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Water Markets, Local Networks, and Aquifer Depletion

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Can Expansion of Markets for Groundwater Decelerate the Depletion of Groundwater Resource in Rural India?*

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Abstract

The development of markets for natural resources can help to ensure that individual users appropriately internalize the opportunity cost of these resources and thus can decrease resource use. However, expansion of markets also makes it possible to sell these resources, which may lead to more rapid extraction. A simple model of markets for groundwater suggests that the latter effect dominates and that water transactions should be increasing in the fixed costs of pumping water. We construct an alternative model in which there are non-convexities with respect to water in the agricultural production process and there are important externalities arising from well interference. We then examine these predictions using a data set from northern India that integrates farm-level information on the buying and selling of water and village-level panel information on water table depths in an instrumental variable framework. As predicted by the alternative model, we find that water transactions are decreasing in the level of fixed costs and that increased market breadth results in lower levels of aquifer depletion.

JEL Classifications: L25, O13, P11, Q01, Q13, Q25

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1 Introduction

The emergence of markets that give rise to the possibility of trade in depletable natural resources like groundwater results in expanded access to the resource which may accelerate the resource depletion. On the other hand, markets may help to internalize the opportunity cost of the resource, and hence decrease the rate of depletion. In this paper, we investigate theoretically and empirically, the effect of development of markets for groundwater on groundwater reserves in the context of rural India.

Markets for groundwater have emerged in rural India in the past few decades and have become a very important source of irrigation along with private tube wells. Ratio of Groundwater irrigated area to net cropped area has increased from 10.4 % in 1970-73 to 21% in 1990-93(Figure1). As much as half the area under private groundwater irrigation is accounted for by the existence of groundwater markets (TERI,1997). In the light of recent reports of rapidly falling water tables, [1]the question of how the markets for groundwater affect the resource depletion becomes central to the design of policies that result in sustainable use.

Since groundwater is a common resource and property rights[2] are not clearly defined, there are co-ordination issues in its usage. Public monitoring of resource usage is not possible since wells are sunk on private property. Groundwater markets can in principal internalize the common resource externality by crowding out of private wells.

An important feature of these markets for groundwater is that these are localized spatially due to high seepage losses that occur along the transportation channels resulting in very high transaction costs. These trade arrangements essentially tend to arise among neighboring farmers who can transport the groundwater easily from one field to another without investing in high cost distribution infrastructure. Incorporating this feature, we construct a simple model that demonstrates that the effect of development of markets on groundwater usage depends on the aggregated land area of neighboring farmers in the areas where these markets could emerge

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[1] Fifteen percent of the administrative blocks in India are considered overexploited where more groundwater is being extracted than is replenished by snow melt or precipitation, and this number is growing by 5.5 percent per annum (CGWB,2004).

[2] Groundwater is considered to be a common resource and rights to access are tied to land ownership (Saleth 1998). In order to obtain legal access, it is only necessary to be able to access the aquifer on land owned. Withdrawal rights seem to be proportional to land ownership (Easement Act of 1882) but there is no clearly defined limit on water withdrawals.

relative to the fixed costs of sinking a well. The model establishes a U-shaped effect of the development of markets on depletion of the resource varying by the land area among neighboring farmers. For very small and large aggregated areas split equally among neighbors, the markets would tend to increase resource depletion. But for intermediate areas with small and medium farmers as neighbors, the markets would result in water conservation provided the aggregate area among the neighbors is not too large.

We test the predictions of this model using a unique combination of data sets from northern India, integrating farm-level information on buying and selling of water, and village-level panel information on water table depths. The data on market activity is from the Uttar Pradesh and Bihar (1997-98): Survey of Living Conditions that was collected by the World Bank. We match this to the two waves of the Minor Irrigation Census of India at the village level which contains the data on water table depths.

In addition to analyzing the effects of market development on water table depths, this paper also establishes why markets for groundwater develop only in certain areas and not others in spite of water being highly divisible and the transactions costs for trading water among neighboring farmers being low. We show that these market exchanges are limited not by transaction or coordination costs, but by the nature of the production technology. Our alternative model with non-convexities in production process rests on arguments analogous to the efficiency wage literature, and demonstrates that water markets arise where fixed costs of sinking a well are low. Our empirical findings and the features of the data strongly support the predictions of this model.

A few recent papers have examined groundwater markets in South Asia. Jacoby et al (2004) investigate the market structure for these markets and evaluate whether these are characterized by monopoly power. Anderson (2005)has examined if social barriers based on Hindu caste system limit the possibility of these trade arrangements.[3]But none of these studies have looked at how these markets for groundwater affect groundwater resources. Also, these studies do not incorporate the externalities arising in groundwater use. Our paper proposes a simple model to show when these markets are likely to emerge accounting for well interference externalities.

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[3] Some recent papers address features of groundwater use for irrigation that are very relevant to the study of markets for groundwater. Aggrawal(2000) has investigated the social conditions under which joint ownership of wells is likely to emerge; Foster and Rosezweig (2008) look at how land inequality affects water tables; Sekhri (2008) studies public provision of groundwater and its impact on water tables.

The rest of the paper is organized as follows: Section 2 describes the groundwater markets and some basic features of the data. We propose our model in Section 3 and describe the data in Section 4. Section 5 and 6 present our empirical analysis, and Section 7 concludes the paper.

2 Groundwater Markets

Groundwater Market refers to a local, informal institutional setup often at the village level through which owners of water extraction mechanisms sell water to others at a price.[4] The sellers are relatively larger farmers who are able to sink a well and instal a pump as this requires a substantial amount of investment. Table 1 depicts that the larger farmers are the ones who have mostly invested in pumping technology in the area under study. Among farmers with holdings larger than 10 acres, 64 percent have sunk their own wells. While among marginal farmers with plots of size less than 1 acre, only 5.5 percent have sunk a well. The percentage of farmers with own wells increases monotonically with the size of land holding. Due to lumpy nature of ivestment, only 20 percent of the farmers own a pump.

The payments for the water transactions are in cash or kind.[5] Water is transported from the seller's well to the buyer's field by lined or unlined field channels (or sometimes underground pipe network). Underlined field channels are the most commonly used transportation channel. In the area under study, unlined channels are the most widely used channels irrespective of the depth of the markets (Figure II). Due to high seepage losses across these unlined channels, the transaction costs of transporting water tend to be very high. As a result, trade arrangements that do emerge are highly localized in nature. Other studies of groundwater markets in South Asia also point to spatial fragmentation and localization of these markets on account of high transportation costs (Jacoby et al,2004).

Figure II.b highlights another interesting puzzle about the nature of markets. The figure plots the probability of being a seller and buyer as a function of the water table depth. Water table depth proxies for fixed cost required to sink a well. Intuitively, one might think that markets should arise when fixed cost needed to sink a well are high and the farmers who can absorb the cost use the opportunity to sell to their neighbors. However, we observe that market

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[4] Although the water is extracted from a common resource, in absence of property rights the well owners treat the extracted water as their own.

[5] Many kinds of contracts like output sharing, labor contracts and input output sharing have emerged in the context of groundwater markets(Shah, 1993).

transactions are more common when fixed cost to sink a well are low. We develop a model that strongly supports this puzzling feature of the market transaction data.

3 Conceptual Framework

In order to better understand how the introduction of markets for groundwater affects the rate of aquifer depletion, we consider a simple parametric model consisting of two farmers who can only irrigate their land if they access the water table through the sinking of wells. To keep the model tractable we assume, in particular, that each farmer has exactly one neighbor and that is unable to transact in water with a farmer who is not his immediate neighbor. Thus, if there is a water market at all, it can only arise between immediate neighbors.

The basic implication of the model is that whether introducing markets results in greater or less water usage depends on the land area of the two farmers relative to the fixed cost of sinking a well. If both farmers have sufficiently large farms then they will sink two wells in autarchy and the effect of introducing markets will be that they continue to each sink a well. Under these circumstances trade in water equates the marginal product of water on the two farms and thus in general leads to increased water use. On the other hand if the combined farm area is intermediate then the result of introducing trade in water will be to move from two to one wells. In this case total water use will unambiguously decline. For pairs of small farmers, opening trade in water can result in increased water use by moving from zero to one wells, while for the smallest farmers there will be no change in water use as no wells will be sunk under either regime.

Initially we consider the case in which the ability to trade with one's immediate neighbor is imposed exogenously. That is we assume a pair of farmers $i \in (1, 2)$ with total land area a_i is endowed with a production function in which yield per acre of irrigated land is quadratic over water w_i per unit irrigated area h_i. Normalizing the yield on un-irrigated land to zero, total output may be written as:

$$y_i = h_i g(w_i/h_i) = h_i(g_1 w_i/h_i - g_2(w_i/h_i)^2) \tag{1}$$

Further, assume that water can only be obtained through sinking a well of depth f. The depth required to sustain a level of water extraction of w_1 by farmer 1 is assumed to be a quadratic function of w_1 and a linear function of the aquifer depth δ and the amount of water extracted, if any, by his neighbor w_2. [6] The annualized price per unit depth of digging the well is normalized to 1 and the energy cost is assumed to be zero. Thus the annualized cost of a well that produces w_i units of water per unit time is:

$$c(w_1, w_2) = f + c_1 w_1 + c_2 w_1^2 + c_3 w_2 \tag{2}$$

Normalizing the price of output to one yields farmer profits of

$$max\Big(0, h_i(g_1 w_i/h_i - g_2(w_i/h_i)^2) - (f + c_1 w_1 + c_2 w_1^2 + c_3 w_2)\Big) \tag{3}$$

For analytic simplicity we focus initially on the case in which there is no externality i.e., $c_3 = 0$.

Consider the equilibrium in which there is no trade between farmers. Farmers will compare the profits of sinking a well and irrigating some fraction of their land to their profits (0) if they do not sink a well. Differentiating (1) with respect to h_i yields the obvious implication that for any given amount of water it is optimal to irrigate all one's land. Solving for the profit maximizing level of water use conditional on having a well yields:

$$w_i = \frac{(g_1 - c_1)a_i}{2(g_2 + c_2 a_i)} \tag{4}$$

Substituting back into own profits, one can then solve for the level of fixed costs at which the farmer is just indifferent between sinking and not sinking a well. He will sink a well if

$$f_i < \frac{a_i(g_1 - c_1)^2}{4(g_2 + c_2 a_i)}. \tag{5}$$

This expression is increasing in a_i–the larger an individual farmer's area the higher fixed cost he will absorb in terms of sinking a well.[7]

Now consider the case in which the farmers may trade water. At this point they will operate as if maximizing joint profits and there are three possible outcomes: neither farmer sinks a well, one farmer sinks a well and trades water, or both farmers sink a well and trade water if

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[6] This expression can be thought of as an approximation to the two-well interference expression in Foster and Rosenzweig (2008). That paper constructs a hydrogeological model of well interference that is derived based on the well known Thiem relation, which describes the hydraulic head that arises around a single well that is pumping at a constant rate in a stylized environment.

[7] We assume that a single farm is never so large that it is profitable to sink two wells in autarchy. In practice given interference $c_3 > 0$ between wells that are nearby will make this an unattractive strategy even for quite large farmers.

needed. Solving for water usage and substituting back into joint profits yields expressions it may be shown that the number of wells depends on aggregate land ownership and the level of fixed costs. In particular, at least one well will be sunk if

$$f < \frac{a(g_1 - c_1)^2}{4(g_2 + c_2 a)}. \tag{6}$$

where $a = a_1 + a_2$, which is analogous to (5) and two wells will be sunk if

$$f < \frac{c_2(g_1 - c_1)^2 a^2}{4(2g_2 + c_2 a)(g_2 + c_2 a)}. \tag{7}$$

Since the right hand side of both expressions are increasing in a, the number of wells will be increasing in combined acreage and decreasing in fixed cost.

We now turn to the question of what happens to total water usage. First, for the same number of wells there will be greater water usage under trade than not. For example, water usage under autarchy with only one farmer (farmer 1) having a well relative to that with one farmer is

$$\frac{g_2 + c_2/h}{g_2 + c_2/h_1} \tag{8}$$

which is less than one as long as farmer two has positive acreage. This result is straightforward and general–with greater land area the marginal return to water rises and so more water is extracted. In the case of two wells the ratio of autarchic to market total water is maximized at one when the farmers have equal acreage and decreasing as the absolute area difference expands. When farms are of equal size and there are no externalities arising from well inference then trade does not have any effect on well usage. If one farm is larger than in autarchy the marginal product of water for that farmer exceeds that of the smaller farmer

$$\frac{dw_a/w_m}{d|a_1 - a_2|} = -\frac{16c_2(2g_2 + c_2 a)^2 |a_1 - a_2| g_2}{a(2g_2 + c_2 a_2)^2(2g_2 + c_2 a_1)}. \tag{9}$$

Because trade results in an increase in water usage for given number of wells there must be a decrease in the total number of wells in order for there to be a decline in the level of water usage. That is two wells must be profitable under autarchy and one well must be profitable in the presence of trade. If the farmers have equal sized farms it is clear that there will be less water used under autarchy

$$w_a/w_m = \frac{2g_2 + 2c_2 a}{2g_2 + c_2 a} > 1. \tag{10}$$

It may also be established that this ratio is decreasing in the difference in land sizes of the two farmers and exceeds one in the case that the smaller of the two farms is just indifferent to building a well under autarchy. Thus we may conclude that trade reduces total water usage under the conditions predicted above in which each farm is large enough to build a well in autarchy, given the fixed costs of acquiring a well, to construct a well but their combined acreage is not large enough, again given these fixed costs, to justify building two wells.

As noted, the above analysis has assumed away the presence of well-interference both in terms of a negative spillover (c_3) and possible strategic complementarity as studied by Foster and Rosenzweig (2008). Allowing for such well-interference complicates matters because it introduces the question of whether decision making on the part of the farmers incorporates this externality. One might argue that if transaction or coordination costs are sufficiently high to preclude trade in water they should also prevent coordination on water extraction and conversely. In this case, there is little change in the qualitative predictions of the model. In particular, it is still the case that water markets always reduce total water use if they result in a transition from two to one wells. Under the alternative assumption that the externality is internalized regardless of the presence of markets there is a qualitative change. In particular

$$w_a/w_m = \frac{(2g_2 + 2c_2a)(g_1 - c_1 - c_3)}{(2g_2 + c_2a)(g_1 - c_1)} \tag{11}$$

This equation is no longer necessarily greater than 1 so there may be scenarios in which markets result in a reduction in wells but water use rises.

An important concern with the above model is that it assumes that markets are imposed exogenously, suggesting that there is substantial variation across farms or villages in the level of transaction or coordination costs. But if one assumes that the above model applied most directly to neighboring farmers it is not clear what this source of variation might be. Indeed, it is not at all clear why farmers with neighboring plots in a setting in which land markets are thin (and thus holdings stable over time) cannot enter into a mutually beneficial arrangement in which the farmers coordinate their activities. While one can imagine that the transaction costs and coordination issues associated with setting up of a village-level public irrigation system that involves many farmers may be large, it seems that the technology associated with transferring water from one farm to that of his immediate neighbors is not complicated and can involve simple unlined channels. It may also be possible that social barriers, such as those posited by Anderson (2005), play some role, it is not clear that this effect should be sufficiently pervasive to produce these kinds of results. After all in any system of social stratification that is occupationally based there must be a place for economics transactions among individuals in the different groups.

We thus think it is useful to adapt the above model to the case in which market transactions are limited not by transaction or coordination costs, but by the production technology, as detailed below. In particular, we assume that low levels of water per irrigated acre are likely to have little or no impact on agricultural yield per irrigated area while moderate levels of water per irrigated acre result in substantial increases in yield. This pattern may emerge for a particular crop but seems particularly reasonable a context in which there is a high complementarity between the adoption of high yielding variety seeds and irrigation (Foster and Rosenzweig, 1996). While high yielding varieties can substantially increase yields if provided with adequate water, they may result in lower yields than if traditional and more robust varieties are used. Thus one needs a certain amount of water per irrigated area before it makes sense to adopt the high yielding seeds at all.

Using an argument analogous to that used in the efficiency wage literature, we show that a model of water-market variation that arises from this non-convexity yields predictions that are consistent with basic features of the data on water transactions. In particular, the resulting model predicts that farmers will not fully irrigate their land, that water transactions are most likely to arise in places where water is not scarce, that those selling water are likely to be of intermediate size. The model also yields a series of empirical predictions that are analogous to the above model with convex production but that are in principle testable under circumstances in which the presence or absence of water markets is not exogenously imposed. Specifically, it shows how the overall level of market activity will depend not only on the size distribution of land holding but on the correlation in land sizes among neighboring farmers. We also establish that given the overall size distribution of farmers, the level of market activity will be an important determinant of overall water usage.

In particular suppose that farm yields can be characterized by the following production function:

$$y_i = \eta_0 \ (2\,\eta_1 - \eta_0)\, h - \left(\frac{w}{h} - \eta_1\right)^2 h \tag{12}$$

with $\eta_1 > \eta_0$. This function incorporates the idea that there is a level of water use per unit irrigated area that maximizes yield per acre on this land and that yields are negative on the irrigated land (relative to the traditional un-irrigated crop) if water usage is sufficiently low.

Indeed yields do not become positive until $w/h > \eta_1 + \sqrt{2\eta_0\eta_1 - \eta_0^2}$

The farmer, as before, maximizes the difference between profits on irrigated land and the annualized cost of accessing the water for the irrigated land. It is helpful to separate this problem into two parts; the farmer chooses a level of water to access and then selects an optimal level of irrigated area given the level of water. The expression for the latter can is just obtained by differentiating (12) with respect to irrigated area subject the constraint that his irrigated area cannot exceed his total area and solving to get

$$h_i = min\Big(a_i, w_i/(\eta_1 - \eta_0)\Big) \tag{13}$$

Thus given the amount of water that is selected, which may depend on access to purchased water, a farmer will in general only irrigate a part of his land. Note that this contrast markedly with the convex case in which a farmer always distributed all his available land over his entire farm. It also makes clear why trade in water between a pair of farmers may not take place. Substituting the expression for optimal irrigated area into the production function and assuming an interior solution gives

$$y_i = 2\eta_0 w_i \tag{14}$$

In this case the marginal product of water does not depend on total area–if a farmer has a well but does not fully irrigate his own land then, for given amount of water, he will have no incentive to sell water to a neighbor who has no water even in the absence of barriers to transaction or coordination.

To make this comment more precise we need to consider the implications, as before, of the number of wells that will be constructed. In so doing we will focus only on fully cooperative equilibria and we will assume an arbitrarily small cost of transporting water from a well owned by one farmer to the farm of his neighbor. The first assumption seems a plausible characterization of the behavior of neighboring farmers, as argued above, and helps focus attention on the effects of the non-convexity on the presence of markets and water use. The second assumption removes the in-determinacy that arises in terms of where a well or wells should be located when the return to irrigated land is the same for both farms but not all land is irrigated. Thus, for example, when a single well is most profitable it will be located on the larger of the two farms.

First, consider the case of one well. In this case there are three possible regimes: (a) the farmer with the well will be partly irrigated and the one without the well will not be irrigated at all (b) the farmer with the well will be fully irrigated and the other farmer will not be irrigated at all (c) both farmers will be fully irrigated. Because we are considering a cooperative solution the objective function under regimes (a) and (b) will be to maximize

$$2\eta_0(w_1+w_2)-f-c_1(w_1+w_2)-c_2(w_1+w_2)^2. \tag{15}$$

Therefore the total water will be : $w^*=w_1+w_2=(2\eta_0-c_1)/(2c_2)$

Thus if farmer 1 is the larger of the two neighbors and $w^*<(\eta_1-\eta_0)a_1$ then one will be in regime (a) and there will be no trading of water. In particular farmer 1 will irrigate

$$h_1=(2eta_0-c_1)/((2c_2)(\eta_1-\eta_0)). \tag{16}$$

If on the other hand, $(\eta_1-\eta_0)(a_1)w^*<(\eta_1-\eta_0)(a_1+a_2)$, then one will be in regime (b) with farmer 1 fully irrigated and

$$h_2=(2eta_0-c_1)/((2c_2)(\eta_1-\eta_0))-a_1. \tag{17}$$

Finally if $w^*>(\eta_1-\eta_0)(a_1+a_2)$ then both farmers will be constrained and the objective function is

$$\eta_0(2\eta_1-\eta_0)a-(w/a-\eta_1)^2a-f-c_1w-c_2w^2. \tag{18}$$

Differentiating with respect to w, solving and substituting, yields an expression for water use and profits in the one-well case.

The two well case also has three regimes: (a) each farmer has a well but neither farmer irrigates all his land (b) the smaller farmer irrigates all his land and sells some water to his neighbor (c) both farmers are constrained. In the first two regimes the objective function is

$$2\eta_0(w_1+w_2)-2f-c_1w_1-c_2w_1^2-c_3w_2-c_1w_2-c_2w_2^2-c_3w_1 \tag{19}$$

The maximand of this expression will be in regime (a) if the maximized values of the farmers' water usage meets the criteria $w_1^*<(\eta_1-\eta_0)a_1$ and $w_2^*<(\eta_1-\eta_0)a_2$. The maximum will be in regime (b) if some of the water extracted from the smaller farmer (say farmer 2) is transferred to farmer 1 so that $w_2^*>(\eta_1-\eta_0)a_2$ but $w^*<(\eta_1-\eta_0)a$. Finally if $w^*>(\eta_1-\eta_0)a$ then both farmers are constrained and there will in general also be water transfers of ω from the smaller to the larger farm. The objective function in this two-well constrained regime is

$$\eta_0(2\eta_1 - \eta_0)(a_1 + a_2) - ((w_1 + \omega)/a_1 - \eta_1)^2 a_1 - ((w_2 - \omega)/a_2 - \eta_1)^2 a_2 \\ - 2f - c_1 w_1 - c_2 w_1^2 - c_3 w_2 - c_1 w_2 - c_2 w_2^2 - c_3 w_1 \quad (20)$$

Because the expressions in the constrained case are too complex, even in the case of this simply parametric model, to examine in detail, we assign parameter values that are illustrative of the underlying process. In particular, we assume $c_1 = c_2 = c_4 = 1/2$, $\eta_0 = 4$, and $\eta_1 = 5$.

Figure 1 plots farmer profits as a function of fixed costs for one and two wells. Not surprisingly, and consistent with what was observed in the convex case the two well case leads to higher profits when fixed costs are low, the one well case dominates when fixed costs are moderate, and no wells will be built if fixed costs are sufficient.

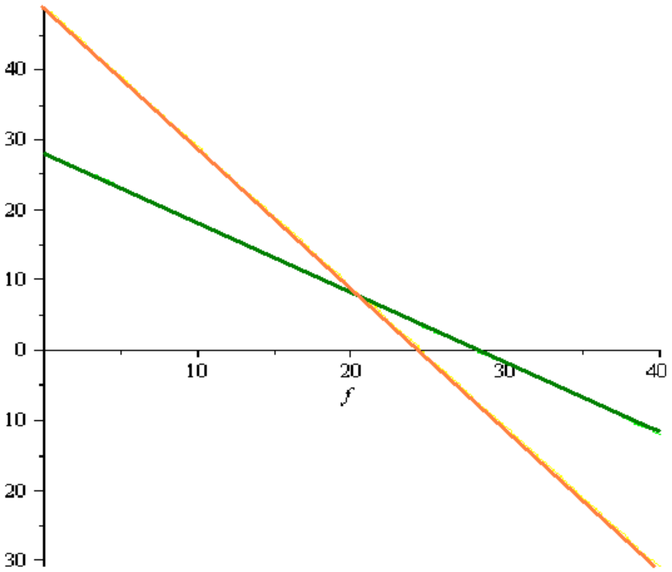

Figure 1: Total profits for one and two wells if unconstrained

Figure 2 sets fixed costs at 20 plots profits as a function of the acreage of the two farmers. It is evident that the key factor determining whether one or two wells are built is the combined acreage of the two farmers. If this combined acreage is high enough then two wells are built. Also if total acreage is sufficiently small now wells are built.

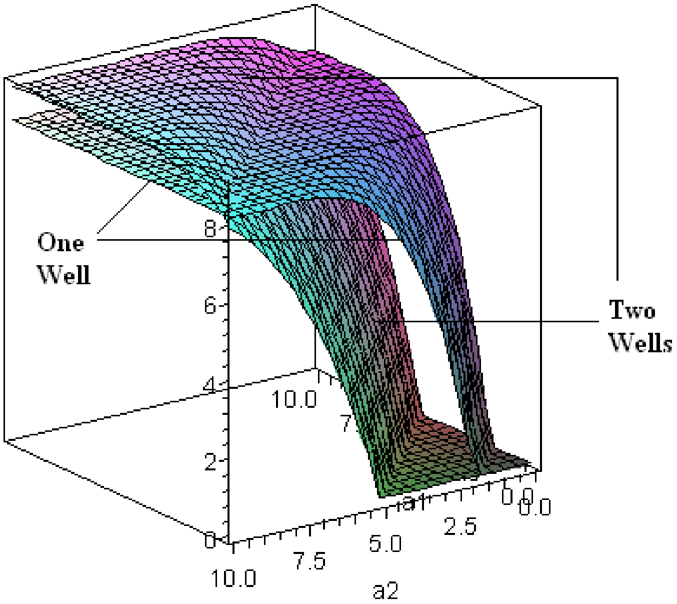

Figure 2: Profits by one and two wells by farmer area

Figure 3 describes the presence of water transactions as a function of farmer areas given a fixed cost of 20 and shows that the relative prevalence of water markets is sensitive to the joint distribution of farmer areas. Note that water transactions are not observed between pairs of large farmers and pairs of very small farmers.They are observed if there is sufficient asymmetry in size among large farmers. It is only when the smaller farmer is large enough to dig his own well but not sufficiently large so that his optimal irrigated area is less than his total acreage. To see how the joint distribution of farmer areas enters the picture, consider two alternatives: that neighbors tend to have similar sized farms and that the size of neighbors' farms is negatively correlated so that the sum of each pair of neighbors' farm sizes is relatively constant. Clearly in the former case neither the largest nor the smallest farmers will tend to be involved in water transactions. On the other hand if the sum of neighbors' farm sizes is in the range of either 8 or 12 acres using these parameter values, markets will be almost universal.

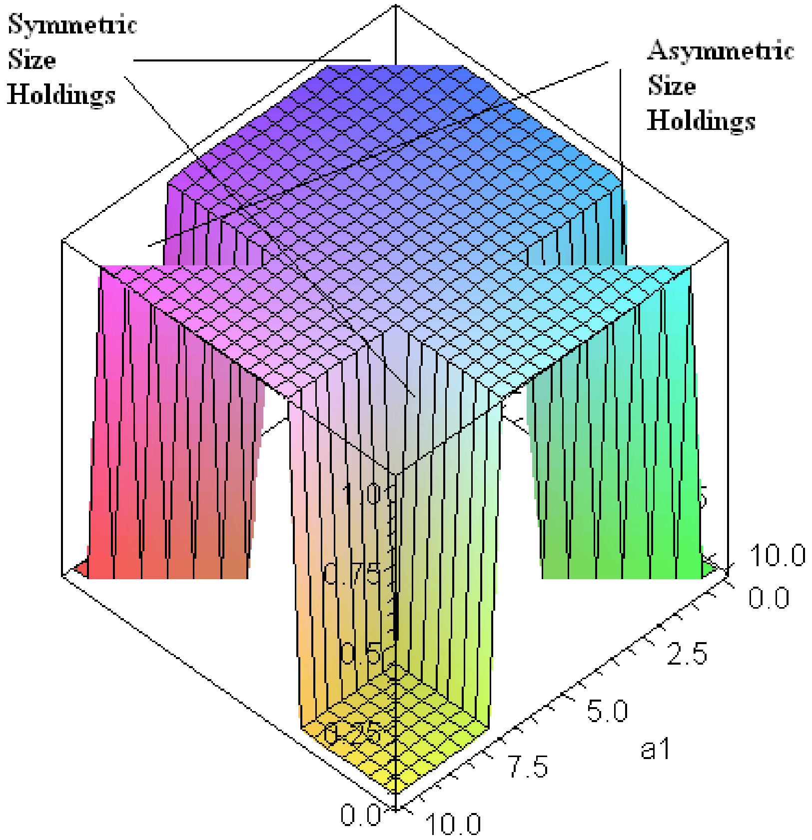

Figure 3: Presence of water trade by farmer area for two neighbors

Figure 4 then turns to the question of water usage and shows how the joint distribution of farm sizes of neighbors influences total water consumption. In particular if farm sizes are highly correlated among pairs of neighbors then large farmers will use substantial water but small farmers will use little. Contrast that with the case of negatively correlated farm sizes. In this case if the sum of farmers' areas is sufficiently small (approximately 8 using these parameter values) there is very low level water use. This low level of usage arises precisely because for these farmers one well is optimal and the farmer with the well fully irrigates his land and then sells additional water to his neighbor.

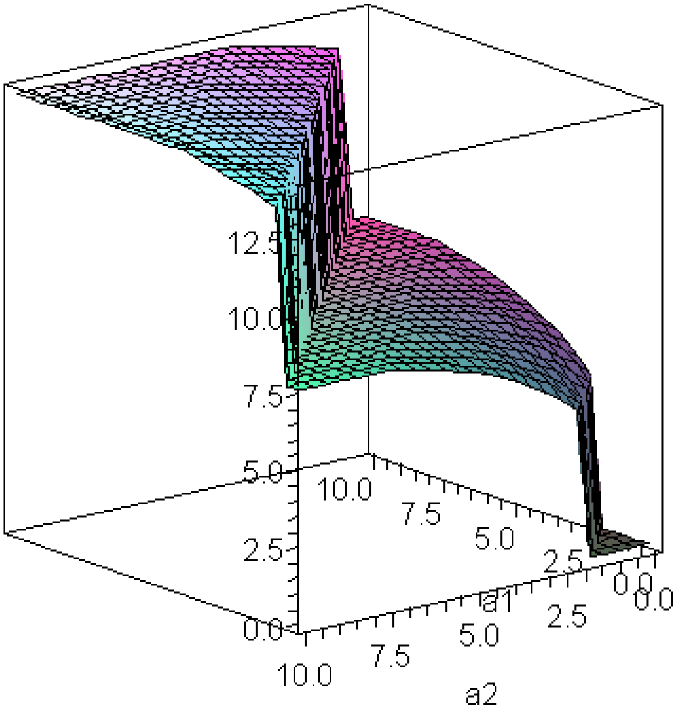

Figure 4: Total water usage by farmer areas for two neighbors

4 Data

The econometric analysis uses combination of two data sets. The first data set used in the following analysis was collected by the World Bank research team in 1997-98 (Uttar Pradesh and Bihar 1997-98: Survey of Living Conditions). There are 120 villages in the sample. These villages are located in South and South Eastern Uttar Pradesh and North and Central Bihar. About 36 percent of India's poor and 27 percent of the total population live in these two states.[8] The sample of villages is drawn at random from 12 districts in UP and 13 districts in Bihar. The overall sample constitutes 2250 households. The Household questionnaire comprises of 10 main modules including household demographics, expenditure, economic activities and farming. The Village questionnaire is made up of 7 modules covering village characteristics like size, caste

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[8] In 1993-94, 55 percent of the population in Bihar and 41 percent in Uttar Pradesh were living in poverty.

composition, political structure, agriculture, irrigation and access to facilities. Mainstay of the economies in these villages is agriculture. We make use of detailed farmer level information on land ownership, pump ownership, sources of irrigation, and selling and buying behavior in conjunction with the village demographic data in our analysis.

This data was matched at the village level to 2 rounds (1993 and 2000) of the Minor Irrigation Census (MI census) conducted by the Government of India on a quinquennial basis. This census accounts for the entire population of wells. The Wells data account for around 1.2 million wells (Census year 2000) and have comprehensive information including details about ownership, holding size of farmers for privately owned wells, sources of finance, energy source of the pumps, and average pumping hours, among other things. In addition, information about village level average depth of the water table, ground water irrigated area, sown area and cultivated area are contained in the Village data.

The *Data Appendix* summarizes the data sources, the variable definitions, and the summary statistics. Table A.I lists the definitions of the variables along with the sources, and Table A.II provides summary statistics of the main variables used in the regression analysis. Our measure of the change in the water table depth for each village is the difference in the average groundwater level across the two waves of the Minor Irrigation Census. Average ground water level is reported in meters below ground level. We construct an index measure for capturing the development of markets for groundwater. Our Index[9] proxies for the breadth or pervasiveness of markets within a village. We have calculated our breadth index (MB)as the ratio of the buyers irrigated area to the total irrigated area in the village.[10] Although not reported, as a robustness check we also carried out the analysis with other measures that captured the level of market development. The results are not sensitive to these different measures.

5 Markets and Crowding Out of Private Wells

In the theoretical framework, we established that the markets arise when the holdings of the neighboring farmers are asymmetrical(large and small size farmers are neighbors) and

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[9] Other case studies (Mukherji (2004); Pant (2004); Shah (1993); Shankar(1992)) that evaluate the effects of these markets on rural poverty have also used this measure to capture market breadth

[10] A farmer is categorized to be a buyer of groundwater if the farmer reports groundwater as major source of irrigation, does not own a pump, and reports buying water.

the total area among the neighbors is large enough to absorb the cost of 1 well but not large enough such that their optimal irrigated acreage is smaller than their total land. In such a scenario, trade among relatively smaller farmers with one well would lead to less aggregate water usage as they will be using one pump. The development of markets essentially crowds out the investment in private wells and that leads to the reduction in water usage. Our theoretical model generates testable predictions about the relationship between pump ownership and the interaction between own holding size and the size of the neighbor's holdings. For a farmer of given size, if the neighbor's holding becomes large, then the farmer is less likely to own a pump. This is because the larger neighbor will be able to instal a pump and sell water. On the other hand, holding constant the neighbor's land, as the holding size of the farmer is increased , we should expect his likelihood of being a pump owner to increase. As the holding size increases,the farmer is more likely to be able to absorb the fixed cost of a pump and thus invest in it. We test this in the data. Figure II.c shows the prediction of the theory in the top panel. The bottom panel plots the likelihood of owning a pump as a function of own land (in log scale) and the average land holdings of all farmers(in log scale) of the same caste as the farmer in the village.[11] Holding constant the size of the farmer, an increase in the average holdings of the farmers of same caste decreases the likelihood of the farmer to own a pump. On the other hand, holding constant the area of the farmers of the same caste, an increase in the area of the farmer makes him more likely to own a pump. The bottom panel provides compelling evidence that indeed the pump ownership is governed by the interaction of the land holding sizes of the neighboring farmers.

The possibility of being able to buy changes the farmer's sinking decision. Therefore, this interaction of the holdings size among the neighbors should also predict the ability to trade. Our theoretical model implies that for a farmer of given size, as the holdings of the neighbors increase, the farmer is more likely to be a buyer. But as the holding size of the neighbor increases even further, the neighbor will have enough land that he will not be able to sell. In other words, the farmer will be less likely to be a buyer. Similarly, for a given holding of size of the neighbor, as the farmer becomes larger, he will buy water but when he is substantially big, he will be able to invest in his well and less likely to be a buyer. The top panel of figure II.d depicts this graphically. The data supports this prediction as well. In the bottom panel of figure II.d, we

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[11] Farmers of same caste are more likely to be neighbors with each other.

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find that as the holding size of the same caste farmers increases, farmer for a given holding size is more likely to buy water at first but this likelihood falls as the holdings of the caste members increases. In the other too, as the farmer become fairly large, he is less likely to buy for given holding size of the same caste farmers.

The mechanism via which markets tend to have a salutary effect on the aquifers is the ‘crowding out’ of private wells when the total land among neighbors is not too large and their holdings are of opposite sizes. Thus, this source of variation in the distribution of land which is predetermined due to the abolition of the ‘zamindari system’ in India is used in the empirical framework next to establish the effects of markets on groundwater depletion.

6 Estimation Strategy

The conceptual framework demonstrates that the markets result in decreased use of groundwater conditional on appropriate spatial distribution of land holdings. We exploit the cross-sectional variation in the extent of market development across villages in the study area in order to estimate the effect of development of markets on water usage. Figure III maps the villages in the quintiles of market development index. There is a substantial variation in the level of development of markets across these villages. In order to isolate the effect of market development on water usage, we estimate the following regression:

$$\Delta GW_j = \beta_0 + \beta_1 (MB)_j + \beta_2 X_j + \epsilon_j \tag{21}$$

where ΔGW is the change in depth of groundwater below ground level in village j , MB is the index of market development or pervasiveness (referred to as breadth of markets) in village j and is calculated as share of land irrigated by bought water in total irrigated land and ϵ_j is the residual term. The village level controls X_j vary in different specifications and include initial groundwater level, land GINI, cultivated area, population in the village, and state fixed effects.

One of the issues with the identification of the effect of development of markets for groundwater on water usage is that there may be unobserved omitted variables that affect market development and also influence the groundwater levels in the village. It may be that the topography for example (specifically the terrain gradient), affects development of markets but at the same time also affects fluctuations in groundwater independently. In order to address this issue, we make use of an instrumental variable approach.

Due to historically determined spatial allocation of land among various castes in India and rigidities built into Hindu Caste system, lower caste dominated villages tend to be ethnically more homogenous[12] and have small to medium size farms in close proximity of each other. We make use of this demographic feature of the villages and use a measure of caste homogeneity as our instrument.[13] Our theoretical framework points out that markets typically arise in situations where small and medium sized farms are situated in close proximity of each other.

Before 1950's upper caste landowners had holdings in many villages and were absentee landlords in places where they did not live. These villages did not have any upper caste population. Abolition of *'Zamindari'* system in 1950's made the lower caste tenants in absentee landlord villages, owners of their land (Jain, 1995). The holdings of these tenants were relatively small compared to the landlord holdings in villages where they resided. As a result, medium and small farmers became neighboring farmers in these villages. However, in high caste dominated which are ethnically more diverse, spatial segregation was practiced. The larger landowners who could absorb fixed costs of sinking a well are not located in close proximity of smaller farmers who would be the potential buyers for water. As we showed earlier (Figure II), water is transported across unlined field channels and transaction costs would be too high to transport water over very large distances.

We construct a Caste Homogeneity Index (CHI) as our instrument. The index is the probability that two randomly chosen individuals belong to the same caste.

$$CHI = \sum_i \left(\frac{P_i}{P}\right)^2 \tag{22}$$

where $\frac{P_i}{P}$ is the fraction of individuals in the caste group i. Figure IV maps the villages by quintiles of the Caste Homogeneity Index. Figure III and IV suggest that the market development index and CHI are correlated positively. While caste homogeneity in a village might be correlated with the degree of market development, it is not likely to affect the changes in groundwater level. Hence, this would meet the exclusion restrictions.

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[12] Anderson(2005) uses the same survey data and shows that in fact the low caste dominated villages are more homogenous along caste lines

[13] It is possible that caste homogeneity affects market development through other channels like lowering the costs of contract enforcement due to norm based punishment in the caste networks. In the absence of actual maps of layout of land parcels in the villages, we cannot rule out this possibility.

To test if the instrument predicts the extent of market development, we estimate the following cross section regression of the form:

$$MB_j = \alpha_0 + \alpha_1 CHI_j + \alpha_2 X_j + \varepsilon_j$$

Where MB_j is the measure of the extent of market development in village j, CHI_j is the Caste Hoomogeneity Index for village j, and ε_j is a residual. The village level controls X_j vary across specifications and include initial water level, land GINI, cultivated area in the village, and demographics like population. Our results indicate that the instrument has substantial predictive power for the extent of development of markets.

7 Results

We now turn to analyzing the predictions of our theoretical framework. One of the analytical predictions is that the farmers actually sell only when they have surplus water. This implies that the probability of being a seller should be increasing in percentage of own irrigated land. Also, intermediate farmers are more likely to have surplus water (very small farmers will not be able to sink a well as they are too small to absorb the fixed costs and very large ones are less likely to be able to fulfil their own needs and have additional water to sell). This would suggest that the probability of being a seller be increasing in land area up to a certain limit.

We explicitly model the probability of being a seller and the results are reported in Table 3. We restrict the sample to cultivators whose main source of irrigation is groundwater. We report results from probit specifications and a linear probability model and find that irrespective of the specification, probability of being a seller increases substantially in percentage of own irrigated land (row 2 in each column). Also, increase in land ownership increases the liklihood of being a seller. The results are robust to specification and strongly statistically significant. Our next main prediction is that development of markets can result is water savings due to reduced overall withdrawal of groundwater. We estimate equation (21) and report the results in table 4. We find that development of markets leads to reduced withdrawal of groundwater and hence less depletion of water tables. Our estimates show that more developed markets reduce the water depletion by about 6 meters. This result is robust to specifications. We include land GINI, and state fixed effects in columns (iii) and (iv) and find no change in the estimates.

To address potential endogeneity issues, we carry out the 2SLS procedure and report the results in Table 5 and Table 6. Table 5 reports the results from the first stage, where we estimate equation (22). We report results from 2 different specifications. In column (ii), we include land GINI to ensure that we are not attributing the effects of land inequality to development of markets. Both the specifications show that the Caste Homogeneity Index has predictive power in explaining the extent of market development. However, the F statistic is very low and the instruments are weak. The second stage results are reported in Table 6. We find that irrespective of the specification, the coefficient on the predicted extent of market development is negative and statistically significant which means that markets have a water saving effect. The 2SLS estimates of the effects of extent of market development on water tables are much higher than the OLS estimates. This is possibly on account of sampling error. Both the OLS and 2SLS estimates are consistently indicate that the development of groundwater markets result is sustainable groundwater use.

7.1 The Driving Mechanism

In our analysis, we have already pointed out that the aggregate land among neighboring farmers and its distribution across the two farmers governs the trade of water among neighbors and the pump ownership decisions of the farmers. We test our hypothesis about the likelihood of pump ownership and report the results in Table 7. The size of own holding increases the farmer's ability to install a pump. The coefficient on own land is positive and significant. As the holdings of the same caste farmers become larger, the farmer is less likely to own a pump. The negative and statistically significant coefficient is robust to different specifications. As expected, the coefficient is positive and significant at conventional levels of significance. Table 8 reports the results of the effect of distribution of land among neighbors on the likelihood of being a buyer. As the holdings of the same caste farmers become larger, the likelihood of being a buyer increases. The coefficient is statistically significant and positive.

8 Conclusion

While economists have typically advocated the use of market-based solutions to promote efficient use and protection of environmental resources, it is often countered that the introduction and development of markets can have perverse effects. Markets may, for example, undermine local institutions that would otherwise protect these resources or exacerbate problems arising from the difficulties associated with monitoring the extraction of these resources or the assignment of property rights. Unfortunately, there are few theoretically-grounded empirical studies examining the relationship between market-based transactions and resource extraction. In this paper we undertake such an assessment and find evidence that trade in water can help protect water resources.

The results of this analysis, of course, do not necessarily imply that markets will always promote protection of environmental resources. Indeed, the theoretical analysis suggests that the effects could operate in either direction depending on the nature of the joint distribution of land among neighboring farmers. But the analysis does, we believe, raise some issues that should be considered in future research on the extraction of common property resources in low-income rural areas.

First, in an assessment of this type it is important to understand the nature of the markets. In this paper we argue that the use of unlined channels to transfer water and the distribution of market activity by farmers size suggests that the primary transactions are between neighboring farmers. The effects of market development on the aquifer may be far less salutary if water were being pumped from a local aquifer and then shipped across the country to other regions. It is also clear that, given this focus on transactions among neighbors, our analysis would be more complete if the data we exploited had included information on the identities of neighbors and transaction partners. Hopefully future agricultural survey data focusing on water issues will include this type of information.

Second, in an assessment of how markets interact with resource extraction it is critical to understand the source of variation in markets. Trade in natural resource is, of course, unlikely to arise randomly but is likely to be tied importantly to the returns to the use of that resource. This link obviously complicates inference, but also has implications for how we think about a problem theoretically. In this paper, we introduce a novel but ultimately compelling explanation for low levels of water transactions. We argue that there are significant non-convexities in the relationship between water usage and yield and these result in a situation in which farmers may neither fully irrigate their land nor find it profitable to sell water to a neighbor without access to water at all. Thus water markets may emerge in situations in which water is not scarce. Moreover, the ability of a given farmer to purchase or profitably sell water will depend on his own land size as well as the land sizes of his immediate neighbors.

Third, in developing models of markets for environmental resources one should consider the complementarity between trade and existing social institutions. Buying and selling of water in the above context is not a transaction involving anonymous agents at a fixed price but trade among neighboring farmers with the potential for substantial communication and long-term interaction. We thus, in the context of this paper, focus on cooperative equilibria in which local (that is between neighbors) externalities are fully internalized. It is, of course, unlikely that such externalities are fully internalized, but for the purposes of this paper this assumption seems a reasonable approximation and, in particular, does not seem to be testable without direct data on neighboring farmers. Assessment of the extent of cooperative and non-cooperative behavior and how this interacts with market development is an important subject for future research on natural resource management.

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Data Appendix

Table A.I Definitions and Sources of Data

Variable	Definition	Source
Change in Average Groundwater Depth	Difference between village Average Groundwater Level in 2000 and 1993	Minor Irrigation Census 1993, 2000
Initial Groundwater Level	Village Average Groundwater level 1993	See Above
Market development Index	Ratio of Buyer Irrigated Area to Total Irrigated Area	Uttar Pradesh and Bihar 1997-98: Survey of Living Conditions
Land Gini	Village Level Land Gini	See Above
Caste Homogeneity Index	Probability that 2 randomly chosen Individuals belong to the same caste	See Above
Land Lord	Dummy equal to 1 if the farmer rents out land	See Above
Tenant	Dummy equal to 1 if the farmer rents in land	See Above

Table A.II Descriptive Statistics -Main Variables

Variable	Mean	Std. dev.
Change in Average Groundwater depth	-7.64	14.66
Market development Index	0.53	0.33
Initial Water Level	15.22	13.46
Land Gini	0.47	0.117
Cultivated Area	238.39	377.64
Caste Homogeneity Index	0.5	0.19
Population	230.35	136.27

Note: Table A.I in the Data Appendix lists the definitions and sources of data

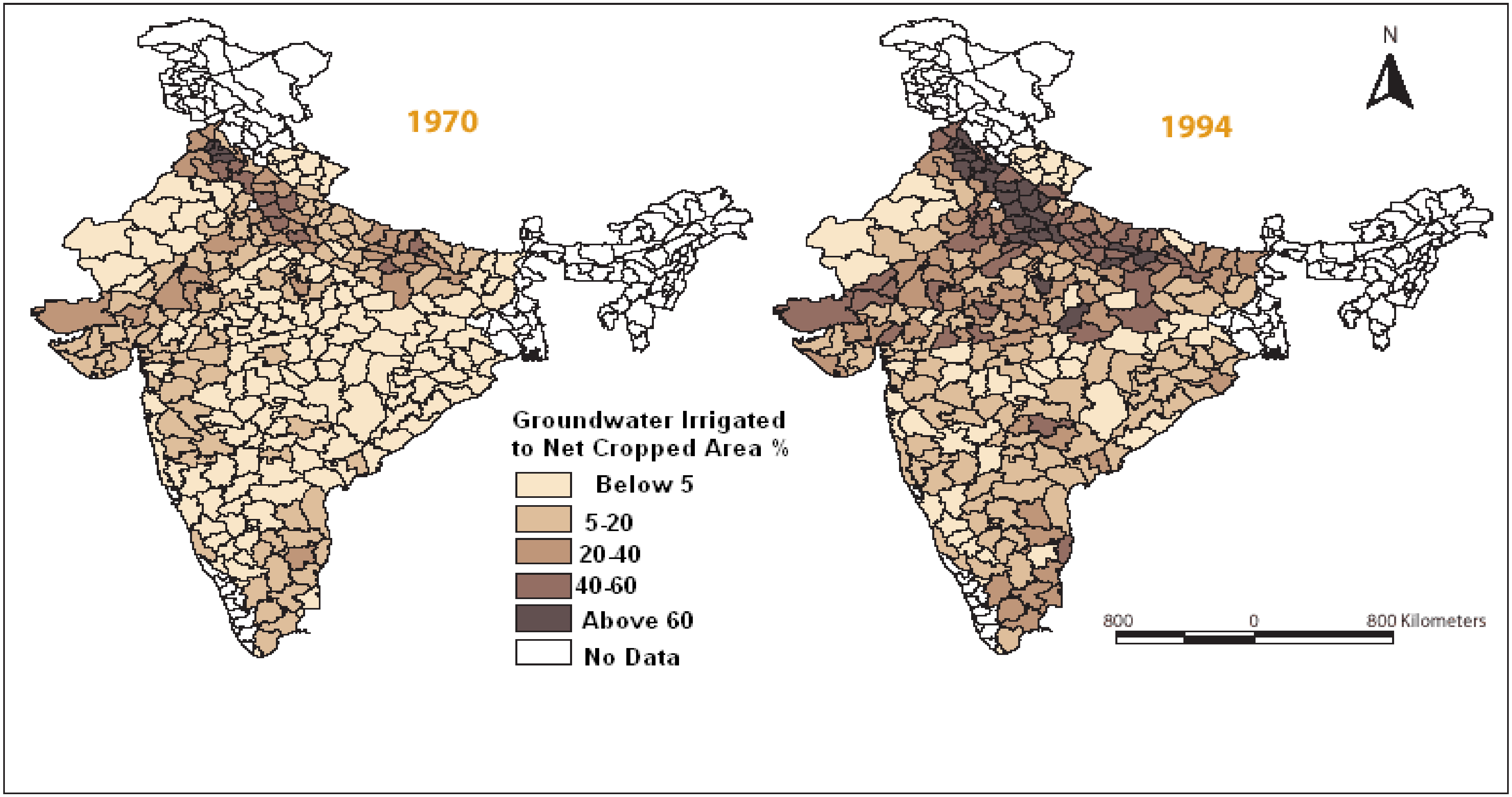

Figure I: Increased Reliance on Groundwater for Irrigation

Ratio of Groundwater irrigated area to net cropped area has increased from 10.4 % in 1970-73 to 21% in 1990-93 and there is spatial variation in this increase (IWMI, 2002)

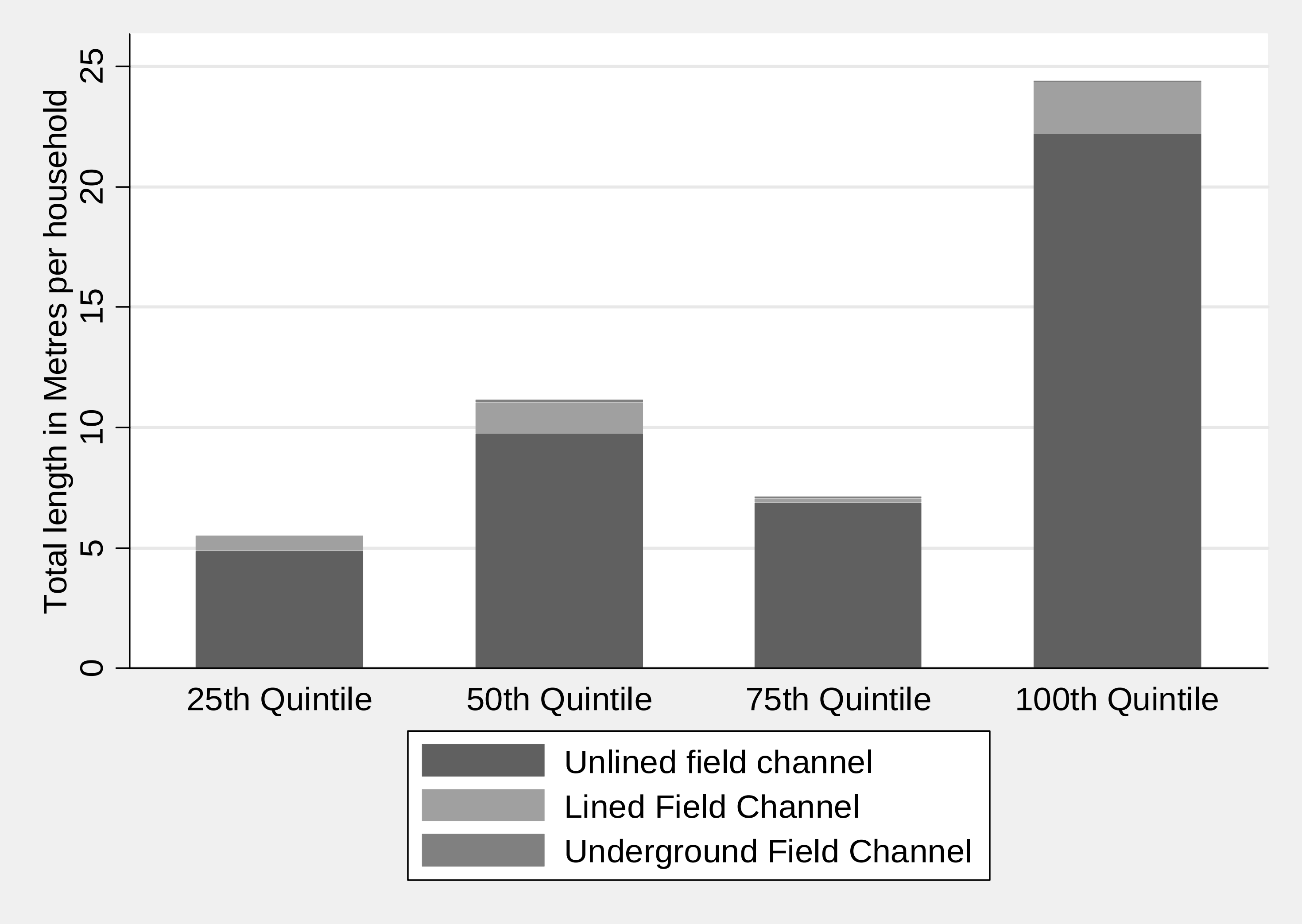

Figure II.a : Types of Field Channels per Household by Quintiles of Market Development

The most pervasive field channels are the unlined field channels irrespective of the intensity of market transactions. More developed village markets have more field channels than less developed markets.

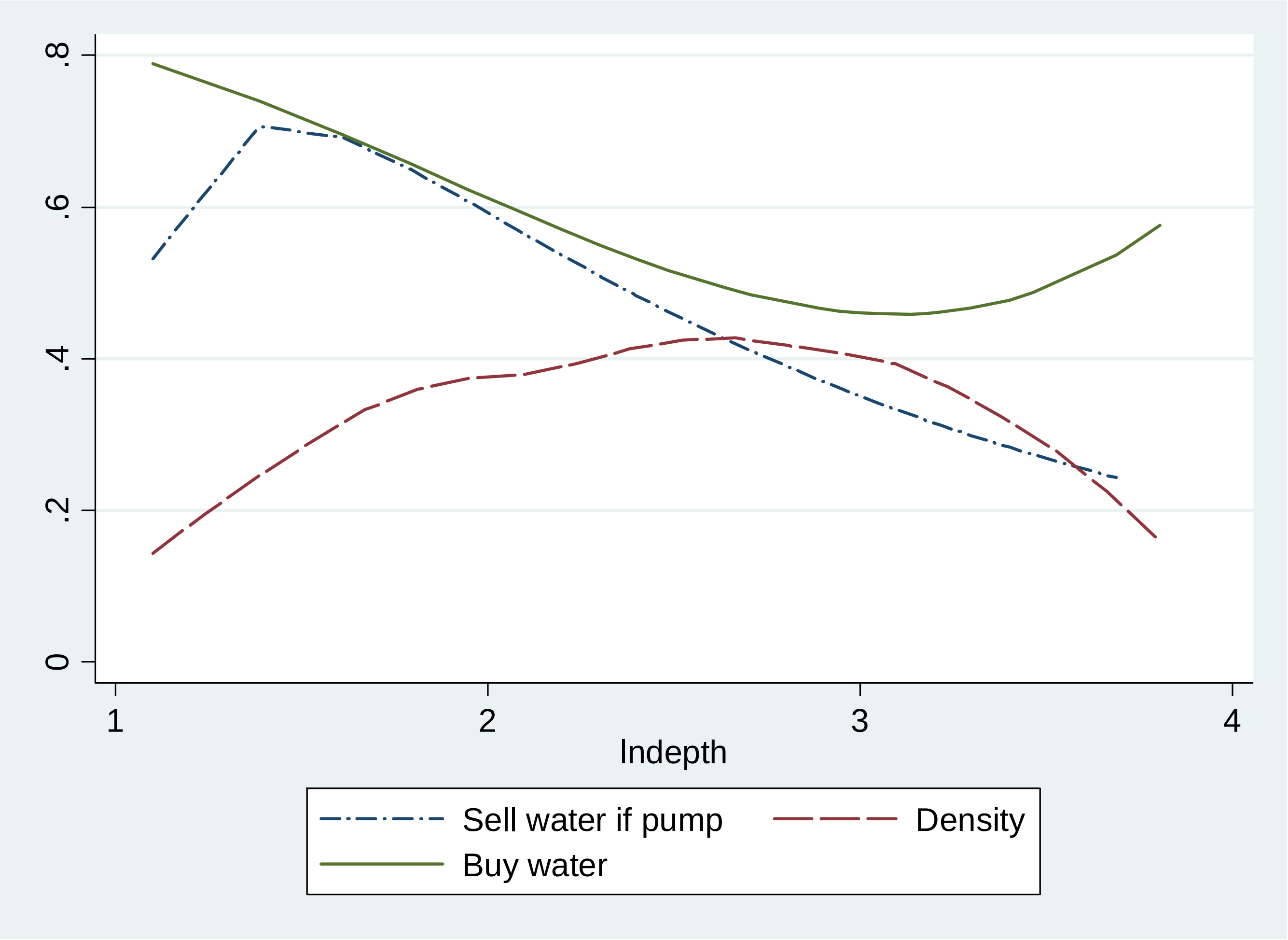

Figure II.b : Water Transactions as a function of Water Table Depth

This figure graphs the probability of water selling and buying as a function of water table depth that captures the fixed costs required to sink a well. As evident, markets are more active at lower fixed costs.

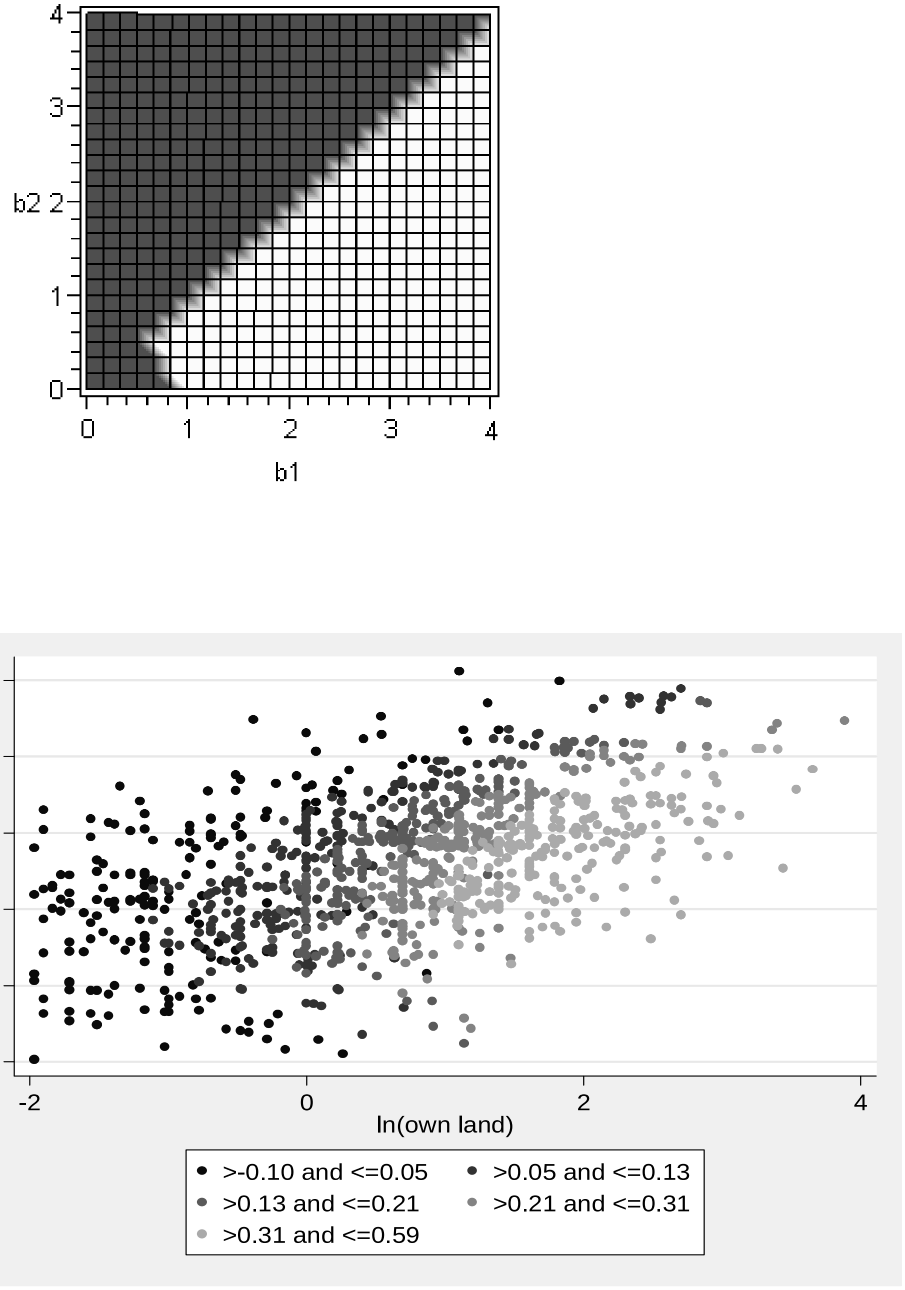

Figure II c: Predicted Likelihood of Owning a Pump

The top panel graphs the theoretical relation between pump ownership and the interaction between the farmers holding size and the holding size of the neighboring farmers. The bottom panel tests the theoretical prediction that holding constant the farmer's land, as the land held by the neighbor's (own caste farmers) increases, the likelihood of being a pump owner falls. However, it is increasing in own land area. These panels provide compelling evidence that supports the theory.

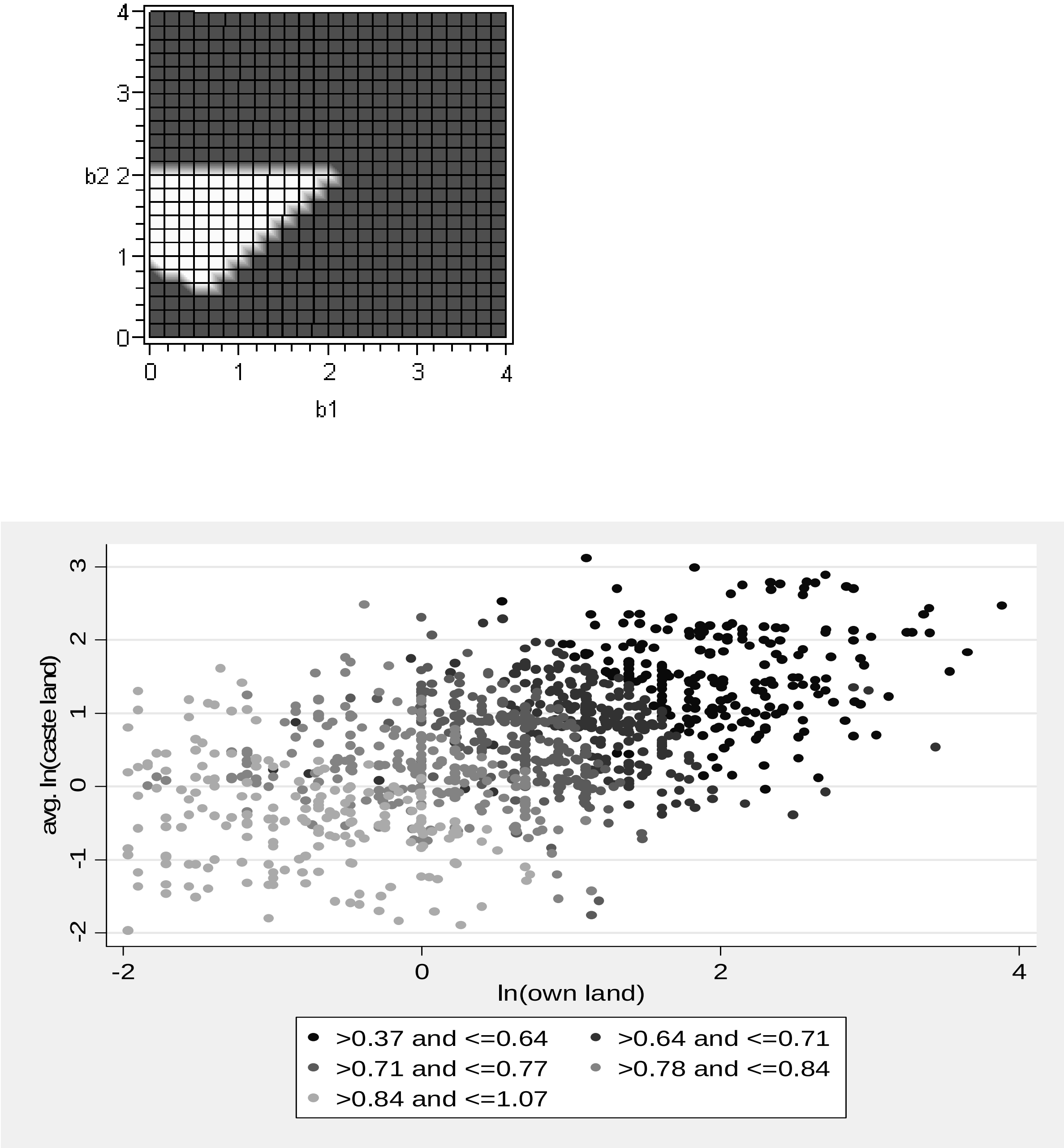

Figure II d: Predicted Likelihood of being a Buyer of Groundwater

The top panel graphs the theoretical relation between being a buyer of water and the interaction between the farmers holding size and the holding size of the neighboring farmers. The bottom panel tests the theoretical prediction that holding constant the farmer's land, as the land held by the neighbor's (own caste farmers) increases, the likelihood of being a buyer increases. However, it is decreasing in own land area. These panels show that the data strongly supports the theory.

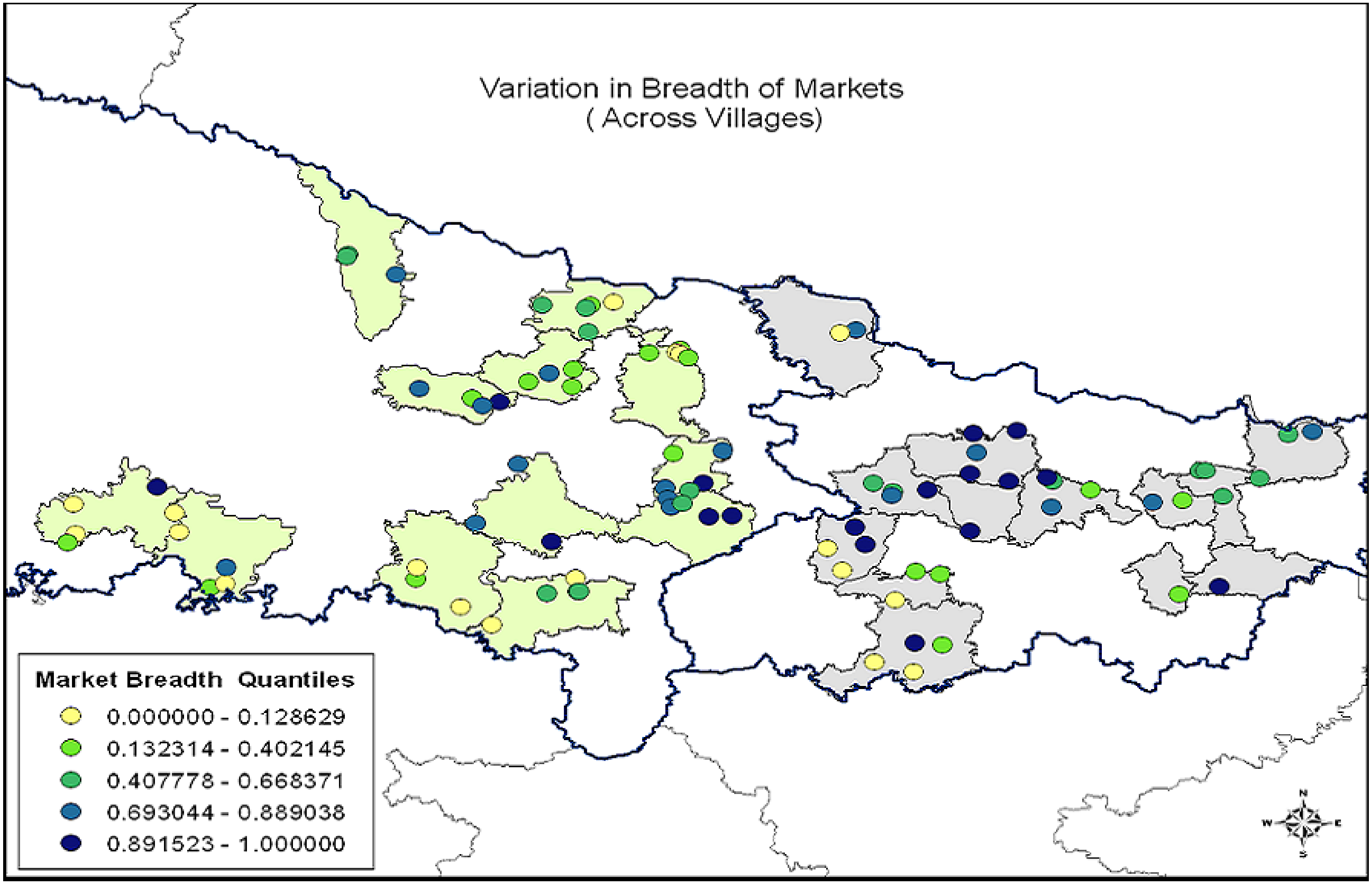

Figure III: Cross Sectional Variation in Development of Markets for Groundwater

This map shows the variation across quintiles of *Market Development Index* which Measures the Breadth of Market Development within villages in the study area.

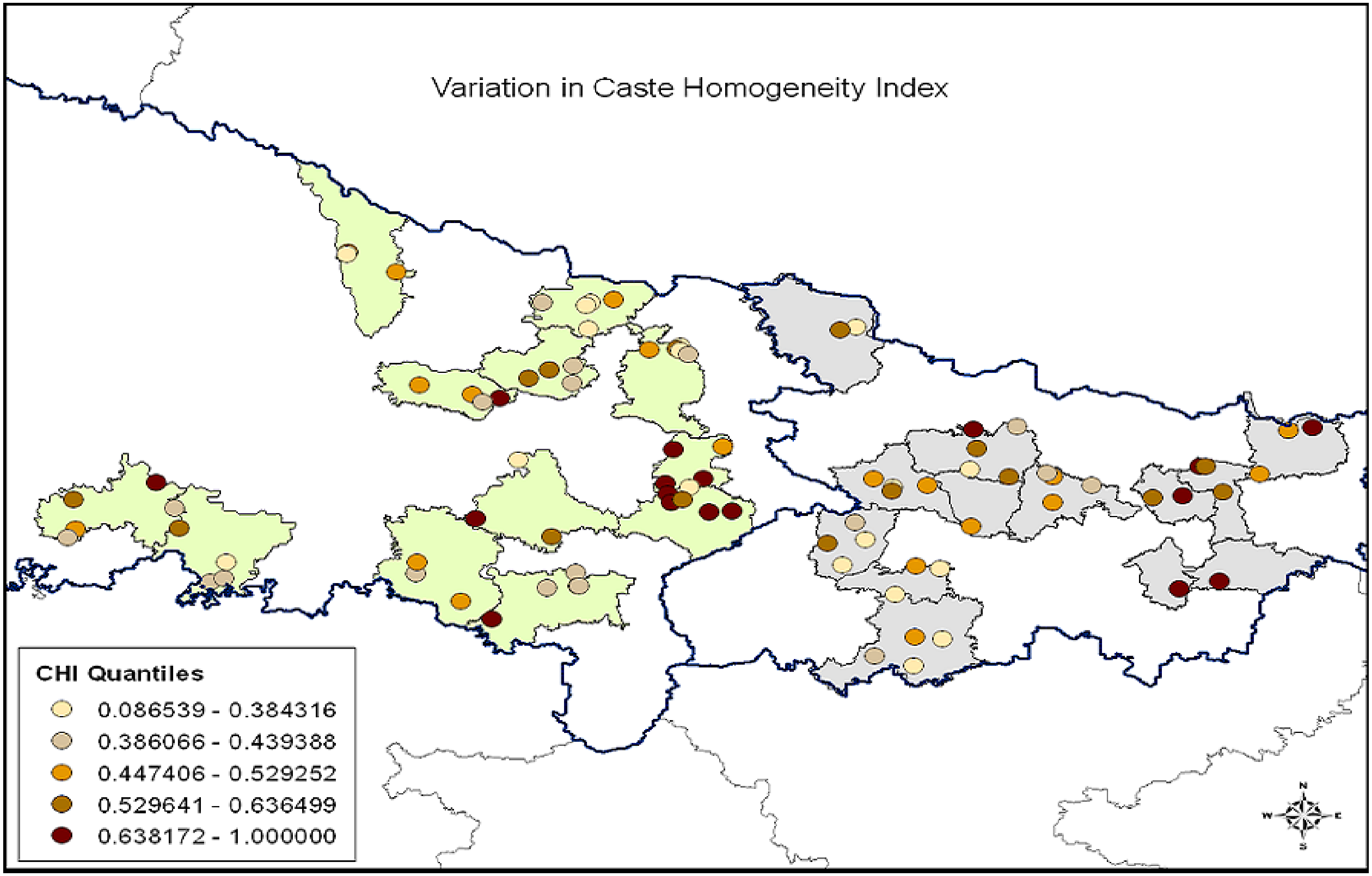

Figure IV: Cross Sectional Variation in Caste Homogeneity Exploited in 2SLS Estimation
This map shows the variation across quintiles of *Caste Homogeneity Index* which Measures the degree of homogeneity along Hindu Caste lines in the Villages in the study area.

Table 1: Composition of Farmers

	Percent in Sample	Holding Size	Pump Owners	Buyers	Sellers
Landless	5.5				
Marginal	34.0	<1	5.5%	80%	4%
Small	19.5	1-2	15%	76%	8%
Semi-Medium	21.0	2-4	27%	67%	16%
Medium	15.0	4-10	41%	59%	18%
Large	5.0	>10	64%	43%	23%

Table 2: Buyers and Sellers by Land Holding

	Percentage of Buyers	**Percentage of Sellers**
Land (in acres)		
0	5.45	0
<1	38.18	12
1-2	21	15
2-4	19.5	33.5
4-10	12.7	27.2
>10	3.14	12

Table 3: Probability of being a Seller among Groundwater Irrigators

Dependent Variable: Binary Indicator for being a Seller

	(i)	(ii)	(iii)	(iv)
	probit	**LPM**	**probit**	**LPM**
log Land owned	0.372	0.062	0.42	0.066
	(.06)	(.01)	(.06)	(.0016)
% irrigated	0.0087	0.0015	0.0095	0.0016
	(.003)	(.0006)	(.0032)	(.00627)
age	0.0046	0.001	0.005	0.001
	(.003)	(.0008)	(.0038)	(.0008)
fertilizer use	0.0005	0.0002	0.0005	0.0002
	(.0001)	0.00003	(.00014)	(.00003)
landlord	-0.63	-0.099	-0.72	-0.1
	(.227)	(.037)	(.233)	(.03)
tenant			0.32	0.04
			(.13)	(.02)
Observations	954	954	954	954

Note: standard errors reported in parenthesis.
Sample restricted to cultivators whose main source of irrigation is Groundwater.
Landlord is a dummy variable which is equal to 1 if the farmer has rented out any land
and tenant is a dummy variable which is equal to 1 if the farmer has rented in any land.
Columns (i) and (iii) report results from a probit specification and columns (ii) and (iv) report results
from a linear probability model.

Table 4: OLS Estimates of the Effect of Development of Markets for Groundwater on Water Table Depth

	Dependent Variable : Change in Average Groundwater Level in a Village			
Index for Market Development	-6.08	-6.08	-5.89	-6.12
	(2.78)	(2.95)	(2.9)	(2.9)
Initial water Level	-0.88	-0.87	-0.84	-0.88
	(.062)	(.09)	(.1)	(.09)
Land GINI				7.68
				(6.5)
Controls	YES	YES	YES	YES
State Fixed Effect	NO	NO	YES	NO
Robust std errors	NO	YES	YES	YES
Observations	87	87	87	87
F	48.41	50.7	41.02	42.4
R- squared	0.7	0.7	0.7	0.7

Note:
All regressions include village level controls.
Standard errors are reported in parenthesis.
Groundwater Level is measured in meters below ground level.
Data Appendix defines the variables.

Table 5: Two stage Least aquare Estimates of the Effect of Development of Markets on Water Table Depth

Dependent Variable- Index for Market Development		
	(i)	**(ii)**
Caste Homogeneity Index	0.488	0.489
	(.19)	(.19)
Initial Water Level	-0.00075	-0.00074
	(.0025)	(.0025)
Controls	YES	YES
Land GINI		0.02
		(.33)
Robust std errors	YES	YES
Observations	88	88
F	2.46	1.94
R-squared	0.115	0.115

Note:
All regressions include village level controls.
Standard errors are reported in parenthesis.
Data Appendix defines the variables.

Table 6: Two stage Least aquare Estimates of the Effect of Development of Markets on Water Table Depth

	Dependent Variable - Change in Average Groundwater Leve	
	(i)	**(ii)**
Predicted Index for Market Development	-23.21	-24.1
	(9.34)	(9.6)
Initial Water Level	-0.889	-0.89
	(.099)	(.09)
Land GINI		-10.3
		(6.3)
Controls	YES	YES
Robust std Errors	YES	YES
Observations	88	88
F	47.17	38.27
R-squared	0.7	0.7

Note:
All regressions include village level controls.
Standard errors are reported in parenthesis.
Groundwater Level is measured in meters below ground level.
Data Appendix defines the variables.

Table 7: Probability of Owning a Pump

	Dependent Variable : Binary Indicator for Pump Ownership	
	(i)	**(iii)**
Own Land	0.135	0.152
	(.011)	(.013)
Average Land Owned by own Caste	-0.045	-0.064
	(.015)	(.017)
Own Land * Average Land Owned by Own caste	0.012	0.0076
	(.006)	(.0073)
Initial Water Level		-0.001
		(.007)
	No	No
N	1695	1284
F	87.9	51.44
R-squared	0.134	0.13
F test for Joint Significance of Own land, Average land of own caste and their Interaction		
F Statistic	87.9	68.24

Note: Standard errors are reported in parenthesis.
Own land and the average land of the farmers of the same caste are in log scale.

Table 8: Effect of Distribution of Land Holdings among Neighboring Farmers on Likelihood of Buying Water

Dependent Variable: Binary Indicator for being a Buyer		
	(i)	(ii)
Own Land	0.026	0.05
	(.013)	(.015)
Average Land Owned by own Caste	0.052	0.042
	(.018)	(.02)
Own Land * Average Land Owned by Own Caste	0.023	0.03
	(.007)	(.008)
Intial Water Level	No	Yes
N	1678	1269
F	31.04	30.79
R-squared	0.05	0.08

Note: Standard errors are reported in parenthesis.

Own land and the average land of the farmers of the same caste are in log scale.