . Thus if a farmer irrigates the most profitable r_i units of his land and employs w_i and z_i units of total water and inputs, respectively, total output on a farm of size a_i is

$$(9) \quad a_i + \theta r_i f\left(\frac{w_i}{r_i}, \frac{z_i}{r_i}\right) - \varphi \frac{r_i^2}{a_i}$$

⁴The source of the discrepancy is easily identified. In particular, the analytic model assumed that all wells other than i were inside the radius $t_i + m_{ai}$, a condition that is clearly violated for a well at the center of the village. Of course it is possible to adjust for this reality but making use of such information in practice would require data on actual well locations, something that is currently unavailable.

Note that this function exhibits constant returns to scale in water, irrigated area, inputs, and total area.

Water for irrigated agriculture may only be obtained from groundwater by sinking a tubewell into the aquifer beneath a farmer's land. The cost of sinking a tubewell of depth d_i has a fixed and variable component,

$$(10) \quad \tilde{p}_o + \tilde{p}_d d_i,$$

and is incurred only once. The production function for water incorporates the assumptions that water can only be obtained from a well if the depth of the well exceeds the water table at that location⁵

$$(11) \quad w_i = \tilde{w}(d_i, \delta_i, e_i) = \begin{cases} n_i / d_i & \text{if } d_i \geq \delta_i \\ 0 & \text{otherwise} \end{cases}$$

where δ_i is the hydraulic head at the point of the well and is n_i energy which, for simplicity, is assumed to be provided costlessly.⁶

⁵Note that we are assuming that water in the the aquifer can make its way vertically to the base of the well even though all horizontal movement occurs within the aquifer, which may lie below this level. Such movement may occur naturally or may be facilitated by drilling down to the aquifer. The key component of the cost (the type of casing and the strength and placement of the pump), however, will be associated with the distance the well is able to pump vertically. An alternative approach would be to model an unconfined aquifer. This is mathematically more complicated and as a consequence the confined aquifer problem is often used to approximate an unconfined aquifer. (Hermance 1998).

⁶Energy costs will in general be proportional to the product of well depth and volume of water extracted. Introducing this term complicates the model because then the marginal price of water is increasing in distance. It should not alter the basic insights, however, as long as these costs are not too high. World Bank (2001) provides evidence on pumping costs in two Indian states. In Andhra Pradesh, where electricity for pumping is subsidized, energy costs for pumping average 12% of total annualized costs for electrical wells. In Harayana energy costs for pumping are 22% of total cost for diesel pumps and 37% for electric pumps. In the latter case, however, electricity prices fall proportionately with well depth and thus would enter the model like a fixed tax on water and thus not affect the comparative statics at all. .

Each farmer is assumed to decide whether or not to build a well (to enter) and then, conditional on entry and the set of farmers who decide to enter, to choose well depth to maximize discounted income given the water table dynamics. In particular, if he decides to build a well the farmer maximizes

$$(12) \quad \int_0^{\infty} \exp^{-\alpha t} (a_i + \theta r_i(t)) f\left(\frac{w_i(t)}{r_i(t)}, \frac{z_i(t)}{r_i(t)}\right) - \phi \frac{r_i^2(t)}{a_i(t)} - p_d z_i(t) dt - \tilde{p}_0 - \tilde{p}_d d_i$$

subject to (7), (12), and the well choices of the other well-building farmers. He will enter if

(13) evaluated at the optimal water use of all entering farmers exceeds the dry-agricultural

expected discounted profits of a_i/τ . Let $e_i=1$ denote the decision to enter. We assume a stationary

sub-game perfect solution, ignoring transitional dynamics of the water table.⁷ Because the well is

a sunk cost and water extraction is costless the well depth will be chosen to just meet optimal

water demand and will be a best response to the well-depths of other extractors. The objective

function can thus be simplified by solving for the levels of irrigated area and inputs conditional

on overall usage $z_i=z^*(w_p, a_p, \theta_i)$ and $r_i=r^*(w_p, a_p, \theta_i)$ and substituting back into (13) to yield the

stationary problem for entering farmers of

$$(13) \quad y(\theta_p, a_p, t_p, w_{-i}) = \max f^*(w_p, \theta, a_i) - p_0 - p_d \delta(w_p, w_{-p}, t_i)$$

where

⁷Because the focus of this analysis is on the local watershed and thus the short-term dynamics of waterflow this assumption of stationarity is likely to be reasonable in the sense that during periods of maximum irrigation the hydraulic head is likely to be well approximated by the Thiem solution in relatively short order. The process of equilibration will, of course, depend on soil characteristics, the distance to the aquifer and can be reasonably characterized using the Theis solution.

$$(14) \quad f^*(w_p, \theta, a_i) = \theta f\left(\frac{w_i}{r^*(w_p, \theta, a_i)}, \frac{z^*(w_p, \theta, a_i)}{r^*(w_p, \theta, a_i)}\right) - \phi \frac{r^*(w_p, \theta, a_i)^2}{a_i} - p_z z^*(w_p, \theta, a_i)$$

and $p_0 = \tilde{p}_0/\tau$ and $p_d = \tilde{p}_d/\tau$ are the annualized fixed and variable prices of the well and entry takes place ($e_i = 1$) if $y(\theta, a_i, t_i, w_{-i}) > 0$.

We establish in the Appendix that if $t_i = t(a_i)$ with $t'(a_i) > 0$ this game has an equilibrium in which there is some minimum acreage \tilde{a} , with all farms above this acreage having a well and all those below this level not having a well. To characterize the properties of these equilibria one must first examine the comparative statics of water use by entering farmers conditional on water usage of other entering farmers. In particular, the first order condition for (13) is

$$(15) \quad f_w^*(\theta, w_p, a_i) - p_d \ln \frac{1}{2\pi K h_q} \ln\left(\frac{w_i R}{(w_i + w_{-i}) b}\right) = 0.$$

There are two noteworthy attributes of (15). First, the distance from the center of the village does not affect the marginal cost of water extraction even though it clearly does affect the total cost of that extraction as indicated by (7). Thus for given water extraction of other households, the level of water extracted by farmer i will not systematically differ by distance from the well.

Second, the marginal cost is increasing in the share of water extracted and thus is decreasing in water extraction from other households. Thus an exogenous increase in his neighbors' pumping (assuming an interior solution) will increase the farmer's own pumping. This result contrasts strikingly with a standard tragedy of the commons problem in which

extraction of the common resource by one agent raises the marginal cost of extraction for his competitors. This strategic complementarity arises from two factors: first, an increase in neighbor's pumping increases on a 1:1 basis the rate at which, in the model, water flows into the aquifer from the constant (and by assumption inexhaustible) head; second, the lower one's well is relative to that of one's neighbor the larger the share of the total water coming into the aquifer that one will be able to extract. But this result should not be interpreted to mean that one actually benefits from an increase in one's neighbor's water extraction. To the contrary, differentiating (13) with respect to w_{-i} yields

$$(16) \quad -\frac{P_d}{2\pi K h_q} \ln\left(\frac{w_{-i} R}{(w_i + w_{-i}) t_i}\right) < 0.$$

Therefore, an increase in neighbors' extraction reduces the profitability of irrigated land while at the same time increasing own water usage. Of course, at sufficient high levels of neighbors' water usage, irrigation will cease to become profitable and thus own water use will fall to zero. This combination of strategic complementarity and a negative spillover suggests there is a particularly large benefit to cooperative management of water resources.

These results contrast markedly with a situation in which farmers are cooperative. In the case, for example, that total profitability from all farms is maximized

$$(17) \quad \begin{aligned} f_w^*(\theta, w_i, a_i) - \frac{P_d}{2\pi K h_q} \left(\ln\left(\frac{w_i R}{(w_i + w_{-i}) b}\right) + \sum_{j \neq i}^N e_j \ln\left(\frac{w_i R}{(w_i + w_{-i}) t_j}\right) \right) \\ = f_w^*(\theta, w_i, a_i) - \frac{P_d}{2\pi K h_q} (\ln(t_i/b) + N_e \ln\left(\frac{w_i R}{W}\right) - T) = 0 \end{aligned}$$

where $T = \sum_{j=1}^N e_j \ln(t_j)$ is the sum of log distances across irrigating farmers. To see the distinction between the cooperative and non-cooperative cases, assume one has N_e identically sized farmers that are equidistant from the center of the well. If these farms are moved farther apart in the cooperative case (thus preserving the share of water used by each farmer as well as total acreage irrigated) overall water usage will increase because the magnitude of the externality created by interference declines with total distance. In the noncooperative case the benefits of being close to the aquifer (and thus smaller R/t_i) are offset by the reduction in strategic complementarity.

II.c Testable implications

With detailed data on well placement and water extraction the implications of this model are readily tested. In the absence of such data, however, key implications of the model may be tested with more limited information with the imposition of some additional structure. First, the fact that water extraction at any given location is subject to diminishing returns yields the implication that large farmers should use proportionately less water than smaller farmers.

Consider, the case that $f(w/r, z/r) = (w/r)^\alpha (z/r)^\beta$ with $\alpha + \beta < 1$. Under this condition it is possible to derive simple closed form expressions that show the relationship between the water usage and the relevant inputs and thus, to the extent that this approximation is reasonable, permit indirect assessment of water usage using data on irrigated area and inputs. In particular, it may be shown that the expressions for z^* , r^* and f^* will also be Cobb-Douglas with, for example,

$$(18) \quad \frac{\partial \ln z_i^*}{\partial \ln a_i} = \eta/\gamma$$

$$(19) \quad \frac{\partial \ln z_i^*}{\partial \ln w_i} = 2\alpha/\gamma$$

$$(20) \quad \frac{\partial \ln r_i^*}{\partial \ln a_i} = (1-\beta)/\gamma$$

and

$$(21) \quad \frac{\partial \ln r_i^*}{\partial \ln w_i} = \alpha/\gamma$$

where $\eta = 1 - \alpha - \beta$ and $\gamma = 1 - \beta + \alpha$. Moreover, letting $w^*(\theta, a_i, t, p, W)$ denote the solution to (14), we

have

$$(22) \quad \frac{\partial \ln w_i^*}{\partial \ln a_i} = \frac{\eta \ln(Rw_i/bW)}{\gamma + \eta \ln(Rw_i/bW)} < 1.$$

To see that this expression is testable note that the difference in the within-village reduced form effects of area on inputs and irrigated area net of village total will be negative if and only if (25)

holds:

$$(23) \quad \left. \frac{d \ln r}{d a_i} \right|_W - \left. \frac{d \ln z}{d a_i} \right|_W = \frac{\alpha}{\gamma} \left(\frac{\partial \ln w_i^*}{\partial \ln a_i} - 1 \right).$$

Intuitively if inputs per irrigated area are decreasing in total area then this is likely because a complementary (but unobserved) input is not growing proportionately with total area.⁸

Second, the fact that larger farms, for given total water use less water per acre than do smaller farms implies that the process of land-consolidation (of medium sized farms) should decrease total water usage and thus, given that total water usage decreases own water usage,

$$(24) \quad \frac{\partial \ln w_i^*}{\partial \ln W} = \frac{\gamma}{\gamma + \eta \ln(Rw_i/bW)} > 0$$

should lead to overall decreases in irrigated area and decreases in total well depth. To see this result, suppose that there are three land-size groups $\{l, m, h\}$, with $a^l = 2a^m = 4a^s$ and that there is an equilibrium such that $a^s < a^*(W(\hat{e})) < a^m$. Let n^k denote the number of households with landsize of k . Then a land consolidation can be thought of as an increase in n^l with n^s constant and the total land area $n^s a^s + n^m a^m + n^l a^l = A$ held fixed. Implicit differentiating yields

$$(25) \quad \left. \frac{d \ln \delta_i}{d n^l} \right|_{n^s, A} = \left(\frac{\partial \ln \delta_i^*}{\partial \ln w_i} \frac{\partial \ln w_i^*}{\partial \ln W} + \frac{\partial \ln \delta_i^*}{\partial \ln W} \right) \frac{1}{W} \left. \frac{dW}{d n^l} \right|_{n^s, A} < 0.$$

Thus this type of consolidation leads to lower irrigated area

$$(26) \quad \left. \frac{d \ln r_i}{d n^l} \right|_{n^s, A} = \frac{\partial \ln r_i^*}{\partial \ln w} \frac{\partial \ln w_i^*}{\partial \ln W} \frac{1}{W} \left. \frac{dW}{d n^l} \right|_{n^s, A} < 0.$$

⁸Inputs on non-irrigated land should not be subject to this source of diminishing returns. Thus to the extent that the measured inputs include irrigated and non-irrigated-land inputs, leading to a bias against finding evidence of diminishing input use per irrigated area.

Moreover, letting $\delta^*(w_i, W, t_i)$ denote well depth needed to pump w_i unit of water given W and t_i ,

consolidation will lower well depth

$$(27) \quad \left. \frac{d \ln \delta_i}{d n^l} \right|_{n^s, A} = \left(\frac{\partial \ln \delta_i^*}{\partial \ln w_i} \frac{\partial \ln w_i^*}{\partial \ln W} + \frac{\partial \ln \delta_i^*}{\partial \ln W} \right) \frac{1}{W} \left. \frac{dW}{d n^l} \right|_{n^s, A} < 0,$$

because

$$(28) \quad \frac{\partial \ln \delta_i^*}{\partial \ln w_i} = \frac{w_i}{\delta 2 \pi K h_q} \ln \left(\frac{w_i t_i}{(W - w_i) b} \right) > 0$$

and

$$(29) \quad \frac{\partial \ln \delta_i^*}{\partial \ln W} = \frac{w_i}{\delta 2 \pi K h_q} \ln \left(\frac{(W - w_i) R}{W t_i} \right) > 0.$$

Similarly, fragmentation (of medium sized farms) may be thought of an increase in the number of small farms holding fixed the number of large farms and total land area should reduce total water by reducing the number of farms actually digging wells

$$(30) \quad \left. \frac{dW}{d n^s} \right|_{n^m, A} = \frac{-w^*(a^m)}{1 - n^l w_W^*(a^m)} < 0$$

and thus decreases depth and irrigated area.. Thus greater landholdings of very large and very small farmers should both result in lower depth and lower irrigated area, but only if, as implied by the model, own water is increasing in total water extracted. Note further that these results do

not necessarily arise in the cooperative model. A decrease in the number of wells and/or expansion in farm area and thus distance from the center in that case has a direct positive effect on water extraction and therefore can yield an increase in irrigated area and depth.

A third prediction of the model can be tested if the relationship between farm area and well distance is sufficiently non-linear. The basic idea is that non-linearities in the relationship between land area and well-distance should affect well depth but not, in the non-cooperative model, water usage and therefore irrigated area or the use of complementary inputs. Suppose, for example, that

$$(31) \quad t(a) = a^v + \tau I(a > \tilde{a})$$

Then we may write

$$(32) \quad \left. \frac{d \ln \delta_i}{d \ln a_i} \right|_{W, \tau=0} = \frac{\partial \ln \delta_i^*}{\partial \ln w_i} \frac{\partial \ln w_i^*}{\partial \ln a_i} + \frac{\partial \ln \delta_i^*}{\partial \ln t_i} v$$

where

$$(33) \quad \frac{\partial \ln \delta^*}{\partial \ln t_i} = - \frac{W - w_i}{\delta 2\pi K h_q} < 0$$

and

$$(34) \quad \left. \frac{\partial \ln \delta^*}{\partial \tau} \right|_{w, a_i} = \frac{\partial \ln \delta^*}{\partial \ln t_i} I(a_i > \tilde{a}).$$

Thus this jump in the relationship between farm size and distance will result in shallower wells if

$\tau > 0$. However, because distance does not affect water usage, this jump will not impact irrigated area and input use,

$$(35) \quad \left. \frac{d \ln r_i}{d \tau} \right|_{w, a_i} = \left. \frac{d \ln z_i}{d \tau} \right|_{w, a_i} = 0.$$

Finally, the above analysis focuses on the notion of a static equilibrium. In practice, however, wells are built at different time with incomplete knowledge of the subsequent trajectory in terms of water available. Once entry has occurred well-depth of one's own well and that of one's neighbors may be thought of as fixed and a farmer must adjust his rate or water extraction accordingly. Assuming the marginal product of water for all farmers exceeds the marginal cost of extracting the water (assumed to be zero above) at the supplied level then water input use will be rationed on the supply side. Given stochastic variation in the level, for example, of the surrounding aquifer the, the hydraulic head in any given year may fall below the depth of a given farmer's well and the well will be dry. Letting $G()$ denote the distribution function of these underlying shocks we may write

$$(36) \quad s_i = G(-w_i) \text{ where } \{d_j = \delta(w_j, \sum_k e_k w_k, t_j) \forall j | e_j > 0\}.$$

For analytic simplicity we evaluate comparative statics under the assumption of symmetry, that is $d_i = \bar{d}$, $t_i = \bar{t}$, $w_i = \bar{w}$, where the bar denotes the village average. As one might expect the probability of having a dry well is decreasing in the depth of one's own well

$$(37) \quad \frac{d \ln s_i}{d \ln d_i} = - \frac{2\pi K h_q}{\ln(\bar{t}/(b(N-1)))} \frac{g(-\bar{w})\bar{d}}{G(-\bar{w})} < 0$$

and increasing in the average depth of wells in the village

$$(38) \quad \frac{d\ln s_i}{d\ln \bar{d}} = \frac{2\pi K h_q M \ln(R(N-1)/(\bar{t}N))}{\ln(\bar{t}/(b(N-1)))(N \ln(R(N-1)/\bar{t}N) + \ln(\bar{t}/(b(N-1))))} \frac{g(-\bar{w})\bar{d}}{G(-\bar{w})} > 0.$$

Similarly, an increase in distance from the aquifer center lowers the probability of becoming dry

$$(39) \quad \frac{d\ln s_i}{d\ln \bar{t}} = -\frac{(N-1)\bar{w}}{\bar{t} \ln(\bar{t}/(b(N-1)))} \frac{g(-\bar{w})\bar{t}}{G(-\bar{w})} < 0$$

but an increase in the average distance

$$(40) \quad \frac{d\ln s_i}{d\ln \bar{t}} = \frac{N(N-1)\bar{w} \ln(R(N-1)/(\bar{t}N))}{\ln(\bar{t}/(b(N-1)))(N \ln(R(N-1)/\bar{t}N) + \ln(\bar{t}/(b(N-1))))} \frac{g(-\bar{w})}{G(-\bar{w})} > 0$$

increases this probability.

2. The Data and the Setting.

To examine the relationships among agricultural productivity growth, the distribution of land and water use we exploit data from a newly-available village and household panel survey that provides information on rural Indian households residing in 242 villages over the period 1982-1999. The new data are from a continuing survey of rural households residing in approximately 250 villages located in the 17 major states of India that began in 1968 and has been carried out by the National Council of Applied Economic Research (NCAER). The first round of the survey for which there is complete village and household information, in 1971, includes 4,527 households in 259 villages and is meant to be representative of the entire rural

population of India residing in the 17 major states. In 1982, 250 of the original 259 villages were revisited (the state of Assam was excluded) and 4,979 households surveyed, approximately two-thirds of which were the same households as in the 1971 round. In 1999, all of the 1971 villages were surveyed, but excluding the 8 sample villages in Jammu and Kashmir.

In this latest survey round, all of the surviving households in the 1982 survey were surveyed again, including for the first time all split-off households residing in the same villages, plus a small random sample of new households. Because of household division and the new sample design incorporating all village-resident male 1982 surveyed household members, the number of households in the 1999 round increased to 7,474. The data in both 1982 and 1999 provide information on agricultural yields by seed type and crop, government irrigation facilities, and proximity to lakes and streams at the village level, and owned and inherited landholdings by irrigation status and irrigation facilities at the household level. In the 1999 round a retrospective history was obtained from each farmer on tubewell construction, including the year of installation for the latest tubewell installed and its depth. In addition, each farmer was asked whether the tubewell became dry in any of last three crop seasons in the crop year 1998-99.

Table 1 provides information on the growth in tubewells, both private and public, the number of farmers with irrigated land and average tubewell depth in the sample villages between 1982 and 1999. As can be seen, the number of private tubewells in the villages almost doubled, while the average number of government tubewells increased more than sixfold, although public tubewells are only a small fraction of all tubewells in the villages. The number of farmers with irrigated lands also rose, by 15 percent, and the average depth of the stock of tubewells almost doubled. The data indicate that there are a limited number of villages with water markets, as

evidenced by the existence of a market price for water in the villages, although their incidence in growing - in 1982 only 14.9 percent of villages had at least some market-priced water; in 1999 31.9 percent had a market for water. Of course, the existence of water prices in a village does not measure the extent to which the within-village market is pervasive, nor the availability of market water for farmers. Clearly, water markets are not common even now.

To what extent was the increase in irrigation investment associated with agricultural technical change? To characterize the growth in agricultural productivity on irrigated lands, we constructed from the village-level data on prices, seed types and yields an index of high-yielding variety (HYV) seed yields for each village for each of the three survey years using a Laspeyres-weighted index for four HYV crops - corn, rice, sorghum and wheat - of output per acre on irrigated lands. Figure 7 displays the average HYV yield index for each of the three survey years. HYV yields grew by 84% between 1971 and 1982 and by 79% between the survey rounds in 1982 and 1999. Over the same period the share of irrigated land also increased substantially, particularly, as the model suggests, in areas with high HYV yield growth. Figure 8 plots the share of irrigated land in total landholdings in 1971 and 1999 by quintiles of HYV yield growth over the same period. Interestingly, shares of irrigated land were lowest in the initial period in those areas experiencing higher subsequent rates of HYV yield growth. As a consequence of higher HYV yields inducing investment in irrigation, the distribution of irrigation land shares across the quintiles is substantially more equal in 1999 than in 1971.

The distribution of land ownership between 1982 and 1999, the period that we will examine more closely in terms of water usage, became more concentrated within the villages, however, as shown in Figure 9. Again consistent with the model, there is a significant reduction

in the ownership of land in the bottom twenty percent of farmers, for whom individual irrigation investment is presumably unprofitable. Between 1982 and 1999, the data indicate that the fraction of total land owned by the bottom 20 percent of landowners fell by over 44 percent, from 26 to 18 percent. Land was increasing concentrated among the larger landholders, except there is a small drop-off for the highest 20 percent.

Is the reduction in small landholdings related to growth in the returns to irrigation associated with the increase in HYV yields? Figure 10 provides the coefficients associated with regressing the change in land shares on the growth in HYV yields across the sample villages in the 1982-1999 period for each of the five land ownership quintiles. As can be seen the drop in landshares for the bottom 20th percentile was greatest in high HYV productivity increase areas - the coefficient indicates that a doubling of HYV yields on irrigated land reduces the share of land owned by the bottom 20 percent by 4.5 percentage points (25 percent). In contrast, the land shares for the landowners in the 20th through 80th percentiles increased, and increasingly so, in high-growth areas. The share of landholdings owned by the top 20 percent of landowners, however, fell somewhat in high-growth areas.

The reduction in small farms and the increase in the share of irrigated land imply greater water usage. However, as the model suggests, the increase in landholding concentration also decreases water usage. The increased depth in tubewells over the period displayed in Figure 1 and Table 1 is consistent with increased overall local water use over the period or decreases in the level of the surrounding aquifer (h_0) due to non-sustainable water extraction at a larger geographical or temporal scale. However, as noted, the increase in average tubewell depth may also be due to the spread of irrigation to marginal areas with pre-existing low water tables or

poor rates of groundwater flow. An analysis that looks at the determinants of changes in water use within geographic areas is needed.

3. The Determinants of Water Usage: The Production Function for Water Usage

We first estimate a linear approximation to the production function for water, as derived from equations (6) and (7), based on the sample of 620 farmers in 1999 who had a tubewell on their land. Water usage for farmer i in village j is given by:

$$(28) \quad w_{ij}(t) = \beta_1 d_{ij} + \beta_2 \tau_j(t) + \beta_3 \theta_j + \beta_4 r_{ij} + \beta_5 a_{ij} + e_{ij},$$

where the β are coefficients to be estimated. One reason for estimating the technology directly, in addition to assessing the plausibility of the model, is to identify the operation of Darcy's law, which suggests that the scale of landholdings, given technology and the depth of own and common water levels, reduces water usage because it reduces the ability to free ride on common aquifers. If evidence of Darcy's law is obtained, this would imply land concentration could increase the efficiency of irrigated lands in terms of water use.

The 1999 round of the data provides an indication of whether the farmer's tubewell was dry, which we will use as an inverse measure of water use $w_i(t)$. 15.1 percent of the farmers had a dry tubewell in the reference period. For the depth of the aquifer in the community $\tau(t)$ we use the average depth of tubewells in the village of the farmer, and for the depth of the farmer's own tubewell d_i we use the information on the farmer's reported own tubewell depth. The amount of water effort $e_i(t)$ is assumed to be a function of the demand for water, which in turn is a function agricultural productivity θ , measured by the village-specific HYV yield on irrigated land, and the farmer's scale of operation r_i , measured by the amount of the farmer's irrigated land. Finally, we include in the specification the farmer's total owned land a_i , which measures the distance

between the farmer's own water table and that of the community, and thus should, given Darcy's law, decrease water usage (reduce the incidence of a dry well.). Land ownership does not have a direct effect on water usage, given irrigated acreage, in the absence of the operation of Darcy's law.

The incidence of dry wells will depend on natural conditions of the environment that are impounded in the error term e_{ij} . Because we only have information on the incidence of dry wells in one round, we cannot identify the effects of variation in village-level tubewell depth or HYV yields and also control for unmeasured differences across villages that may affect water flows, such as rainfall histories. We can include district-level fixed-effects and estimate all of the parameters. We also can include village-level fixed effects to assess the robustness of the coefficients on the individual farmer coefficients to a more spatially precise control for agro-climate conditions.

The first column of Table2 reports the estimated coefficients and robust t-ratios for the full specification including district fixed-effects. The estimates indicate that for given technology level and the depth of the village aquifer, deepening the tubewell reduce the incidence of tubewell dryness. The point estimate suggests that every one meter increase in depth reduces the probability of a dry well by approximately 5 percent. The estimates also indicate that the incidence of a dry tubewell for a farmer is increased the lower the tubewell depth in the farmer's village. This is consistent with the existence of spillover effects, but the average depth of village tubewells may also in part proxy for the depth of the farmer's own water table. The fact , however, that farmers with larger landholdings use less water, experience a lower incidence of dry wells, must reflect a relationship between a farmer's own water use and water supplied from

common sources as well as the operation of Darcy's law. Although the coefficient is estimated with somewhat low precision, when village fixed-effects are included in the specification (column 2), the coefficient becomes larger in absolute value and we can reject the absence of Darcy's law at the .03 level (one-tailed test). The precision and magnitudes of the other farmer-specific variables are essentially unaffected when all differences across villages, as opposed to across districts, are accounted for.

4. The Determinants of Tubewell Investment and the Number of Irrigated Farms

Table 2 indicated that increasing overall farm scale decreases individual water use, given the existence of a tubewell and irrigable landholdings. If there are fixed costs of tubewell investment, as indicated in the model, the scale of operation will also influence whether a farmer installs a tubewell. We thus estimate a linear approximation to the reduced-form decision rule for digging a tubewell, in which the probability that a farmer installs a tubewell is a function of his owned land, the average level of HYV yields on irrigated lands in his village, and the distribution of land ownership in the village, as measured by the share of total village land owned by the bottom 20 percent of landowners and by the top 40 percent. We use information on HYV yields and landholdings from the 1982 and 1999 surveys. To construct an indicator of whether or not a farmer invested in a tubewell around those survey dates, we used the 1999 tubewell histories: a farmer who constructed his most recent tubewell between 1980 and 1985 is considered to have invested in a tubewell in the 1982 round; a farmer who constructed a tubewell between 1994 and 1999 is considered to have invested in the 1999 round.

We exploit the panel data and include village fixed-effects to absorb all local agro-climate conditions. As is well-known, within-estimators exacerbate the effects of measurement

error. In addition, shocks to irrigation investments in the earlier period could influence subsequent investment in land (by raising profits), so that landholdings may be correlated with the error term. To deal with both of these problems, we use an instrumental-variable approach, treating the farmer's landholdings as endogenous and the HYV yield as error-ridden. We use as instruments, land, both dry and irrigated, inherited prior to 1982 (which should not be correlated with the 1982 error term), and whether the village was rice or wheat-growing in 1971, HYV yields in 1971, and natural access to water - proximity to ponds or lakes.

Our theoretical framework indicated that increasing the concentration of land among large landholders should reduce overall water usage in an area due to the Darcy effect and thus should permit a farmer to install a less deep and thus less costly tubewell to the extent that there are common aquifer spillovers. Concentration of land among small landowners has an ambiguous effect on tubewell cost and thus tubewell investment, however, due to these external effects - if more land is concentrated among farmers below the threshold a^* , this will also reduce the number of irrigated farmers and thus overall water demand and cheapen tubewell investment for a given farmer; however, concentrating more land among more small farmers who are above the threshold means more irrigated farms, which will increase overall water demand, lower the common aquifer, and increase tubewell costs.

Column one of Table 3 reports the fixed-effects-IV estimates of the probability of tubewell investment. The estimates indicate that farmers with a greater scale of operation are more likely to invest in a tubewell and that higher levels of HYV productivity on irrigated lands are also associated positively with tubewell investment, consistent with Figure 4. However, the village-level distributional variables are not statistically significant. The second column reports a

specification in which the number of government tubewells is included. The estimates indicate that government and private tubewell construction are substitutes, although not perfect substitutes - adding one government tubewell in the village decreases the probability of an individual farmer digging a tubewell by only 0.89 percent (.000187/.021).

In columns three and four of Table 3 we estimate the determinants of the number of irrigated farms in the village, again treating HYV yield as an endogenous variable and controlling for village fixed-effects. The estimates indicate that higher HYV yields on irrigated lands significantly increase the number of irrigated farms. The estimates also, however, suggest that greater concentration of lands among small farmers, in the bottom quintile, reduces the total number of irrigated farms, suggesting that such farmers are below the profit threshold for irrigation investment. Concentration of land among the top 40 percent of farmers however does not affect the number of irrigated farmers. Theoretically, there are two offsetting effects of increased concentration of land among large farmers - for given overall land size in the village, impounded in the village fixed-effect, more concentration mechanically implies fewer farms among those farmers most likely to irrigate. On the other hand, larger farmers use less water per acre (Darcy) and thus make it cheaper for every farmer to irrigate. Finally, more government tubewells is associated with a lower number of irrigated farmers. This may suggest that public tubewell investment increases where there is smaller growth in the number of irrigated farmers.

5. The Determinants of Tubewell Depth

Changes in tubewell depth within a village reflect the depletion of the water table. We now look at the relationships between changes in tubewell depth, farm scale, the local productivity of HYV seeds on irrigated land, and the village land distribution across the period

1982-1999. We use as observations the reported tubewell depth of the farmers who installed tubewells in the 1980-85 and 1994-99 periods and estimate these relationships controlling for village fixed-effects. We again use instrumental variables to eliminate the effects of measurement error in the HYV yield variable and also the possibility that local water table depth affects average HYV yields on irrigated land. Given that higher yields evidently increase tubewell investments and thus increase water usage, tubewell depth should be greater in villages where higher HYV yields can be obtained.

The model simulations in Figure 2 and the estimates of the water production technology in Table 2 suggest that farm scale has a non-linear relationship with tubewell depth, consistent with Darcy's Law, so we include in addition the farmer's total owned acreage a dummy variable indicating if the farm was in the top 20 percent of farms in terms of acreage, over 9 acres. The largest farms, who are less able to exploit common aquifers, should have tubewells of lower depth. To characterize the distribution of landholdings in the village we again use variables measuring the share of landholdings among farmers in the bottom 20 percent and farmers in the top 40 percent of the village-specific landholding distribution. Given the finding in Table 3 that an increase in the concentration of landholdings among the small farmers reduces the number of irrigating farmers, we should, given the model simulations, expect to also see less deep tubewells because of lower water use in areas with landholdings more evenly distributed. Similarly to the extent that concentration of land among large landholders reduces water use, tubewell depth for farmers in areas with a more positively skewed distribution of land should also be lower.

The first column of Table 4 reports the FE-IV estimates of the determinants of the log of farmer tubewell depth. The estimates indicate that an exogenous increase in HYV yields on

irrigated land does lower the water table, given the distribution of landholdings - doubling of HYV yields evidently lowers tubewell depth for new tubewells by 19%. Increased farm scale also increases tubewell depth, but then decreases it at the highest levels. As expected, and, consistent with the non-linear relationship at the individual farm level, concentration of land in the village among larger farmers results in less water use, as reflected in less deep tubewells being installed. The point estimate indicates that a 10 percentage point increase in the share of total land held by the large farmers reduces average new tubewell depth by 9.1 percent. On the other hand, increasing the land share for the smallest farmers also reduces average tubewell depth - increasing the fraction of land held by the bottom 20 percent of landowners reduces average tubewell depth by 6.3 percent. Note, however, that the reasons for decreased water use arising from the changing distribution of land by skewing it to the left or right are very different. Shifting more land to the bottom 20 percent lowers water use by reducing the number of irrigators (Table 3) - there are less farmers exploiting therefore the new agricultural technology and thus lower incomes and growth. Concentration of land among the largest farmers reduces water use, not by reducing the number of irrigators (Table 3) or new technology adopters, but because there is less opportunity to free-ride off common aquifers, so that water use is more efficient (less water per acre), reflecting mainly own costs.

To further check that the relationships between the distribution of landholdings and tubewell depth reflect common water-table effects, we first add the number of government tubewells to the specification. If overall water use in the village affects a farmer's own water use, then, given the village distribution of land, adding government tubewells (as this evidently does not crowd out all private tubewells as seen in Table 3) should increase private tubewell depth.

This is confirmed in column two of Table 4. The point estimate suggests that for every 10 government tubewells added to the village, average tubewell depth for new private tubewells is increased by 2.2 percent. In column 3 we report estimates from a specification that includes the total number of wells per acre in the village. We also treat this variable as endogenous, using as instruments additionally to the ones used for HYV yields the number of village wells per acre in 1971. The coefficient estimate indicates that a farmer's tubewell depth when he digs a new tubewell is deeper by 2.9 percent if the number of wells in the village is higher by 10 percent.⁹ Finally we add to the specification the number of government wells per acre. Again adding government wells in addition to private wells increases tubewell depth for newly-constructed private tubewells - a 10 percent increase in government wells lowers average tubewell depth by 0.27 percent.¹⁰

6. Conclusion

Our results suggest that in the absence of effective water markets there are important constraints on simultaneously achieving the goal of rapid, equitable, and environmentally sustainable agricultural productivity growth. Fixed costs associated with sinking a well make it difficult for the poor to fully benefit from the availability of groundwater and thus to benefit from changes in agricultural productivity that are tied to irrigated land. Indeed, we have shown that there has been a decline in the share of land owned by small farmers, particularly in areas with more rapid growth in HYV yields on irrigable land, a possible response to this (and other) returns to scale that arise with new agricultural technologies. To the extent to which this lack of

⁹In the sample villages in 1999 there are .084 wells per acre, up from .069 in 1982.

¹⁰The number of government tubewells per acre is .0012 in 1999 and .00030 in 1982.

access is due to capital constraints there may be a case for providing subsidized loans for wells, as has been advocated, but our results indicate that this will increase the over-use of water and hasten the decline of the water table. Mid-range farmers may be able to profitably use such pumps but our results also indicate that such farmers do not fully internalize the costs of groundwater pumping. Further consolidation of agricultural lands would make water use more efficient, but encouraging additional consolidation may be unattractive on equity grounds in the absence of opportunities outside of the farm sector. From a policy perspective, there seems relatively little alternative to finding ways to overcome some of the technological and ethical barriers to the buying and selling of water at the local level.

As noted there is some evidence that water markets may be developing. And, as shown in Table 5, small landholders are evidently giving up their lands in high- productivity growth areas but the emergence of water markets (as measured by whether a price for water was reported at the village level) has also been significantly higher in those areas with relatively high rates of HYV productivity growth. Clearly the concentration of land, and the reduction in the water table, in high-growth areas would have been much greater without the development of water markets. Thus, not only does the development of a water market likely ensure better management of the local water table, which may be critical for sustaining the productivity benefits of agricultural productivity growth, but it may differentially benefit poorer farmers who have traditionally been excluded from access to this important resource at all due to scale issues. The design and testing of policy interventions that can promote the development of water markets would seem to be a priority area for future research.

References

- Aggarwal, Rimjhim (2000) “Possibilities and limitations to cooperation in small groups: The case of group-owned wells in southern India”, *World Development*, 28(8):1481-97.
- Anderson, Siwan (2006) “Caste as an Impediment to Trade”, University of British Columbia, manuscript.
- Bardhan, Pranab (2000) “Irrigation and Cooperation: An empirical analysis of 48 irrigation communities in South India”, *Economic Development and Cultural Change*, 48(4):847-65.
- Bardhan, Pranab (2002) “Inequality and the governance of water resources in Mexico and South India”, Chapter 5 in *Economic Inequality, Collective Action and Environmental Sustainability*, Santa Fe Institute.
- Bardhan, Pranab (1993), “Symposium on management of local commons”, *Journal of Economic Perspectives*, 7(4): 87-92.
- Bose, Vasudeva, Gupta and Sinha, (1998) “Water”, TERI report 97/ED/52
- Darcy, H. (1856) “Les fontaines publiques de la Ville de Dijon”, Paris: Victor Dalmont.
- Duflo, Esther and Rohini Pande, (2004) “Dams”, manuscript.
- Hernance, John F. *Mathematical Primer on Groundwater Flow*, Prentice, Hall.
- IWMI (2002), “The socio-ecology of groundwater in India”, Briefing Paper, International Water Management Institute.
- Sampath, Rajan, (1990) “On some aspects of irrigation distribution in India”, *Land Economics*, 66(4): 448-463.
- World Bank (2001), “India: Power supply to agriculture”, Volume 1, Energy Sector Unit, South

Asia Regional Office, World Bank Report No. 22171-IN.

Appendix

To construct an equilibrium, let $\mathbf{e}=[e_i]$ denote the vector of entry conditions. The first order condition for (14) assuming an interior solution is

$$(41) \quad f_w^*(\theta, w_i, a_i) - p_d \ln \frac{1}{2\pi K h_q} \ln \left(\frac{w_i R}{(w_i + w_{-i}) b} \right) = 0.$$

This expression is continuous and increasing in w_{-i} . In addition, the choice of water is continuous and is bounded by the fact that the hydraulic head cannot be below the bottom of the aquifer or above h_0 . Thus the second-stage game is supermodular and has a unique Nash equilibrium conditional on \mathbf{e} . We substitute $w_{-i} = W - w_i$ into (41) and then solve implicitly for equilibrium water as a function of total water and land area, $w^*(a_i, W)$. Further, let $W^*(\mathbf{e})$ be the equilibrium solution to the level of total water extracted given entry

$$(42) \quad W = \sum_{i=1}^N w^*(a_i, W) e_i.$$

Because irrigation profits are negative if an individual enters and uses little or no water and increasing in acreage for any given level of total water usage

$$(43) \quad \frac{dy(\theta, a_i, t(a_i), W - w_i^*)}{da_i} = f_a^*(\theta, w_i, a_i) + \frac{p_d W t'(a_i)}{2t_i K h_q \pi} \mp \frac{p_d}{2K h_q \pi} \ln(R(W - w_i)/(W t_i)) w_w^*(a_i, W) > 0$$

as long as $t'(a) > 0$. There will thus be a minimum land size $a^*(W)$ below which entry cannot occur in an equilibrium of the full game if total water is W . Moreover, if we consider the set of candidate equilibria consisting of irrigation by all farmers up to the index I , $\hat{e}_I = [e_i = J(i \leq I)]$ where $J(\cdot)$ denotes the index function, then the largest of such candidate equilibria such that $a^*(W^*(\hat{e})) \geq 0$ will be one equilibrium of the game. Let $\tilde{a} = a^*(W^*(\hat{e}))$.

There may be other equilibria if the a_i are sufficiently closely spaced. In particular, if the farmer with $a_i = \tilde{a}$ does not enter then a farmer with slightly less land than \tilde{a} may profitably enter and induce a sufficiently high level of usage that it would not be profitable for the farmer with land \tilde{a} to enter. We assume below that the support of the distribution of a_i is sufficiently separated in the vicinity of \tilde{a} to rule out such equilibria.

Table 1
Change in Percentage of Villages with Water Markets, Mean Number of Irrigation Facilities
and Irrigated Farms per Village and Tubewell Depth, 1982-99

	1982	1999
Water market in village	14.9	31.8
Number of private tubewells per village	12.4 (34.1)	24.6 (45.0)
Number of government tubewells per village	.268 (2.14)	1.71 (19.4)
Number of farmers with irrigation per village	87.1 (116.5)	100.3 (107.8)
Mean depth of new tubewells (meters)	31.9 (28.3)	61.2 (87.0)

Number of villages=250. All differences are statistically significant.

Table 2
 Determinants of the Probability of a Dry Tubewell in 1999:
 Water Use Production Technology

Variable/estimation procedure:	FE-District	FE-Village
Tubewell depth (meters)	-.0080 (2.71)	-.0066 (2.32)
Mean village tubewell depth in 1999 (meters)	.0221 (2.30)	-
Log of HYV yield in village on irrigated land	.120 (4.80)	-
Owned irrigated land (acres)	.00182 (0.30)	.00570 (0.80)
Owned irrigated land over 6 acres	.153 (2.34)	.152 (2.21)
Total owned land (acres)	-.00823 (1.53)	-.0113 (1.89)

Number of farmers with tubewells built since 1970=620. Absolute values of robust t-ratios in parentheses.

Table 3
Village FE-IV Estimates: Determinants of the Probability of a Farmer Digging a Tubewell
and the Number of Irrigated Farms in the Village

Variable	Dig Tubewell		Number of Irrigated Farms	
Owned land (acres) ^a	.00194 (3.33)	.00193 (3.31)	-	-
Log of HYV yield on irrigated land in village ^a	.0155 (1.95)	.0157 (1.97)	29.4 (1.87)	30.4 (1.86)
Share of total village land owned by bottom 20% of landowners	-.0136 (0.99)	-.0140 (1.01)	-54.0 (1.72)	-55.5 (1.75)
Share of village land owned by top 40% of landowners	.00621 (0.35)	.00535 (0.29)	24.8 (0.95)	22.1 (0.84)
Number of government tubewells in village	-	-.000187 (2.61)	-	-.549 (4.65)
N	11,605 farmers	11,605 farmers	240 villages	240 villages

^aEndogenous variable. Instruments include pre-1982 inherited dry and irrigated land, whether a rice-growing or wheat growing village in 1971, log of HYV yields on irrigated land in the village in 1971, whether the village had a pond or river.
Absolute values of robust asymptotic t-ratios in parentheses.

Table 4
Village FE-IV Estimates: Determinants of the Log of Tubewell Depth

Variable	(1)	(2)	(3)	(4)
Log of HYV yield on irrigated land in village ^a	.189 (1.78)	.183 (1.69)	.238 (1.62)	.221 (1.53)
Total owned land (acres)	.0167 (1.35)	.0164 (1.32)	.0204 (1.69)	.0193 (1.58)
Total owned land > 9 acres (20 th percentile)	-.467 (2.21)	-.467 (2.20)	-.468 (2.21)	-.466 (2.20)
Owned irrigated land (acres)	-.00554 (0.32)	-.00530 (0.30)	-.00976 (0.58)	-.00883 (0.52)
Owned irrigated land > 6 acres (20 th percentile)	.0596 (0.25)	.0616 (0.26)	.0740 (0.31)	.0733 (0.31)
Total village wells per acre ^a	-	-	3.51 (1.79)	3.17 (1.65)
Total village government wells per acre ^a	-	-	-	22.8 (2.12)
Share of total village land owned by bottom 20% of landowners	-.632 (1.32)	-.558 (1.15)	-	-
Share of village land owned by top 40% of landowners	-.910 (1.92)	-.820 (1.66)	-	-
Number of government tubewells in village	-	.00218 (2.04)	-	-
N	337	337	337	337

^aEndogenous variable. Instruments include whether a rice-growing or wheat growing village in 1971, log of HYV yields on irrigated land in the village in 1971, whether the village had a pond or river, number of village wells per acre in 1971. Absolute values of robust asymptotic t-ratios in parentheses.

Table 5
 Village FE Estimates: Relationships between Log of HYV Yields on Irrigated Land
 and the Proportion Total Landholdings Owned by the Bottom 40% of Landowners
 and the Presence of a Village Water Market

	Proportion of Land Held by Bottom 40%	Water Market in Village
Log of HYV yield on irrigated land	-.0298 (2.16)	.0612 (3.25)
N	484	484

Absolute values of robust asymptotic t-ratios in parentheses.

Figure 1
Model of hydraulic head around a pumping well

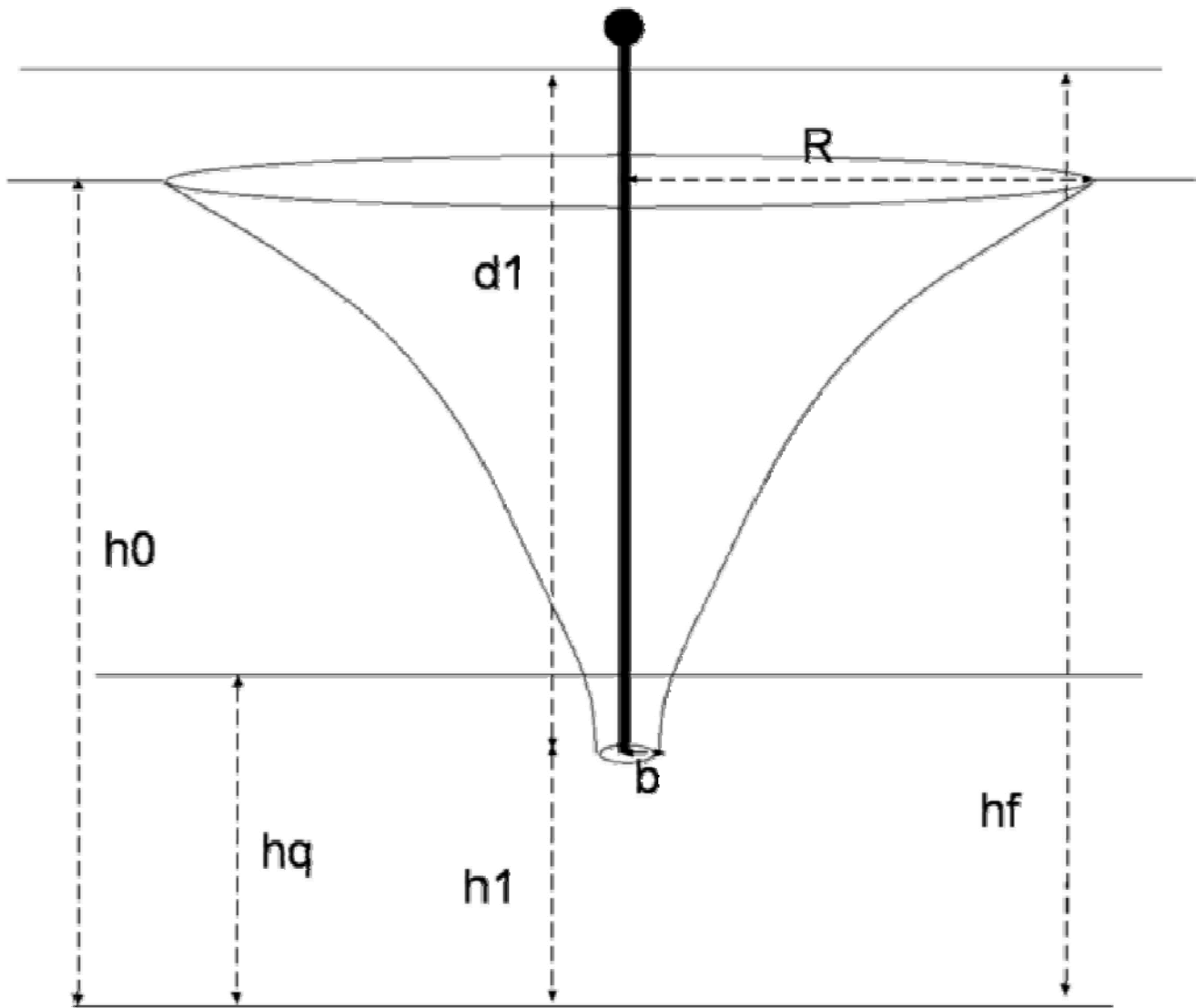


Figure 2
Contour map of hydraulic head and aquifer ceiling in two well using discrete simulation
 $R=300, w_1=560, w_2=1170, K=3, h_q=20, h_0=195, t_1=450, t_2=70$

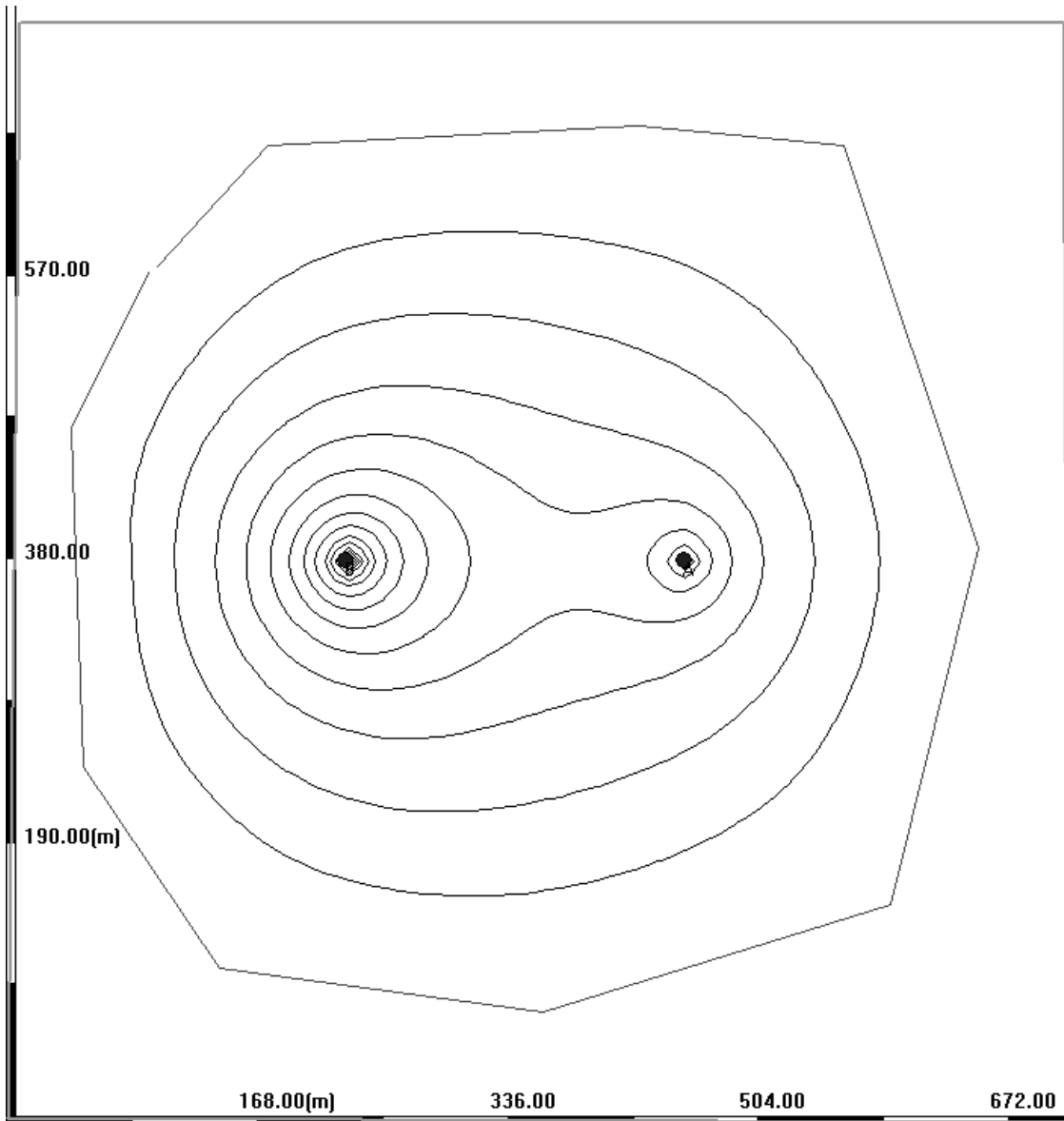


Figure 3
Model of two well interference

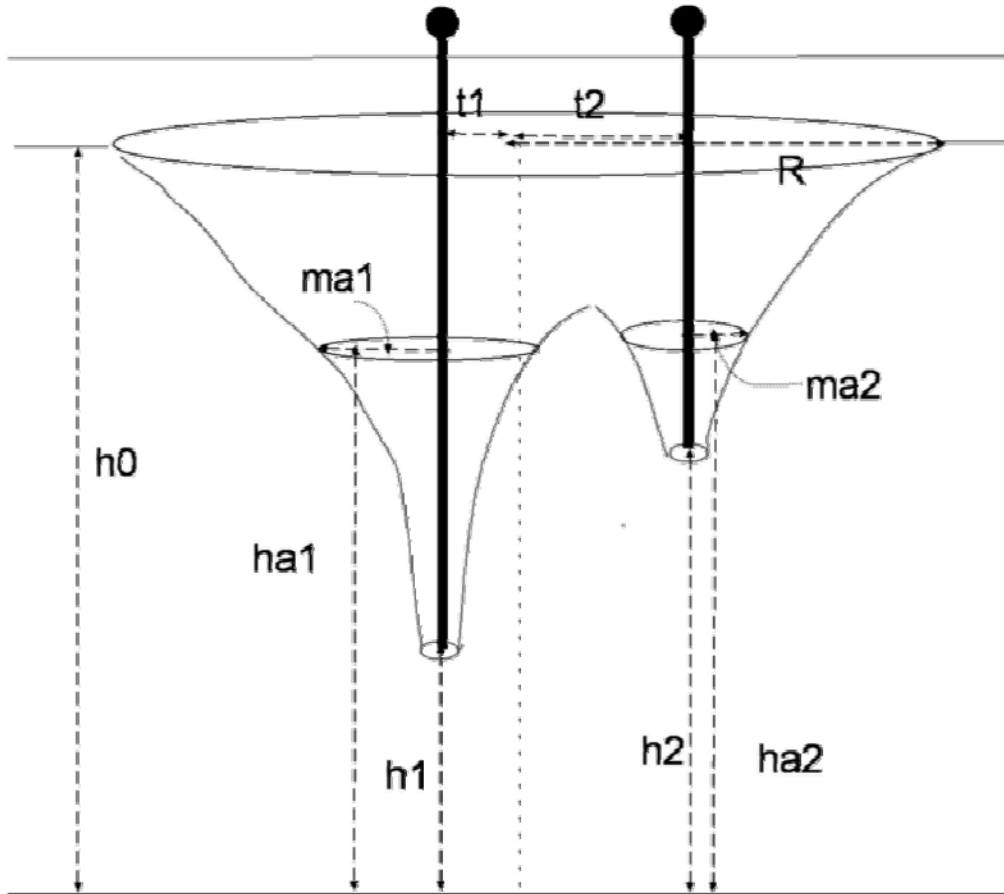


Figure 4a
Contour map of hydraulic head for village 1 with
randomly selected well locations and pumping rate

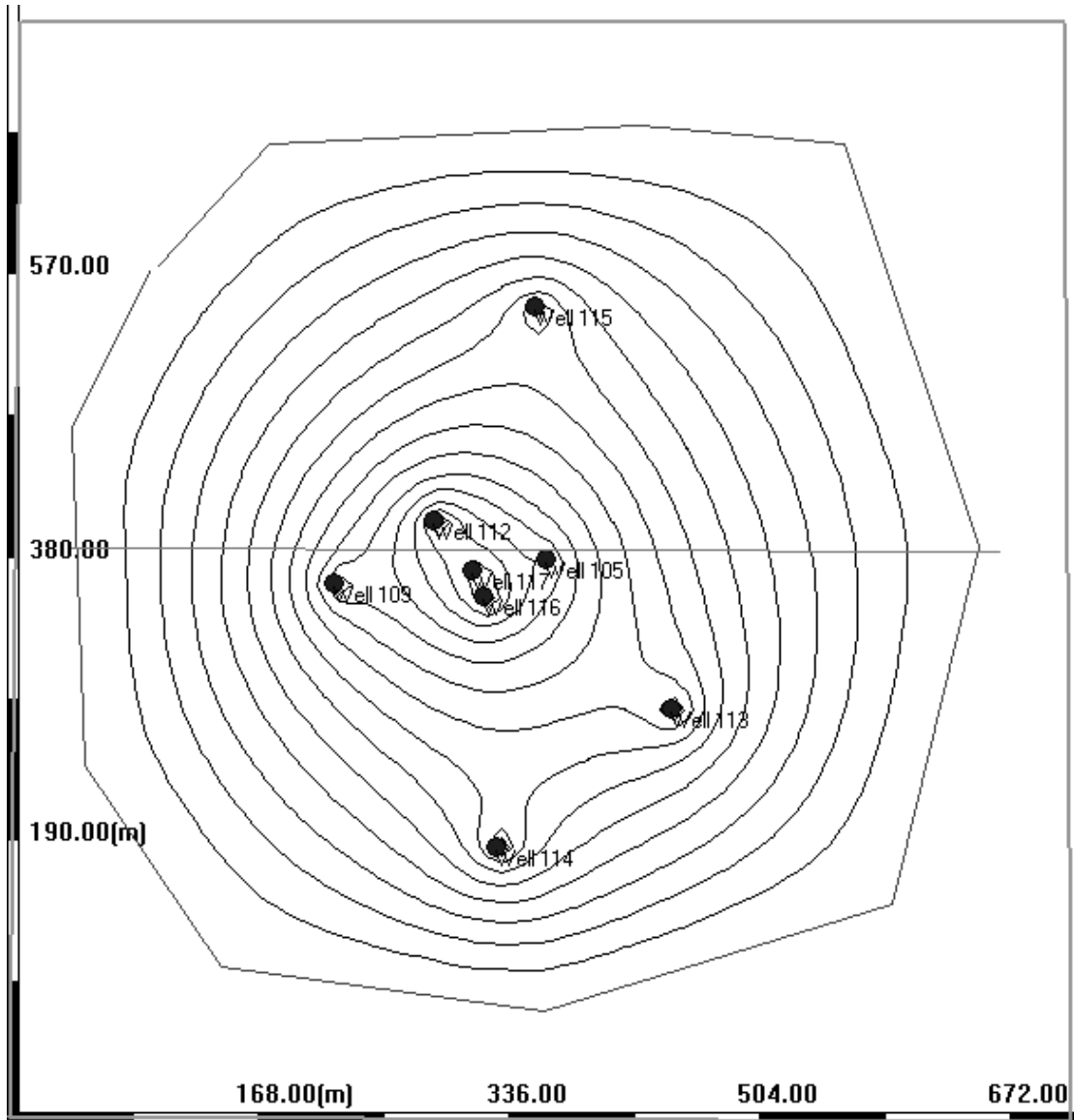


Figure 4b
Contour map of hydraulic head for village 2 with
randomly selected well locations and pumping rate

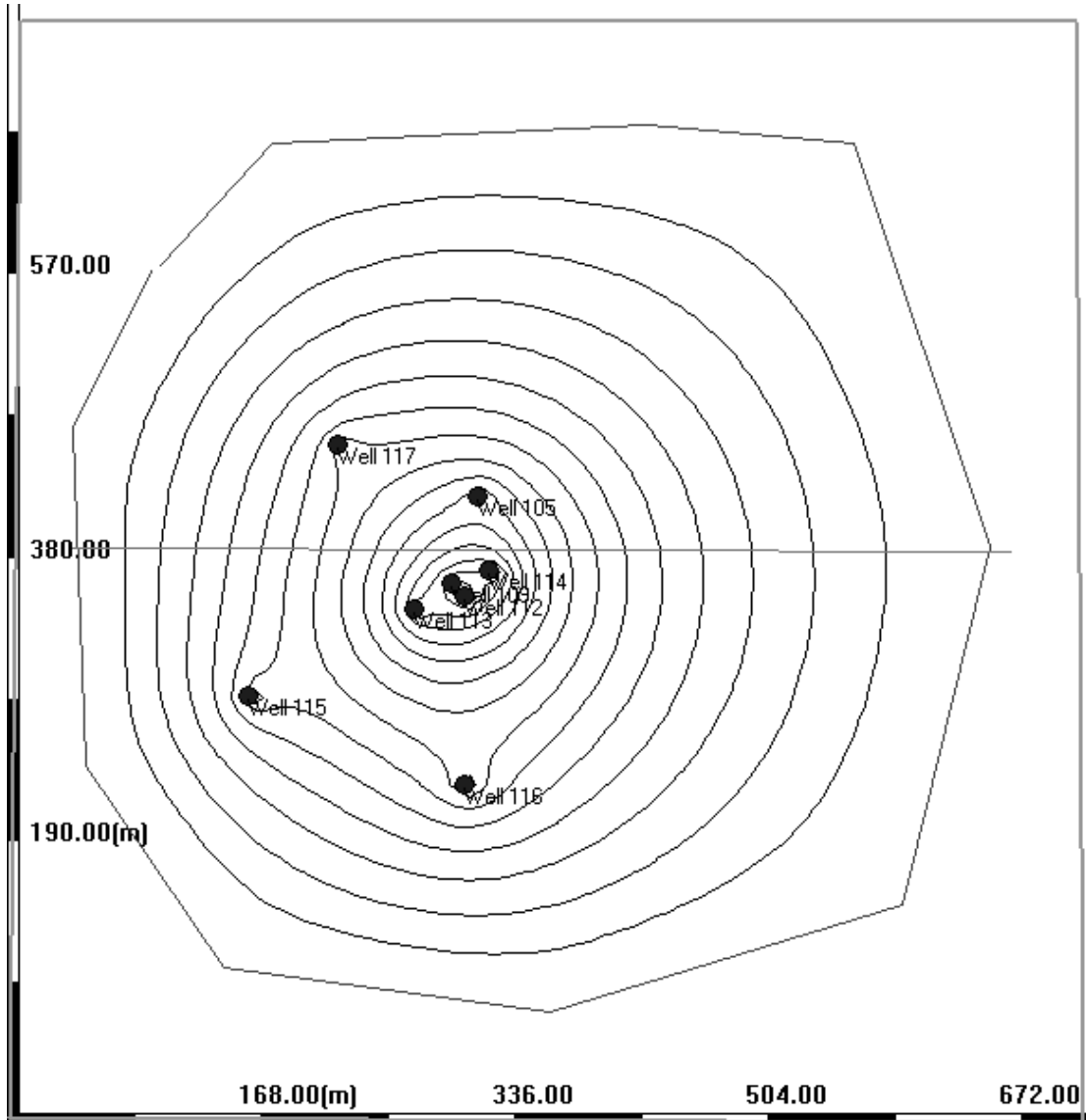


Figure 5
Relationship between numerical and analytic predictions
of water table depth at wells in two simulated villages.

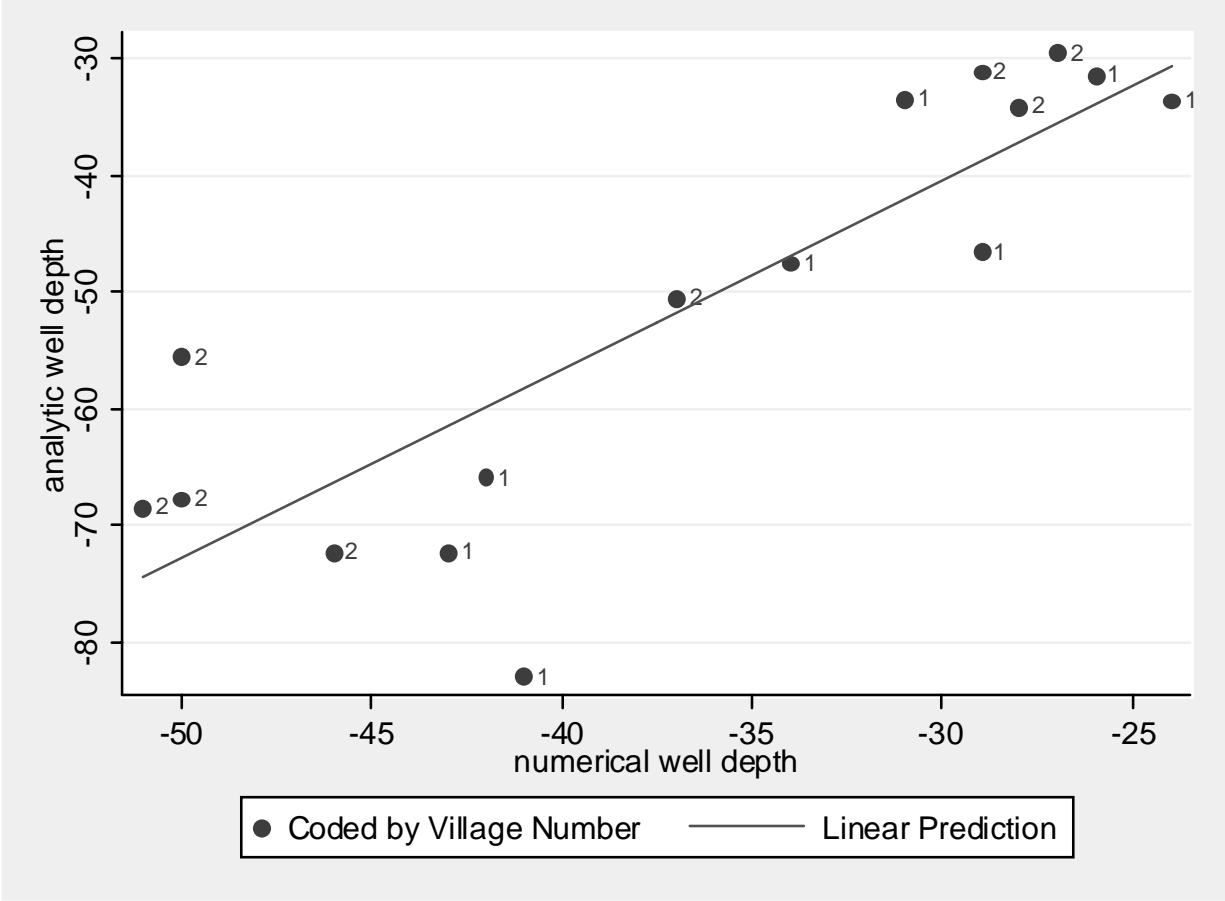


Figure 1
Average Tubewell Depth (Meters x 10) by Year of Installation, 1982-1999

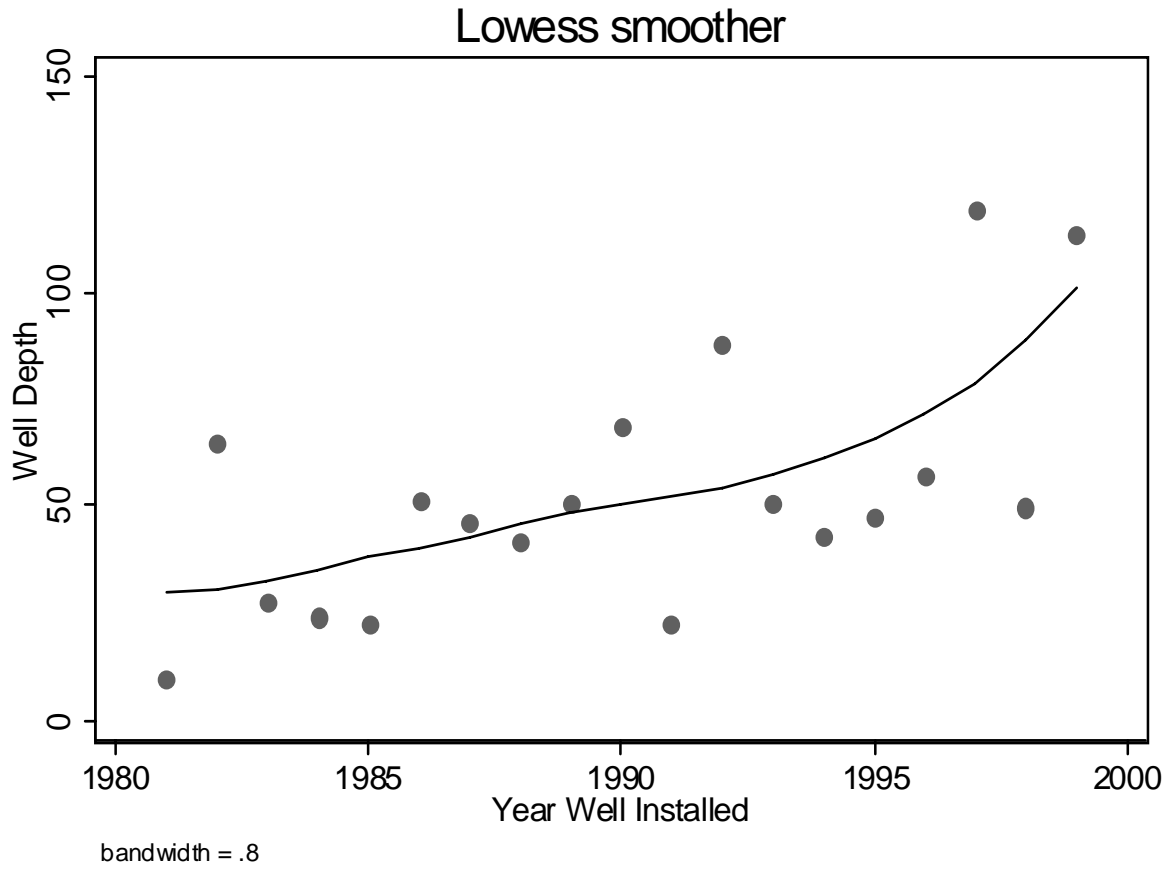
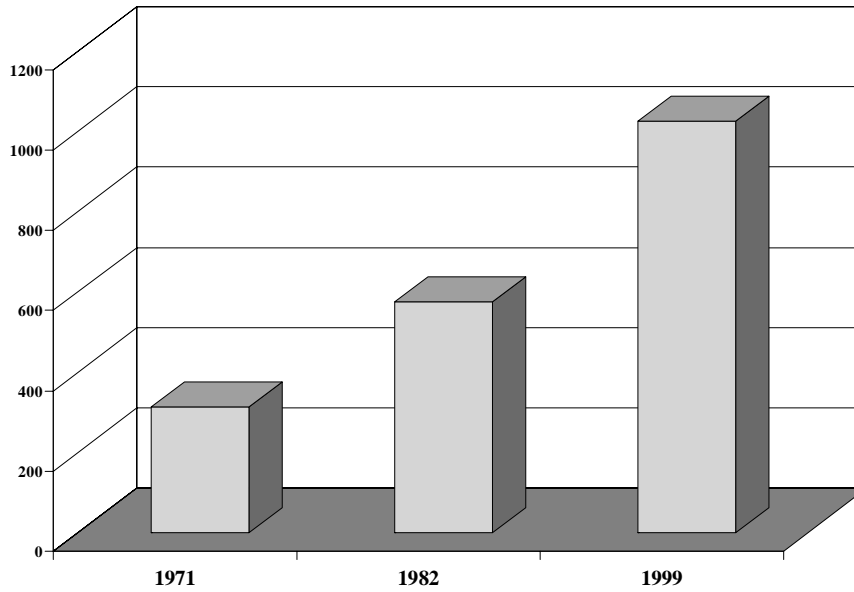


Figure 2: Average HYV Yield Index (Laspeyres-weighted HYV Crops) on Irrigated Land, by Year: 1971-1999



Equilibrium Well Depth for Farmer i , by Size of his Farm and Number of Total Village Farms

Figure 4: Share of Irrigated Land, by Year and HYV Yield Growth Quintile

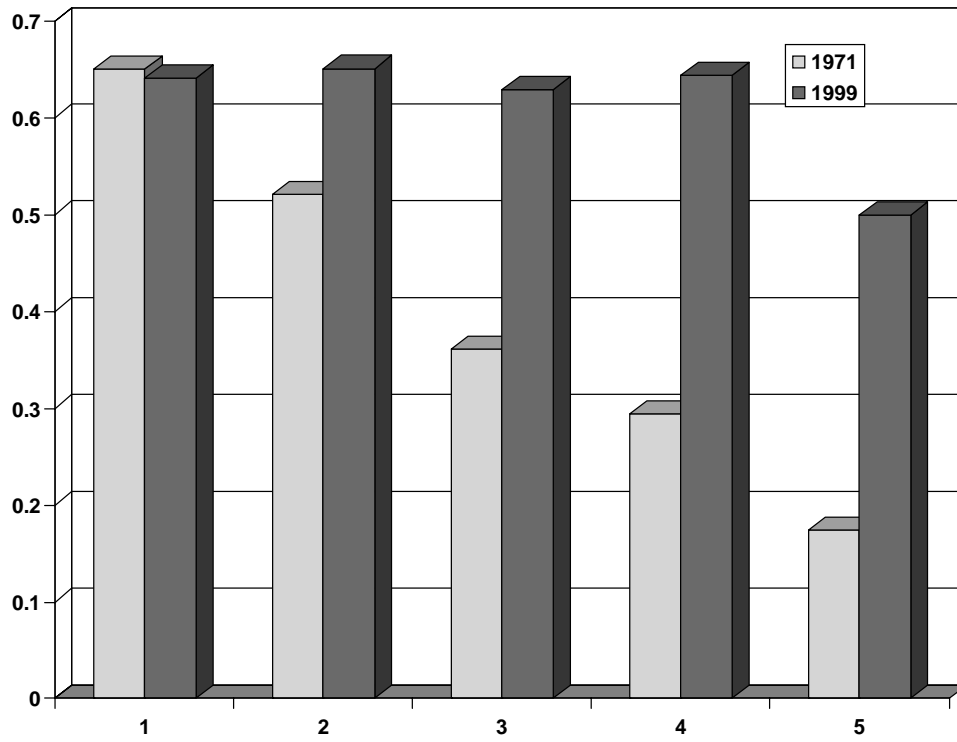
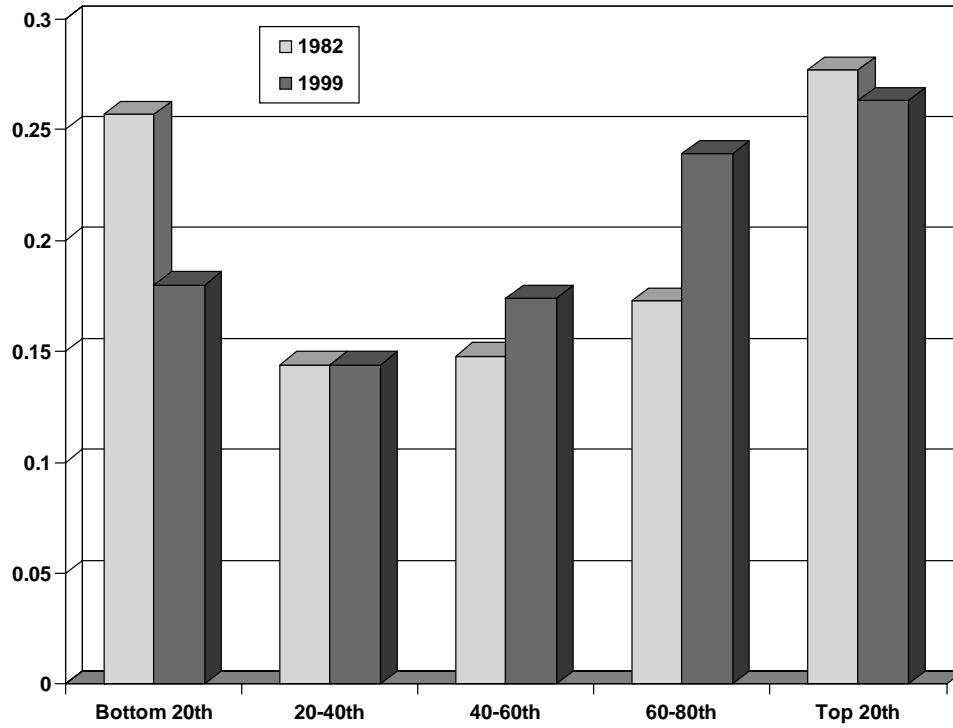


Figure 5: Share of Total Land Owned by Ownership Quintile and Year



**Figure 6: FE Estimates:
Effects of HYV Growth on the Fraction of Total Land Owned by Ownership Quintile**

