Free Power, Irrigation and Groundwater Depletion: Impact of the Farm Electricity Policy of Punjab, India

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Abstract

This paper provides causal evidence of the impact of a change in the policy regime from flat rate to free farm electricity pricing, introduced in Punjab, India in February 1997 using a difference-in-differences framework. Based on village-level data from the second and the third rounds of the Minor Irrigation Census, the study finds a differential increase in the number of electric-operated tubewells and horsepower load of pumps in Punjab as compared to an agriculturally-similar and neighbouring state, Haryana, which is taken as the control group. Through these channels, the study finds that percentage deviation in groundwater depth from its mean in the baseline period increased by 16 per cent more in Punjab. Nationally-representative well-level data on groundwater depths from Central Ground Water Board shows impact heterogeneity with sharper effect on groundwater depth for wells that are lying closer to the cut-off of about 10 meters where a technological shift from centrifugal to submersible is required to maintain access to groundwater pumping.

Keywords: Water Pricing, Power Subsidies, Groundwater Depletion, Irrigation, Agriculture

JEL Codes: O13, Q18, Q25, Q48

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1 Introduction

India is the world's largest user of groundwater for irrigation and has seen increasing reliance on electricity-operated tubewells for extracting water (Fishman et al., 2016). Power supply to agriculture is heavily subsidized, leading to concerns about over-extraction and sustainable use of groundwater (Badiani-Magnusson and Jessoe, 2018).

Policies governing the pricing of electricity for agriculture vary by state. In most states, farmers pay a flat rate based on the horsepower rating of the water pump. The system of flat rate pricing originated in the 1970s to recover costs of electricity provision. It was felt that a flat rate would be easier to implement, given the high transaction costs of installing meters on every tubewell, at a time when the electricity grid was expanding rapidly, as were the number of tubewells. While the intent was to revise these rates periodically to recover at least average costs of electricity provision, in practice this has been far from the case. Upward revision in rates have been politically unpalatable. Instead, some states provide electricity to farmers free of charge; states that implement volumetric pricing of irrigation water are rare.

Therefore, several questions arise on what impacts on groundwater extraction, and implications thereof, follow from (a) unit (volumetric) pricing of electricity for tubewells, as distinct from (b) variations in the horsepower-based flat rates across states and time? While there is an increasing literature on these and related questions, well-identified studies of impacts and their channels are relatively few, and often limited to the first category. In contrast, this paper focuses on a question belonging to the latter category.

In particular, this paper exploits a policy change brought about by a newly-formed state government in Punjab, India, in February 1997, that made farm electricity free. Prior to this, farmers paid a flat rate of ₹50/horsepower (HP) per month.[1] I examine the impact of this switch from a flat-rate, to zero price regime on the number and type of tubewells installed, and groundwater depth. Against an overall backdrop of declining water tables

[1] INR 50 is equivalent to USD 0.67 in 2020 prices.

in the north-western part of the Indo-Gangetic plains, I examine whether the move to free farm pricing further exacerbated the decline in groundwater levels. I do this by employing a difference-in-differences strategy using an agriculturally-similar and neighbouring state of Haryana.

By what channels would a switch to free electricity impact groundwater depth? In principle, at the margin, the price of electricity continues to be zero both before and after the policy change. For a given electric pump and tubewell, there is therefore no reason to expect much of a first-order change in pumping. However, one would expect purchase or replacement decisions to be made increasingly in favour of electric-operated tubewells, and those of higher horsepower at that. This would lead to an increased volume of pumping, and contribute to the further deepening of water tables.

Tubewells can be powered with centrifugal (non-submersible) pumps that can be operated using diesel (volumetric) or electricity, or submersible pumps, that operate only on electricity. A centrifugal pump can lift water to a height of approximately 10 meters; however, in practice they operate at levels of about 8 meters since pumps are not 100 per cent efficient (see Gibson and Singer, 1969, p. 116).[2] On the other hand, the submersible pumps are capable of lifting water from greater depths. A pre-policy charge tariff of ₹50/HP per month translates into an expenditure of ₹3000 per year for a centrifugal pump, and ₹7200 per year for a submersible pump. To put these numbers in perspective, it is useful to look at costs of cultivation of paddy, a water-intensive crop that predominates the cropping pattern in the *Kharif* (July-November) season. In 1996-97, irrigation charges accounted for 17 per cent of paid-out costs in Punjab (see Government of India, 2007, p. 17-18). Thus, the change in policy would translate into substantial savings in power bills over the life of the water pump. With electric pumps becoming cheaper to operate, farmers would have an incentive to invest in these, rather than diesel pumps. And because the flat rate fee was increasing in pump horsepower, they would invest in pumps of higher horsepower. Therefore, an increase in the number of electric pumps and

[2]The idea of exploiting the 8-10 meters technological cut-off for centrifugal pumps in the context of regression discontinuity was introduced by Sekhri (2014).

a shift towards pumps of higher horsepower rating can be expected to lead to greater extraction of the groundwater resources and deepening of the water tables.

Farmers may anticipate that greater investment in electric-operated tubewells and pumps of higher horsepower rating by others will lead to a rapid fall in the water table. This may reinforce behavioural response to increase pump capacity in regions closer to the cut-off of 10 meters below which centrifugal pumps are not feasible to operate. If this happens, and more submersible pumps with greater water lifting capacity are used, there may be a sharper impact on groundwater depths for regions where the water table is just below 10 meters.

This discussion guides the choice of outcomes that I focus on in this paper, namely, the overall number of wells, number of electric-operated tubewells, horsepower load of all the pumps, and groundwater depth in terms of levels and percentage deviation from the mean in the baseline period.

There is suggestive evidence that these channels may be operating. In 1993-94, there were 5,89,485 electric irrigation pumps in Punjab (Government of India, 2001). By 2000-01, this number increased to 7,89,143 (Government of India, 2005). Over the same period, the number of diesel pumps declined from 3,57,372 to 2,87,484. As a result of this, and an increase in pumping of water, the groundwater level in Punjab has fallen by more than one meter per year (Malik, 2016). As a consequence, by 2017, 80 per cent of blocks[3] in Punjab were deemed to be critical or over-exploited in water.[4] Groundwater utilization was 166 per cent of its recharge, the highest in the country (see Central Ground Water Board, 2019, p. 63).

While groundwater exploitation has increased in neighbouring state of Haryana as well, the pattern in Punjab is far more stark. In 1992, 59 per cent of the blocks in Punjab were deemed as critical and over-exploited (World Bank and CGWB, 1999), which increased

[3]A block is an administrative sub-unit. States are divided into districts, and each district is divided into tehsils (for administration of land and revenue) or into blocks (for planning and development purpose). A tehsil may consist of one or more than one block.

[4]Blocks are considered to be "critical" when the ratio of annual groundwater draft to the net annual groundwater availability is between 90% and 100%, while they are considered as "over-exploited" when annual groundwater draft exceeds its net annual availability.

to 79 per cent in 2004 (Central Ground Water Board, 2006). The corresponding figures for Haryana are 47 per cent and 58 per cent, respectively.

In this paper, I provide causal evidence of the impact of a change from a flat rate to free electricity pricing regime in agriculture in Punjab on the number of electric and diesel tubewells and groundwater depth. As noted earlier, I employ a difference-in-differences framework comparing Punjab to its agro-ecologically comparable neighbour, Haryana, which remained on a flat-rate pricing structure.

I rely on two sources of data for the analysis. The first is the Minor Irrigation Census, the second (1993-94) round of which corresponds to the pre-intervention period and the third (2000-01) round of which is the post period. The unit of analysis is the village, with *patwari* or village-level worker reported measures of water depth and farmer reported measures of number of wells and horsepower of each type of water pump. The second is the Central Ground Water Board (CGWB) data which captures depth in observation wells for the years 1995-96 to 1997-98 (pre-policy) and 2002-03 to 2005-06 (post-policy).

I provide here a brief preview of the results. There was a differential increase in the average number of shallow tubewells and dugwells in a village by 40 in Punjab as compared to Haryana relative to baseline figures of 76 (Punjab) and 92 (Haryana) wells. Much of this increase came from increased investment in electric pumps as shown by a differential increase of 42 electric-operated shallow tubewells and dugwells in the treatment group. I also show a differential increase in the average horsepower load of all wells in Punjab as compared to Haryana.

Further, with tubewell expansion and greater horsepower load, the average groundwater depth, in terms of levels as well as percentage deviation from its mean in the baseline year, increased more in Punjab as compared to Haryana. There was a differential increase in the percentage deviation in groundwater depth from its mean in the pre-intervention period by 16 percent. The increase in groundwater depth was sharper for wells lying in the regions that are closer to the cut-off of about 10 meters where farmers using centrifugal pumps lose access to groundwater much faster, necessitating a switch to submersible pumps for groundwater pumping.

To my knowledge, this is the first paper to provide causal estimates of channels and outcomes in the context of non-volumetric pricing.

The rest of the paper is organised as follows. Section 2 attempts to situate the contribution of this paper in the literature as it pertains to India. Section 3 describes the data used in the study. Section 4 discusses the difference-in-differences methodology used to quantify the impact of the free farm electricity pricing policy on various outcome variables. Section 5 elaborates the results of the impact of policy and its implications for groundwater depletion in Punjab. Section 6 concludes.

2 Contribution to the Literature

The study contributes to the growing literature that examines questions relating to the linkages between pricing of electricity and groundwater depletion.[5] It has been argued that power subsidies have huge environmental costs in terms of inefficient utilisation of groundwater resources (Shah and Chowdhury, 2017; Kumar, 2005; Kumar et al., 2011) and increasing regulation can exacerbate these inefficiencies (Sekhri and Nagavarapu, 2013). However, literature on evaluation of the impact of electricity subsidies in the power sector in India is relatively scant.

Flat-rate pricing of farm electricity which does not reflect the true cost of irrigation water, creates a disincentive for the farmers to use groundwater resources efficiently, contributing to groundwater depletion. Most studies in India examine the impact of a policy shift from flat-rate pricing to volumetric pricing on groundwater use. Banerji et al. (2012) simulates the impact of unit pricing on groundwater extraction and agricultural yields in North India. They show that lowering of the power price leads to increase in irrigation volumes. A study based in Gujarat by Fishman et al. (2016) illustrate the impact of

[5]An empirical review of literature comparing studies based on flat-rate and volumetric pricing of agricultural electricity are discussed in Sidhu et al. (2020), focusing on the impact of these policies on the farmers' pumping behaviour and the differential access of groundwater resources for marginal and large farmers.

a pilot intervention in 2012 where farmers with previously no meters were voluntarily asked to install meters and compensation was given for every unit of electricity saved by the farmers below some pre-specified threshold, following the adoption of meters. The authors did not find any decline in electricity or water use of the farmers with this intervention. Kumar (2005) uses data from a district in North Gujarat and finds a reduction in demand for groundwater and electricity use when unit pricing of water is implemented. Meenakshi et al. (2012) study the impact of metering of tubewells on groundwater use in West Bengal. Using data from a primary survey, they find a reduction in pumping hours in the summer season with a shift in policy from flat-rate tariff to unit pricing of electricity.

A few studies, such as those by Malik (2016), Sarkar (2020) and Singh (2012) highlight the increasing trends in energy consumption and falling trends in water tables in Punjab over time and attribute these to the free supply of electricity. They elaborate on various measures like shifting away from water-intensive paddy cultivation and use of water saving technology in the state for sustainable use of groundwater for irrigation. None of these studies quantify the extent to which groundwater tables have depleted as a consequence of power subsidies in Punjab using causal methods.

The closest paper to this study is by Badiani-Magnusson and Jessoe (2018) that examines the impact of agricultural electricity subsidies on groundwater extraction by exploiting year-to-year variation in state electricity prices, controlling for district unobservables and aggregate time shocks. For a panel of 344 districts in India where flat rate pricing regime was followed between 1995 and 2004, they find that groundwater extraction declined by 1.05 million cubic meters with every rupee increase in monthly fixed rate per HP of electricity. Similar to their study, the findings of this paper also suggest greater groundwater depletion as a result of reduction of electricity price from flat rate to zero. In particular, I find a differential increase of average groundwater depth by 0.86 meters for a well in Punjab as compared to Haryana.

This paper makes four contributions to the literature. Firstly, as distinct from earlier literature, this is the first paper that provides causal evidence of the impact of the shift in policy from flat rate to free farm electricity in Punjab, India.

Secondly, it focuses attention on the channels by which free electricity, rather than a flat-rate price affect groundwater depletion.

Thirdly, unlike previous literature, the paper uses more granular Minor Irrigation Census data at the village-level which provides detailed measures of number and types of wells and groundwater level, and multiple years of groundwater level data from the Central Ground Water Board at the observation well-level to provide causal estimates of mechanisms and outcomes in the context of free farm electricity pricing regime.

Fourthly, the paper provides evidence for heterogenous impact on groundwater depth for wells lying in regions where depths are closer to the cut-off of 10 meters that is based on the technological differences of the two kinds of irrigation pumps. I argue that in the expectation of rapid decline in water tables due to increased investment in electric-operated tubwells and pumps with higher horsepower rating by others, it is imperative for farmers to switch to submersible technology to maintain access to groundwater since centrifugal pumps are not functional at deeper groundwater levels.

3 Data and Descriptive Statistics

This paper employs data from two sources, namely the Minor Irrigation Census and the Central Ground Water Board.

3.1 Minor Irrigation Census

The data on village-level average groundwater depth[6] and various minor irrigation schemes used for groundwater irrigation are taken from the second (with reference year 1993-94)

[6]Note that the terms groundwater depth and groundwater level are used interchangeably in this paper.

and the third (with reference year 2000-01) rounds of the Minor Irrigation Census[7] which is conducted by the Ministry of Water Resources, Government of India. The minor irrigation schemes are broadly classified under the three categories of dugwells, shallow tubewells and deep tubewells.[8] The data is collected under six schedules, one each for the three types of wells used for groundwater irrigation, two for the surface irrigation, and a village schedule. This study uses data from the three schedules on the groundwater wells and the village schedule.

Each of these schedules provides village-level data on the distribution of the three categories of wells in each village by water lifting device (electric, diesel, and others), by horsepower (0-2 HP, 2-4 HP, 4-6 HP, etc.), and by status (in use, not in use - dried up, destroyed, etc.). The informant is the owner of the well or his/her neighbour in case of the absence of owner.

The average groundwater depth in each village is captured in the village schedule. The data on groundwater depth in meters is collected by the enumerators through enquiries from *patwaris* or the village-level workers.[9]

In Haryana, there are 5,556 villages in 1993-94 and 6,739 villages in 2000-01 while in Punjab, there are 12,342 villages in 1993-94 and 12,643 villages in 2000-01 where dugwells, shallow tubewells and deep tubewells were employed for the extraction of groundwater.[10] The proportion of shallow tubewells in Haryana is about 90 per cent whereas in Punjab, it is about 98 per cent and the proportions of dugwells and deep tubewells each are roughly less than or equal to 5 per cent in both the states.

[7] Minor Irrigation Census comprises all the wells used for groundwater and surface water irrigation having a cultivable command area of upto 2000 hectares individually.

[8] Dugwells are ordinary open wells of varying dimensions that usually belong to individual cultivators. Shallow tubewell consists of a bore hole built into the ground for drawing out groundwater. The depth of a shallow tubewell usually does not exceed 60-70 meters and their discharge capacity is double or triple than that of a dugwell. Deep tubewells have a depth of 100 meters of more so that their discharge capacity is nearly 15 times that of a shallow tubewell. They are usually constructed as public schemes and are owned and operated by the government departments.

[9] According to the time schedule given for the 2nd Minor Irrigation Census, the field work took place in March 1995 (Government of India, 2001, p. 9). The field work for the 3rd Minor Irrigation Census started in July 2001 (Government of India, 2005, p. 6).

[10] In this paper, I use years 1993-94 and 2000-01 to refer to the Second and the Third Minor Irrigation Census, respectively which were conducted with these as reference years.

The average number of dugwells and shallow tubewells in a village in the two periods in Punjab and Haryana is presented in Figure 1 with light-shaded regions depicting the average number of wells that are electric-operated and dark-shaded regions depicting the average number of wells that are diesel-operated. There is an increase in the average number of dugwells and shallow tubewells in Punjab from 1993-94 to 2000-01. Also, the average number of electric-operated wells has gone up in the state across the two periods. However, the average number of dugwells and shallow tubewells and those operated on electricity have declined in Haryana over the two rounds of the Census. One of the reasons for this decline in the average number of wells in Haryana could be well failures pertaining to deeper average groundwater depth in the state.[11,12]

[Insert Figure 1 here]

The average groundwater depth in Punjab is 8.6 meters in 1993-94 and it has increased to 12.5 meters in 2000-01. In Haryana, the average groundwater depths in the two periods are 20.2 meters and 26.1 meters respectively. Note that the percentage increase in average groundwater depth in Punjab is 45 per cent which is much greater than a 29 per cent increase in Haryana (Figure 2).

[Insert Figure 2 here]

Table 1 presents the summary statistics for the variables taken from the Minor Irrigation Census data. The top panel presents the mean and the standard deviation of the variables for the baseline period and the bottom panel corresponds to the endline period. There is not only an increase in the average number of electric-operated dugwells and shallow tubewells in Punjab but their proportion has also increased over time. The proportion of electric-operated dugwells and shallow tubewells in Punjab has increased from 67 per cent in 1993-94 to 73 per cent in 2000-01. There is a decline in the average number of

[11] Figure A1 shows a thicker right tail of the kernel density plot of village-level groundwater depth in Haryana as compared to Punjab which shows deeper groundwater depths in the villages of the former state.

[12] The number of dugwells not in use has approximately doubled in an average village of Haryana whereas there is a decline in the number of dugwells not in use in an average village of Punjab across the two periods. Also, the number of shallow tubewells not in use has increased by about 34 per cent in an average village of Haryana while it has declined by about 10 per cent in an average village of Punjab from 1993-94 to 2000-01.

diesel-operated wells in both the states although the decline is sharper in Punjab.

[Insert Table 1 here]

3.2 Central Ground Water Board

Another source of data is the Central Ground Water Board (CGWB), Government of India. This dataset provides the depth of groundwater measured in meters below ground level (mbgl) for a sample of observation wells in four different months with spatial coordinates of the observation wells for the period 1996 to 2018. It is recorded in the months of January, April/May, August and November for a network of test wells spread throughout India. Observation wells or test wells are implanted by Central Ground Water Board and State groundwater departments for the purpose of regular monitoring of the groundwater levels and these are not in use for irrigation by the farmers.

This study uses data on pre-monsoon groundwater levels for Punjab and its neighbouring state, Haryana. Amongst the four readings recorded over a year by CGWB, the pre-monsoon groundwater levels which are deepest as compared to groundwater levels at other points of time, are used in this analysis because I expect these to be a more accurate measure of a permanent fall, if any, in groundwater depths. The tests wells are evenly spread across both the states. This is demonstrated in Figure 3 which shows the sample of observation wells for which data on groundwater levels is recorded by CGWB.[13] The dataset consists of 1099 well-year observations in Haryana and 915 well-year observations in Punjab in the baseline period. The corresponding sample sizes for the endline period are 1402 well-year observations in Haryana and 802 well-year observations in Punjab. In this sample, about 80 per cent of the observations correspond to dugwells while the remaining 20 per cent correspond to tubewells in Haryana in both the periods. In Punjab, 90 per cent of the observations correspond to dugwells and about 10 per cent correspond to tubewells in the two periods. The majority of the sample correspond to dugwells in the CGWB data whereas shallow tubewells constitute the majority of the Census data.

[13] The wells in Figure 3 correspond to year 2002 for representation purpose only. The spread of observation wells in other years also look similar i.e. they are evenly spread throughout the entire region.

[Insert Figure 3 here]

As is the case with Census data, there are a greater number of wells with deeper groundwater depths in Haryana as compared to Punjab in the sample for both the pre- and the post-treatment periods (See Figure A2 in the appendix).[14] The average pre-monsoon groundwater depths in the pre-treatment period is depicted by blue bars and in the post-treatment period by red bars for both the states in Figure 4.[15] The average pre-monsoon groundwater level in Punjab is 7.7 meters in the baseline period and it has increased to 10.1 meters in the endline period. In Haryana, the average pre-monsoon groundwater level in the two periods is 8.7 meters and 10.8 meters respectively. Consistent with the Census data, the relative increase in depths was greater in Punjab (31 per cent) than in Haryana (25 per cent). The average pre-monsoon groundwater depth in Punjab for the sample of test wells in CGWB data is similar to the average groundwater depth observed from the Census data while the average groundwater depth in Haryana is not of the same order of magnitude across the two datasets.

[Insert Figure 4 here]

Using two datasets acts as a robustness check on the measured impacts. The CGWB measures groundwater depth every year, so that impacts of the policy can be separated from time trends quite finely. The Minor Irrigation Censuses, though separated by more than five years, can also capture the double difference impacts on groundwater depth, while at the same time providing data to measure impacts on the channels (electric-operated tubewells and horsepower) through which groundwater depths are impacted. Using CGWB data has an additional advantage. It allows us to examine impact heterogeneity in terms of groundwater depth for regions with depths between 6 to 10 meters and those above 10

[14]The kernel density plots in Figure A2 depict the distribution of test wells according to the groundwater depth in Punjab and Haryana in the pre- and the post-treatment periods, respectively. There is a decline in the number of wells with lower groundwater depths in both Punjab and Haryana over time. However, post the policy in 1997, the decline in the number of wells with lower groundwater depths is more sharply observed in Punjab as depicted by a flatter plot in the bottom panel of the figure as compared to the corresponding plot for Haryana in the top panel.

[15]The average groundwater depths for all the years in the baseline period (1995/96 to 1997/98) are not significantly different from each other. This also holds true for all the years in the endline period (2002/03 to 2005/06). Thus, these years constitute the pre- and post-treatment periods, respectively.

meters, the cut-off where a shift from centrifugal to submersible technology is required for groundwater extraction.

4 Estimation Strategy

The impact of the free farm electricity policy introduced in Punjab in 1997 is examined using the difference-in-differences (DID) framework. This is a state-level policy, thus all the villages/wells in Punjab are taken as the treatment group while those in its neighbouring state, Haryana where the farmers continued to pay a non-zero flat-rate fee based on their pumps' power rating, are taken as the control group.

I estimate the following model using the Minor Irrigation Census data,

$$Y_{ijst} = \sum_{s}\sum_{j}\gamma_{js}\, dDistrict_{js} + \theta\, dPost_t + \beta\,(dPunjab_s \,.\, dPost_t) + \epsilon_{ijst} \tag{1}$$

where i denotes village, j denotes district, s denotes state and t denotes year. Y_{ijst} represents various outcome variables of interest for village i in j^{th} district in state s in year t. The district dummies[16] denoted by $dDistrict_{js}$ take a value 1 for the j^{th} district in s^{th} state and 0 otherwise. These capture the time-invariant variation across districts which is expected to affect the outcome variables differently. For instance, soil type and topography[17] vary across the districts and groundwater pumping is affected by each of these. The dummy variable $dPost_t$ takes a value 1 for the post-treatment period (2000-01) and 0 for the pre-treatment period (1993-94). It captures the aggregate factors that would cause changes in the outcome variable over time. $dPunjab_s$ is a dummy variable that takes a value 1 for all the villages in the treatment state (Punjab) and 0 for all the villages in the control state (Haryana). The coefficient of the interaction term $(dPunjab_s \,.\, dPost_t)$ represented by β gives the impact estimate of the policy change on

[16]The district boundaries of Punjab and Haryana have changed across the two rounds of Census. I combine the new districts essentially keeping the district boundaries from the 2^{nd} Minor Irrigation Census intact for both the states.

[17]Soil type and topography are expected to remain the same in short-run so that they are considered as time-invariant here.

various outcome variables. ϵ_{ijst} is the random error term. Robust standard errors are clustered at block-level.[18,19]

First, I examine the impact of the policy on the number of wells used for groundwater irrigation in a village, separately for all types of wells and for shallow tubewells and dugwells, the number of electric-operated shallow tubewells and dugwells and their proportion. Since the policy lowers the operational cost of electric pumps, it is expected to lead to an increase in the number of electric-operated pumps.

Second, I examine the impact of the policy on horsepower load of all the wells in a village.[20] Since no charges according to the horsepower rating of the pump are to be paid post policy, it is expected that farmers will invest in pumps with higher horsepower rating leading to an increase in horsepower load in the treatment state.

Third, I assess the policy impact on groundwater depth in Punjab. As discussed in Section 3, the average groundwater depth in Haryana is much higher than that in Punjab and thus, when looking at their changes, it is more meaningful to take the percentage deviation of groundwater depth from its mean in the baseline period in that state as the

[18]Clustering is done at the block-level instead of district-level since too few cluster leads to over-rejection. A rule of thumb is to have atleast 50 clusters. For detailed discussion on problems caused due to few clusters, see Cameron and Miller, 2015.

[19]The boundaries of blocks have changed across the two periods for both the states. Wherever possible, I have kept the block boundaries from the 2^{nd} Minor Irrigation Census intact. However, there were cases where multiple blocks were carved out of more than one block in 1993-94 in which case I consider these blocks as one cluster.

[20]Horsepower load is the sum total of the HP rating of all the pumps attached to various types of wells in a village. It is computed using the distribution of wells by horsepower rating of the pump. Horsepower load of all the wells (HPL_{it}) in village i and year t is computed as,

$$HPL_{it} = \sum_{m} \sum_{c_m} (n_{mc_m it} \times HP_{c_m})$$

where m denotes the type of well (shallow tubewell, dugwell or deep tubewell), i denotes village, t denotes year, and c_m denotes the class intervals or ranges for horsepower of the pump for the m^{th} type of well. The number of wells of each type is recorded according to the horsepower of the pump. The data is collected on the number of shallow tubewells and dugwells in a village with pumps of horsepower in the ranges of 0 to 2 HP, 2 to 4 HP, 4 to 6 HP, 6 to 8 HP, 8 to 10 HP, and greater than 10 HP. The corresponding data is collected for deep tubewells in every village with pumps of horsepower in the ranges of 0 to 6 HP, 6 to 12 HP, 12 to 18 HP, and greater than 18 HP. The variable HP_{c_m} represents the mid-point of the c_m^{th} class interval for m^{th} type of well or the horsepower-rating closest to the mid-point for the pumps available in the market. For shallow tubewells and dugwells, HP_{c_m} is taken as 1 HP, 3 HP, 5 HP, 7.5 HP, 10 HP and 15 HP respectively for the class intervals 0 to 2 HP, 2 to 4 HP, 4 to 6 HP, 6 to 8 HP, 8 to 10 HP, and greater than 10 HP. For deep tubewells, these are taken as 3 HP, 10 HP, 15 HP and 25 HP respectively for the class intervals 0 to 6 HP, 6 to 12 HP, 12 to 18 HP, and greater than 18 HP.

outcome variable.[21] With greater investment in electric-operated tubewells and pumps with higher horsepower load in Punjab as a result of free electricity, groundwater pumping would increase and it is expected that the groundwater levels would become deeper and we would observe a higher percentage deviation in groundwater depth in Punjab as compared to Haryana.

Using the Central Ground Water Board data, I estimate the following model,

$$Y_{wjst} = \sum_{s}\sum_{j}\gamma_{js}\, dDistrict_{js} + \sum_{t=1}^{T-1}\theta_t\, dYear_t + \beta\,(dPunjab_s\,.\,dPost_t) + \mu_{wjst} \qquad (2)$$

where w denotes observation wells in the sample, j denotes district, s denotes state and t denotes year. Y_{wjst} represents the outcome variable of interest for observation well w in j^{th} district in state s in year t. The district dummies denoted by $dDistrict_{js}$ take a value 1 for the j^{th} district in s^{th} state and 0 otherwise. The time dummies $dYear_t$ take a value 1 for t^{th} year and 0 otherwise. $dPunjab_s$ is a dummy variable that takes a value 1 for all the test wells in the treatment state (Punjab) and 0 for all the test wells in the control state (Haryana). The dummy variable $dPost_t$ takes a value 1 for the post-treatment period and 0 for the pre-treatment period. The pre-treatment period[22] is composed of the years before the implementation of the policy i.e. 1995-96 to 1997-98 and the post-treatment period from 2002-03 to 2005-06 cover the years post the policy. Time dummies for each of these years are included in the model. The coefficient of the interaction term of $dPunjab_s$ and $dPost_t$ denoted by β gives the impact estimate of the free farm electricity policy on the outcome variables of interest. μ_{wjst} is the random error term.

The primary outcome variable of interest using the CGWB data is the pre-monsoon

[21] Percentage deviation of groundwater depth from its mean in the baseline period is estimated as,

$$\%devGW_{ist} = \frac{GW_{ist} - \overline{GW}_{is,1993-94}}{\overline{GW}_{is,1993-94}}$$

[22] I have included the pre-monsoon groundwater levels for 1997-98 in the pre-treatment period even when the free farm electricity policy was introduced in Punjab in February 1997 because the implementation of the policies usually take time.

groundwater level[23] (in meters below ground level) in Punjab. I examine the impact of the policy on the percentage deviation of the pre-monsoon groundwater level for every well from their mean in the baseline period, for each state.[24] Increased groundwater depths resulting from the policy of free electricity in Punjab should translate to higher average percentage deviation of the pre-monsoon groundwater depth in the state.

There can be correlation between groundwater depths of wells lying close to each other. Groundwater pumping from one well may affect the water level for the neighboring wells. I account for the possibility of spatial correlation of residuals using the approach proposed by Conley (1999). Spatial dependence is characterized by physical distance between the test wells which is computed using the GIS coordinates of these wells from CGWB data.[25] Spatial correlation is assumed to decay linearly with distance (Bartlett kernel) upto a distance cut-off of 25 kilometers, become zero after that cut-off and remain zero for larger distances.[26]

Further, I assess the heterogeneity of impact across regions with groundwater depth between 6 to 10 meters and above the cut-off of about 10 meters where a switch in technology from centrifugal to submersible is required for groundwater pumping.[27] The impact on groundwater depth is expected to be sharper for regions where groundwater depth is between 6 to 10 meters since submersible pumps have a higher discharge capacity.

The key assumption for the estimation of difference-in-difference model is that of parallel trends which requires that in the absence of the policy change, the difference in outcomes

[23] The pre-monsoon groundwater depths are usually the deepest among the four readings recorded across the entire year by CGWB.

[24] Percentage deviation of pre-monsoon groundwater level from its mean in the baseline period is estimated as,

$$\%devPreMonGW_{wst} = \frac{PreMonGW_{wst} - \overline{PreMonGW}_{ws,1995/96-1997/98}}{\overline{PreMonGW}_{ws,1995/96-1997/98}}$$

[25] Due to non-availability of shapefiles and/or village coordinates for the Minor Irrigation Census data, spatial-robust standard errors cannot be computed while estimating Model 1.

[26] The results are also robust to cut-offs of 15 and 35 kilometers. The standard errors are computed using code by Solomon Hsiang (Hsiang, 2010).

[27] In the case of this policy intervention, regression discontinuity is not the most appropriate design since post the policy of free electricity, the choice for farmers is not just between centrifugal pump (diesel) and submersible pump (electric) around the cut-off of 10 meters, but the impact of the policy is also seen for depths greater than 10 meters in terms of investing in another electric-operated well or buying an electric pump of higher horsepower rating.

in Punjab and Haryana would have been the same before and after 1997. I check for this assumption by conducting a pre-trend test using data on groundwater depths in Punjab and Haryana for the pre-treatment years. The impact estimate should be insignificant in order to support the underlying assumption for the estimation of DID model.

5 Results

5.1 Difference-in-difference estimates: Minor Irrigation Census data

Table 2 presents results from difference-in-differences (DID) regressions pertaining to Model 1 for a range of variables relating to number of wells in a village. The odd-numbered columns control only for state-specific effects and do not account for variation within the state i.e. these do not include district dummies.[28] For the entire census of wells (columns (1) and (2)), the double difference impact estimates are positive and significant at 1% level of significance. Qualitatively similar results hold if the number of shallow tubewells and dugwells in a village are taken as the outcome variable (columns (3) and (4)). The average number of shallow tubewells and dugwells in a village has increased by 40 more in Punjab as compared to Haryana post the policy change. Much of this increase in wells comes from the electric-operated shallow tubewells and dugwells. The average number of electric-operated wells in a village in Punjab has increased by 42 more than the increase in the control group after the policy is introduced (columns (5) and (6)).

Further, not only has there been an increase in the number of electric-operated dugwells and shallow tubewells but there is also a differential increase in their average proportion by 14 per cent in Punjab as compared to Haryana post 1997 (columns (7) and (8) of Table 2). This implies that the increase in number of wells is coming from increased number of

[28]The following model specification is estimated,

$$Y_{it} = \alpha + \gamma_1 \, dPunjab + \gamma_2 \, dPost + \beta \, (dPunjab \, . \, dPost) + \epsilon_{it}$$

The notations are same as described in Section 4. Note here that R-squared values are considerably lower than the corresponding regressions with district dummies (See even-numbered columns of Table 2). This implies that the district-specific characteristics are part of the error term in these regressions and these explain considerable variation in the impact variables.

electric-operated wells.

I also examine the horsepower load of all the wells in a village. There is an increase in the average horsepower load of all the wells employed for groundwater irrigation from 431 HP to 478 HP in Punjab, whereas it has declined from 684 HP to 491 HP in Haryana (Table 1). I focus on the specification that includes district dummies because it is better determined. It show a positive and significant differential increase in the average horsepower load of all the wells in a village in Punjab by 217 HP as compared to Haryana with the policy change (columns (9) and (10) of Table 2). A differential increase in horsepower load implies greater groundwater pumping in Punjab with the provision of free electricity in the state.

[Insert Table 2 here]

A greater increase in the average number of wells and average horsepower load had an impact on the groundwater level in Punjab. The difference-in-difference estimates of the impact on groundwater depth in terms of percentage deviation from the mean are presented in column (1) of Table 3. The average percentage deviation of the groundwater depth from its mean in the baseline period increased by 16 per cent more in Punjab as compared to Haryana.

Since much of the border between Punjab and Haryana is the river Ghaggar, it is likely that wells lying on borders of both the states are pumping from the same aquifer. A greater groundwater pumping in Punjab after the policy change would lead to increase in groundwater depth for wells on the borders of Haryana, which may attenuate the impact of the policy on groundwater depth. To check for this, I remove the villages in the bordering blocks from both the treatment and the control groups and re-estimate the DID model. As expected, the magnitude of the impact estimate increases to 26 per cent after removing villages lying on the borders of both the states (column (2) of Table 3).

[Insert Table 3 here]

5.2 Difference-in-difference estimates: CGWB data

Table 4 presents the difference-in-difference impact estimates on the pre-monsoon groundwater levels, both in terms of absolute depths measured in meters, and their percentage deviation from mean in the pre-treatment period.[29] The standard errors account for spatial dependence.[30] The results for the full sample of wells are qualitatively similar to those obtained using the Minor Irrigation Census data.

[Insert Table 4 here]

With percentage deviation of pre-monsoon groundwater levels from their mean as the outcome variable (columns (1), (2) and (3) of Table 4), a positive and significant coefficient of the DID parameter is obtained for the entire sample of wells. There is a differential increase of 14 per cent in the percentage deviation of the groundwater levels in Punjab as compared to Haryana. This result is in line with the findings from the Census data discussed previously.

For farmers closer to the cut-off, switch to submersible technology is required once the groundwater depth becomes deeper than 10 meters. When the sample is restricted to the wells lying in those regions where pre-monsoon groundwater depth is between 6 and 10 meters, the observed impact is even sharper. The percentage deviation in groundwater depth increases by 21 per cent more in Punjab as compared to Haryana under this restriction.[31] These results indicate a greater depletion of groundwater resources in Punjab as compared to Haryana post the policy change with a greater effect observed where centrifugal technology is feasible.

Qualitatively similar results hold with pre-monsoon groundwater level as the outcome

[29] Here, the pre-monsoon groundwater depth for year 1997-98 is also included as part of the pre-treatment period despite the policy being introduced in February 1997. However, the results remain robust if we exclude 1997-98 from the estimation which confirms that the implementation of such policies take time. See Table B1 in the Appendix for detailed results.

[30] The results are qualitatively similar if standard errors are clustered at the block-level, i.e. residuals are uncorrelated across blocks while residuals across wells within each block are correlated.

[31] χ^2 test for checking the difference between the coefficients across various specifications shows that the coefficients of the DID parameter are significantly different across columns (1), (2) and (3) of Table 4. Similarly, with pre-monsoon groundwater level as the outcome variable, the coefficients of the DID parameter for various specifications are also significantly different from each other.

variable (columns (4), (5) and (6) of Table 4). For the entire sample of wells, the mean difference in average pre-monsoon groundwater depth has increased between the treatment and control groups. In particular, the pre-monsoon groundwater depth has increased by 0.86 meters more in Punjab than in Haryana post implementation of the policy. A sharper differential increase of 1.44 meters in the average pre-monsoon groundwater depth is observed when only those wells are considered that are closer to the cut-off where a technological shift is required for groundwater pumping. These coefficients are indicative of greater groundwater depletion in regions which are closer to this cut-off. Consistent with these findings, the Minor Irrigation Census data shows an increase in the number of electric pumps from 1993-94 to 2000-01, which is clustered around the depth of 10 meters (Figure 5). Since the increase in depth was more in the regions where groundwater depth was between 6 to 10 meters than above 10 meters, this reinforces the channel through which the average groundwater depth increased, namely increase in electric tubewells, which is a causal consequence of the free farm electricity policy.

[Insert Figure 5 here]

In order to take into account the same aquifer effect across the borders Punjab and Haryana, I remove wells in the border tehsils of the treatment and the control states. The magnitude of impact on pre-monsoon groundwater levels, both in terms of percentage deviation from mean and in terms of absolute depths measured in meters, is higher when wells lying close to the borders are excluded (Table 5). There is a differential increase of 18 per cent in the percentage deviation of the groundwater levels in Punjab as compared to Haryana. Also, when the sample is restricted to the wells lying in those regions where pre-monsoon groundwater depth is between 6 and 10 meters, the percentage deviation of the groundwater levels increase by 28 per cent more in Punjab as compared to Haryana. Taking pre-monsoon groundwater level as the dependent variable, the impact estimates are 1.17 meters and 1.99 meters respectively for full sample of wells and for wells lying in those regions where pre-monsoon groundwater depth is between 6 and 10 meters which are higher than the case when wells in the border tehsils are included in the estimation.

[Insert Table 5 here]

5.3 Robustness Checks

Identification of the difference-in-differences model is based on the underlying common trend assumption. This assumption requires that the difference in outcomes in Punjab and Haryana would have been the same pre and post 1997, in the absence of the policy change, that is, there are parallel trends in outcomes of both the states and any deviation from the common trend is due to the policy change in 1997. Punjab and Haryana are agriculturally-similar states with paddy and wheat being the dominant crops. Area under paddy cultivation increased in both the states at roughly about the same rates of 20 to 25 per cent between periods 1995-96 and 2000-01.[32] Since there was no differential rate of change in area under rice cultivation, it cannot explain the observed impacts. Also, rural electrification increased roughly at similar rates of about 75 to 80 per cent in both the states between 1991 and 2001.[33] Therefore, differential progress of rural electrification cannot account for the observed impacts.

I conduct a test of parallel trends in the pre-treatment periods. Using district-level data[34] from the first (reference year 1986-87) and the second (reference year 1993-94) rounds of the Minor Irrigation Census, I examine the impact on the number of wells, the number of electric and diesel operated shallow tubewells and dugwells and the cultivable command area using data from the two pre-treatment years.[35] Table B2 presents the impact estimates. The coefficient of the interaction term is insignificant for all the outcome variables

[32] Data on area under paddy cultivation for Punjab and Haryana is taken from the state government websites of Department of Agriculture for each of the states.

[33] Data from the Census of India shows that the number of households in rural areas with electricity increased from 12.1 lakh in 1991 to 57.8 lakh in 2001 in Haryana. The corresponding number of households in Punjab are 18.1 lakh and 74.5 lakh, respectively.

[34] Village-level data from the first round of Minor Irrigation Census is not available. District-level data on number of wells and cultivable command area is taken from the census report. Refer to: Government of India, 1993 (`http://micensus.gov.in/sites/default/files/First-MI-report.pdf`) for details.

[35] The following model specification is estimated,

$$Y_{jst} = \alpha + \phi_1\, dPunjab_s + \phi_2\, dPost_t + \beta\,(dPunjab_s\,.\,dPost_t) + \epsilon_{jst}$$

The notations are same as described in Section 4. Here, $dPost$ takes a value 1 for 1993-94 and 0 for 1986-87.

which shows that there is no differential change in the number of wells and cultivable command area across the two states in the absence of the policy change.

Parallel trend assumption is also checked using data from the Central Ground Water Board. I use the same specification as in equation (2) with data for two pre-treatment years, 1995-96 and 1996-97.[36] Note that the policy was not implemented in either of these time periods and for the identifying assumption to hold, the coefficient of the DID parameter should be insignificant. Table B3 shows that there is no evidence for differential trend in groundwater depths since the coefficient of the interaction term for all the specifications is statistically insignificant. These results support the common trend assumption required for identification of the model in this paper.

Another check can be done by examining the impact of the policy on diesel-operated wells. The policy is not expected to have a first order impact on diesel-operated tubewells and it should have an impact on diesel pumps only through the channel of influencing electric pump decisions. While purchases of electric-operated tubewells are expected to increase, there would possibly be no impact on diesel pumps in the short term. Over a longer term, as diesel pumps get older, we expect them to be replaced by electric pumps. However, this effect is expected to be small in the short term. It is indeed the case that the double difference model with diesel-operated shallow tubewells and dugwells as the outcome variable results in a small, negative and insignificant coefficient of the DID parameter.[37] This supports the reliability of impact estimates in this study.

6 Conclusion

The link between power subsidies and groundwater depletion is an important feature of Indian agriculture, and Punjab best exemplifies this. While State Electricity Boards incur huge costs for provision of electricity to the agricultural sector, farmers in most

[36] In this estimation, $dPost_t$ takes a value 1 for 1996-97 and 0 for 1995-96. Also, $dYear_t$ would be replaced by $dPost_t$ since there are only two periods in this estimation.

[37] See Table B4 in the Appendix for detailed results.

states in India pay fixed charges for electricity used for groundwater pumping, which are independent of the actual units of consumption. Such pricing policies provide an incentive for over-utilisation of groundwater resources.

Based on the data from two sources, namely the Minor Irrigation Census and the Central Ground Water Board, this study has quantified the impact of the policy shift from flat rate pricing to free pricing of the farm electricity in Punjab in 1997 and implications for groundwater use through the channel of tubewell expansion and rising groundwater depth. Using a difference-in-differences framework, the study finds a differential increase in the average number of wells in Punjab as compared to an agriculturally-similar and neighbouring state Haryana, which is taken as the control group. The results reveal that much of this rise in wells is coming from increased investment in electric-operated tubewells due to lower operational cost of electric pumps post the policy change. The study also finds a differential increase in horsepower load of all the wells in Punjab as compared to the control group. Through the channels of increased investment in electric-operated tubewells and pumps of higher horsepower rating, the study shows a differential increase in the average groundwater depth in Punjab. A sharper increase is observed for regions with groundwater depth closer to the cut-off of about 10 meters where farmers using centrifugal pumps lose access to groundwater faster since these cannot operate at deeper water levels and a technological shift to submersible pumps is required for groundwater pumping.

Unlike previous literature that examine the impact of power subsidies on groundwater depletion, to my knowledge, this is the first study to provide causal estimates of channels and outcomes in the context of flat-rate electricity pricing regime in agriculture. The groundwater level could be influenced by various factors like change in cropping patterns, topographic elevation and slope, rainfall, etc. Data from the Minor Irrigation Census shows that the average groundwater depth in a village in Punjab and Haryana has increased by 45 per cent and 29 per cent respectively, over the period 1993-94 to 2000-01. A distinct feature of this study is that the marginal cost of electricity is zero in both treatment and control states in the pre and the post intervention period, and the study shows the deepening of groundwater levels in Punjab over and above the falling trend of water table in both the states. The average percentage deviation in groundwater depth from the mean in the pre-policy period increased by 16 per cent more in Punjab as compared to Haryana.

The findings of this paper have important policy implications. Electricity subsidies in agriculture in Punjab have encouraged intensive groundwater irrigation in the state, leading to depletion of these resources to the extent that Punjab has the highest percentage of groundwater utilization with respect to its recharge in India. This paper provides causal impact estimates of the farm electricity subsidy in Punjab on groundwater depth, highlighting the need for agricultural reforms in the form of alternative pricing policy for farm electricity that will promote efficient utilization of water and energy resources and foster sustainability of groundwater as a means for irrigation.

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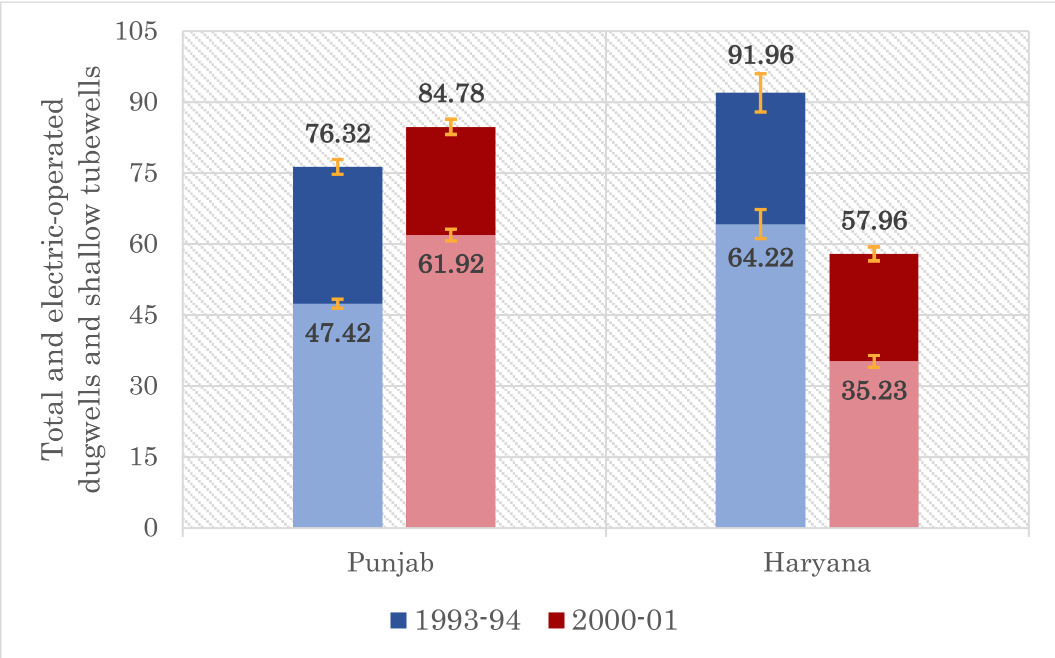
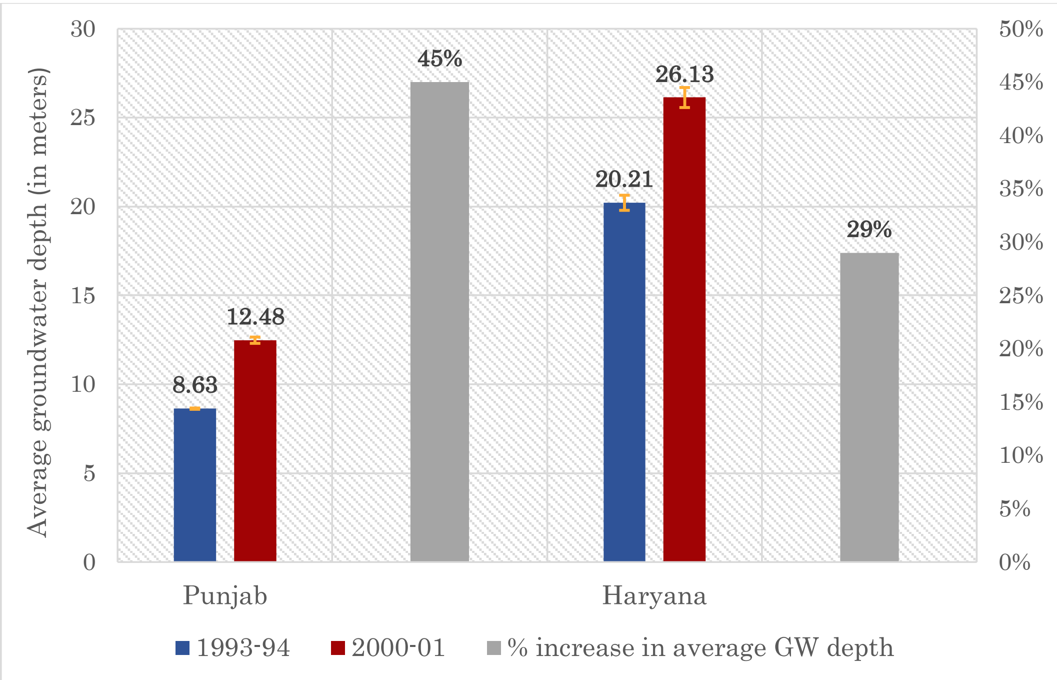
Figures

FIGURE 1: AVERAGE NUMBER OF DUGWELLS AND SHALLOW TUBEWELLS



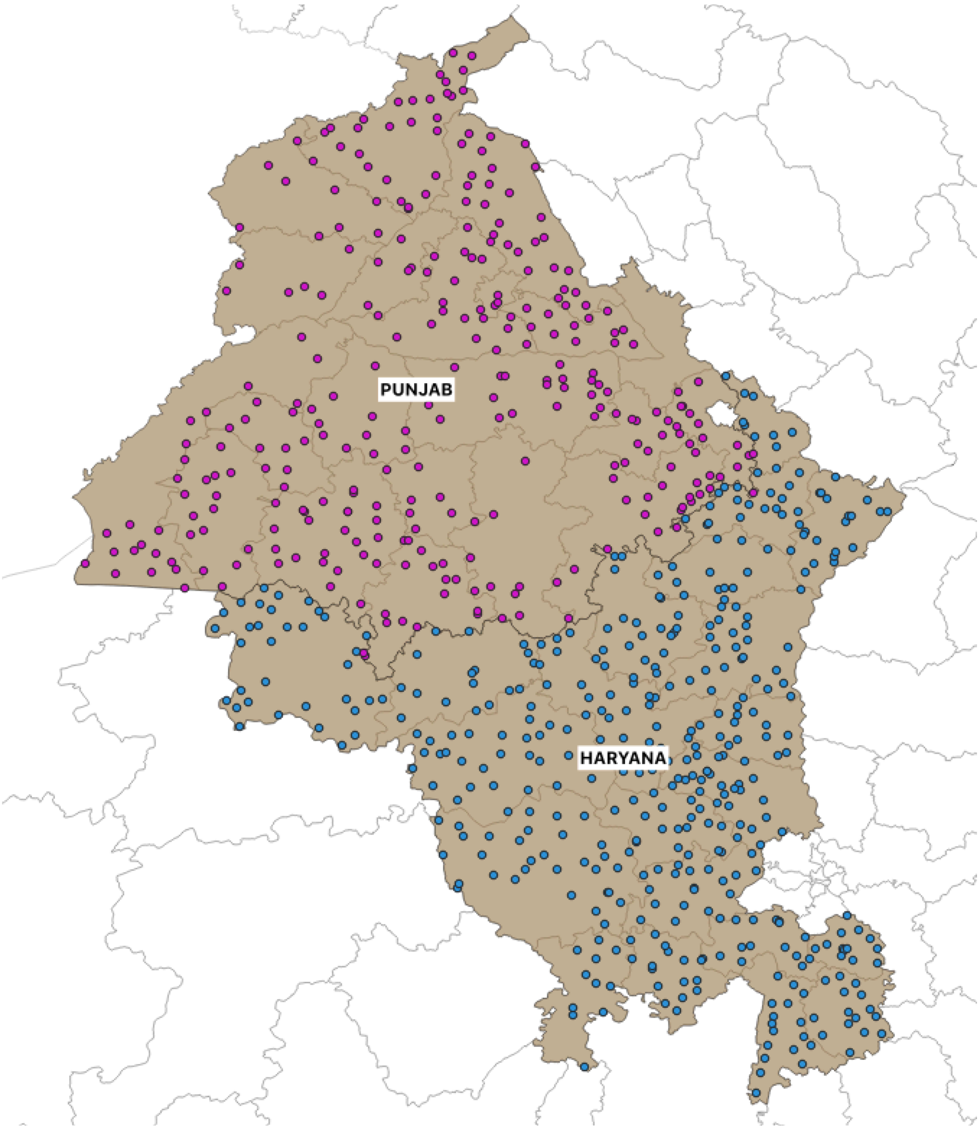
Notes: i. The light-shaded bars represent average number of electric-operated wells and the dark-shaded bars represent average number of diesel-operated wells; ii. The error bars represent 95% confidence intervals.
Source: Computed using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Figure 2: Percentage increase in GW depth in Punjab and Haryana



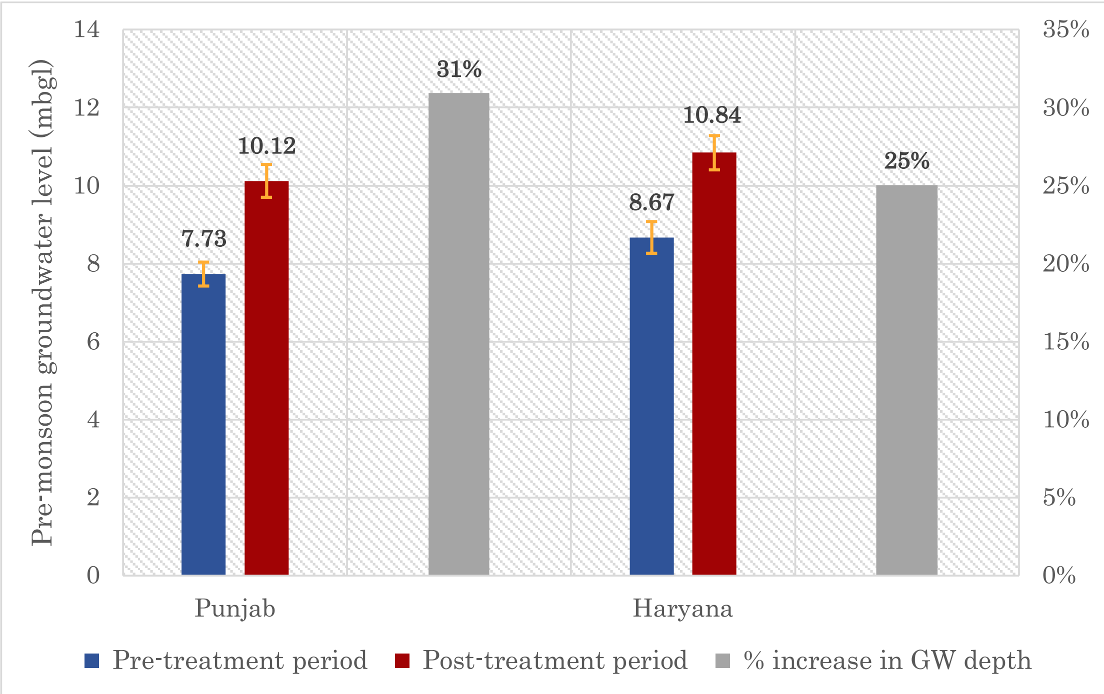
Note: The error bars represent 95% confidence intervals.
Source: Computed using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Figure 3: Spread of observation wells in Punjab and Haryana



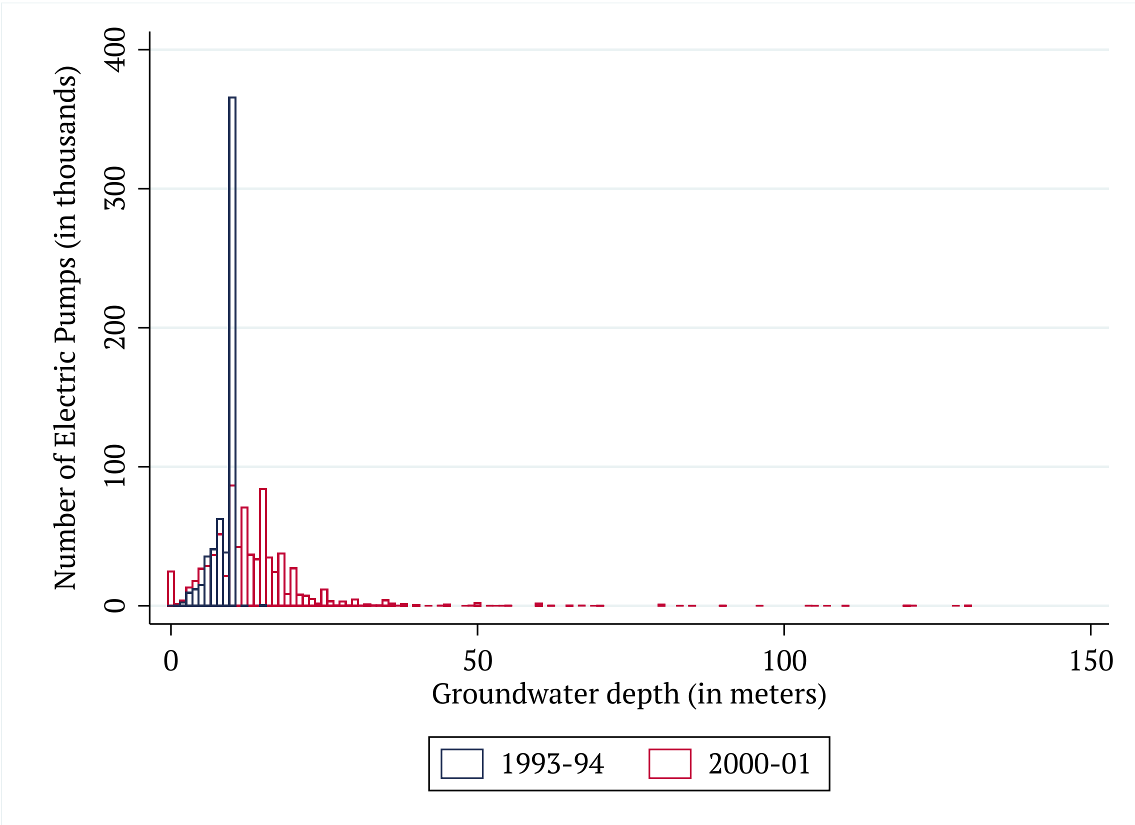
Notes: The sample of observation wells are plotted using the GIS coordinates for each well. Each dot represents one test well.
Source: Based on data from Central Ground Water Board, Government of India.

Figure 4: Percentage increase in average pre-monsoon groundwater levels in Punjab and Haryana



Notes: i. The mean of pre-monsoon groundwater levels are not significantly different from each other in the three pre-treatment years (1995/96 to 1997/98) in both the states. This also holds for all the four post-treatment years (2002/03 to 2005/06); ii. The error bars represent 95% confidence intervals.
Source: Computed using data from Central Ground Water Board, Government of India.

Figure 5: Number of electric pumps in Punjab by groundwater depth



Note: Top 1% data has been trimmed to deal with possible outliers.
Source: Computed using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Tables

Table 1: Summary Statistics: Minor Irrigation Census

	Control Group (Haryana)					Treatment Group (Punjab)				
Variable	No. of Obs.	Mean	Std. Dev.	Min	Max	No. of Obs.	Mean	Std. Dev.	Min	Max
Pre-treatment period (1993-94)										
Total number of groundwater schemes	5,556	93	154.5	1	999	12,342	77	88.8	0	1003
Total number of STW & DW	5,516	92	152.9	0	996	12,289	76	88.1	0	1003
Proportion of electric STW & DW	5,505	0.69	0.4	0	1	12,286	0.67	0.3	0	1
Electric pumps	5,516	64	116.6	0	994	12,289	47	53.8	0	896
Diesel pumps	5,516	28	71.6	0	660	12,289	29	55.0	0	793
Groundwater depth (meters)	4,732	20.2	14.9	0	85	12,744	8.6	2.1	0	15
Horsepower load of wells	5,556	684	1106.9	0	7453.5	12,344	431	556.8	0	7316
Post-treatment period (2000-01)										
Total number of groundwater schemes	6,739	62	64.3	1	879	12,643	85	91.6	1	1826
Total number of STW & DW	6,512	58	60.9	0	776	12,500	85	91.3	0	1826
Proportion of electric STW & DW	6,456	0.62	0.4	0	1	12,498	0.73	0.3	0	1
Electric pumps	6,512	35	51.4	0	775	12,500	62	70.8	0	1129
Diesel pumps	6,512	23	42.4	0	578	12,500	23	43.0	0	870
Groundwater depth (meters)	7,032	26.1	24.1	0	150	12,796	12.5	10.2	0	130
Horsepower load of wells	6,739	491	551.9	0	7454	12,643	478	583.3	0	11444

Notes: i. Top 1% data from each state-year combination has been trimmed to deal with possible outliers; ii. STW: shallow tubewells, DW: dugwells; iii. While computing the horsepower load, shallow tubewells and dugwells with HP less than and equal to 10 HP and deep tubewells with HP less than and equal to 18 HP are considered.
Source: Computed using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Table 2: Difference-in-difference estimates of impact on channels

	Number of deep tubewells, shallow tubewells and dugwells		Number of shallow tubewells and dugwells		Electric-operated shallow tubewells and dugwells		Proportion of electric-operated shallow tubewells and dugwells		Horsepower load of all the pumps in a village	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
dPunjab	-16**		-16*		-17***		-0.03		-253***	
	(8.1)		(7.9)		(5.3)		(0.05)		(58.1)	
dPost	-31***	-29***	-34***	-32***	-29***	-28***	-0.08***	-0.07***	-193***	-175***
	(3.5)	(3.3)	(3.7)	(3.6)	(3.2)	(3.2)	(0.02)	(0.02)	(27.2)	(25.9)
dPunjab.dPost	39***	36***	42***	40***	43***	42***	0.14***	0.14***	240***	217***
	(3.9)	(4.0)	(4.2)	(4.2)	(3.5)	(3.4)	(0.02)	(0.02)	(30.7)	(31.0)
Constant	93***		92***		64***		0.69***		684***	
	(6.7)		(6.6)		(4.6)		(0.04)		(50.0)	
District dummies	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Observations	37,282	37,282	36,817	36,817	36,817	36,817	36,745	36,745	37,282	37,282
R-squared	0.010	0.478	0.012	0.474	0.021	0.422	0.014	0.859	0.015	0.461

Notes: i. Horsepower load in a village is computed as the sum of products of all types of wells in the HP class interval and the mid-point of that interval or the pump-rating closest to the mid-point which is available in the market; ii. The coefficients of district dummies have been suppressed; iii. Cluster-robust standard errors are reported in the parentheses with clustering at the block-level; iv. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.10.
Source: Estimated using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Table 3: Difference-in-difference estimates of impact on average groundwater depth

	Dependent variable: Percentage deviation of groundwater depth from its mean in the baseline period (%)	
	All villages	Excluding villages in border blocks
	(1)	(2)
dPost	0.29***	0.20**
	(0.082)	(0.087)
dPunjab.dPost	0.16*	0.26**
	(0.099)	(0.104)
District dummies	Yes	Yes
Observations	37,304	31,109
R-squared	0.199	0.215

Notes: i. Top 1% data from each state-year combination has been trimmed to deal with possible outliers; ii. The coefficients of district dummies have been suppressed; iii. District dummies are jointly significant; iv. Cluster-robust standard errors are reported in the parentheses with clustering at the block-level; v. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.1.
Source: Estimated using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Table 4: Difference-in-difference estimates of impact on pre-monsoon groundwater levels

	Dependent variable: % deviation of the pre-monsoon GW level from its mean in the baseline period			Dependent variable: Pre-monsoon groundwater level (in meters)		
	Full Sample	GW level in the baseline period < 10 m	6 m ≤ GW level in the baseline period ≤ 10 m	Full Sample	GW level in the baseline period < 10 m	6 m ≤ GW level in the baseline period ≤ 10 m
	(1)	(2)	(3)	(4)	(5)	(6)
$dPunjab.dPost$	0.14**	0.17***	0.21***	0.86*	1.14***	1.44**
	(0.06)	(0.05)	(0.08)	(0.49)	(0.42)	(0.62)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
District dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,218	2,872	1,292	4,218	2,872	1,292
R-squared	0.352	0.502	0.417	0.766	0.846	0.937

Notes: i. The pre-treatment period comprises years from 1995-96 to 1997-98 and the post-treatment period comprises years from 2002-03 to 2005-06. Time dummies for each of these years are included in the model; ii. The coefficients of time dummies and district dummies have been suppressed; iii. District dummies are jointly significant; iv. Spatial-robust standard errors proposed by Conley (1999) are reported in the parentheses with distance cut-off at 25 kilometers and the spatial weighting kernel decaying linearly with distance (Bartlett kernel); v. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.10.
Source: Estimated using data from Central Ground Water Board, Government of India.

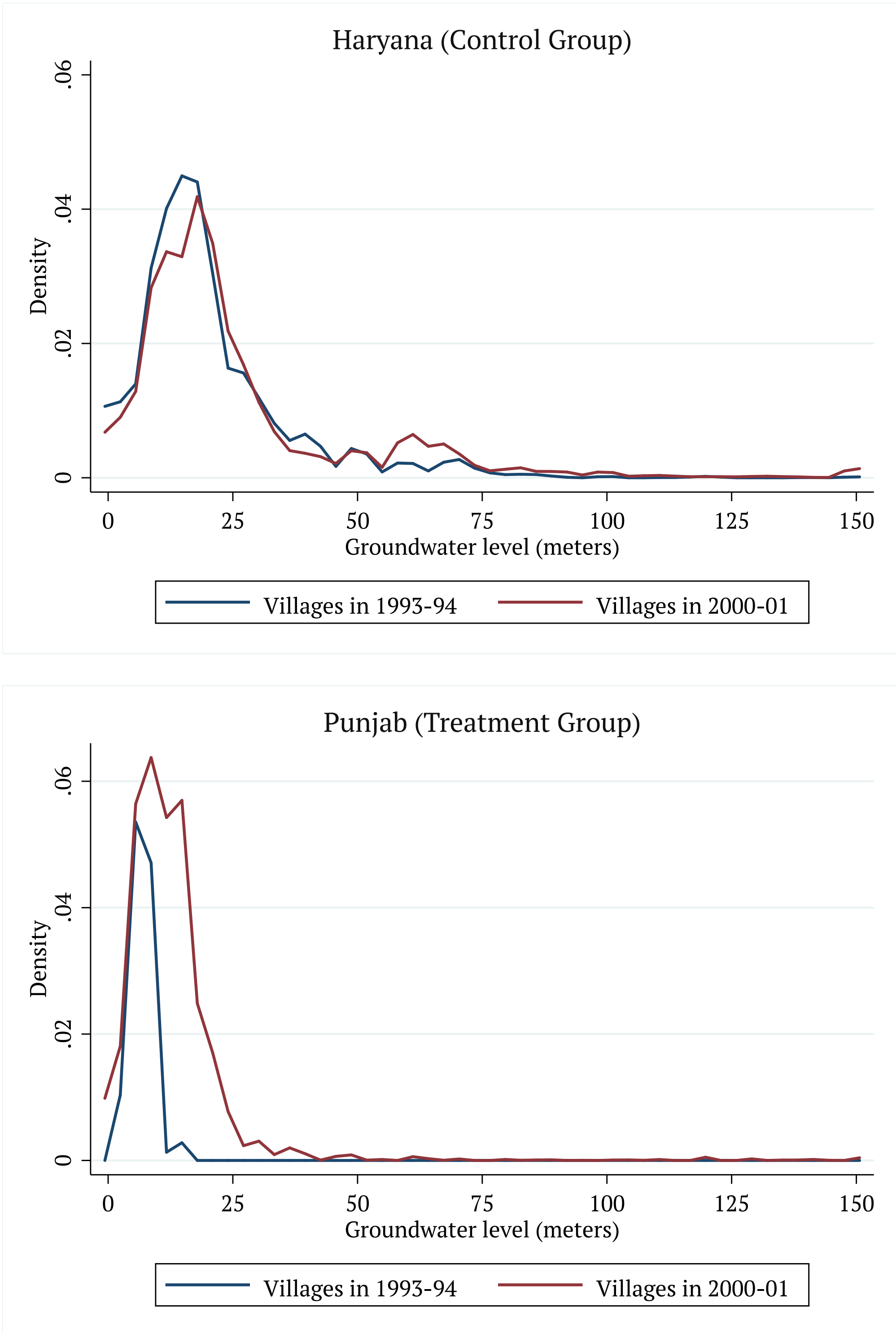
Table 5: Difference-in-difference estimates of impact on pre-monsoon groundwater levels (excluding wells in border tehsils of Punjab and Haryana)

	Dependent variable: % deviation of the pre-monsoon GW level from its mean in the baseline period			Dependent variable: Pre-monsoon groundwater level (in meters)		
	Full Sample	GW level in the baseline period < 10 m	6 m $\leq$ GW level in the baseline period $\leq$ 10 m	Full Sample	GW level in the baseline period < 10 m	6 m $\leq$ GW level in the baseline period $\leq$ 10 m
	(1)	(2)	(3)	(4)	(5)	(6)
$dPunjab.dPost$	0.18**	0.21***	0.28***	1.17**	1.47***	1.99***
	(0.07)	(0.06)	(0.09)	(0.60)	(0.49)	(0.72)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
District dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,097	2,114	880	3,097	2,114	880
R-squared	0.379	0.541	0.502	0.761	0.847	0.943

Notes: i. The pre-treatment period comprises years from 1995-96 to 1997-98 and the post-treatment period comprises years from 2002-03 to 2005-06. Time dummies for each of these years are included in the model; ii. The coefficients of time dummies and district dummies have been suppressed; iii. District dummies are jointly significant; iv. Spatial-robust standard errors proposed by Conley (1999) are reported in the parentheses with distance cut-off at 25 kilometers and the spatial weighting kernel decaying linearly with distance (Bartlett kernel); v. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.10.
Source: Estimated using data from Central Ground Water Board, Government of India.

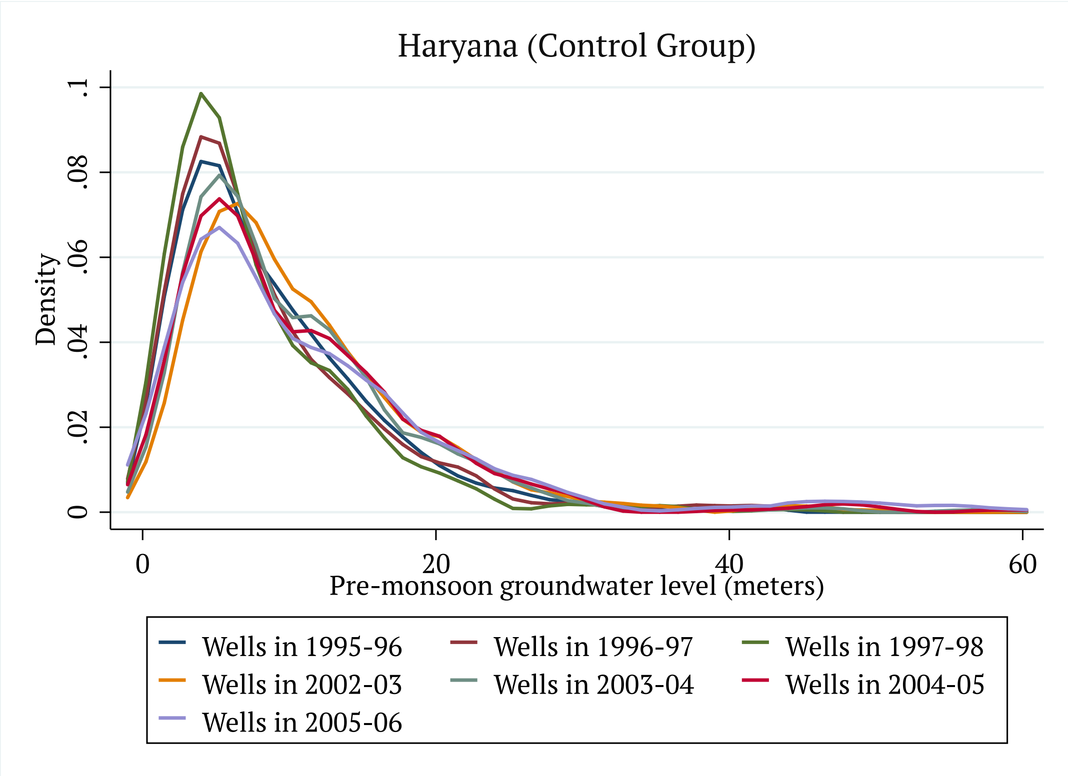
Appendix A: Figures

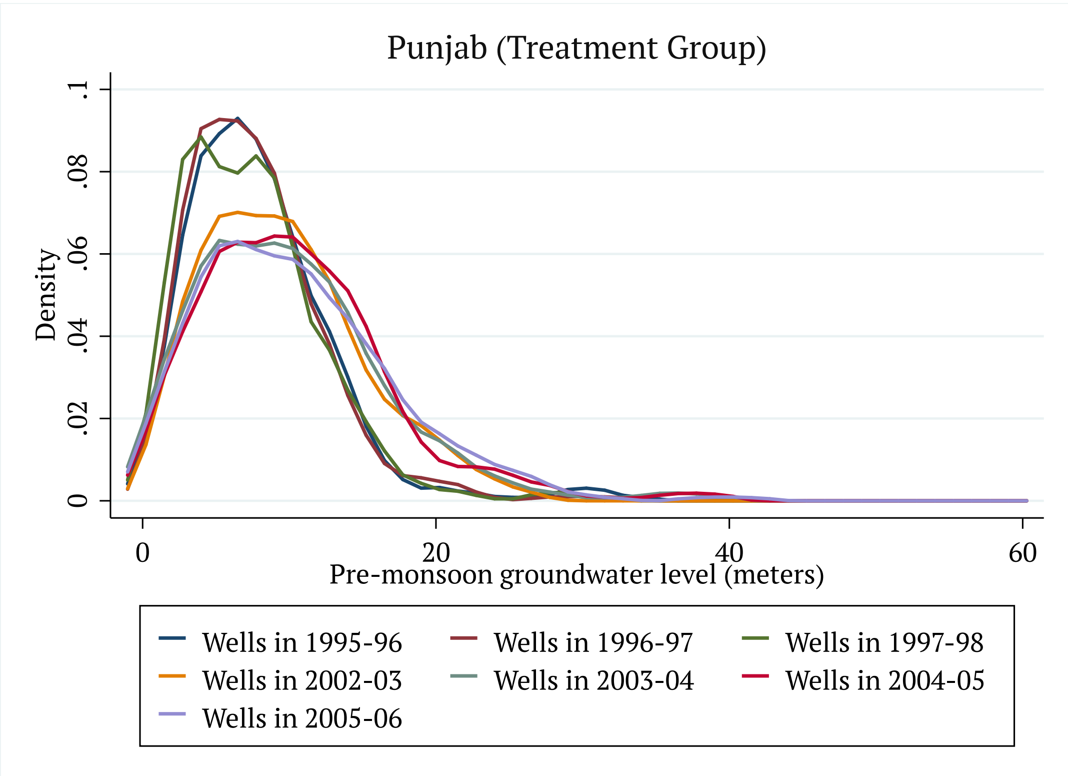
Figure A1: Density plots of village-level groundwater depths in Punjab and Haryana



Source: Based on data from 2^{nd} and 3^{rd} Minor Irrigation Census from Ministry of Water Resources, Government of India.

Figure A2: Density plots of pre-monsoon groundwater levels in Punjab and Haryana





Source: Based on data from Central Ground Water Board, Government of India.

Appendix B: Tables

TABLE B1: DIFFERENCE-IN-DIFFERENCE ESTIMATES OF IMPACT ON PRE-MONSOON GROUNDWATER LEVELS USING SAMPLE OF WELLS (1997-98 EXCLUDED)

	Dependent variable: % deviation of the pre-monsoon GW level from its mean in the baseline period			Dependent variable: Pre-monsoon groundwater level (in meters)		
	Full Sample	GW level in the baseline period < 10 m	6 m ≤ GW level in the baseline period ≤ 10 m	Full Sample	GW level in the baseline period < 10 m	6 m ≤ GW level in the baseline period ≤ 10 m
	(1)	(2)	(3)	(4)	(5)	(6)
$dPunjab.dPost$	0.164***	0.165***	0.213***	1.07**	1.14***	1.50**
	(0.06)	(0.05)	(0.08)	(0.49)	(0.43)	(0.63)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
District dummies	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,580	2,387	1,066	3,580	2,387	1,066
R-squared	0.357	0.507	0.444	0.769	0.847	0.937

Notes: i. The coefficients of time dummies and district dummies have been suppressed; ii. District dummies are jointly significant; iii. Spatial-robust standard errors proposed by Conley (1999) are reported in the parentheses with distance cut-off at 25 kilometers and the spatial weighting kernel decaying linearly with distance (Bartlett kernel); iv. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.10.
Source: Estimated using data from Central Ground Water Board, Government of India.

Table B2: Parallel trends: DID estimates of impact on number of wells and cultivable command area, using MIC data

	Number of deep tubewells, shallow tubewells and dugwells	Number of shallow tubewells and dugwells	Electric-operated shallow tubewells and dugwells	Diesel-operated shallow tubewells and dugwells	Cultivable command area (in hectares)
	(1)	(2)	(3)	(4)	(5)
dPunjab	40,040***	40,135***	-2,827	9,136**	132,758***
	(10,773.9)	(10,764.5)	(1,820.0)	(4,118.4)	(29,420.1)
dPost	-2,163	-2,318	-1,885	-1,666	-4.930
	(7,106.5)	(7,094.5)	(1,844.9)	(3,173.7)	(15,811.4)
dPunjab.dPost	-2,608	-2,489	2,168	7,293	41,884
	(14,278.3)	(14,256.0)	(1,850.9)	(6,358.8)	(45,263.0)
Constant	33,172***	32,949***	3,043	10,763***	88,103***
	(6,384.8)	(6,378.3)	(1,817.6)	(2,654.2)	(13,996.4)
Observations	55	55	55	55	55
R-squared	0.391	0.394	0.112	0.276	0.504

Notes: i. The pre-treatment period is 1986-87 and the post-treatment period is 1993-94; ii. Robust standard errors are reported in the parentheses; iii. Asterisks denote the significance levels: *** $p<0.01$, ** $p<0.05$, * $p<0.10$.
Source: Estimated using data from 1st and 2nd Minor Irrigation Census from Ministry of Water Resources, Government of India.

Table B3: Parallel trends: DID estimates of impact on pre-monsoon groundwater levels for years 1995-96 and 1996-97, using CGWB data

		Dependent variable: % deviation of the pre-monsoon GW level from its mean in the baseline period			Dependent variable: Pre-monsoon groundwater level (in meters)		
		Full Sample	GW level in the baseline period < 10 m	$6 \text{ m} \leq$ GW level in the baseline period ≤ 10 m	Full Sample	GW level in the baseline period < 10 m	$6 \text{ m} \leq$ GW level in the baseline period ≤ 10 m
		(1)	(2)	(3)	(4)	(5)	(6)
$dPunjab.d1996$	coeff.	-0.02	-0.03	-0.003	-0.17	-0.26	-0.03
	std. error	(0.04)	(0.02)	(0.03)	(0.31)	(0.21)	(0.26)
	p-value	0.534	0.247	0.915	0.570	0.211	0.913
District dummies		Yes	Yes	Yes	Yes	Yes	Yes
Observations		1,376	903	369	1,376	903	369
R-squared		0.296	0.685	0.384	0.307	0.243	0.195

Notes: i. The pre-treatment period is 1995-96 and the post-treatment period is 1996-97; ii. The coefficients of district dummies have been suppressed; iii. District dummies are jointly significant; iv. Spatial-robust standard errors proposed by Conley (1999) are reported in the parentheses with distance cut-off at 25 kilometers and the spatial weighting kernel decaying linearly with distance (Bartlett kernel); v. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.10.
Source: Estimated using data from Central Ground Water Board, Government of India.

Table B4: Difference-in-difference estimates of impact on diesel-operated wells

	Dependent variable: Diesel-operated shallow tubewells and dugwells	
	(1)	(2)
$dPunjab$	1	
	(4.9)	
$dPost$	-5**	-4*
	(2.4)	(2.5)
$dPunjab.dPost$	-1	-2
	(3.0)	(3.3)
Constant	28***	
	(3.9)	
District dummies	No	Yes
Observations	36,817	36,817
R-squared	0.003	0.362

Notes: i. The coefficients of district dummies have been suppressed; ii. Cluster-robust standard errors are reported in the parentheses with clustering at the block-level; iii. Asterisks denote the significance levels: *** p<0.01, ** p<0.05, * p<0.10.
Source: Estimated using data from 2nd and 3rd Minor Irrigation Census from Ministry of Water Resources, Government of India.