Public Provision and Protection of Natural Resources: Groundwater Irrigation in Rural India

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Abstract

This paper examines the trade-off between resource intensive development and preservation of natural resources in the context of groundwater. Use of public schemes that expand groundwater irrigation to mitigate poverty is challenged as being unsustainable, especially when water tables around the world are rapidly depleting. This paper evaluates the effects one such scheme on groundwater use in northern India with the intent to determine if these schemes accelerate water depletion. On the contrary, I find that the program decreased total use of groundwater. I propose a mechanism that explains these findings, and test it using village-level longitudinal census data on wells and aquifer depth. The model predicts that public provision has a heterogeneous impact on the aquifers and it leads to sustainable use, when the fixed costs for private well provision are high. Consistent with the predictions, I find that there is a significant jump in the water-saving effects of the scheme at the water table depth at which the fixed costs of water provision rise substantially due to the technological limitations of surface pumps.

JEL Classifications: H54, O12, O13, Q01, Q25, Q56

1 Introduction

A fundamental challenge to resource intensive development initiatives is that these are argued to be unsustainable. Poverty reduction through channels of increasing access to scarce resources and protecting those resources seem to be contradictory objectives. This paper addresses the question of whether it is possible to pursue and promote these two goals at the same time in the context of groundwater in rural India.

Groundwater irrigation has been instrumental in enhancing food security and mitigating poverty in developing countries. Groundwater provides timely irrigation leading to an increase in crop intensity and productivity (FAO, 2003). But groundwater irrigation also contributes the most to the depletion of groundwater reserves. Countries with significant groundwater irrigated areas, including Mexico, United States, Yemen, Pakistan, India, and China are experiencing substantial declines in their water tables due to over-exploitation of groundwater reserves.[1]

This paper examines the economic underpinnings of the trade off between increasing access and sustaining reserves of groundwater in India. Rural India is a very pertinent and important setting to study how resource intensive development schemes affect the stock of resources particularly groundwater. As in many other countries, water tables in India are declining. Fifteen percent of the administrative blocks in India are considered overexploited[2] (CGWB, 2004), and this number is growing at an alarming rate of 5.5 percent per annum. At the same time, increasing groundwater access for large numbers of marginal and small land holdings is a priority for policy makers.[3]Almost 62 percent of the land holdings in India are smaller than 1 hectare. Since the fixed costs required to sink a well in order to access groundwater are very high, poor farmers find it challenging to access groundwater for irrigation.

One measure adopted to enhance access to groundwater resources is public provision of groundwater for irrigation by installing large capacity wells in rural areas. A priori, one would expect that

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[1] Collectively, annual ground water depletion in India, China, the United States, North Africa and the Arabian Peninsula totals 160 billion cubic meters a year - an amount roughly double the total annual flow of the River Nile (UNFPA, 2003).

[2] Blocks are considered overexploited if more groundwater is extracted than is replenished.

[3] This concern over the environment development trade-off is vividly expressed by policy makers as reflected in the remarks of Mrs. Indira Gandhi the prime minster of India in early 1980s, “We do not wish to impoverish the environment any further, and yet we cannot for a moment forget the grim poverty of large numbers of people...How can we speak to those who live in villages and slums about keeping the oceans and rivers and air clean when their own lives are contaminated at source? The environment cannot be improved in conditions of poverty.”

public provision would exacerbate the decline of already falling water tables by enhancing access to those farmers who could otherwise not afford wells. Since irrigation would expand to previously un-irrigated farms, overall groundwater use would increase. However, the evidence from a public provision program in northern India suggests that in fact public provision can lead to conservation of the resource.

In this paper, I propose an explanation for this finding. Introducing public provision of groundwater has two effects on water table depth. First, as noted, it tends to increase irrigation among farmers who otherwise would not sink a well. This extensive margin effect would increase water usage and have a negative impact on water tables. But since public provision is a substitute for privately extracted water and the fixed cost required to sink a well is very high, public provision may forestall installation of some private wells. This second intensive margin effect can lead to a lower water usage if the price charged is higher than the marginal cost of private water extraction. Such a 'crowding out' of private wells accompanied with a reduction in water usage on the intensive margin can offset the negative impact of increased irrigation and lead to overall conservation of groundwater. Although applied to the case of groundwater provision, this theory is more generalizable. It is applicable to other situations where the fixed costs of private provision are relatively high and public provision can be used to improve access.[4]

In the context of groundwater, I model the choice faced by farmers between sinking their own wells, using publicly provided water, or farming without groundwater irrigation. The analysis of this choice delivers the conditions under which public provision of groundwater leads to reduction in groundwater use. The model shows that while public provision increases access for small sized farmers, larger farmers decrease their overall usage. In the model, the depth of the water table plays a key role in determining the balance between the intensive and extensive margin effects. Because the fixed cost is relatively low at shallow depths, a large fraction of farmers own wells. Therefore the negative effect arising from the extensive margin is small. Also, due to low fixed costs, very few farmers are dissuaded from sinking their own wells. Hence, the intensive margin is small as well. In such a scenario, the two opposing effects cancel each other and there is little change in water usage. But as depth, and hence the fixed cost increases, more farmers choose to use public wells instead of sinking their own wells. Therefore, it is more likely that the positive

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[4] An example is the use of automobiles versus light rail or subways in developing countries. A metro system has recently become operational in New Delhi which might help with the automobile congestion and pollution issues in the city as the intensive margin users switch to using the metro system rather than investing in cars.

intensive margin effect dominates. As long as there is a sufficient number of these larger farmers who forgo sinking their own wells, the positive effect on aquifers on account of the intensive margin can offset the negative extensive margin effect. In sum, the key prediction is that when the fixed cost is high but not prohibitive, these schemes can benefit the local water tables.[5] In addition to this key prediction, the model also predicts that the number of private wells given public provision falls as the fixed cost required to access groundwater rises.

I evaluate these predictions using detailed village-level longitudinal data on wells and water tables from the Minor Irrigation Census of India. In the empirical analysis, I exploit the fact that a low cost surface pump becomes infeasible to lift water from below a depth of around 25 feet. If the depth of the water table exceeds this cutoff, then the farmers are precluded from using the low cost surface pumps. In that case, they need to employ more sophisticated and consequently more expensive pumps. So the fixed cost of accessing the groundwater has a discrete jump at 25 feet. Taking advantage of this discrete jump in fixed cost, I divide the villages into high and low cost categories depending on the depth of water table in the initial period. From this, I am able to isolate the effect of public provision of groundwater on local water tables by varying degree of cost required to access the resource.

The source of variation in public provision that I exploit is an expansion in public tube wells under a program that was initiated in 8 districts of eastern parts of the state of Uttar Pradesh with the intent of reducing poverty. I use triple differences - across time, across treated and comparison villages, and across categories of cost - to isolate the effect of public provision of groundwater on local water tables in high fixed cost category relative to low fixed cost category. Villages were not randomly selected into the program. I perform a number of tests that make a compelling case that the results are not confounded by selection bias.

The main finding is that public provision schemes can lead to sustainable water use in areas with high fixed costs of private well provision and it happens on account of crowding out of private wells. My results show that water tables in the treated villages where the initial depth precluded the use of low cost pumps fell less than in comparison villages. However, no difference was detected

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[5] In developing countries, due to large fraction of small holdings, the well density is very high. Wells are generally clustered at the level of villages and the effects they have on water tables in the village are localized spatially. Moreover, the lateral flow velocity of groundwater is not high enough for the water to flow across large areas in short spans of time. Depending on the medium, lateral flow velocities of 2 centimeters per year are considered normal (Todd, 1980). Therefore, local effects on village water tables are analyzed in spite of the interconnected nature of the aquifer.

between treated and comparison among low cost villages. Consistent with the predictions of the model, the expansion in the number of private wells per village reduced in the high cost treated villages relative to comparison villages, whereas there was no change in treated versus comparison among low fixed cost villages. From policy perspective, the results suggest that well designed public provision schemes can be used to further access in a sustainable way.

While groundwater management in developing countries has become a pressing global policy concern, it has received very limited attention from economists.[6] Most of the existing research in developing countries explores local groundwater markets. Jacoby et al. (2004) address market power and efficiency issues related to rural groundwater markets. Anderson (2006) contends that ethnic barriers along caste dimensions can impede these markets, which results in low agricultural productivity of low-caste farmers in high-caste dominated villages. Foster and Sekhri (2007) study where and how these markets emerge, and how does the development of these markets impact the water tables. Foster and Rosenzweig (2008) investigate the interaction of land inequality and groundwater usage, and find that there is a concave relationship between land inequality and groundwater depletion. None of these studies focus on public provision and sustainable use of groundwater.

The paper is organized as follows. Section 2 discusses the background and context. Section 3 presents the theoretical framework. Section 4 describes the data that I use in the empirical analysis. Section 5 discusses the kind of water pumps used in irrigation and associated fixed costs. Section 6 contains the estimation strategy, and Section 7 the results. I conclude by performing robustness checks to address selection in section 8 and discussing caveats and extensions in Section 9.

2 Background and Context

Groundwater sustains about sixty percent of India's agriculture. The high yielding varieties(HYV) of crops that ushered in the 'Green Revolution' in India are very sensitive to the timing and level of

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[6] Groundwater Management has been studied extensively in the developed country context especially in United States (Brill and Burness, 1994; Gisser and Sanchez, 1980). Most of these studies examine the common pool externality associated with groundwater irrigation and the role of water policies in addressing them. However, groundwater management in a developing country context warrants an alternative analysis. Majority of the farmers tend to be very small and poor. Most of the farms in India for example are smaller than 1 hectare. As a result, water policies have been designed to further development goals. Evidence of significant depletion of the resource is now bringing a shift in policies towards sustaining the groundwater reserves. But at the same time, increasing access remains a high priority for public policy.

irrigation. Groundwater irrigation has increased more rapidly than other sources of irrigation such as tanks and canals and is called ‘water by demand’ as it is readily available in times of moisture stress. Irrigated agriculture was dominated by gravity systems until the 1970s but the next two decades saw a rapid acceleration in groundwater use. By late 1990s, groundwater irrigation had become the major source of irrigation in India [Figure 1]. HYV crops require timely, reliable and adequate water supply and using groundwater for irrigation gives farmers the control to meet such needs. Farmers with access to groundwater are able to water their crops in crucial stages of growth. They are also able to meet the water needs of *rabi*, or summer crops, without having to rely on good monsoon rainfall.

As a result, there has been a substantial private investment in wells in recent decades. According to one estimate, the number of wells has increased from less than 1 million in 1960 to more than 19 million in 2000 (IWMI, 2002). This phenomenal increase in access to groundwater has mitigated poverty, enhanced food security and increased rural population growth. In 1965-66, rainfall was 20 percent below normal and food production fell by 19 percent.[7] In contrast, in 1987-88, rainfall was 18 percent below normal but food production only declined by 2 percent (GOI and World Bank, 1998). Research at the Indian Council of Agricultural Research has attributed this change to the increased access to groundwater. In addition, groundwater now supplies 80 percent of domestic use water in rural India. The downside to this pattern of development is that groundwater is not sustainable if more water is extracted than is recharged through rainfall and snow melt. Various parts of the country are already experiencing declines in water tables.

Groundwater irrigation development has largely been a private initiative. The government has facilitated the development of groundwater irrigation by providing subsidies for pump sets and energy. In addition, there is also institutional credit support in the form of loans from the banking industry. However, due to the high fixed cost associated with the technology, poor and marginal farmers cannot afford to invest. Postel (1999) reports that the fixed cost in some parts of India is as high as $2,950. Therefore, small farmers would not find it profitable to invest in well technology. Also, lands in some regions are so fragmented that farmers cannot invest in a pump on each parcel of their holdings (Shah, 1993). The government has attempted to increase access by sinking large capacity wells in rural areas and making water available for irrigation. Between 1968-69 to 1984-85, there was a three-fold rise in public wells in the three poorest Indian states.

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[7] In eastern plains of India, where the study districts are located, the decline was 33 percent.

2.1 Public Tube Wells in Uttar Pradesh

Uttar Pradesh has the highest number of public tube wells in the country. It is a very pertinent setting to evaluate how public provision might affect groundwater resources. It is the the most populous state of India, with a population density that is double the national average. The state is also one of the poorest in the country. The eastern part of the state, where the program districts are located, is poorer than the western part. Agriculture relies heavily on groundwater for irrigation[8], and is characterized by a very large share of marginal holdings (less than 1 hectare). The trends indicate that water tables are falling rapidly. Over the ten years from May 1988 to May 1997, 68 percent of the 989 observation wells showed a declining trend in mean water tables (CGWB, 1997-98).

Since the setup costs for the deep public wells are very high and their discharge capacity can serve several irrigators, the state government has often sought financial partnership with international donors in establishing these wells. International aid agencies and donors have actively targeted construction of public tube wells in Uttar Pradesh with the aim of helping the resource poor marginal farmers in raising their standard of living.

In 1988, the Indo-Dutch tube well project was started in 8 districts of eastern Uttar Pradesh. It involved construction of 750 new tube wells, and rehabilitation of 325 old wells. At the time of completion in 1993, 80 percent wells were put into operation (Alberts, 1998). The expansion in public tube wells that occurred on account of this program is used as the source of variation in public provision in the analysis that follows. The project was modeled after the World Bank 1983 public tube well expansion scheme. These programs were concentrated on the construction of deep tube wells that have a command area of about 100 hectares (Cunningham, 1992). Like the World Bank program, the wells in this program had underground distribution channels and independent electrical connections from the power substations. These features made the wells more efficient than their precursors which used traditional field channels for distribution and rural electricity supply for energy, but at the same time the total cost of providing the wells increased.

3 Conceptual Framework

To assess the impact of the introduction of public provision on groundwater, I develop a model that relates the aquifer depth to the fixed cost of groundwater extraction. The model examines

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[8] In 2000-01, 80 percent of the total irrigation was on account of groundwater.

the well sinking choice of farmers in the absence and presence of public provision for groundwater in areas with significant variation in land holdings. The model establishes that when fixed costs relative to marginal costs are very high, public provision crowds out private investment in wells by relatively larger farmers. The choice between sinking and not sinking own well influences the overall usage of water, and hence the average effect on water table depth, which is the subject of study in the empirical analysis. The conditions that would lead to overall conservation of the resource are formulated for a Pareto distribution of land.

Fixed costs are a very high percentage of the total cost[9] of sinking and operating wells and the scale of operation determines the viability of investment in private wells. The theoretical model developed in this section incorporates the lumpy nature of investment required to access groundwater.

3.1 Model Setup

Consider a micro watershed[10] with N farmers. The water table is located at depth d below ground level. If a farmer sinks a well of depth δ and extracts water W, he incurs the fixed cost of installing a well, variable cost that depends on how deep a well he sinks and the cost of water extraction. A key aspect of the problem is the relationship between well depth and maximum water flow rate that can be achieved. In mathematical hydrology, *Theim 's* equilibrium condition provides this relationship:

$$\delta - d = \frac{1}{2\pi\kappa}\Big(W \ln \frac{R}{r}\Big) \tag{1}$$

where d is the depth of the aquifer at reference distance R from the center of the well, r is the radius of the well, κ is a constant characterizing soil porosity, and W is the amount of water extracted.

The cost of installing a well of capacity W gross of water extraction cost includes an annualized fixed cost p_0 and an annualized variable cost p_1 incurred per unit of depth δ. This is expressed as :

$$C = p_0 + p_1\delta \tag{2}$$

Since equation 1 describes the relation between depth of the well δ and water extracted W,

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[9] According to a World bank study(World Bank, 2001) the share of fixed cost in total cost of sinking and operating a well is around 60 to 80 percent irrespective of the size of the farmers and is particularly high among smaller farmers.

[10] A micro-watershed is a coherent ecosystem at the smallest viable geographical area. It is administratively as well as operationally the most meaningful planning unit (Shukla, 1992).

total cost[11] can be expressed as:

$$C = c(d) + tW \tag{3}$$

Intuitively, in shallow aquifers[12], digging costs are lower and we can use simpler pumping technology. As the aquifers get deeper, more sophisticated technologies like submersible pumps are required to access the aquifer and the sinking costs rise. Therefore, the fixed cost of sinking a well is an increasing function of *d*, the depth of water table below ground level.

The farm production function uses water as the only variable input and the productivity of per unit land is determined by water employed per unit land. The price of output is normalized to 1. The production process is assumed to be Cobb Douglas.[13] When a farmer does not irrigate using his own well, his profits are assumed to be 0. The profit when the farmer with plot size a sinks his own well is given by:

$$\Pi_0 = \theta a(\frac{W}{a})^{\alpha} - c(d) - tW \tag{4}$$

The farmer decides how much groundwater to pump conditional on sinking a well. His water demand on maximizing his profits is :

$$W^*_{NP} = \Big(\frac{\theta\alpha}{t}\Big)^{\frac{1}{1-\alpha}} a \tag{5}$$

Demand for water is, not surprisingly, increasing in farm area and technology parameter θ and decreasing in marginal cost t. His profit, which is decreasing in depth d, is given by

$$\Pi^*_0(W^*_{NP}) = a\theta^{\frac{1}{1-\alpha}}[\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{1-\alpha}}]t^{\frac{\alpha}{\alpha-1}} - c(d) \tag{6}$$

Because profit from not sinking one's own well is 0, a farmer will choose to sink a well if $\Pi^*_0(W^*_{NP}) > 0$ i.e if

$$\Pi^*_0(W^*_{NP}) = a\theta^{\frac{1}{1-\alpha}}[\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{1-\alpha}}]t^{\frac{\alpha}{\alpha-1}} - dc(d) > 0$$

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[11] I assume that water can be extracted costlessly. Because the incremental energy costs to lift water relative to fixed costs are very low, this assumption does not change the qualitative results of the model, although it makes the analysis more tractable. In the case of electric pumps, due to a flat tariff policy, this would be like a proportional tax on farmers and would not affect comparative statics.

[12] In shallow aquifers, the depth at which water table is reached is closer to ground level

[13] A general functional form gives the same qualitative implications for analyzing the choice that farmers make about sinking wells or using public water, but the parametric assumption is made to determine analytically the water saving effect of the program.

Government Provision

Now suppose that groundwater for irrigation is extracted by the government from a single source well and publicly provided at a price $p > t$ [14]

If the farmer chooses to sink his own well, then the profit is the same as before and is given by (6). On the other hand if the farmer does not sink his well, he does not incur the fixed cost and variable cost for a particular well depth. His only expense is the price he pays to procure groundwater. So, profit from publicly provided irrigation water is:

$$\Pi_P = \theta a^{1-\alpha} W^{\alpha} - pW \tag{7}$$

Under, public provision the water demand from profit maximization is:

$$W_P^* = \Big(\frac{\theta\alpha}{p}\Big)^{\frac{1}{1-\alpha}} a \tag{8}$$

Maximum profit from using water $W = W_P^*$ is increasing in farm area and decreasing in aquifer depth and is given by:

$$\Pi_p^*(W_P^*) = a\theta^{\frac{1}{1-\alpha}}[\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{1-\alpha}}]p^{\frac{\alpha}{\alpha-1}} \tag{9}$$

The farmer will sink his own well if $\Pi_0^*(W_{NP}^*) > \Pi_p^*(W_P^*)$

Based on these choice rules, there are two scales of land equal to (i) a_{NP}^* and (ii) a_p^* such that only farmers with bigger holdings will sink a well when (i) no public groundwater is available and (ii) when public water is available. As the depth of the aquifer increases, the scales above which it is profitable to sink a well increase too because the fixed cost of well installation goes up. Finally, the minimum scale above which a farmer sinks his own well is higher when public water is available than when it is not available. So, the public water in essence crowds out private investment over the range $a_P^* - a_{NP}^*$. The range of crowding out increases as depth increases [15].

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[14] Water Prices were set by the UP government such that they varied by season. Evidence suggests that a part of the cost of improved distribution infrastructure was passed on to the users through groundwater price (IFAD, 1983). The cost of water at the farm under previous public well programs that used traditional methods for distribution of water was higher. Shah(1993) reports that these public tube-well schemes charged a higher price than the price being charged in groundwater sharing arrangements among neighboring farmers. Also, in the empirical analysis, I find that the villages with public provision where fixed cost to access the water table is high experience less rapid expansion in groundwater irrigated area relative to comparison villages indicating a decline in use of groundwater. This would not be consistent with a situation in which t exceeds p.

[15] Proof is available on request

The evaluation of the effects of the program on water usage, and thus aquifer depletion, requires an assessment of how a farmer's behavior changes with his land area and an aggregation of this over the entire distribution of land. Overall differential water usage under public provision is examined to determine the conditions that lead to conservation of groundwater.

Water Usage

When publicly provided groundwater is available, water usage increases on account of increase in irrigated area of the farmers who are too small to sink a well, which is the extensive margin effect. But since fixed costs are high, there is also an intensive margin water saving effect that accrues because larger farmers substitute towards using publicly provided groundwater. These farmers would have sunk a well if public provision was not available. The price that these farmers pay under public provision is higher than the marginal cost of private extraction, so their net usage would reduce. Since demand for groundwater is increasing in farm area and the farmers in the intensive margin are larger than those in the extensive margin, the reduction in their total water usage can offset the increase in water usage of the smaller farmers in the extensive margin.

In a regime when both extensive and intensive margins operate(i.e. $a_P^* > a_{NP}^* > a_m$, where a_m is the minimum holding size), the difference in water usage when the publicly provided groundwater is available versus when it is not available can be expressed as:

$$\triangle W = \int_{am}^{a_{NP}^*} W_p^*(a)g(a) + \int_{a_{NP}^*}^{a_P^*} [W_p^*(a) - W_{NP}^*(a)]g(a) \tag{10}$$

The first term is the increase in water usage that results from the extensive margin, while the second term in (10) captures the intensive margin effect. Since price charged exceeds private marginal costs, this term is negative. The net effect on aquifers will depend on whether the intensive margin effect outweighs the extensive margin effect or not.

To fully characterize the conditions under which net savings of water occur, we need to assume a distribution for land. It is conventional to parameterize the land distribution as Pareto distribution since it is considered to approximate land distributions very well.[16]The density function is given by:

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[16] I fit a Pareto density to the land distribution at village level using a data-set that is representative of the region and find that it is a good fit over the range where the intensive margin effect can operate. Results are available on request

$$g(a) = \frac{\mu a_m^{\mu}}{a^{\mu+1}} \tag{11}$$

where μ is the Pareto Index that governs how thick the tail of the distribution is. For low values, the tail is thick implying more wealthy farmers in the distribution.

We can then identify the conditions under which the intensive margin effect would dominate and we would observe net water savings.

Proposition 1 *For a micro watershed with land distribution represented by Pareto density where a_m is the minimum land holding size and μ is the Pareto Index, the differential water usage under public provision of groundwater for irrigation, $\triangle W$ can be characterized as follows:*

(1) If $a_m > a_P^* > a_{NP}^*$, $\triangle W = 0$

(2) If $a_{NP}^* < a_m < a_P^*$, $\triangle W < 0$

(3) If $a_m < a_{NP}^* < a_P^*$, $\exists$ a $\rho(\frac{p}{t})$ and a $d^*(a_m, \theta, \mu, \frac{p}{t}, \alpha) > 0$ such that whenever

- *(i) $\mu < 1 - \rho$, $\triangle W < 0$*
- *(ii) $\mu \geq 1 - \rho$, $\triangle W < 0$ for $d < d^*(a_m, \theta, \mu, \frac{p}{t}, \alpha)$and $\triangle W > 0$ for $d > d^*(a_m, \theta, \mu, \frac{p}{t}, \alpha)$*

The Proof can be found in the Mathematical Appendix .

The proposition can be understood in terms of Figure 2. Part (1) arises when the water table depth is small. In this case, we are in regime A such that a_m exceeds both a_P^* and a_{NP}^*. This implies that fixed costs are so small that all farmers prefer to sink their own wells even when public provision is available. In such a scenario, neither the intensive margin, nor the extensive margin exist. So when public provision is available, there is no change in water usage. At greater depth in regime B, a_m exceeds a_{NP}^*, so all farmers sink wells in absence of public provision, hence there is no extensive margin effect. However, a_m is less than a_P^* reflecting the fact that drilling cost is high enough so that some farmers do not sink their own wells. This intensive margin effect is negative, therefore the overall water usage is negative. In regime C, where the water table depth increases further, a_m is less than both a_P^* and a_{NP}^*. So, both extensive and intensive margin effects operate. The extensive margin effect results in increased water usage whereas the intensive margin effect offsets this. At sufficiently high depths, $a^*_{NP} - a_m$ becomes large so the extensive margin is bigger, although the farm size of farmers is relatively small. If the Pareto density is such that it has a thick tail, then even at very large depths, there will be large sized farmers who would be precluded from sinking their own wells given public provision. In this case, the intensive margin will dominate and the net effect will result in negative water usage. On the other hand, if there are not enough large sized farmers, then the extensive margin will outweigh the intensive margin and there will be increased water usage.

4 Data

The empirical analysis uses detailed panel data on village water table depth, geology, shallow and deep wells, and demographic and economic characteristics of the villages[17]. The main source of data are 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, and I make use of a data set for 30 districts in north eastern plains of India. The Wells data account for around 1.2 million wells 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.

I matched this data set across two time periods to form a panel for the villages. This was further matched to the Primary Census Abstract and the Village Directories of the Population Census of India for years 1991 and 2001. The demographic characteristics are available in the Primary Census Abstract and the village level infrastructure details including availability of surface irrigation and power are in the Village Directory of the Population Census. The geological data (elevation, slope and solar radiation) were obtained by using the Digital Elevation Model SRTM at 1 km resolution[18] for the relevant area in India and the spatial locations of these villages. Finally, the spatial data was

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[17] The unit of analysis is the village. The village level water tables are considered to be micro aquifers that are affected by highly localized anthropogenic interventions. Village is the smallest unit of administration at which government initiatives in public goods are implemented. In fact, natural resource planners at ISRO do consider village as the micro unit of planning and village level aquifers are referred to as micro-watersheds.

[18] Source for this data was the Global Land Cover Facility, www.landcover.org

matched to the *University of East Anglia Climatic Research Unit (CRU) Global 0.5 deg Monthly Time Series, Version 2.1* to get average annual rainfall and temperature details. The public tube well sites were selected in 1988-1990. I use the Census of India 1991 data to proxy for the demographic and infrastructure conditions at the time of selection given the absence of any other source of such information for these years.

Table A1 provides summary statistics for the main variables. The *Data Appendix* summarizes the data sources, the variable definitions, and the constructed samples. The main sample used has 7667 villages in all with 426289 shallow tube wells in year 2000. As a preliminary exploration, Figure 3 plots the predicted difference in the impact of public provision of groundwater for irrigation on changes in water table depth by initial depth. This graph indicates that the difference in water table depth change across treated villages relative to comparison villages is negative (which implies positive effect on aquifers) and this difference increases as initial depth increases.

5 Irrigation Pumps and The Fixed Cost of Investment

In this section, I describe the kind of pumps used in irrigation, highlight the differences in their fixed costs and establish that there is a critical value of water table depth at which the cheaper and low maintenance pumps are rendered infeasible. Several kinds of pumps can be used to draw water from a tube well. Irrigation Pumps vary along the dimensions of cost and vertical lift provided. Most commonly used pumps in irrigation are volute centrifugal pumps (Raghunath, 1982, p.363). These surface pumps create low pressure in the tube well so the atmospheric pressure pushing down on water outside the well causes the water level in the well to rise. This suction process continues till there is no pressure difference inside and outside the tube well[19]. If a perfect vacuum could be created, the water would rise to a height of 34 feet as the weight of the column of this height exerts pressure equal to atmospheric pressure. However, since perfect vacuum cannot be created, the accepted practical standard for vertical lift using these pumps is 25 feet (Gibson and Singer, 1969, p.116).

This means that if the water table[20] is beyond 25 feet below the ground level, then suction lift based surface pumps cannot be used to lift water. In that case, submersible pumps that are placed inside the well tube are used in lifting water (Gibson and Singer, 1969, p.116 &124). There is a significant difference in the fixed cost of these pumps. The submersible pumps cost 3 times as much

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[19] Pressure inside the well is due to the weight of the water in the tube and outside the well is due to the atmosphere.

[20] Water table is defined as the depth below ground level at which water is at atmospheric pressure

as centrifugal pumps that operate on the ground surface and the total installation of the deep wells costs about 4.5 times more than the shallow wells (Raghunath, 1982,Table E3 and E4,p.446-447).

6 Estimation Strategy

The model demonstrates that the impact of public provision of groundwater on the water table may vary by fixed costs required to sink a well. Hence, I want to isolate the effect of public provision of groundwater on the treated villages (i.e. average treatment effect on the treated) by varying degree of fixed cost required to access groundwater.

For evaluating the effect on the treated villages by varying degree of fixed cost, I exploit the fact that cheaper surface pumps with suction technology can only be used if the vertical distance that the water has to be lifted from below the surface of earth is less than 25 feet. This allows me to characterize villages by initial depth of water table as either being low cost or high cost depending on whether or not the cheaper surface pumps can be used. I can then implement differences-in-differences by categories of cost.Another major concern in identifying the effect of public provision of groundwater on water table depth is that the selection of villages for the deep public well program might have been based on village characteristics that may be correlated with water table depth. For example,since soil properties are an important determinant of water table depth, if the villages where soil is very permeable were targeted for the public tube well program, water table depth and selection into the program could be jointly determined by soil properties. In such a scenario, we would not be able to isolate the effect of public provision of groundwater on water table depth. In order to address this issue, I use a triple difference approach.

The identification strategy relies on the fact that the deep public tube well program generates variation in exposure to public provision of groundwater across region and time. Within each fixed cost category, by comparing the water table depth within villages at the time when the public wells were put into operation and afterwards, I difference out the unobserved time invariant village characteristics which may affect water table depth. Comparing treated villages to comparison villages within each category of cost differences out changes that are not due to exposure to public provision of groundwater. I then evaluate the differences across cost categories to isolate the estimate for the effect of public provision of groundwater for irrigation on high cost category relative to low cost category. The distribution of the depth of the water tables in the initial period for the treated and comparison villages overlaps irrespective of the cost categories[21]. Hence, the average treatment effect on the treated can be estimated consistently. The key identifying assumption is that in absence of exposure to public provision of groundwater, secular trends in depth of groundwater in treated and comparison villages would not vary in villages associated with high fixed cost relative to those associated with low fixed cost. In other words, this strategy breaks down only if there are changes over time that vary across treated and comparison villages and these differential trends are systematically different across the two cost categories.

This triple difference model can be specified as follows:

Let $y_{it}^{b}, b \in [L, H]$ be the the average outcome of village i in period t and cost category b. Then, conditional on time varying observed characteristics of the village, $y_{it}^{b}, b \in [L, H]$ can be written as follows:

For low cost category,

$$y_{it}^{L} = \alpha^{L} + \beta^{L} * post + \gamma^{L} * T_i + \delta * T_i * Post + \varepsilon_{it} \tag{12}$$

For high cost category,

$$y_{it}^{H} = \alpha^{H} + \beta^{H} * post + \gamma^{H} * T_i + (\delta + \eta) * T_i * Post + \varepsilon_{it} \tag{13}$$

where post is an indicator variable that equals one if the year of measurement is the post treatment year and 0 otherwise, T_i is an indicator variable that is equal to 1 if the village i is treated and 0 otherwise.The standard errors are clustered at the village level to allow for an arbitrary covariance structure across time.

Upon differencing these, I isolate η which is the parameter of interest.

Specifically, indexing category of fixed cost as $b \in [H, L]$, I estimate:

$$y_{itb} = \sum_{b} \alpha_b * I_b + \sum_{b} \beta_b * (I_b * post) + \sum_{b} \gamma_b * (I_b * T_i) + \sum_{b} \delta_b * (I_b * T_i * Post) + \varepsilon_{it} \tag{14}$$

where I_b are indicator variables such that I_L equals 1 if the village falls in the low cost category and 0 otherwise and I_H equals 1 if the village falls in the high cost zone and 0 otherwise. The parameter of interest is then calculated as: $\eta = \delta_L - \delta_H$

This difference measures the effect of public provision of groundwater in high cost villages relative to low cost villages.

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[21] The figure that plots these distributions is available on request

7 Results

7.1 Results on Water Table Depth

The estimation results of (14) are reported in Panel A, Column(i) [22] of Table 1. I find that the public provision of groundwater is associated with a 5.15 m less decline of water table depth in the high cost category whereas it has no effect on water tables in low cost category. Panel B reports the difference in impact across cost categories. The high cost category villages experienced less decline in the water table depth relative to low cost category villages. The F statistic that tests for a significant difference across cost categories is 3.85 and the difference is statistically significant at the 5 % level.

In order to address the concern that time varying characteristics of villages may be joint determinants of groundwater water depth and selection into the public tube well program , I control for a number of observed time varying demographic, economic, and geographical variables. In Column (ii), I report the results that control for economic and demographic variables. The estimate of η, which is the impact of public provision of groundwater on high cost villages relative to low cost villages is unchanged from Column (i). Neither the point estimates for η, nor the significance is affected by including these controls. In Column (iii), I further control for contemporaneous mean annual rainfall level, its first lag, and contemporaneous mean monthly temperature. The estimated impact and significance remain unchanged.

If the depth of the water table beyond which low cost surface pumps become infeasible is the correct critical value dividing the villages into high and low costs, then on dividing the villages in low and high costs using a depth smaller than this critical value, we should expect η to be biased downwards. In other words, if fixed cost really changes at 25 feet and the results are driven by change in fixed costs, then on dividing the villages using a depth below 25, one should see a less significant water saving effect. In Figure 3, I show the results of such a placebo test. I use various depths to the left and right of the breakpoint of 25 feet (approximately 8 meters) to divide the villages into low and high cost categories. On moving from left to the depth of 25 feet, the estimate of η is close to zero and statistically insignificant. At the critical value of 25 feet at which surface pumps with suction technology become infeasible, the estimate of η jumps to -4.79 and is statistically significant at the 5 percent level. When the same experiment is conducted to the

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[22] Since we are measuring depth below ground level, negative coefficient would mean that the effect on water table depth is positive as depth declines less in treated villages compared to comparison villages.

right, the estimate seems stable up till the theoretical maximum of 34 feet (+9 feet from the cutoff point) although the significance drops to the 10 percent level. As the placebo break point is moved further, the difference becomes insignificant at conventional levels of significance. This test lends credibility to the identification procedure.

7.2 Results on Number of Wells and Groundwater Irrigated Area

The model predicts that the public provision of groundwater crowds out investment in private wells in high cost villages whereas, little or no change occurs in the low cost villages. Moreover, it is the relatively large farmers who do not sink their own wells and begin using public water when it becomes available. Because the price for groundwater that they face now is higher than under private provision, they use less of it. If this is the case, then we should observe a decline in the expansion of private wells in high cost villages after the program had been introduced. I formally test these predictions stated above that the theoretical framework generates. First, I test whether or not private investment in wells in high cost villages expanded less under public provision, and little change occurred in low cost villages. Next, I examine whether it is the relatively larger farmers who forego sinking a well when public water is available.

Table 2 reports the results for the average number of private wells. Column (i) of Panel A shows that while there is no change in investment in private wells in low cost villages, public provision leads to a relative decline in private wells in high cost villages. The expansion in the number of private wells is 4.35 less in treated villages relative to comparison villages in the high cost category. The difference between high cost and low cost categories is shown in Panel B. The coefficient is statistically significant at the 5 percent level. On controlling for demographic and economic covariates , the estimate of the difference in number of private wells between high cost villages and low cost villages is unchanged (Panel B, Column (ii)). However, on controlling for geographical covariates, the estimate is significant at the 12 percent level. These results further reinforce the crowding out hypothesis proposed in the theoretical framework.

The model suggests that relatively large farmers would forgo sinking their own wells when public provision is available. The data classifies the holding size of well owners into 4 categories : less than 1 ha, between 1-2 ha, 2-10 ha and greater than 10 ha. The last category comprises all farmers of holdings greater than 10 ha irrespective of scale. I compute a difference-in-difference estimate of the expansion in private wells [23] by holding size across both cost categories. Figure 4 shows the

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[23] The number of cultivators in each of these holding size categories was imputed for the villages using block level

estimate for each of the 4 land size categories. We observe that in low cost category, there is no difference in the number of private wells between treated and comparison villages irrespective of the scale. However, in high cost category, the larger farmers sink fewer wells. This evidence is also consistent with the predictions of the model.

8 Selection

8.1 Selection into the Public Tube Well Program

The main objective of the public tube well program was to improve the standard of living of resource poor farmers by aiding them in adopting irrigated farming. It was initiated in very poor eastern districts of Uttar Pradesh that were almost contiguous. It is possible, however, that the determinants of selection into the program were correlated with water table depth or factors that affect water table depth.

The main variables that determined selection into the program were fixed characteristics of the villages. For example, if villages had government canal irrigation available, then these did not make compelling targets for the program as there was not enough un-irrigated area to make the program cost effective in such areas. As the tube wells had to be energized using an independent power line, proximity to electric substations was important. If the area was flood prone, it was not considered for the public wells as in such areas, demand for water would be relatively low. In principal, there could be other economic, demographic, and geological variables that were relevant in making the selection decision. I therefore, explicitly model the probability of being selected into the program as a function of a set of village time varying and time invariant characteristics. In particular, I estimate a probit specification and report the results in Table 3. Among the demographic and economic controls, the only variable that significantly affects the probability of selection is the number of households. Access to government canals, and tube well irrigation have a significant and negative effect on being selected, although other forms of irrigation like tanks and rivers do not matter. Geographical factors like rainfall, the lag of rainfall[24] and temperature also have a significant effect on the probability of selection. Other factors that influence water table depth like elevation and slope do not effect the selection probability. Finally, connection to the electricity

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data from the Agricultural Census of Uttar Pradesh for 1995-96. I then computed percentage of cultivators who own wells in each of the holding size categories. There is little evidence of change in land distribution over this period.

[24] These results are unchanged if I include deviation of rainfall from long run average instead of the level.

grid is an important positive determinant of selection. No measurements on water table depth are available prior to 1990. In column (ii) , I include the water table depth from the time when the wells were put into operation and the results indicate that this measure is not correlated with the probability of selection into the program. In the regression analysis, I control for the demographic, economic, and geographical variables that could change over time and across villages to ensure that the results are not driven by trends in these variables. If the land distribution or the pattern of crops differ across the high and low cost villages, then the estimates will not be consistent. However, a comparison of the village level imputed land distributions shows that these are not systematically different. The results are available on request. Also, there is no systematic difference in crop choice. Availability of public wells could have induced migration from the villages that were not treated into the treated villages.This would bias the results if land owning farmers move across villages. However, this seems unlikely. First, land markets in rural Uttar Pradesh are thin at best. It is highly unlikely for a farmer to sell his or her plot in one village and buy a parcel in another village in response to these public wells. But land can be rented-in. Hence, I check migration patterns in the World Bank Survey data *1997-98 Uttar Pradesh and Bihar Survey of Living Conditions* which is representative of this area. The most reported reason for out-migration is labor and more than 70 percent of those who migrate, move to another state. Among entrepreneurial work, weaving and brick making are cited as types of work for which inhabitants of the villages migrate. No out-migration is reported for farming. In light of this evidence, it seems unlikely that these public wells caused land owning farmers to relocate to treated areas.

8.2 Heterogeneity in Selection

Since I want to estimate the heterogenous impact of the program on high fixed cost relative to low fixed cost categories, I also estimate a probit model to determine the probability of selection by cost category. I then check if the effect of any co-variate on the likelihood of selection into the program varies between low and high cost categories. Results are reported in Table 4. Column (i) reports the results of a probit regression to determine probability of selection into the program for the low cost villages. Column (ii) reports the results of a similar probit model but restricted to high cost villages. The results from a Chow test for equivalence of the coefficients across the two probit models are reported in the last column along with the significance level. The only variables that seem to indicate a differential effect on selection probability across two cost categories are the percentage of literate population, and the number of primary schools. Lagged literacy data is unavailable and hence it cannot be ascertained if time trends in literacy differentially affect probability of selection across cost categories. However, I provide further evidence that percentage of literate population does not affect results. As a robustness check, I re-estimate equation (14) including all covariates previously controlled for but excluding literate percentage. Results are reported in Table 5, column (iv). Both the coefficients and the standard errors are unchanged compared to the benchmark results from Table 1, which are restated in columns (i)-(iii). In column (v) and (vi), I re-estimate the benchmark model by first controlling economic and demographic covariates and then including additional geographical variables but now the sample is restricted to villages with percentage literates more than the median in the benchmark sample. Results across these sub-samples are not different from the results obtained earlier (Columns (i),(ii) and (iii)). This result suggests that literacy is not driving the conclusions.

9 Caveats and Extensions

The paper demonstrates that the public tube well programmes initiated by the government to mitigate poverty in fact result in sustainable use of groundwater. Sinking a well requires a substantial investment. Two issues arise in this context. Market failure that results in the inability of the smaller farmers to obtain credit to sink their well can be corrected by collective action. It is possible that the farmers could co-operate and sink joint wells in order to share fixed costs. In such a case, public provision may not be necessary to facilitate adoption of groundwater irrigation. For the data used in this study, less than .01 percent wells were jointly owned. Case studies have demonstrated that such contracts suffer from hold-up problems (Appudarai, 1986; Meinzen-Dick and Sullins, 1994). In a recent study of joint ownership of wells, Aggarwal (2000) finds that the villagers did not co-operate in activities involving lumpy investments like maintenance, rehabilitating of dry wells, or sinking new wells. Villagers perceived these to be very risky. On the other hand, programs that facilitate subsidized credit for sinking wells may not lead to sustainable use. Foster and Rosenzweig (2008) demonstrate that an increase in number of wells in the hands of smaller farmers leads to increased groundwater usage.

It is also possible for private markets for water to arise. The model used here does not address that possibility explicitly. Most of the existing literature on markets for water points out that these are bilateral trade arrangements among neighbors (Jacoby et al., 2004; Foster and Sekhri, 2007). In such a case, a group of buyers and seller can be thought of as one large farmer. This would only result in a shift of the perceived land distribution for the purposes of the model. The amount of water that can be extracted from a well depends on its depth and other investment in well technology. To the extent that the intermediate farmers are constrained in deepening their wells freely, the model captures functioning markets. For large farmers to operate in a more integrated market, an extensive distribution network would be needed which is not only very expensive to lay out but also infeasible on account of property rights issues as the channels would have to pass through privately owned land. A number of case studies point that such permissions in case of unlined field channels result in conflict.

The analysis here implies that these schemes increase efficiency of groundwater use. A reallocation of water from a larger farm with lower marginal product for water to a smaller farm with higher marginal product would increase efficiency. Distributional consequences have not been explicitly studied in the paper because of the constraints of the data. The analytical framework does generate testable implications about the distributional impact of this scheme. Under the assumption that returns from groundwater irrigation are positive, the smaller farmers would be better off from adopting irrigation. The intermediate farmers use less water and their yields may decline but the overall profitability increases. The paper suggests that the schemes are welfare enhancing. The effect on total agricultural output would depend on whether the increase in output from smaller farms offsets the decrease in output from larger farms. A large body of research has demonstrated that the per unit yield of smaller farms is greater than the larger farms. Disaggregated agricultural data at the level of farmers in villages is unavailable. Exploratory analysis of the aggregated data suggests that agricultural output does not fall in blocks with program villages. An important avenue of future research would be to analyze the welfare and productivity impact of such programs.

This paper abstracts from addressing externalities arising from well interference. When several pumps irrigate in the vicinity of each other, the extraction from one well affects the extraction of other wells due to underlying hydrological features of the aquifer. The proposed mechanism in the paper establishes that the number of private wells in the high cost areas that received public wells expanded less than in comparison villages. Under this scenario, fewer wells are pumping in the vicinity of each other. The immediate affect of this is a reduction in water usage as the rate of flow of water moving towards fewer wells is smaller. This paper cannot quantify this effect. But the magnitude of this effect may not be large if the well reduction occurs in a dispersed rather than spatially concentrated manner in the village.

Under the general conditions of thick tailed land distribution, and aquifers where water tables are not so deep that the cost to access them are prohibitive for private irrigators, the results of this paper generalize to any aquifer. The results suggest that a price can be charged such that it leads to sustainable use of water. In that sense, the results are externally valid. However, in order to address the normative question of what price should be charged that would lead to sustainable adoption of groundwater irrigation, aquifer level characteristics would have to be considered and price would be sensitive to these conditions.

10 Conclusion

This paper demonstrates that public provision of groundwater through large capacity wells can lead to overall savings in groundwater use in areas where fixed costs for accessing the aquifers are high. The conceptual framework hypothesized that when fixed costs are high, public provision crowds out private provision of wells and net use of water can decline. Using a triple difference approach in which I compare villages that received public tube wells to similar villages that did not receive public tube wells over time and across high and low fixed cost categories, I find consistent evidence that shows that when fixed costs are high, public provision benefits the aquifers over the range of depths observed in the data. Using the same method, I find further supporting evidence that shows that in fact the water conservation is a result of crowding out of private wells and an overall reduction in the share of irrigated area.

The division of villages across high and low fixed cost categories is based on the physical limitations of relatively inexpensive surface pumps. These pumps cannot be used for a vertical lift of water beyond a critical value. As a result, the cost of accessing water goes up at a particular depth. The villages were not randomly assigned to the program but robustness checks indicate that the results are not biased due to selection. Moreover, villages were not differentially selected across cost categories.

From a policy perspective, the results suggest that the goal of increasing access to groundwater in a sustainable manner can be furthered using well designed public provision schemes. This paper also suggests that providing irrigation infrastructure can have progressive distributional consequences and that achieving distributional objectives can be complementary with achieving environmental objectives.

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Mathematical Appendix

Proof of Proposition I :

Differential water usage is expressed as

$$\triangle W = \int_{am}^{\max(a_{NP}^*, a_m)} W_p^*(a)g(a) + \int_{\max(a_{NP}^*, a_m)}^{\max(a_P^*, a_m)} [W_p^*(a) - W_{NP}^*(a)]g(a)$$

Case (1): $a_m > a_P^* > a_{NP}^*$

$$\triangle W = \int_{am}^{a_m} W_p^*(a)g(a) + \int_{a_m}^{a_m} [W_p^*(a) - W_{NP}^*(a)]g(a) \tag{1}$$

$$\Rightarrow \triangle W = 0$$

Case (2): $a_{NP}^* < a_m < a_P^*$

$$\triangle W = \int_{am}^{a_m} W_p^*(a)g(a) + \int_{a_m}^{a_P^*} [W_p^*(a) - W_{NP}^*(a)]g(a) \tag{2}$$

$$\Rightarrow \triangle W = \int_{a_m}^{a_P^*} [W_p^*(a) - W_{NP}^*(a)]g(a)$$

$$\Rightarrow \triangle W = \int_{a_m}^{a_P^*} \theta^{\frac{1}{1-\alpha}} \alpha^{\frac{1}{1-\alpha}} [(\frac{1}{p})^{\frac{1}{1-\alpha}} - (\frac{1}{t})^{\frac{1}{1-\alpha}}] a.g(a)$$

$$\Rightarrow \triangle W = \theta^{\frac{1}{1-\alpha}} \alpha^{\frac{1}{1-\alpha}} (\frac{\mu}{1-\mu} a_m^\mu)[(a_P^*)^{1-\mu} - (a_m)^{1-\mu}][(\frac{1}{p})^{\frac{1}{1-\alpha}} - (\frac{1}{t})^{\frac{1}{1-\alpha}}]$$

since $[(\frac{1}{p})^{\frac{1}{1-\alpha}} - (\frac{1}{t})^{\frac{1}{1-\alpha}}] < 0$

The sign of $\triangle W$ is determined by sign of $\frac{[(a_P^*)^{1-\mu} - (a_m)^{1-\mu}]}{1-\mu}$ which is always positive

Hence, $\triangle W < 0$

Note: at $\mu = 1$, The function does not exist.

case (3): $a_m < a_{NP}^* < a_P^*$

$$\triangle W = \int_{am}^{a_{NP}^*} W_p^*(a)g(a) + \int_{a_{NP}^*}^{a_P^*} [W_p^*(a) - W_{NP}^*(a)]g(a) \tag{3}$$

Intensive margin term dominates if

$$\int_{am}^{a_{NP}^*} W_p^*(a)g(a) + \int_{a_{NP}^*}^{a_P^*} [W_p^*(a) - W_{NP}^*(a)]g(a) < 0$$

$$\Rightarrow \int_{am}^{a_{NP}^*} \theta^{\frac{1}{1-\alpha}} \alpha^{\frac{1}{1-\alpha}} \big(\frac{1}{p}\big)^{\frac{1}{1-\alpha}} a.g(a) < \int_{a_{NP}^*}^{a_P^*} \theta^{\frac{1}{1-\alpha}} \alpha^{\frac{1}{1-\alpha}} \big[\big(\frac{1}{t}\big)^{\frac{1}{1-\alpha}} - \big(\frac{1}{p}\big)^{\frac{1}{1-\alpha}}\big] a.g(a)$$

$$\Rightarrow \frac{\left(\frac{1}{p}\right)^{\frac{1}{1-\alpha}}}{\left[\left(\frac{1}{t}\right)^{\frac{1}{1-\alpha}} - \left(\frac{1}{p}\right)^{\frac{1}{1-\alpha}}\right]} < \frac{\int_{a_{NP}^*}^{a_P^*} ag(a)}{\int_{am}^{a_{NP}^*} ag(a)}$$

let $k = \frac{p}{t}$ and $g(a) = \frac{\mu a_m^\mu}{a^{\mu+1}}$

Previous expression simplifies to

$$\frac{1}{k^{\frac{1}{1-\alpha}} - 1} < \frac{(a_P^*)^{1-\mu} - (a_{NP}^*)^{1-\mu}}{(a_{NP}^*)^{1-\mu} - (a_m)^{1-\mu}}$$

$$\Rightarrow \frac{1}{k^{\frac{1}{1-\alpha}} - 1} < \frac{\frac{(a_P^*)^{1-\mu}}{(a_{NP}^*)^{1-\mu}} - 1}{1 - \frac{(a_m)^{1-\mu}}{(a_{NP}^*)^{1-\mu}}}$$

$$\Rightarrow \frac{1}{k^{\frac{1}{1-\alpha}} - 1} < \frac{\Big[\frac{(\frac{1}{t})^{\frac{\alpha}{1-\alpha}}}{\big(\big(\frac{1}{p}\big)^{\frac{\alpha}{1-\alpha}} - \big(\frac{1}{t}\big)^{\frac{\alpha}{1-\alpha}}\big)}\Big]^{1-\mu} - 1}{1 - \frac{(a_m)^{1-\mu}}{(a_{NP}^*)^{1-\mu}}}$$

$$\Rightarrow \frac{1}{k^{\frac{1}{1-\alpha}} - 1} < \frac{\Big[\frac{1}{\big(\big(1-\big(\frac{1}{k}\big)^{\frac{\alpha}{1-\alpha}}\big)}\Big]^{1-\mu} - 1}{1 - [\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{cd}]^{1-\mu}}$$

$$\Rightarrow \Bigg[1 - [\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{cd}]^{1-\mu}\Bigg] < \Bigg[\Big[\frac{1}{\big((1-\big(\frac{1}{k}\big)^{\frac{\alpha}{1-\alpha}}\big)}\Big]^{1-\mu} - 1\Bigg](k^{\frac{1}{1-\alpha}} - 1)$$

$$\Rightarrow \Bigg[1 - [\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{cd}]^{1-\mu}\Bigg] < \Bigg[\Big[\frac{1}{\big((1-\big(\frac{1}{k}\big)^{\frac{\alpha}{1-\alpha}}\big)}\Big]^{1-\mu}](k^{\frac{1}{1-\alpha}} - 1)\Bigg] - (k^{\frac{1}{1-\alpha}} - 1)$$

$$\Rightarrow \Bigg[k^{\frac{1}{1-\alpha}} - [\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{cd}]^{1-\mu}\Bigg] < \Bigg[\Big[\frac{1}{\big((1-\big(\frac{1}{k}\big)^{\frac{\alpha}{1-\alpha}}\big)}\Big]^{1-\mu}](k^{\frac{1}{1-\alpha}} - 1)\Bigg]$$

$$\Rightarrow \Bigg[k^{\frac{1}{1-\alpha}} - 1 - \Bigg[\Big[\frac{1}{\big((1-\big(\frac{1}{k}\big)^{\frac{\alpha}{1-\alpha}}\big)}\Big]^{1-\mu}(k^{\frac{1}{1-\alpha}} - 1)\Bigg] < [\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{cd}]^{1-\mu}$$

$$\Rightarrow \Big[k^{\frac{1}{1-\alpha}} - \Big[\Big[\frac{1}{((1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}})}\Big]^{1-\mu}(k^{\frac{1}{1-\alpha}}-1)\Big]^{\frac{1}{1-\mu}} < [\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{cd}]$$

$$c(d) < \left[\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{\Big[k^{\frac{1}{1-\alpha}} - \Big[\Big[\frac{1}{((1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}})}\Big]^{1-\mu}(k^{\frac{1}{1-\alpha}}-1)\Big]^{\frac{1}{1-\mu}}}\right] \tag{4}$$

$$d < (\frac{1}{p_1})\left[\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{\Big[k^{\frac{1}{1-\alpha}} - \Big[\Big[\frac{1}{((1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}})}\Big]^{1-\mu}(k^{\frac{1}{1-\alpha}}-1)\Big]^{\frac{1}{1-\mu}}}\right] - p_0 \tag{5}$$

Let $d^* = (\frac{1}{p_1})\left[\frac{(a_m\theta\phi(\frac{1}{t})^{\frac{\alpha}{1-\alpha}})}{\Big[k^{\frac{1}{1-\alpha}} - \Big[\Big[\frac{1}{((1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}})}\Big]^{1-\mu}(k^{\frac{1}{1-\alpha}}-1)\Big]^{\frac{1}{1-\mu}}}\right] - p_0$

Differential water usage becomes positive when $d > d*$

However, d^* is a real number only if :

$$k^{\frac{1}{1-\alpha}} > \Big[\frac{1}{((1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}})}\Big]^{1-\mu}(k^{\frac{1}{1-\alpha}}-1)$$

$$\Rightarrow \frac{ln(k^{\frac{1}{1-\alpha}}) - ln(k^{\frac{1}{1-\alpha}}-1)}{ln[1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}}]} > 1-\mu$$

let $\rho = \frac{ln(k^{\frac{1}{1-\alpha}}) - ln(k^{\frac{1}{1-\alpha}}-1)}{ln[1-(\frac{1}{k})^{\frac{\alpha}{1-\alpha}}]}$

Then this is written as

$$\mu > 1-\rho \tag{6}$$

So, if (6) holds then the total differential water usage will become positive at d* ,while there will be net water savings for depth $d < d*$

(Note :The function $\triangle W$ is continuous and the $\lim_{d\to\infty} \triangle W > 0$ for $\mu > 1$ so that d* is unique.)

However, if $\mu < 1-\rho$, then $\triangle W$ is always negative

Data Appendix

Variable	Definition	Source
Average Ground Water Level for the Village	Depth in meters below ground level at which water is found	Minor Irrigation Census, 1993 and 2000
Average Number of Private wells	Average number of shallow tube wells owned by farmers	Minor Irrigation Census, 1993 and 2000
Ground Water Irrigated Area	Ratio of area irrigated by ground water to the total sown area	Minor Irrigation Census, 1993 and 2000
Total Population	Total Population of the village	Census of India, 1991 and 2001 *Primary Census Abstract*
Number of Households	Number of residing households in the village	Census of India, 1991 and 2001 *Primary Census Abstract*
Percentage Workers	Main workers as percentage of total population in the village	Census of India, 1991 and 2001 *Primary Census Abstract*
Percentage Scheduled Caste	Percentage of total population that is classified as scheduled caste	Census of India, 1991 and 2001 *Primary Census Abstract*
Percentage Literate	Percentage of the Population that is literate	Census of India, 1991 and 2001 *Primary Census Abstract*
Density	Total Population over the total area of the village	Census of India, 1991 and 2001 *Primary Census Abstract*
Power	Dummy variable=1 if the village is electrified, and 0 otherwise	Census of India, 1991 Village Directory
Primary	Dummy variable=1 if the village has a primary school, and 0 otherwise	Census of India,1991 Village Directory
Community Health Workers	Dummy variable=1 if the village has Community health workers, and 0 otherwise	Census of India,1991 Village Directory
Government Canal	Dummy variable =1 if the village has Government canal irrigation, and 0 otherwise	Census of India,1991 Village Directory

(cont.)

Tubewell	Dummy variable=1 if the village has tube well irrigation, and 0 otherwise	Census of India,1991 Village Directory
Tank	Dummy variable=1 if the village has tank irrigation, and 0 otherwise	Census of India,1991 Village Directory
River	Dummy variable=1 if the village has river irrigation, and 0 otherwise	Census of India,1991 Village Directory
Elevation	Elevation of the village above sea level in meters	Digital Elevation Model, SRTM 1km (India)
Slope	Slope of the village terrain	Digital Elevation Model, SRTM 1 km (India)
Rainfall	Average Annual Rainfall in mm	UEA CRU TS2p1 monthly prcp
Temperature	Mean monthly temperature	UEA CRU TS2p1 monthly mean
Number of Holdings (< 1 ha) (1-2 ha) (2-10 ha) (>10 ha)	Number of Holdings of various sizes in administrative blocks of the program districts	Agricultural Census of Uttar Pradesh, 1995-96

Working Sample (common support of baseline groundwater depth)

1) There are three observations for treated villages for which there are no comparable comparison villages in terms of water table depth at the time when the public tube wells were put into operation. These are in the extreme right tail of the baseline depth distribution. Also, there are 43 comparison villages for which there are no comparable treated observations.
I exclude these observations in the regressions to detect heregenous impact following Heckman et al. 1996 and Heckman et al. 1997. These observations are 0.6 percent of the total.

2) In the regressions controlling for covariates, 93.2 percent of the sample is retained as around 6.8 percent of the observations did not match across various data sources.

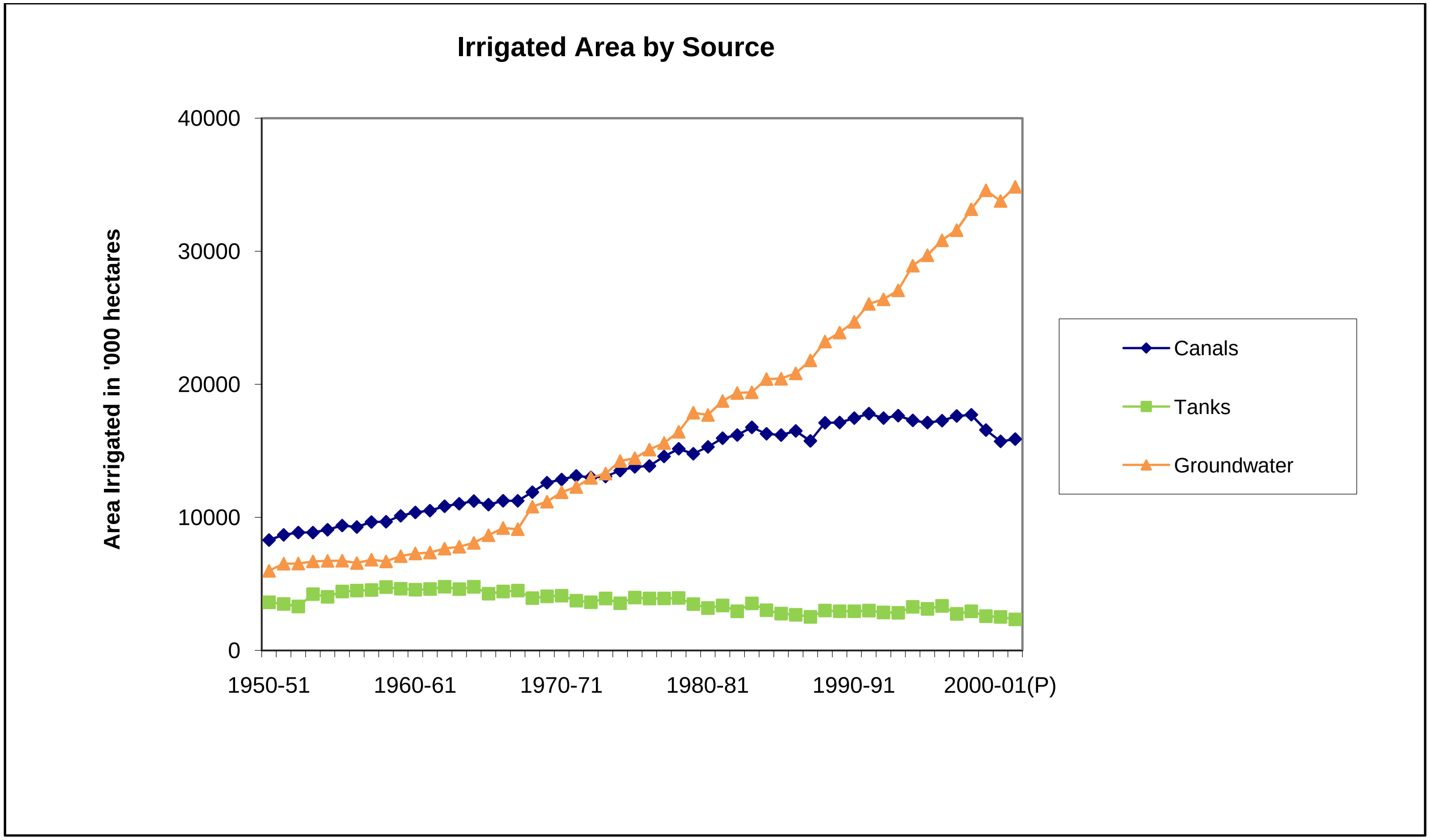
Table A1: Descriptive Statistics

	Period 1		Period2	
	Mean	Std Dev.	Mean	Std. Dev
A. Outcome Variables				
Village Average Depth of Groundwater	7.59	9.53	9.64	31
Ratio of Groundwater Irrigated to Sown Area	0.36	1.29	0.55	0.34
Ground Water Irrigated Area	42.85	75.34	75	82.17
Sown Area	147.71	216.7	155	134.03
Number of Shallow Tubewells	19.95	26.81	42.89	42.18
B. Demographic and Economic Variables				
Total Population	1138.94	1111.34	1437.34	1379.36
Number of Households	187.15	182.79	222.57	211.6
Percentage Scheduled Caste Population	0.2	0.16	0.21	0.163
Percentage Literate Population	0.26	0.12	0.39	0.13
Percentage Working Population	0.305	0.09	0.356	0.12
Density of Population	7.3	7.78	9.36	10.12
C. Geographical Variables				
Average Annual Rainfall	81.55	18.65	65.24	14.75
Mean Monthly Temperature	25.65	0.331	26.16	0.241

Unit of Observation is Village

Data Appendix lists the Sources

Figure 1: Expansion in Groundwater Irrigation in India



Source: Ministry of Agriculture, Govt. Of India, data provided by Indiastat.com

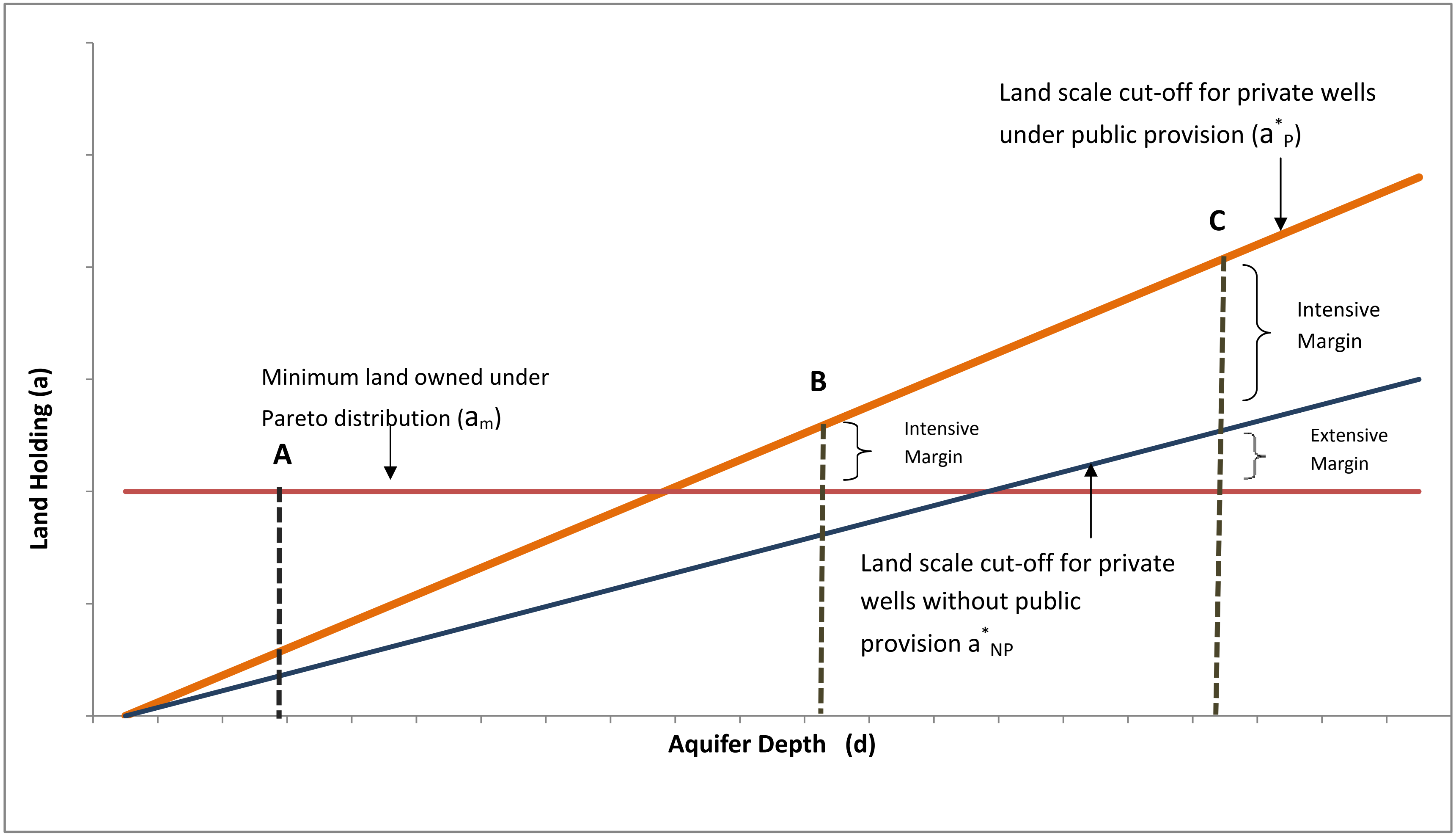
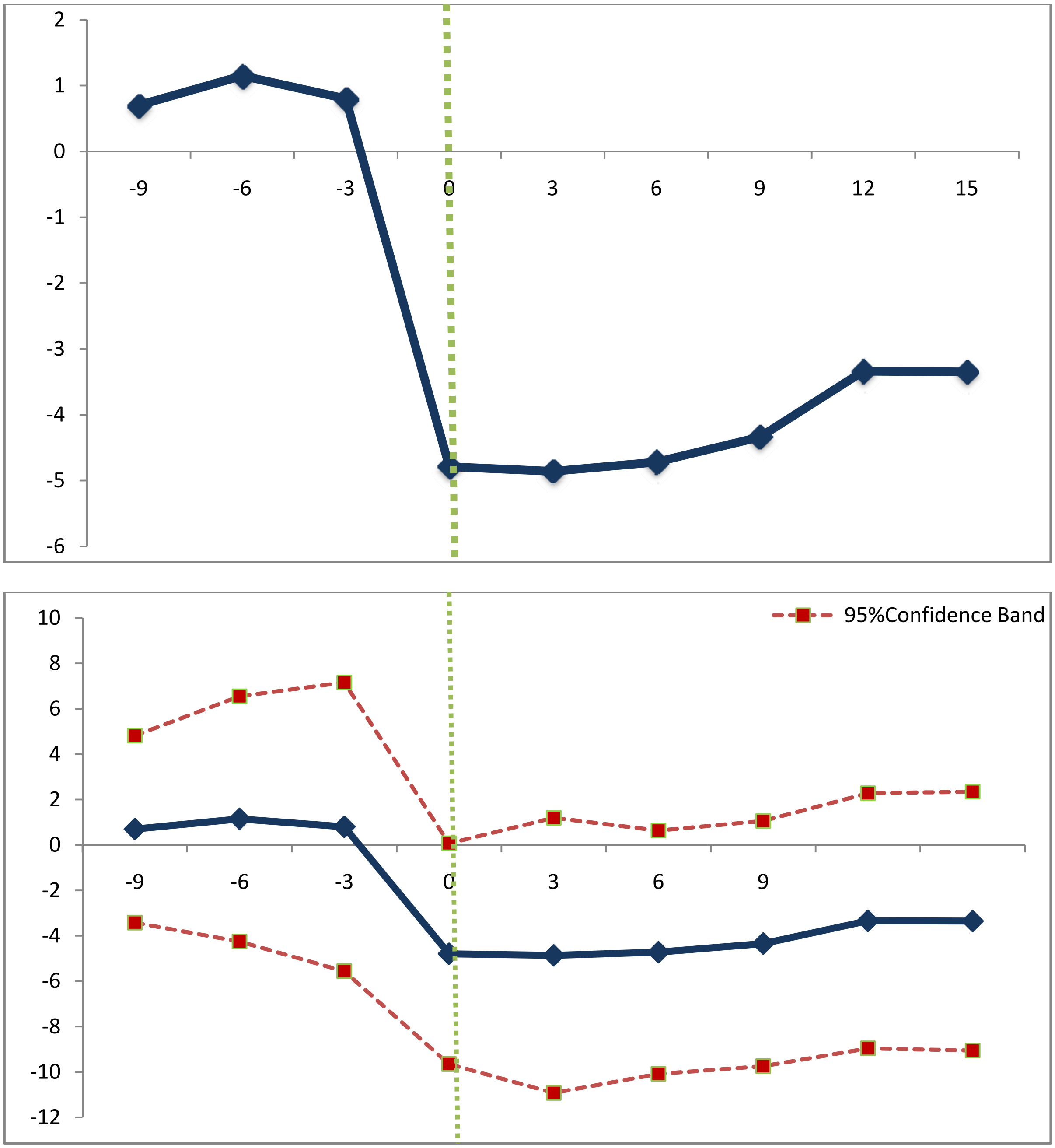


Figure 2: Characterization of Differential Water Usage under Public Provision of Groundwater for Irrigation

Figure 3: Difference between Impact of Public Provision on Groundwater Depth across Low and High Fixed Cost Categories



These figures plot the regression coefficients of difference between the impact of public tube well on depth of groundwater across high cost and low categories assuming a different cutoff depth at which fixed cost changes. Fixed cost changes at 25 feet (represented by 0) as low cost surface pumps become infeasible at 25 feet. The second panel shows a 95% confidence band around the difference plotted in the first panel.

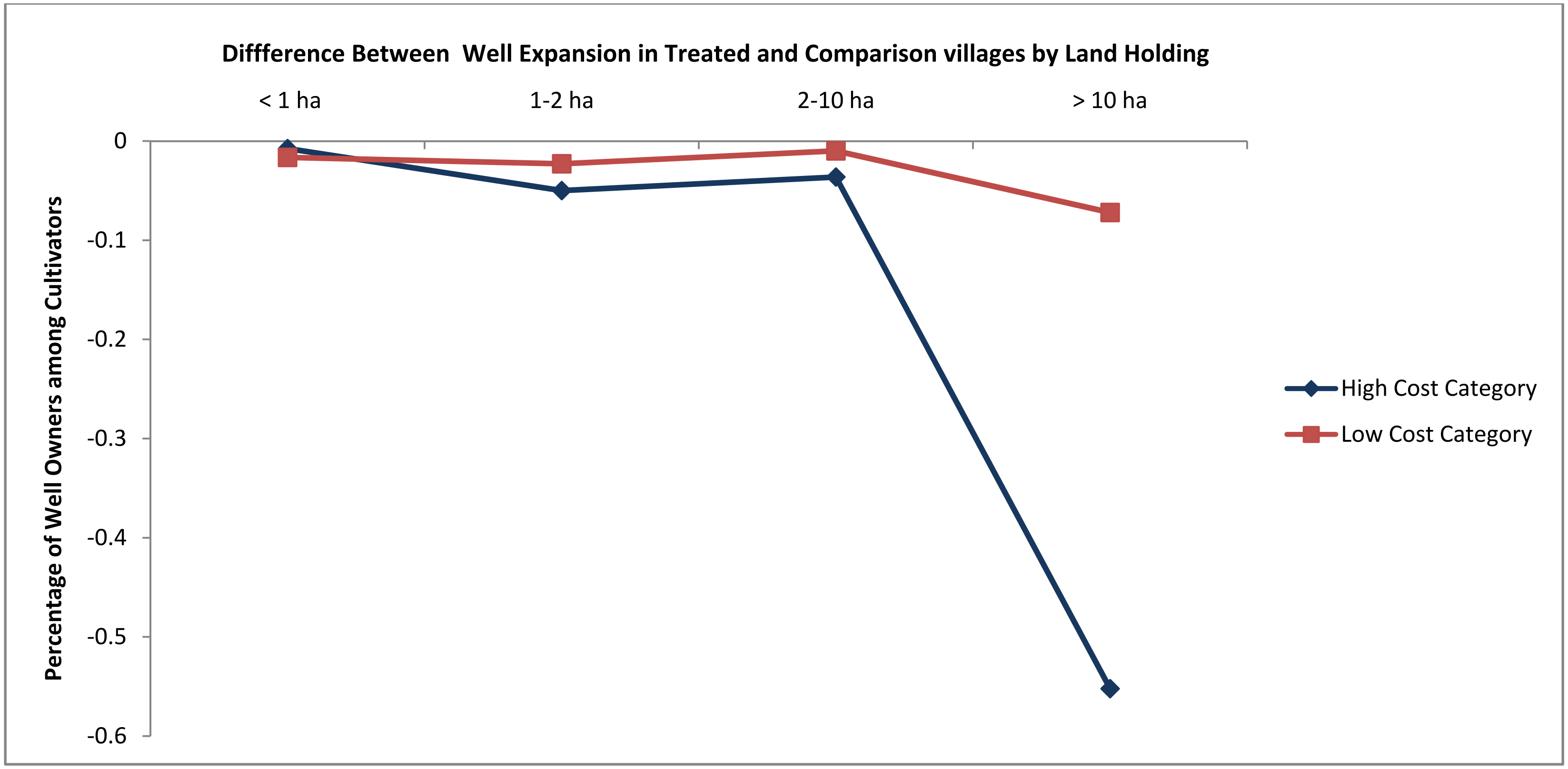


Figure 4: Difference Between Well Expansion in Treated and Comparison villages by Holding Size: This figure shows the Difference in Well Expansion over time between Treated and Comparison villages by size of land holding. In the low cost villages, the difference is negligible irrespective of land holding size. However, in the villages characterized by high cost, the difference is negligible for smaller farmers. In contrast, there is a sizable negative impact on the sinking decision in treated villages for relatively larger farmers. This is consistent with the hypothesis that the publicly available water crowds out investment for larger farmers in high cost areas.

Table 1 : Differences-in-Differences Estimates of Public Tubewell on Local Water Table Depth by Category of Fixed Cost

Coefficients of interactions between Dummies indicating whether the village is in Public Tubewell Program or not, Dummies indicating whether the Water Table depth is measured at the time wells are set in operation or 7 years later and Dummies indicating the fixed cost category

	Dependent Variable :Depth of Water Table Below Ground Level		
	(i)	**(ii)**	**(iii)**
Public Tube Well * Post	**-0.15**	**-0.2**	**-0.16**
*Low Cost	(1.2)	(1.20)	(1.2)
Public Tube Well * Post	**-5.15**	**-5.18**	**-5.28**
*High Cost	(2.25)	(2.25)	(2.23)
Demographic and Economic time varying controls	No	Yes	Yes
Geographical time varying controls	No	No	Yes
Observations	14204	14204	14204
R-Squared	0.16	0.16	0.17

Panel B

Heterogeneity in Impact of Public Tube Well Program between High and Low Cost Category

	(i)	**(ii)**	**(iii)**
Difference Between Point estimates from Panel A	**-5**	**-4.98**	**-5.12**
F statistic (testing if the difference is 0)	3.85	3.78	3.97
Significance level	0.049	0.052	0.046

Notes:

Columns (i), (ii) and (ii) in Panel A report results based on the baseline groundwater depth common support sample matched to various other data sources as described in Data Appendix. Robust std errors are reported in parentheses and are clustered at village level.

Low cost category is charaterized by the depth below ground level upto which low cost surface pumps are physically feasible.

Demographic and economic controls include number of households, fraction of scheduled caste population, fraction of literate population, and fraction of workers in the population. Geographical variables include rainfall ,first lag of rainfall and average monthly temperature.

Table 2 : Differences-in-Differences Estimates of Public Tubewell on Private Wells by Category of Fixed Cost

Coefficients of interactions between Dummies indicating whether the village is in Public Tubewell Program or not, Dummies indicating whether the Water Table depth is measured at the time wells are set in operation or 7 years later and Dummies indicating the fixed cost category

	Dependent Variable : Number of Private Wells in the village		
	(i)	(ii)	(iii)
Public Tube Well * Post *Low Cost	**-0.28** (1.2)	**-1.48** (1.15)	**-0.81** (1.15)
Public Tube Well * Post *High Cost	**-4.35** (1.6)	**-5.5** (1.54)	**-3.8** (1.55)
Demographic and Economic time varying controls	No	Yes	Yes
Geographical time varying controls	No	No	Yes
Observations	14295	14295	14295
R-Squared	0.47	0.56	0.57

Panel B:

Heterogeneity in Impact of Public Tubewell Program on Number of Wells between High and Low Cost Categories

	(i)	**(ii)**	**(iii)**
Difference	-4.07	-4.02	-2.99
F statistic	4.14	4.32	2.43
significance	0.0418	0.0376	0.119

Note:

std errors are reported in parantheses and are clustered at village level .

Regressions (i), (ii) and (ii) in Panel A are based on the Wells data set matched to baseline groundwater depth common support sample and various other data sources as described in Data Appendix. Wells exclude dug wells.

Low cost category is charaterized by the depth below ground level upto which low cost surface pumps are physically feasible.

Demographic and economic controls include number of households, fraction of scheduled caste population, fraction of literate population, and fraction of workers in the population. Geographical variables include rainfall ,first lag of rainfall and average monthly temperature.

Table 3: Probit Estimates of Probability of Selection

Dependent Variable : Dummy variable Indicating whether or not village is a part of the Deep Tube Well Program

	(i)		(ii)	
	coeff	**std err**	**coeff**	**std err**
Economic & Demographic Variables				
Workers	-0.101	0.2921	-0.1007	0.292145
Schedule Caste	0.17597	0.1428	0.17598	0.142844
Literate	0.3651	0.2229	0.36615	0.223111
Density of Population	-0.0045	0.0028	-0.0045	0.002774
Number of Households	**0.00071**	0.0001	**0.00071**	0.000117
Infrastructure				
Power (=1 if electrified)	**0.4469**	0.0759	**0.44696**	0.075868
Community Health Workers (=1 if engaged)	**-0.1187**	0.0479	**-0.1186**	0.047871
Primary School (=1 if has one)	**0.29531**	0.0533	**0.29532**	0.053252
Irrigation *(variable =1 if any land irrigated by source)*				
Tubewell	**-0.1217**	0.048	**-0.1218**	0.048008
Government Canals	**-0.5038**	0.0568	**-0.504**	0.056795
Tanks	0.09587	0.0925	0.09596	0.092557
Rivers	0.04264	0.2526	0.04221	0.252619
Geology & Geography				
Rainfall in selection year	**-0.0195**	0.0024	**-0.0195**	0.00237
Lag 1 of rainfall	**0.01156**	0.0024	**0.01157**	0.002393
temperature	**-0.5297**	0.1511	**-0.5296**	0.151087
elevation	0.00279	0.0036	0.00279	0.003644
slope	0.00075	0.0019	0.00075	0.001911
baseline groundwater depth			-0.0003	0.002257

Based on the baseline groundwater depth common suppport sample described in Data Appendix

Table 4: Probit Estimates of Probability of Selection across two Categories of Fixed cost

Dependent Variable : Dummy variable Indicating whether or not village is a part of the Deep Tube Well Program

	Low Cost (i)		High Cost (ii)		Equivalence of Coefficient Chow Test (iii)	(iv)
	coefficient	std err	coefficient	std err	Statistic	Significance
Economic & Demographic Variables						
Fraction of Village Population						
Workers	0.0719111	0.321	-0.751853	0.768	1.1	0.297
Schedule Caste	0.2187286	0.158	-0.084597	0.355	0.68	0.408
Literate	**0.0175341**	**0.25**	**1.908248**	**0.534**	**11.68**	**0.0006**
Density of Population	-0.003117	0.003	-0.013018	0.007	1.6	0.206
Number of Households	0.0008208	1E-04	0.0003554	2E-04	2.84	0.09
Infrastructure						
Power (=1 if electrified)	0.4690655	0.084	0.3190244	0.192	0.51	0.47
Community Health Workers (=1 if engaged)	-0.095227	0.053	-0.253187	0.114	1.47	0.224
Primary School (=1 if has one)	**0.2474967**	**0.059**	**0.5476381**	**0.131**	**4.42**	**0.035**
Irrigation						
(variable =1 if any land irrigated by source)						
Tubewell	-0.106351	0.053	-0.197477	0.116	0.53	0.465
Government Canals	-0.51185	0.062	-0.532467	0.154	0.02	0.897
Tanks	0.0747679	0.099	0.1642316	0.294	0.09	0.769
Rivers	-0.07617	0.275	0.8409716	0.738	2.2	0.137
Geology & Geography						
Rainfall in selection year	-0.019613	0.003	-0.026985	0.007	1.35	0.245
Lag 1 of rainfall	0.0113887	0.003	0.0202163	0.007	1.93	0.164
temperature	-0.468975	0.163	-0.732807	0.429	0.41	0.524
elevation	0.002003	0.004	0.0126146	0.01	1.09	0.297
slope	0.0008303	0.002	0.0028743	0.007	0.14	0.711
Observations	**5720**		**1384**			

Note: Columns (i) and (ii) report the probit estimates of selection into the program by different cost categories. Column (iii) and (iv) report the results of the Chow Test that tests whether any determinants of selection vary across cost categories.

(Robustness checks for the effects of fraction of literate population)

Table 5: Differences-in-Differences Estimates of Public Tubewell on Local Water Table Depth by Category of Fixed Cost

Coefficients of interactions between Dummies indicating whether the village is in Public Tubewell Program or not, Dummies indicating whether the Water Table depth is measured at the time wells are set in operation or 7 years later and Dummies indicating the fixed cost category.

Panel A	**Dependent Variable :Depth of Water Table Below Ground Level**					
				excluding fraction literate	Fraction Literate > Median	
	(i)	**(ii)**	**(iii)**	**(iv)**	**(v)**	**(vi)**
Public Tube Well * Post	-0.15	-0.23	-0.16	-0.15	-0.58	-0.72
*Low Cost	(1.2)	(1.20)	(1.2)	(1.18)	(1.15)	(1.12)
Public Tube Well * Post	-5.15	-5.17	-5.28	-5.28	-6.43	-6.65
* High Cost	(2.25)	(2.25)	(2.28)	(2.28)	(2.58)	(2.65)
Demographic and Economic time varying controls	No	Yes	Yes	Yes	Yes	Yes
Geographical time varying controls	No	No	Yes	Yes	No	Yes
Observations	14204	14204	14204	14204	7206	7206
R-Squared	0.16	0.16	0.17	0.17	0.19	0.19

Panel B: Heterogeneity in Impact of Public Tube Well Program between High and Low Cost Categories

	(i)	**(ii)**	**(iii)**	**(iv)**	**(v)**	**(vi)**
Difference Between Point estimates from Panel A	-5	-4.94	-5.12	-5.13	-5.85	-5.93
F statistic (testing if the difference is 0)	3.85	3.7	3.91	4	4.26	4.3
Significance level	0.049	0.054	0.048	0.045	0.039	0.038

Notes:

Std errors are reported in parantheses and are clustered at village level. All regressios in Panel A are based on the baseline groundwater depth common support sample matched to various other data sources as described in Data Appendix. Columns (i) - (iii) show the results reported in Table 1. Column (iv) reports the results of a regression where fraction of literate population is not controlled. Columns (v) and (vi) report results from regressions where the working sample is restricted to villages with fraction of literates > median of the full sample. Low cost category is charaterized by the depth below ground level upto which low cost surface pumps are physically feasible. Demographic and economic controls include number of households, fraction of scheduled caste population, fraction of literate population, and fraction of workers in the population. Geographical variables include rainfall ,first lag of rainfall, and average monthly temperature.