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

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This paper evaluates the effects of a public groundwater provision program on water tables in Northern India. I theorize that public provision leads to sustainable use of groundwater when the fixed costs for private well provision are high. I use village-level longitudinal data on aquifers and wells, and exploit the physical and technological limitations of surface pumps that generate a cost difference at a specific water depth to test this model. My findings suggest that public provision can be used as an alternative in scenarios where prohibitive monitoring costs might preclude the use of other regulatory approaches to prevent over-extraction. (JEL O13, O18, Q15, Q25, Q28, Q53, Q58)

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

This paper examines the economic underpinnings of the trade-off between increasing access to groundwater and sustaining reserves of groundwater in India. Rural India is a 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 (Central Groundwater

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1 Water-table is defined as the depth below ground level at which water is found at atmospheric pressure. This is the depth at which we first encounter water below the surface of the earth.

2 Collectively, annual groundwater 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 (United Nations Population Fund 2003).

3 Blocks are considered overexploited if more groundwater is extracted than is replenished.
Board 2004), and this number is growing at a rate of 5.5 percent per annum. At the same time, increasing groundwater access for marginal and small landholders is a priority for policymakers. 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 significant, 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 through the installation of large-capacity wells in rural areas. Public provision of groundwater for irrigation is advocated in developing countries as a mechanism to increase local agricultural productivity. Yet a potential cost of such investments may be an excessive depletion of groundwater, which may reduce agricultural productivity. Moreover, excessive depletion can potentially threaten food and water security in rural areas of developing countries. Given these welfare consequences, it is important to evaluate how public provision affects water tables. A priori, one would expect that public provision would exacerbate the decline in water-tables by expanding access to those farmers who could not otherwise afford wells. However, in this paper I show evidence from a public provision program in northern India that suggests that, on the contrary, public provision can lead to conservation of the resource.

I evaluate a deep public tube-well program, The Indo-Dutch Tube Well Program (IDTP), using detailed village-level longitudinal data on wells and water tables from the Minor Irrigation Census of India. The IDTP led to an expansion in public tube wells in eight districts of eastern parts of the state of Uttar Pradesh. These wells were installed with the aim of reducing poverty in the region. I use this variation to evaluate the effects on water tables. Since the cost of private extraction is significant, the effect of the program may vary by the cost of private extraction. I estimate heterogeneous effects of the program for different cost groups. In evaluating whether public provision of groundwater affects local water tables, a central innovation of the empirical analysis is to show that the effect of public provision varies with cost of private extraction at different groundwater depths.

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 eight meters. If the depth of the water table exceeds this cutoff, then 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 groundwater has a discrete jump at around eight meters. Taking advantage of this discrete change in fixed cost, I divide the villages into high- and low-cost categories depending on the depth of water table in the initial period. Using this division, I am able to isolate the effect of public provision of groundwater on local water tables for different fixed costs required to access the resource. I use triple differences—across time, across treated and comparison villages, and across the categories of cost—to isolate the effect of public provision of groundwater on local water tables in the high-fixed-cost category relative to the low-fixed-cost category. The main finding is that public provision schemes can prevent depletion in areas with high-fixed-cost of private well provision because public wells crowd out private wells. The results show that water tables in the treated villages in the high-cost areas fell less than in comparison
villages. However, in villages where the water table depth was accessible by low-cost private pumps, no difference was detected between treated and comparison villages.

In the paper, I propose an explanation for this finding. Introducing public provision of groundwater has two effects on water-table depth. First, it tends to increase irrigation among farmers who otherwise could not afford to sink a well. This effect would increase water usage and have a negative impact on water-tables. But since publicly supplied water is a substitute for privately extracted water, and the fixed cost required to sink a well is very high, public provision may forestall the installation of some private wells. This second effect can lead to lower water usage if the price charged for the public water is higher than the marginal cost of private water extraction. Such a “crowding out” of private wells, accompanied by a reduction in water usage, can offset the negative impact of increased irrigation and lead to overall conservation of groundwater. In sum, the key prediction is that when the fixed cost of private wells is high but not prohibitive, these schemes can benefit local water tables. In addition to this key prediction, the model also predicts that in areas with public provision, the number of private wells falls as the fixed cost required to access groundwater rises. Consistent with the predictions of the model, the expansion in the number of private wells per village was 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 a policy perspective, the results suggest that well-designed public provision schemes can be used to promote groundwater access in a sustainable way. These results also have important normative implications. The price of groundwater does not capture its scarcity rent, and the menu of options available to correct the price are limited on account of difficulties in monitoring and limiting private groundwater use. This paper suggests that public provision schemes can provide a solution that brings a voluntary change in the behavior of the farmers, and consequently leads to a price correction in areas where the private cost of extraction is high.

Since villages were not randomly selected into the program, I perform a number of tests that make the case that the results are not confounded by selection bias. I control for a number of demographic, economic, and geographical time-varying covariates that can potentially confound the results. I find consistently robust estimates that do not vary across specifications. I match the treated and control groups on the pre-period groundwater levels, and then estimate a triple differences model using this matched sample. Finally, I examine whether any time-varying determinants of selection into the treatment group vary across high-cost and low-cost categories and demonstrate that the results are not driven by the characteristics that determine differential selection.

While groundwater management in developing countries has become a pressing global policy concern, it has received very limited attention from economists. Most
of the existing research in developing countries explores local groundwater markets. Hanan G. Jacoby, Rinku Murgai, and Saeed Rehman (2004) address market power and efficiency issues related to rural groundwater markets. Siwan Anderson (2011) contends that ethnic barriers along caste dimensions can impede these markets, resulting in low agricultural productivity of low-caste farmers in high-caste-dominated villages. Andrew Foster and Sekhri (2007) study where and how these markets emerge, and analyze the impact of the development of these markets on the water-tables. Foster and Mark Rosenzweig (2008) investigate the interaction between land inequality and groundwater usage and find that there is a concave relationship between land inequality and groundwater depletion. This paper is the first study to focus on the public provision and sustainable use of groundwater in developing countries. In addition, the previous studies have used increasing depths of private wells as a proxy for groundwater depletion. Besides being a function of the depth of the water-table, the depth of a private well is also a function of the farm characteristics, such as size and crop choice. Thus, using this proxy can result in biased estimates due to measurement error or other confounding omitted variables that affect the crop choice decisions. The empirical analysis in this paper uses a novel dataset that provides actual water table depths at the village level, which allows me to circumvent these concerns.

The paper is organized as follows. Section I discusses the background of groundwater irrigation in India and provides details of the program being evaluated. Section II discusses the data used in the empirical work, presents the empirical strategy, and describes the main results. Section III proposes a mechanism to explain the findings. Section IV presents the results from robustness tests, a discussion of selection into the program, and additional results to substantiate the proposed mechanism. Section V provides the conclusion.

I. Background and Program Information

In this section, I provide the background on groundwater irrigation in India, and the details of the public wells program that I evaluate. I also present the differences in the fixed costs of private wells used for extracting groundwater, highlighting that there is a critical value of water table depth at which the cheaper and low-maintenance pumps are rendered infeasible. This feature will be used to evaluate the heterogeneous program effects at different fixed costs required to operate private wells.

A. Background on Groundwater Irrigation and Resulting Agricultural Productivity

Groundwater irrigation sustains about 60 percent of India’s agriculture. 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

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.
use. By the late 1990s, groundwater irrigation had become the major source of irrigation in India (online Appendix: Figure W.A.I).

Farmers with access to groundwater are able to water their crops in crucial stages of growth 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 (International Water Management Institute 2000). This phenomenal increase in access to groundwater has plausibly enhanced food security. In 1965–66, rainfall was 20 percent below normal, and food production fell by 19 percent. In contrast, in 1987–88, rainfall was 18 percent below normal, but food production only declined by only 2 percent (Government of India and World Bank 1998). Researchers at the Indian Council of Agricultural Research have attributed this change to 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. This decline is on account of rapid water extraction from private tube-wells, public tube-wells, and dug wells.

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. Sandra 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 (Tushar 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 and 1984–85, there was a threefold rise in the number of public wells in the three poorest Indian states.

B. Irrigation Pumps and Differences in Fixed Costs Induced by Physical Constraints

The technology and associated cost of wells appropriate for groundwater extraction depend on the depth of the water tables from which water is extracted. Water can be lifted to the surface by using mechanized pumps. Several kinds of pumps can be used to draw water from a tube well. Most commonly used pumps in irrigation are volute centrifugal pumps (H. Raghunath 1982). These surface pumps create a low pressure in the tube well so that the atmospheric pressure pushing down on water outside the well causes the water level in the well to rise. This suction process

5 A recent article in The Economist, “India’s Water Crisis: When the Rains Fail” (September 10, 2009), reports that according to the World Bank, 15 percent of India’s food is produced by mining or overextraction of groundwater.
continues until there is no pressure difference inside and outside the tube well. If a perfect vacuum could be created, the water would rise to a height of 34 feet (10.36 meters), as the weight of a column of this height exerts pressure equal to atmospheric pressure (Frank R. Spellman 2004). However, since a perfect vacuum cannot be created, the accepted practical standard for vertical lift using these pumps is around eight meters (U. P. Gibson and R. D. Singer 1969).

This means that if the water table is more than eight meters below the ground level, then the centrifugal surface pumps cannot be used to access water. In that case, submersible pumps that are placed inside the well tube are used in lifting water (Gibson and Singer 1969). There is a significant difference in the fixed cost of these pumps. The submersible pumps cost 3 times as much 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, Tables E3 and E4). The submersible pumps cost 16,000 rupees, and the centrifugal pumps cost 5,000 rupees. In the early 1980s (around the time of the rollout of the program that I evaluate in the empirical analysis), a relatively shallow well using a centrifugal pump cost around 12,000 rupees to operationalize, whereas a deeper well with a submersible pump could cost around 54,000 rupees.

This cost differential in the pump is induced by the laws of physics and provides an exogenous variation in costs as a function of water table depth (changing at 8 meters), which I exploit in the empirical analysis. I examine the impact of public provision by varying fixed costs required to extract water by private means. In the subsequent analysis, I divide the villages into low- and high-cost categories depending on the water table depth in the initial period. If the water table depth was less than eight meters in 1993, the village is considered low-cost. If the water table depth exceeded eight meters, then the village is characterized as high-cost.

C. Public Tube Well Program in Uttar Pradesh

This empirical study evaluates a public well program in Uttar Pradesh, which is the most populous, and one of the poorest states in the country. Agriculture relies heavily on groundwater for irrigation, and is characterized by a very large share of marginal holdings (less than 1 hectare). As in other parts of the country, the trends in Uttar Pradesh also indicate that the 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 (Central Groundwater Board 1997–98).

Uttar Pradesh has the highest number of public tube wells in the country. 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 poor marginal farmers raise their standard of living.

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6 Pressure inside the well is due to the weight of the water in the tube, and the pressure outside the well is due to the atmosphere.
7 In 2000–01, 80 percent of the total irrigation was supported by groundwater.
**Indo-Dutch Tube Well Project.**—In 1988, the Indo-Dutch Tube Well project was initiated in eight districts of eastern Uttar Pradesh. The expansion in public tube wells that occurred on account of this project is used as the source of variation in public provision in the following analysis. This scheme involved construction of 750 new tube wells, and rehabilitation of 325 old wells. When this project was rolled out, no other concurrent public well schemes were introduced in the project districts. The wells were located in villages within the project districts. The project also had an agricultural research and extension component.

The project progressed in several sequential phases as a result of the involvement of multiple agencies, including the irrigation department, the electricity board, and the donor agency. Selection of sites, construction, and energizing was done between 1988 and 1992. The initial two years in the first stage of the project were dedicated to planning and identifying villages to be treated. In this phase, various sites for construction were analyzed from an engineering design feasibility perspective. Construction of wells began in phase 2. These wells require very large rigs to make the bore holes, which had to be transported between sites. Hence, the boring activities continued for several years. The distribution of water and the powering of the wells were significantly improved. Each well in this program had underground distribution channels and independent electrical connections from the power substations. The underground channels were laid in phase 3. The electricity connections were established in the final stages after the construction was concluded. A total of 776 wells were constructed or rehabilitated out of the targeted 1,075. Overall, the planning and construction phase took 5 years and was concluded in 1993. On average, it took around 1.5 years to construct a well. At the time of commencing water provision in 1993, only 80 percent of the target wells were put into operation (J. H. Alberts 1998). The remaining wells were not completed by the planned completion date and hence were not operationalized.

The project wells were deep tube wells that have a command area of about 100 hectares (John F. Cunningham 1992). The construction costs for a new public well were NLG 95,000, or Rs 557,900, of which 55 percent was spent on the PVC distribution pipes and electrification. The wells were operated by state irrigation department employees, who were also put in-charge of the stations where the wells were housed. Well stations were centrally located. Each command area had two loops of distribution on either side that could be served simultaneously. The underground distribution channels had several valves that were controlled by the well operator. The water was ejected from these valves and supplied to the farms based on purchase agreements. These wells were more efficient than their precursors, which used traditional field channels for distribution and rural electricity supply for energy. But the new wells were more costly due to the improvements in distribution design and energy supply. Evidence suggests that a part of the cost of improved distribution

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8This project was modeled after the World Bank 1983 public tube well expansion scheme.
9I restrict the empirical analysis to wells that were put into operation. The district boundaries changed during this period for some of the districts and administrative blocks were reshuffled. The sample is restricted to the districts for which data for all the parent blocks was available.
10Approximately 2.2 Dutch Guilder (NLG) are equal to 1 euro. By way of comparison, these wells cost 10 times as much as private deep wells and 50 times as much as private shallow wells at the time the program was rolled out.
infrastructure was passed on to the users through groundwater price (International Fund for Agricultural Development 1983).

Water prices were set by the Uttar Pradesh government at the state level, and they varied by season and not local conditions (International Fund for Agricultural Development 1983). Information on how the public water price compared to the private provision cost is not available directly. However, according to the department of irrigation in Uttar Pradesh, the rate for groundwater irrigation for public schemes is 8 rupees per hour in the kharif (monsoon) season, and 16 rupees per hour in the rabi (dry) season (these are current available prices). In contrast, the private costs are much lower. According to a recent study conducted by the Consultive Group on International Agriculture Research (CGIAR) in eastern Uttar Pradesh, the cost of irrigating 1 acre of land (for sugarcane) with private electric tube wells is 1.04 rupees per hour (Yashwant Singh 2007). These figures suggest that the marginal cost of irrigation using a private well is much lower than the price of publicly provided water.

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. As a result, the program was initiated in the eastern part of Uttar Pradesh, which is relatively poor. The aim was to target poor and backward areas with average holdings of around 0.65 ha where irrigation access was limited. The chosen districts, which are in the eastern poor belt of Uttar Pradesh, qualified on these characteristics. Within the districts, some villages received the public wells and some did not.

The analysis is based on the comparison of villages within the selected districts. I compare the villages across time and across treatment status. According to the project documentation, the main variables that determined selection of villages into the program were predetermined 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 unirrigated area to make the program cost-effective. 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 the returns to irrigation would be relatively low in such areas. I follow a number of approaches to address the issue of selection. First, I identify what variables affected selection by explicitly modeling selection and control for these in the regression analysis. Second, I provide contextual information to demonstrate that selection or attrition due to migration is

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11 This rate works out to 200 rupees for 5 irrigations of 5 hours each in the monsoon season applied to an acre of land. Similar prices (194.6 rupees per acre) are reported for 1997–98 for another program, by Orissa Lift Irrigation Corporation, an undertaking by the government of Orissa that oversees public groundwater provision in Orissa. Orissa is a state located in the same region of the country as Uttar Pradesh, and is also among the poorest states of the country.

12 Thus, the charge for 5 irrigations of 5 hours each will be 26 rupees.

13 In 1993–94, the head count ratio in eastern Uttar Pradesh was around 48 percent, while it was close to 30 percent in western Uttar Pradesh. The irrigated area in Eastern region was much lower than in the western region. In 1985–86, 34 percent of the net cropped area was tube-well-irrigated in eastern Uttar Pradesh, and around 50 percent was groundwater-irrigated in western Uttar Pradesh.
not a significant issue in interpreting the results. Third, I exploit the features of well technology and exogenously determined differences in costs of private extraction of groundwater at various depths to rule out the possibility of selection confounding the results. Finally, I carry out the estimation on a matched sample of treatment and control villages. The details are provided in Subsection IVC and the online Appendix. The focus of the program was not water conservation. Thus, it is unlikely that the results are driven by selection. However, I cannot rule out with my data the possibility that there is some time-varying unobservable that is not mentioned in the project documents that simultaneously drives differential selection into the program across cost categories and the variation in groundwater levels. Although this seems unlikely, it is important to keep this caveat in mind.

II. Program Evaluation: Data, Estimation Strategy, and Results

This section discusses the data used in the empirical work, describes the estimation strategy for the evaluation of the program, and presents the main results. Results for the overall program evaluation and the heterogeneous effects of the program at differential depths of groundwater are discussed and interpreted.

A. 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. The main source of data is rounds 1993 and 2000 of the Minor Irrigation Census (MI Census) conducted by the government of India on a quinquennial basis. The first MI Census was conducted in 1986, but the village schedule was not compiled in that round. Consequently, water table data at the level of villages are not available before 1993. This census accounts for the entire population of wells, and I make use of a dataset for select districts in the north eastern plains of India. The wells data include comprehensive information such as ownership details, holding size of farmers for privately owned wells (four categories identified), sources of finance, energy source of the pumps, and average pumping hours, among other characteristics. In addition, information about village-level average water table depth, ground-water-irrigated area, sown area, and cultivated area is contained in the village data.

I match this dataset across two time periods to form a panel for the villages. This panel is 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

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14 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. The village is the smallest unit of administration at which government initiatives in public goods are implemented. In fact, natural resource planners at Indian Space Research Organization (ISRO) do consider the village as the micro unit of planning, and village-level aquifers are referred to as micro-watersheds.

15 The Census of India is not available at the village level before 1991.
contained in the Village Directory of the Population Census. The geological data (elevation, slope, and solar radiation) are obtained by using the Digital Elevation Model SRTM at 1 km resolution\(^{16}\) for the relevant area in India and the spatial locations of these villages. Finally, the spatial data is matched to the University of East Anglia Climatic Research Unit (CRU) Global 0.5 deg Monthly Time Series, Version 2.1 to obtain average annual rainfall and temperature details. The public tube well sites were selected in 1988–90. 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 1 provides summary statistics for the main variables. The online Appendix: Data Appendix summarizes the data sources, the variable definitions, and the constructed samples. The main sample used has a total of 7,667 villages containing 426,289 shallow tube wells in year 2000. There are 695 treated villages (which have newly constructed public wells). Out of these, 80 percent are in the low-cost areas, while 20 percent are in high-cost areas. Similarly, 80 percent of the control villages are in low-cost areas.

Overall, the average water table depth in 1993 was 7.59 meters below ground level (mbgl), and it was 9.58 mbgl in 2000 (Table 1). However, the mean water table depth in 1993 in the high-cost villages was 20.67 mbgl, and the standard deviation was 15.48. There was a very significant expansion in private wells. The average number of private wells per village was around 20 in 1993 and 43 in 2000. A total of 96 treated low-cost villages (around 17 percent), crossed over to a water table depth that exceeded eight meters (high-cost cutoff), and 992 control low-cost villages (close to 19 percent) transitioned.

\(^{16}\)The source for this data is the Global Land Cover Facility, www.landcover.org.
The land distribution data are not available at the village level. This data is publicly available for the selected districts at the district level from the Agricultural Census of India for 1995 and 2000.\(^\text{17}\) The Ministry of Agriculture provided data at the block level for the year 1995.\(^\text{18}\) Village-level land distributions (in four farm size categories: 0–1 ha, 1–2 ha, 2–10 ha, greater than 10 ha) are imputed from the block level data for the year 1995. District growth rates are used to impute these for the year 2000.\(^\text{19}\)

Other secondary datasets have been used to provide ancillary information. The World Bank 1997–98 Uttar Pradesh and Bihar Survey of Living Conditions is a representative household survey conducted in this region, and is used to substantiate the analysis. I also provide supporting evidence from ICRISAT village-level studies, which track farmers in four states of India over time.

### B. Estimation Strategy

I employ a differences-in-differences strategy to evaluate the impact of the deep tube well program on water tables. The objective is to isolate the effect of public provision of groundwater on the treated villages (i.e., average treatment effect on the treated). I also want to examine the program effect by varying degree of fixed cost required to access groundwater.

In order to evaluate the effect on the treated villages by varying degree of fixed cost, I exploit the fact that cheaper surface pumps with suction technology can be used only if the vertical distance that the water has to be lifted from below the surface of the earth is less than eight meters. This fact allows me to characterize villages by initial depth of water table as being either 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. This approach is a triple difference estimation strategy.

The identification strategy relies on the fact that the deep public tube well program generates a variation in exposure to public provision of groundwater across region and time. Within each fixed cost category, by comparing the water table 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 the water table. Comparing treated villages to comparison villages within each category of cost, I difference out the changes that are not due to exposure to the 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 the high-cost category relative to the 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.\(^\text{20}\) Hence, the average treatment effect on the treated can be estimated consistently. The key identifying assumption is that in

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\(^\text{17}\) The census prior to this was conducted in 1990–91 but was not digitized by the Ministry of Agriculture.

\(^\text{18}\) Blocks are administrative units above villages but below districts.

\(^\text{19}\) This information is used only in testing secondary predictions of the model developed in Section III.

\(^\text{20}\) Online Appendix: Figure WA.II shows the plots of these distributions. Note that this figure highlights the fact that there is a common support over which the differences-in-differences approach is implemented.
the absence of exposure to public provision of groundwater, secular trends in depth of groundwater and private wells 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.

As mentioned earlier, the MI Census, which is the primary data source, reports data on water tables for the first time in 1993. In the absence of data needed to examine the trends in groundwater levels prior to the site selection, I employ a differences-in-differences with matching. I use propensity score matching to isolate “control villages” that are comparable to the “treated villages” in the preperiod groundwater levels. I use the sample over which the propensity scores based on initial period groundwater levels overlap in order to carry out the triple difference estimation. I report the bootstrap standard errors. In addition, I also carry out the triple differences estimation on a propensity score-based matched sample, where propensity score is calculated using percentage of literate population, fraction of working population, number of households, elevation of the village, slope, solar radiation received by the village, and indicators for whether the village is electrified and whether it has access to canal irrigation.

The triple difference model can be specified as follows:

Let \( y_{it}^b, b \in [L, H] \) be 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 the low-cost category,

\[
(1) \quad y_{it}^L = \alpha_L + \beta_L \times post + \gamma_L \times T_i + \delta \times T_i \times post + \varepsilon_{it}.
\]

For the high-cost category,

\[
(2) \quad y_{it}^H = \alpha_H + \beta_H \times post + \gamma_H \times T_i + (\delta + \eta) \times T_i \times post + \varepsilon_{it},
\]

where \( post \) is an indicator variable that equals 1 if the year of measurement is the post-treatment year and 0 otherwise, and \( T_i \) is an indicator variable that is equal to 1 if 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 equations, I isolate \( \eta \), which is the parameter of interest. Specifically, indexing category of fixed cost as \( b \in [H, L] \), I estimate:

\[
(3) \quad y_{it}^b = \sum_b \alpha^b \times I^b + \sum_b \beta^b \times (I^b \times post)
+ \sum_b \gamma^b \times (I^b \times T_i) + \sum_b \delta^b \times (I^b \times T_i \times post) + \varepsilon_{it}
\]

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 the high-cost villages relative to the low-cost villages.

C. Program Evaluation Results

I evaluate the effects of the program on water table depths. First, I demonstrate that the comparison areas experienced a much more rapid decline compared to the treated areas. I then show that the program leads to water savings in high-cost treated areas.

**Overall Program Highlights: Differences-in-Differences Estimates.**—I report the basic comparison of villages before and after the program in Table 2. In column 1, I show the pre-program average water table depth in meters below ground level. Column 2 shows the average depth of the water table in the post-program period, and column 3 shows the difference. The data for the treated villages are reported in the first row. Water tables in the treated areas decline by 0.4 meters over the 7 years, but this decline is not statistically significant. The second row reports the data for the comparison villages. These villages experience an average decline of 2 meters, which is statistically significant at the 1 percent level. Hence, water tables in the comparison villages fell more rapidly, which suggests that the program may have a water saving effect in treated areas. The differences-in-differences estimate is reported in the last column. Although statistically significant at 10 percent, the estimate is negative. The last row reports the DID estimator controlling for time-varying demographic, economic, and geographical covariates. I also control for power and canal accessibility to account for selection. Overall, the program effect is now
−1.6 meters \(^{21}\) and is significant at 5 percent. This overall assessment masks any variation in the effects of the program in areas with different costs of private irrigation. Since the cost differential is significant, the economic incentives can change the behavior of the farmers. Therefore, I examine whether the effects of the program vary by the cost of private extraction.

**Table 3—Differences-in-Differences Estimates of Public Tube well on Local Water Table Depth by Category of Fixed Cost**

<table>
<thead>
<tr>
<th>Dependent variable: Depth of water table below ground level</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public tube well (\times) post (\times) Low cost</td>
<td>−0.54</td>
<td>−0.78</td>
<td>−0.8</td>
</tr>
<tr>
<td></td>
<td>(0.28)</td>
<td>(0.8)</td>
<td>(0.8)</td>
</tr>
<tr>
<td>Public tube well (\times) post (\times) High cost</td>
<td>−5.15</td>
<td>−5.34</td>
<td>−5.53</td>
</tr>
<tr>
<td></td>
<td>(2.25)</td>
<td>(2.25)</td>
<td>(2.3)</td>
</tr>
<tr>
<td>Demographic and economic time varying controls</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Geographical time varying controls</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>14,202</td>
<td>14,202</td>
<td>14,202</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Panel B. Heterogeneity in impact of public tube well program between high- and low-cost category</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference between point estimates from panel A</td>
<td>−4.61</td>
<td>−4.56</td>
<td>−4.73</td>
</tr>
<tr>
<td>(F)-statistic (testing if the difference is 0)</td>
<td>3.73</td>
<td>3.62</td>
<td>3.85</td>
</tr>
<tr>
<td>Significance level</td>
<td>0.053</td>
<td>0.057</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Notes: Coefficients of interactions between dummies indicating whether the village is in public tube well 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. Columns 1, 2, and 3 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 standard errors are reported in parentheses and are clustered at village level. Low-cost category is characterized by the depth below ground level up to 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. In addition, columns 2 and 3 also control for year interacted with power and canal indicators at baseline.

Results for Water Table Depth across Cost Categories.—The estimation results of equation (3) are reported in panel A, column 1 of Table 3. 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 the low-cost category. These are the differences-in-differences estimates for each of the cost categories. The reported results show that the water tables in the treated high-cost villages fall less in comparison to those in control villages. This effect is statistically significant at the 1 percent level. However, in the low-cost villages, decline in the water tables is no different in treated than comparison villages. Panel B reports the difference in impact across cost categories, that is, the triple difference. The \(F\)-statistic that tests for a difference across cost categories is 3.73, and the difference is statistically significant at the 5 percent level.

\(^{21}\) Since we are measuring depth below ground level, a negative coefficient would mean that the effect on water table depth is positive, as depth declines less in treated villages compared to comparison villages. Suppose \(Y_i^T\) is the groundwater depth in treated villages post-treatment, \(Y_i^C\) is the depth in treated villages pre-treatment, \(Y_i^L\) is the groundwater depth in control villages post-treatment, and \(Y_i^C\) is the depth in control villages pretreatment. Then, if \((Y_i^T - Y_i^L) - (Y_i^C - Y_i^C) < 0\), this implies that \((Y_i^T - Y_i^L) < (Y_i^C - Y_i^C)\).
In order to address the concern that time-varying characteristics of villages may be joint determinants of groundwater depth and selection into the public tube well program, I control for a number of observed time-varying demographic, economic, and geographical variables. These include number of households in the village, fraction of the village population that is literate, fraction of the population that works, fraction of the population that is scheduled caste, mean annual rainfall, the first lag of mean annual rainfall, and mean annual temperature. In column 2, I report the results that control for economic and demographic variables, as well as indicators for access to canals and electricity interacted with year dummies. The estimate of \( \eta \), which is the impact of public provision of groundwater on high-cost villages relative to low-cost villages, is unchanged from column 1. Neither the point estimates for \( \eta \) nor the significance is affected by including these controls. In column 3, I further control for contemporaneous mean annual rainfall level, its first lag, and contemporaneous mean monthly temperature. The estimated impact and significance remain unchanged.

I report the results from the triple difference estimation using the matched sample in Table 4. Column 1 restates the benchmark results from Table 3. The second column reports the differences-in-differences estimates that use the matched sample. The matching is based on the water table depth in the initial period, and the sample is restricted to the region of overlap between the propensity scores of the treated and control villages. The sample is restricted to the distribution of treated and comparison villages between the first and the 99th percentiles of the propensity scores. Bootstrap standard errors are reported in brackets. There is no change in the estimates compared to the results in column 1. These results indicate that the villages were not selected into treatment based on the water table depths prior to selection of sites. Finally, I also evaluate triple difference estimates with matching where the matching is done on demographic, economic, and geological characteristics of the villages in the benchmark sample from column 1. The propensity scores are based on fraction of literate population, fraction of working population, number of households, elevation, slope, solar radiation received, access to government canal irrigation, and electrification status. Results are reported in column 3 of Table 4. Bootstrap errors are in brackets. The point estimate and the standard errors are similar to the benchmark results reported in column 1.

Holding constant the population rates and incentives to sink wells, the results indicate that the program slowed the depletion of the local aquifers in the high-cost treated villages by approximately 0.65 meters per year. The World Health Organization stipulates 7.5 liters of water as the daily survival need of a human being. Assuming that the surface area of the underlying aquifers is the same as the total area of the treated villages, and that the aquifers are saturated with water, this water saving can help 0.5 million people meet their basic survival water needs for a day. Also, if we assume that 1 ton of grain production requires 1,000 cubic meters of water (Postel 1999), then this water saving would result in an additional 0.01 million tons of grain. The results are economically significant.

In this sample, the average water level in the high-fixed-cost villages in the year 1993 is 20.67 meters below ground level, and the standard deviation is 15.48. The effect corresponds to almost a third of the standard deviation. In the absence of any
other program evaluation results that inform about the magnitude of the effects, I compare the magnitudes to recent trends in water table levels in this region. The northern plains of India, where the study region is located, are experiencing rapid declines in groundwater levels. Maps available from the Central Groundwater Board of India for year 2007 indicate a groundwater level fall of 0–4 meters for the year relative to the decadal mean for most of this region.\textsuperscript{22} The groundwater yearbook for 2004–05 also reports that more than 50 percent of the observation wells in program areas experience a decline of 0 to 4 meters in the year relative to the decadal mean (Groundwater Year Book 2004–05). Hence, the magnitudes of the program effects over the seven year period are consistent with the trends in this area and are statistically and economically significant.\textsuperscript{23}

### III. Mechanism and Theoretical Framework

I interpret the findings by providing an extension of the conventional economic framework used to analyze natural resources. When several private actors have

\begin{table}[h]
\centering
\caption{Differences-in-Differences Estimates of Public Tube well on Local Water Table Depth by Category of Fixed Cost (Differences-in-differences with matching)}
\begin{tabular}{|l|c|c|c|}
\hline
Dependent variable: Depth of water table below ground level & Benchmark & DID with matching & (3) \\
\hline
\textbf{Panel A} & & & \\
Public tube well \times post & –0.8 & –0.8 & –0.5 \\
\phantom{Public tube well \times post} \times Low cost & \(0.8\) & \(0.8\) & \(0.8\) \\
Public tube well \times post & –5.53 & –5.4 & –5.21 \\
\phantom{Public tube well \times post} \times High cost & 2.3 & [1.9] & [2.10] \\
Demographic and economic time varying controls & Yes & Yes & No \\
Geographical time varying controls & Yes & Yes & Yes \\
Observations & 14,202 & 14,002 & 14,202 \\
\(R^2\) & 0.17 & 0.16 & 0.17 \\
\hline
\textbf{Panel B. Heterogeneity in impact of public tube well program between high- and low-cost category} \hspace{2cm}
Difference between point estimates from panel A & –4.73 & –4.6 & –4.71 \\
\textit{F}-statistic (testing if the difference is 0) & 3.85 & 6.06 & 4.24 \\
Significance level & 0.049 & 0.013 & 0.0395 \\
\hline
\end{tabular}
\end{table}

\textit{Notes:} Coefficients of interactions between dummies indicating whether the village is in public tube well 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. Column 1 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 standard errors are reported in parentheses and are clustered at village level. Column 2 reports results from a matched sample on common support of groundwater depth. Bootstrap errors are reported in brackets. Column 3 reports results from a regression where the benchmark sample is used and villages are matched based on socio-economic, demographic, and geological characteristics including fraction of literate population, fraction of working population, number of households, elevation, slope, solar radiation, access to canal, and electricity. Low-cost category is characterized 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.

\textsuperscript{22} The maps are available at \url{http://cgwb.gov.in/images/Fluctuation-decadle.pdf}. This information is for a single year, and the study period spans 7 years.

\textsuperscript{23} These results exclude a large outlier at eight meters. Results from a previous version of the paper that included this outlier are similar, and are available from the author.
access to the resource, each agent bases extraction decisions on individual private marginal cost and not the social cost, which is much higher. So the resource extraction is much larger than the optimal amount. The usual policy prescriptions of corrective taxes may not work due to the prohibitive costs of monitoring. In this setting, if we allow government to extract as well, conventionally this would shift out the market-wide supply curve and accelerate the depletion of the resource. The theoretical underpinnings of the effect of public provision on water tables are primarily motivated by the large fixed costs required for private extraction. I argue that the above-mentioned logic does not extend to a case where the supply decisions are characterized by a sufficiently large fixed cost, and hence in such settings where the private fixed cost is high, public provision can aid in reducing extraction levels.

I analyze the well-sinking decision of farmers in a village economy with heterogeneity in landholdings. Wells involve a high fixed cost to sink, but conditional on sinking, the marginal cost is small. Every period, a set of farmers are at the margin of making the decision to sink or not. Two types of farmers could be in this set. The first type are those who are considering investing for the first time. The second type are those who are considering reviving their wells. Note that, once sunk, wells may have a long life span. Therefore, the farmers whose wells are still working are not in the pool of those making this investment decision. In the data from the program districts, we observe that the number of wells is increasing over this period (online Appendix: Figure W A.III, panel A). Also, well ownership among intermediate to large farmers is increasing (online Appendix: Figure W A.III, panel B). Therefore, a significant fraction of farmers among the ones considering the sinking decision in any given period are most likely the first type, who have not invested in a well before. While I do not have direct evidence on the second type of farmers for the program districts, I observe some evidence from ICRISAT data that a fraction of farmers try to revive wells every year. The farmers who are reviving wells actively make decisions about incurring the fixed cost and are at the margin of their decision making. These farmers compare the profit from irrigation using private wells over the life span of a well to profits without irrigation in order to decide whether to sink a well. If a government program is introduced, it absorbs the fixed cost of water provision. In such a scenario, some intermediate farmers who would have chosen to sink a private well would be persuaded not to invest in private wells. So fewer private wells will be installed. I test this prediction and provide results in Subsection VB.

Overall water usage changes due to two opposing effects. When publicly provided groundwater is available, water usage increases due to an increase in the

24 According to a World Bank study (World Bank 2001), the share of the fixed cost in the 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.

25 Even if credit constraints prevent farmers from sinking a well and they save in order to afford the fixed costs, every period there are some farmers who have saved enough that they are on the margin of decision making. Therefore, the time over which the two effects—the intensive margin and extensive margin are realized is not different.

26 In the village-level data from ICRISAT India, which spans four states of the country, 4.08 percent of the farmers with area of 5–10 hectares, and 8.06 percent of the farmers with area greater than 10 hectares tried to revive wells in 2003. Similarly, in 2002, 2.72 percent of the farmers with area of 5–10 hectares and 1.82 percent of the farmers with area greater than 10 hectares tried to revive wells. The life span of the well may be greater than 7 years, but what is important is that every year some wells are being revived.
irrigated area belonging to farmers who are too poor 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 shift towards using publicly provided groundwater. These farmers would sink a well if public provision were not available but choose otherwise. As discussed in Subsection IC, the price that these farmers pay under public provision is higher than the marginal cost of private extraction, so their net usage is reduced. 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 the total water usage of the larger farmers can offset the increase in water usage of the smaller farmers in the extensive margin. This implies that as long as the price of the public well water (whether the farm-level price-per hour of 1 irrigation or price per cubic meter of water provided) is chosen to be higher than the marginal cost of private extraction, we may see water savings.

Fixed costs play a pivotal role in determining the net effect of the program on overall water use, as the size of the intensive margin depends on the fixed cost. When the water table depth is small, the fixed costs are so small that all farmers prefer to sink their own wells even when public provision is available. In such a case, even when public provision is available, there is no change in water usage. At a greater depth, a large fraction of farmers sink their own wells in the absence of public provision; hence there is a negligible extensive margin effect. However, the well technology costs enough that some farmers forgo sinking their own wells. This intensive margin effect is negative and can be larger than the extensive margin effect; therefore, the overall water usage can be negative. When water table depth increases further, both extensive and intensive margin effects are significant. At sufficiently great depths, fixed cost becomes large, so the extensive margin is bigger. If the land distribution is such that it has a thick tail, then even at very great depths, there will be large-scale 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. If there are not enough large-scale farmers, then the extensive margin will outweigh the intensive margin and there will be increased water usage.

**IV. Additional Evidence: Robustness Checks, Supplementary Results, and Selection into the Program**

In this section, I report the results from additional robustness checks, describe additional predictions of the model, and discuss in detail selection into the program and across cost categories. I also discuss some caveats and possible extensions.

27 The price and marginal cost comparisons from a recent program in Subsection IC show a huge wedge between the cost of extracting water privately and the price at which it is sold. From various documents on well mechanics, it seems that, if anything, variable/marginal cost of water extraction falls with the capacity of the pump motor (typically used in high-cost areas). What we can substantiate given this information is that as long as there is a wedge between the price and the marginal cost of extraction, there is water savings. It could be that the price and the marginal cost are no different in the high-fixed-cost areas and low-cost-areas, but that there is a wedge between the price and the marginal cost. As intensive margin farmers switch, this wedge generates water savings. It could also be that the marginal cost is lower in the high-fixed-cost areas but the price is the same as low-cost areas. In this event, the wedge between the price and the marginal private cost will be greater, and we will still see water savings. Due to lack of data, the paper does not discuss optimal pricing.

28 An earlier draft, which develops a formal model of this theory, is available from the author.
A. Robustness Check: Falsification Test for the Cut-off that Determines Fixed Cost of Private Extraction

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 into low and high costs using a depth smaller than this critical value, we should expect to see negligible program effect. In other words, if fixed cost really changes at around eight meters and the results are driven by change in fixed costs, then on dividing the villages using a depth of less than eight meters, we should not observe a significant water-saving effect. In Figure 1, I show the results of such a placebo test. I use various depths to the left and right of the break point of eight meters to divide the villages into low- and high-cost categories. Using a synthetic cutoff for classifying villages as high- and low-cost for depths of less than eight meters, the estimate of $\eta$ ranges from close to zero to around 1.8 but is statistically insignificant. I repeat the estimation for several such synthetic cutoffs. At the critical value of eight meters at which surface pumps with suction technology become infeasible, the estimate of $\eta$ jumps to $-4.61$ and is statistically significant at the 5 percent level.30 When the same experiment is conducted to the right, the

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29 The results of the individual regressions are reported in online Appendix: Table W A.I.
30 The theory discussed in the last section sheds light on the mechanism. When the division into high and low fixed cost is done using 7 meters, a significant number of villages (446) are considered as high-cost but are actually low-cost. Naturally, the underlying economic behavior should still be consistent with their being low-cost villages. As discussed, in low-cost villages, farmers do not alter their well-sinking decisions in response to the public wells program, as fixed costs are not too high. Therefore, the results should look similar to the ones observed for low-cost areas. In other words, synthetic alteration of the cutoff at which fixed cost changes should not reflect changes in underlying economic behavior.
estimate seems stable up to the theoretical maximum of approximately 10 meters, 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 falsification test lends credibility to the identification procedure.

B. Additional Predictions: Results for the Number of Wells

The theory 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-scale 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 the marginal cost 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’s introduction. I formally test these predictions. 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. The prima facie evidence is provided in Figure 2. The panels in the figure plot average number of wells per village by water table depth, which pins down the fixed cost of well technology. Panel A shows that prior to the public wells’ availability, there was no difference in the number of private wells in treated and control villages across either of the two cost categories. However, in the post treatment period, the number of private wells in the high-cost treated villages are systematically lower than in the high-cost control villages, while we observe no difference in the low-cost treated and control villages.

Table 5 reports the estimation results for the average number of private wells. Column 1 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 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 2). However, on controlling for geographical covariates, the estimate is close to 3 and is significant at the 12 percent level. These results further reinforce the crowding-out hypothesis proposed in the theoretical framework.

An additional prediction of the model is that the relatively larger intensive margin farmers would forgo sinking a well when public water is available. I provide further evidence that is consistent with this prediction in online Appendix: Figure WA.IV.
C. Selection on Observables

The main estimation analysis relies on a differences-in-differences approach. As mentioned before, villages were not randomly assigned to the program. Therefore, I explicitly model the probability of being selected into the program as a function of a set of village time-varying and time-invariant characteristics. I estimate a probit model that examines the determinants of selection. The regressors include demographic characteristics, including the percentage of working population, the percentage of literate population, the percentage of scheduled caste population, the population density, and the number of households. The geographical variables include slope, elevation, rainfall, lag of rainfall, and temperature. I also include indicator variables for electrification, availability of canal irrigation, and availability of other forms of irrigation. The above-mentioned variables (canal irrigation and proximity to the power grid) are statistically significant and of the expected signs. Geographical variables, including temperature and rainfall, are also correlated with the selection indicator.

The canal system and the electricity grid have been very stable over the period of the program. But to rule out the possibility of selection bias on account of these observables, the estimation controls for an interaction of indicators for access to canals and electricity, respectively, with indicators for years. In addition, all regressions control for the time-varying demographic variables and geographical variables. Another concern might be that the historical water stress determined selection. To shed light on this possibility, I also include the initial period water table as a regressor. Although this groundwater level is from a period after well sites had been selected but before the wells started extraction, this measure still provides some insight into whether historical water stress was a determinant of selection. The coefficient on the initial period water table is close to zero and is statistically insignificant.

Selection across Different Cost Categories of Private Extraction of Groundwater.—In the empirical analysis, I estimate the impact of the program across high- and low-cost category villages. As discussed, the cost differential is generated by a physical limitation of centrifugal pumps that use atmospheric pressure to lift water. There is no evidence to suggest that villages were differentially selected across these cost categories. The outreach activities were also uniform across the cost categories. I formally assess whether the factors that matter for selection, such as

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32 The correlation of the treatment indicator with rainfall is very small in magnitude.
33 The government of Uttar Pradesh in partnership with the World Bank launched an initiative to refurbish the canals in 2009 under the Uttar Pradesh Participatory Irrigation Management Act of 2009.
34 An important observation is that the percentage of scheduled castes in a village is not an indicator of selection, implying that villages with a high percentage of scheduled castes were just as likely to receive the public wells, as the villages with dominant high castes. Since scheduled castes are historically marginalized, this result suggests that lobbying by the elite did not influence site selection.
35 Results are available from the author.
36 The geological conditions, such as soil type and elevation of the villages, heavily influence the depth of the water table. These factors generate a natural variation in water table depths that influences whether one can use a centrifugal (low cost pump) or one must use a submersible (high cost pump). The fact that the average number of wells in high-cost areas is smaller than in low-cost areas in the pre-period is consistent with this natural variation. If prior extraction had generated this division to a large extent, then we should have seen more private wells in the high-cost areas.
proximity to the power grid and government canals, differentially affect the probability of selection into the program across the cost categories.\footnote{It is important to note that the empirical concern is whether villages were selected in different ways in the low-cost and high-cost areas. For example, it does not matter if the demand for publicly provided water is high in the high-cost areas (where initial water table depth is greater than eight meters) relative to the low-cost areas. What is important is whether this demand varies in treated villages relative to comparison villages in high-cost areas, and whether this variance is systematically different from the demand differential between treated and control villages in low-cost areas.}

I estimate a probit model to determine the probability of selection by cost category. I then check whether the effect of any covariate on the likelihood of selection into the program varies between low- and high-cost categories. Results are reported in Table 6. Column 1 reports the results of a probit regression to determine probability of selection into the program for the low-cost villages. Column 2 reports the results of a similar probit model 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. Electrification or access to canal irrigation does not lead to differential selection across cost categories. Geographical variables such as temperature and rainfall do not affect the selection probability

Table 6—Probit Estimates of Probability of Selection across Two Categories of Fixed Cost

<table>
<thead>
<tr>
<th>Dependent variable: Dummy variable indicating whether or not village is a part of the deep tube well program</th>
<th>Low cost</th>
<th>High cost</th>
<th>Equivalence of coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>SE</td>
<td>Coefficient</td>
</tr>
<tr>
<td>Economic and demographic variables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fraction of village population</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workers</td>
<td>0.07</td>
<td>0.32</td>
<td>-0.75</td>
</tr>
<tr>
<td>Schedule caste</td>
<td>0.22</td>
<td>0.16</td>
<td>-0.08</td>
</tr>
<tr>
<td>Literate</td>
<td>0.02</td>
<td>0.25</td>
<td>1.91</td>
</tr>
<tr>
<td>Density of population</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
</tr>
<tr>
<td>Number of households</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Infrastructure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power (=1 if electrified)</td>
<td>0.47</td>
<td>0.08</td>
<td>0.32</td>
</tr>
<tr>
<td>Community health workers (=1 if engaged)</td>
<td>-0.10</td>
<td>0.05</td>
<td>-0.25</td>
</tr>
<tr>
<td>Primary school (=1 if has one)</td>
<td>0.25</td>
<td>0.06</td>
<td>0.55</td>
</tr>
<tr>
<td>Irrigation (variable =1 if any land irrigated by source)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube well</td>
<td>-0.11</td>
<td>0.05</td>
<td>-0.20</td>
</tr>
<tr>
<td>Government canals</td>
<td>-0.51</td>
<td>0.06</td>
<td>-0.53</td>
</tr>
<tr>
<td>Tanks</td>
<td>0.07</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>Rivers</td>
<td>-0.08</td>
<td>0.27</td>
<td>0.84</td>
</tr>
<tr>
<td>Geology and geography</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall in selection year</td>
<td>-0.02</td>
<td>0.00</td>
<td>-0.03</td>
</tr>
<tr>
<td>Lag 1 of rainfall</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.47</td>
<td>0.16</td>
<td>-0.73</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Slope</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Observations</td>
<td>5,719</td>
<td>1,384</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Columns 1 and 2 report the probit estimates of selection into the program by different cost categories. Columns 3 and 4 report the results of the Chow test that tests whether any determinants of selection vary across cost categories.
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 are unavailable, and hence it cannot be ascertained whether time trends in literacy differentially affect the probability of selection across cost categories. I control for percentage of literate population in all regressions. In addition, I conduct several checks to ensure that the results are not driven by literacy rates. The results of these tests are discussed below.

Table 7—Differences-in-Differences Estimates of Public Tube well on Local Water Table Depth by Category of Fixed Cost

<table>
<thead>
<tr>
<th>Dependent variable: Depth of water table below ground level</th>
<th>Excluding % literacy</th>
<th>% Literacy &gt; median</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public tube well × post</td>
<td></td>
<td></td>
</tr>
<tr>
<td>× Low cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public tube well × post</td>
<td></td>
<td></td>
</tr>
<tr>
<td>× High cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demographic and economic time varying controls</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Geographical time varying controls</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Observations</td>
<td>14,202</td>
<td>14,202</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Panel B. Heterogeneity in impact of public tube well program between high- and low-cost categories</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference between point estimates from panel A</td>
<td>−4.61</td>
<td>−4.56</td>
</tr>
<tr>
<td>$F$-statistic (testing if the difference is 0)</td>
<td>3.73</td>
<td>3.62</td>
</tr>
<tr>
<td>Significance level</td>
<td>0.053</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Notes: Robustness checks for literacy. 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. Standard errors are reported in parentheses and are clustered at village level. All regressions in panel A are based on the baseline groundwater depth common support sample matched to various other data sources as described in the online Data Appendix. Sample is restricted to villages with percentage literacy > median in column 5. Low cost category is characterized by the depth below ground level up to which low cost surface pumps are physically feasible. Demographic and economic controls include number of households, percentage of scheduled caste population, percentage of literate population, and percentage of workers in the population. Geographical variables include rainfall, first lag of rainfall, and average monthly temperature. In addition, columns 2 to 5 also control for year interacted with power and canal indicators at baseline.

Literacy Rates and Differential Selection across Cost Categories.—In the first robustness check, I reestimate equation (3) including all covariates previously controlled for but excluding the percentage of literate population. Results are reported in Table 7, column 4. Both the coefficients and the standard errors are unchanged compared to the benchmark results from Table 3, which are restated in columns 1–3. I carry out an additional test. In columns 5 and 6, I reestimate the benchmark model by first controlling for economic and demographic covariates and then including additional geographical variables, but now the sample is restricted to villages where the percentage of literate population is more than the median in the benchmark sample.

38 I also examine whether an interaction of percentage of literate population and scheduled caste population influences the probability of selection across cost categories. This is in order to explore whether more literate and consequently more aware people may have effectively lobbied to obtain the wells. This interaction shows up as statistically insignificant. In addition, it does not affect the selection probability differentially across cost categories.
Results across these subsamples are not different from the results obtained earlier (columns 1, 2, and 3). This result suggests that literacy is not driving the conclusions.

D. Caveats and Extensions

The paper demonstrates that the public tube well programs initiated by the government to mitigate poverty also result in less depletion of groundwater reserves. Two issues arise in this context. Market failure that results in the inability of the smaller-scale farmers to obtain credit to sink their own wells 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. In the data used in this study, less than 0.01 percent of wells were jointly owned. Case studies have demonstrated that such contracts suffer from holdup problems (Rimjhim Agarwal 2000; Ruth S. Meinzen-Dick and Martha Sullins 1994). In a recent study of joint ownership of wells, (Agarwal 2000) found that villagers did not cooperate in activities involving lumpy investments like maintenance or rehabilitating of dry wells. On the other hand, programs that facilitate subsidized credit for sinking wells may not lead to sustainable use. Foster and Rozensweig (2008) demonstrate that an increase in the number of wells in the hands of smaller-scale farmers leads to increased groundwater usage. The other possibility is that large-scale farmers sell water to smaller farmers, a system which could potentially lead to water conservation. A discussion of water markets and their implications for my results is provided in the online Appendix.

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, smaller-scale farmers would be better off adopting irrigation. The intermediate farmers use less water, and their yields may decline, but their 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 that of larger farms. Disaggregated agricultural data at the level of farmers in villages are 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.

Under the general conditions of a thick-tailed land distribution and aquifers where water tables are not so deep that the cost to access them is 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. 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. In other words, data on variation in water price across aquifer conditions will be required to assess the optimal pricing schedule.

V. Conclusion

This paper uses a novel dataset to demonstrate 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 hypothesizes 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 with matching approach, in which I compare villages that received public tube wells to similar villages that did not receive public wells, over time and across fixed cost categories, I find consistent evidence 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 evidence to support the idea that water conservation is a result of crowding out of private wells.

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. 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. The findings suggest that public provision can be used as an alternative policy for preventing over-extraction when the use of other regulatory approaches, such as taxes is precluded due to prohibitively high monitoring costs.

REFERENCES


