The Impact of Electricity Subsidies on Groundwater Extraction and Agricultural Production *

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Abstract

In this paper, we estimate the environmental and agricultural effects of agricultural electricity subsidies in India. To isolate the causal effect of the subsidy, we evaluate the differential impact of annual state electricity prices in districts with different hydrogeological characteristics. Electricity subsidies increase groundwater extraction, where the estimated elasticity is -0.13, and the production of water intensive crops, particularly rice. We find that they operate through the extensive margin by expanding the area on which water intensive crops are cultivated. And while these subsidies are estimated to have small deadweight costs, with roughly 88 percent of expenditure transferred to agricultural producers, they increase the output of water intensive crops and the probability of groundwater exploitation, suggesting potential long-term costs.

JEL: H20, O13, Q4, Q25

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1 Introduction

In developing countries energy subsidies are significant, totaling over $220 billion (in 2005) for the largest twenty non-OECD countries (UNEP 2008). Nearly one-half of these subsidies are directed at rural households, primarily as electricity subsidies (UNEP 2008). Agricultural electricity subsidies act as a tool to increase agricultural production through enhanced groundwater irrigation, and in doing so aim to benefit poor rural households and stabilize food prices. Yet, despite their economic importance (Birner et al. 2007, Fan et al. 2008, Gandhi and Namboodiri 2009, Kumar 2005, Mukherji and Shah 2004, Scott and Shah 2004), little is known about the causal impact of these subsidies on groundwater usage and agricultural output.[1,2] Of importance is the possibility that subsidized groundwater may come at the cost of groundwater over-extraction and future agricultural production. We investigate these questions within the context of India, where approximately $US 10 billion was spent in 2005 alone on electricity subsidies.

Electricity subsidies are the single largest drain on state spending in India (Tongia 2003) and as such are widely discussed in policy circles.[3] Anecdotal evidence has linked India's growth in groundwater irrigation, largely fueled by electricity subsidies, to increased agricultural yields, lower food prices and increased demand for agricultural labor (Briscoe and Malik 2006, Modi 2005, Murgai 2001, Rosegrant et al. 2009). However, it has also been argued that these subsidies have substantial environmental costs, including groundwater over-exploitation (Kumar 2005; Shah et al. 2003, Shah 2009). Between 1995 and 2004, groundwater extraction in India increased by 18 percent and the number of over-exploited districts - those in which annual demand exceeds annual recharge - grew by 18 percent. Largely driven by data limitations, few studies have isolated the impact of these subsidies on groundwater extraction and over-extraction, or their potential to increase welfare by raising agricultural output (Banerji et al. 2012, Ray and Williams 1999, Sekhri 2011a, Somanathan and Ravi 2006).[4]

[1]There is however (in India) a long literature discussing the linkages between electricity subsidies, groundwater extraction and agricultural output (Gandhi and Namboodiri 2009, Mukherji and Shah 2004, Scott and Shah 2004). Some of these studies rely on interviews or survey data to show a strong positive correlation between subsidies, extraction and agricultural output (Birner et al. 2007, Fan et al. 2008, Kumar 2005, Scott and Shah 2004).

[2]See Schoengold and Zilberman (2005) for an overview of irrigation, including a discussion on the role of electricity subsidies, in developing countries.

[3]Badiani, Jessoe and Plant (2012) provide an overview of agricultural electricity subsidies in India.

[4]Of note is recent work in India that estimates the effect of the depth to the water table on agricultural

In this paper, we measure the extent to which electricity subsidies have impacted groundwater extraction and agricultural production in India. We begin with a simple theoretical framework in which farmers allocate water and land between a water intensive and a non-intensive crop to maximize profits. The model predicts that electricity subsidies should increase demand for groundwater and agricultural output, particularly for water intensive crops.

We empirically test these predictions using novel panel data from 370 districts in India (the U.S. equivalent of a county) between 1995 and 2004. Simply estimating the effect of electricity prices on extraction and agricultural production is unlikely to provide a consistent estimate. In India, electricity tariffs vary over time and across states since state governments have the authority to set electricity prices and often respond to political and economic pressures by changing them (Min 2010). Because of these features, it is possible that state electricity prices will be systematically correlated with other state level agricultural policies such as fertilizer subsidies that also impact both groundwater extraction and agricultural production. We use the interaction of electricity prices and (confined) aquifer depth to measure the effective price of groundwater, as is common in the water resources literature (Domenico et al. 1968, Martin and Archer 1971). As the minimum aquifer depth - a fixed hydrogeological characteristic that differs across districts - increases, the cost to pump a unit of groundwater will increase. Our regressions also control for district unobservables and state-year shocks. As such, the interaction term exploits variation in responses to annual changes in electricity prices within districts with different aquifer depths.

One issue with electricity prices in our setting is that customers are charged a flat monthly fee instead of a flat rate per kilowatt hour (kWh).[5] This rate structure stems in part from the fact that electricity usage for agricultural users is determined by pump size. Knowing this, the regulator can set monthly fixed fees that vary across pump capacity to achieve a flat implicit price per kWh. In most states, customers (in 2004) face an implied uniform rate per kWh across pump capacities, though in a few states the implied rate varies by pump size.[6] In the latter instance, a

production, finding that reductions in the water table meaningfully reduce the output of food grains (Sekhri 2011a). A closely related study simulates the impact of removing electricity subsidies on groundwater extraction and agricultural yields in North India, and suggests that marginal cost pricing would increase yields and farm profits (Banerji et al. 2012). Other work estimates the elasticity of demand for agricultural water and then simulates the effect of marginal cost electricity pricing on water demand (Somanathan and Ravi 2006)

[5]Some states such as West Bengal have introduced metering (Mukherji et al. 2009).

[6]For example, assume that one household has a pump that utilizes 400 kWh in a month while another has a

change in the observed price of electricity may be indicative of a shift in the composition of pumps owned rather than a change in the fixed fee. To control for this, we restrict the sample to states where the implied rate is uniform across pump capacities.

Our results indicate that electricity subsidies increased groundwater extraction. They suggest that a 10 percent reduction in the average subsidy, which amounts to roughly a 50 percent increase in the price of electricity, would lead to a 6.6 percent reduction in extraction. The estimated elasticity of -0.13 fits within the range of elasticities reported in a recent meta-analysis (Scheierling, Loomis and Young 2006). Subsidies are also positively correlated with groundwater over-exploitation, suggesting that there may be long-run environmental costs to this policy.

Electricity subsidies also increase water intensive agricultural output, where we estimate a price elasticity of -0.058. The implied water usage elasticity of water intensive output is 0.46.[7] Disaggregating water intensive output into crop specific output highlights that at least in terms of agricultural output, rice is the only crop that is statistically responsive. It is also the most economically responsive. Several factors could drive the output result, or lack thereof, including (i) an expansion on the extensive margin in the area cultivated; (ii) a yield response driven by changes in the intensity of production per hectare cultivated; and (iii) an effect of electricity prices on the demand for other inputs.

We find that the area cultivated is responsive to electricity prices, both for water intensive crops as a group and for three individual crops - sugar, rice and sorghum. In contrast, yields are largely insensitive to price changes. One potential reason for the lack of a yields (and output response) is that farmers respond to subsidies by cultivating less productive land. Once we control for land quality, we find that the three crops responsive to electricity prices along the extensive margin - sugar, rice and sorghum - now exhibit an output response. And while we cannot rule out the hypothesis that farmers are cultivating less productive land in response to cheaper electricity, we find evidence that suggests farmers also respond to subsidies by increasing both crop acreage

pump that uses 800 kWh per month. If the fixed fee for the farmer with the larger pump is double that of the smaller farmer, then the two users would face the same implicit price per kWh.

[7]Though this is larger than some of the elasticities of yields or acreage to irrigation (expenditure or share of irrigated land) (Rosegrant et al. 1998, Lahiri and Roy 1985), it fits within the range of the elasticities of output reported by others (Kanwar 2006).

and output on productive land.

A change in electricity prices could affect agricultural production through changes in demand for other agricultural inputs. If this is the case then the water-output elasticity may be overestimated. We examine the extent to which subsidies affect the equilibrium quantity and prices of two other key inputs - fertilizer and labor. While electricity subsidies have no measurable impact on fertilizer use, agricultural wages increase in response to higher electricity prices. If anything, these results would attenuate the effect of electricity prices on output, suggesting that demand for groundwater is driving the relationship between electricity prices and agricultural output. These results may also explain the insensitivity of yields to price changes.

Finally, we explore the efficiency cost of these subsidies by calculating the efficiency gains of reducing them by 10 percent. Our back of the envelope calculation reveals that on average 88 paise of every rupee spent by the government is transferred to agricultural producers.[8] While electricity subsidies may create distortions in agricultural production, groundwater consumption and electricity usage, the deadweight loss from them are estimated to be low (Gisser 1993).

Our contributions to the literature are three-fold. First, our study adds to recent evaluations of India's energy policy which to date have focused on the effects of electrification (Khandker et al. 2012, Rud 2011) and the restructuring of electricity markets (Cropper et al. 2011). It also fits within a long literature on the open-access nature of groundwater and the institutional frameworks available to govern it (Ostrom 2011, Sekhri 2011b, Strand 2010, Provencher and Burt 1993, Ostrom 1990, Gisser 1983). Lastly, we contribute to recent research on the long and short-run agricultural impacts of access to groundwater (Hornbeck and Keskin 2011, Sekhri 2011a). Hornbeck and Keskin (2011) examine the effects of improved irrigation technology in the U.S., while we evaluate a separate policy aimed at increasing access to groundwater irrigation and show that in the short-run it impacted both the quantity and composition of agricultural output.

[8]There are 100 paise in 1 Rupee and, in 2004, there were roughly 45 Rupees in a dollar.

2 Background: Agricultural Energy Policy in India

Upon independence in 1947, the Government of India implemented a series of policies to bring the economy under state control. This included the Electricity Act of 1948, which transferred electricity generation, transmission and distribution from private ownership to public control. As part of this act, each state formed a vertically integrated State Electricity Board (SEB) responsible for transmission, distribution and generation of electricity, as well as the setting and collection of tariffs (Tongia 2003).

Prior to the Green Revolution, though agriculture played a dominant role in the Indian economy, agricultural yields were low and food shortages were frequent (Tongia 2003, World Bank 2010). To spur agricultural production, the government enacted a series of policies including the subsidization of key agricultural inputs in the 1960s. An agricultural electricity subsidy was implemented to encourage groundwater irrigation. Indeed, this subsidy increased agriculture's share of energy use, which jumped from just 3% of total energy use to 14% by 1978 (Pachauri 1982).

As agricultural profits increased and farmers started to recognize the importance of agricultural input subsidies, they began to organize themselves into powerful political coalitions. Around the same time, political competition among state political parties was growing. To attract the agricultural vote, politicians began to use electricity pricing as a campaign tool. We see the first evidence of this in 1977, when one political party in Andhra Pradesh promised free power for agricultural electricity users if elected (Dubash and Rajan 2001). This practice only intensified over time and by the 1980s cheap agricultural electricity was a common campaign strategy, especially in agricultural states (Dubash 2007). Electricity pricing remains a powerful political tool - Indian politics is often said to come down to bijli, sadak, pani (electricity, roads, water), an observation that has been corroborated in household data (Min 2010, Besley et al. 2004).

The electricity pricing strategies of SEBs have been linked to a number of negative features of the electricity sector (Cropper et al 2011, World Bank 2010). First, it has been argued that they are partly responsible for the financial insolvency of the sector. Though SEBs are required to generate a 3 percent annual return on capital, they operate at huge annual losses, totaling US $6 billion or -39.5% of revenues in 2001 (Lamb 2006). Second, the financial instability of the electricity sector combined with low retail prices, likely contributes to the intermittent, unpredictable and low quality electricity service that characterizes electricity provision in India (World Bank 2010, Lamb 2006, Tongia 2003). Third, these subsidies may impose a drag on industrial growth. To partly recover costs, the SEBs charge commercial and industrial users rates that often exceed the marginal cost of supply.

Perhaps, most concerning is the magnitude of these subsidies. The revenue losses from the electricity sector were the single largest drain on state spending and were estimated to amount to roughly 25% of India's fiscal deficit in 2002 (Mullen et al. 2005, Tongia 2003, Monari 2002). As context, the amount spent on agricultural electricity subsidies was more than double expenditure on health or rural development (Mullen et al. 2005, Monari 2002). Therefore, these expenditures were likely to come at the cost of other social programs. Given the resources dedicated to these subsidies, it is important to quantify if and to what extent they encouraged groundwater extraction and agricultural production, and to understand the efficiency costs. We now investigate these questions.

3 Theoretical Framework

We present an agricultural production model which draws heavily on Provencher and Burt (1993). The economy is comprised of many farmers who choose water usage and the fraction of water and land to devote to two crops that differ in their water intensity. The farmers draw water using electric pumps from an open access replenishable groundwater stock. The model predicts that an increase in electricity subsidies will increase demand for groundwater, which will in turn increase agricultural output, particularly for water intensive crops.

3.1 Groundwater

The economy consists of N identical farmers who have access to a common groundwater stock in district i.[9] The total groundwater stock in time t is given by x_{it}. In each period, farmers

[9]We assume that any farmer who owns or has access to a tube well may extract groundwater.

choose groundwater consumption, w_{it}, and the resource is recharged at the rate r_{it}. Putting these together, the stock of groundwater available for use in period $t+1$ is given by,

$$x_{i,t+1} = x_{it} - Nw_{it} + r_{it} \tag{1}$$

A farmer's choice of groundwater usage will depend on the cost of groundwater extraction, among other things, where the cost is given by,

$$p^E_{jt} c(x_{it}, \mu_i) \tag{2}$$

The cost of extraction is a function of the retail price of electricity, p^E_{jt}, since electricity is used to pump groundwater from the aquifer to the surface. The farmer faces a subsidized electricity price, $p^E_{jt} = p_{jt} - s_{jt}$, where p_{jt} is the cost of electricity in state j at time t and s_{jt} denotes the subsidy. The cost of extraction also depends on the depth to the water table which we separate into two characteristics - depth to the (confined) aquifer (μ_i) and the groundwater stock (x_{it}. We assume that extraction costs are decreasing in the groundwater stock and increasing in the depth to the aquifer; $\partial c/\partial x < 0$ and $\partial c/\partial \mu > 0$.

3.2 Profit Maximization

Assume that each farmer is endowed with A units of land and that the agricultural sector uses two inputs - land and water - to produce two crops.[10] Production of both crops is modeled using a Cobb-Douglas technology. Further, assume that land and water are complements in production and that the crops vary in the output shares of inputs.

Landowners choose groundwater extraction, the fraction of land ($A_{1,it}$) and groundwater inputs (ξ_{it}) to devote to a water intensive and water non-intensive crop to maximize profits, given input

[10] We assume no rental market for land.

and output prices $(p_{1jt},\, p_{2jt})$[11],

$$\begin{aligned}\Pi(A) &= \max_{A_{1,it},w_{it},\xi_{it}} \quad p_{1jt}F_1(w_{it}\xi_{it}, A_{1,it}) \quad + \quad p_{2jt}F_2(w_{it}(1-\xi_{it}), A_i - A_{1,it}) \quad - \quad p_{jt}^E c(x_{it}, \mu_i)w_{it} \\ &= \max_{A_{1,dt},w_{it},\xi_{it}} \quad p_{1jt}(w_{it}\xi_{it})^\alpha A_{1,it}^\beta \quad + \quad p_{2jt}w_{it}^\gamma(1-\xi_{it})^\gamma(A_i - A_{1,it})^\delta \quad - \quad p_{jt}^E c(x_{it}, \mu_i)w_{it}\end{aligned}$$

Crop 1 is more water-intensive than crop 2, so $\alpha > \gamma$. Further, assume that $\alpha + \beta \leq 1$, $\delta + \gamma \leq 1$ and that $\alpha + \beta = \delta + \gamma$. The fraction of land and water devoted to crop 1 in district i and year t is given by $A_{1,it}$ and ξ_{it}, and the fraction allocated to crop 2 is given by $A_i - A_{1,it}$ and $1 - \xi_{it}$. For notational convenience, we now drop district and state subscripts.

Since drawing water in period t will affect the stock of water available in period $t+1$, the farmer faces the following dynamic optimization problem:

$$\begin{aligned} v(x_t) \quad &= \quad max_{w_t,\xi_t,A_{1,t}}[p_{1t}(w_t\xi_t)^\alpha A_{1,t}^\beta + p_{2t}(w_t(1-\xi_t))^\gamma(A - A_{1,t})^\delta - p_t^E c(x_t,\mu)w_t \\ &\qquad +\beta v(x_t - (N-1)u^*(x_t) - w_t + r_t)] \\ &s.t. \quad x_t - (N-1)u^*(x_t) - w_t \geq 0 \end{aligned} \tag{3}$$

When choosing groundwater extraction and input shares to maximize profits, the farmer faces three costs (in addition to the price of electricity). First, extraction today will impact the value of returns from the groundwater stock tomorrow. This is captured by $\beta v(x_t - (N-1)u^*(x_t) - w_t + r_t)$, where β represents the discount rate and $v(x_t)$ is the present value from agricultural production over an infinite planning horizon when the initial groundwater stock is x_t. Second, extraction may affect the groundwater stock tomorrow. This cost is reflected in the resource constraint, which restricts the groundwater consumption in period t to the total groundwater stock available in time t. Third, extraction today will influence future pumping costs.

Maximizing equation (3) with respect to w_t yields the following first order conditions:

$$\frac{\partial F_1}{\partial w_t} + \frac{\partial F_2}{\partial w_t} = c(x_t,\mu)p_t^E + \lambda_t + \beta\frac{\partial v_{t+1}}{\partial x_{t+1}} \tag{4}$$

$$\lambda_t(x_t - (N-1)u_t^*(x_t) - w_t) = 0 \tag{5}$$

[11]Landowners may also use surface water, a perfect substitute for groundwater, as an input.

Equation (4) equates the marginal benefits of groundwater extraction to the marginal costs of extraction.[12] Since groundwater is an open-access resource and farmers maximize profits, scarcity rents will be dissipated and farmers will not consider the private opportunity cost of extraction. The farmer also chooses the optimal allocation of water and land by equating the marginal product of water and land across crops

3.3 Testable Predictions

This conceptual framework generates four testable predictions:

1.1 Groundwater extraction should increase as the price of electricity decreases.

1.2 The groundwater response to a change in electricity prices should be larger the lower the stock of groundwater and the greater the distance to the aquifer.

2.1 Total agricultural production should be increasing in the subsidy, with a larger increase for water intensive crops.

2.2 The fraction of land and water devoted to the water intensive crop should increase as the subsidy increases.[13]

4 Estimation strategy

In this section, we first connect our theoretical framework to the empirical methods. We then describe the empirical strategy, including robustness tests.

4.1 From the Theory to the Empirics

Rearranging the first order condition presented in equation (4), we have,

$$\alpha p_{1t} A_{1,it}^{*\beta} (w_{it}^{*})^{\alpha-1} \xi_{it}^{*\alpha} + \gamma p_{2t} (A_i - A_{1,it}^{*})^{\delta} (w_{it}^{*})^{\gamma-1} (1-\xi_{it}^{*})^{\gamma} = c(x_{it}, \mu_i) p_{jt}^{E} + \lambda_t + \beta \frac{\partial v_{t+1}}{\partial x_{t+1}}$$

[12] The final term in equation (4) represents the private opportunity cost of current groundwater extraction, since consuming water in the current period reduces the groundwater stock available for future consumption. We must also account for the scarcity rent of extracting a unit of groundwater, λ, when the resource constraint is binding.

[13] Since $\alpha > \gamma$, $\frac{\partial A_1}{\partial p^E} < 0$ and $\frac{\partial \xi}{\partial p^E} < 0$, while $\frac{\partial (A-A_1)}{\partial p^E} > 0$ and $\frac{\partial (1-\xi)}{\partial p^E} > 0$.

This equation implies that the conditional demand for groundwater is a function of the retail price of electricity (p^E_{jt}), the stock of groundwater (x_{it}), the minimum depth to the aquifer (μ_i), crop prices (p_{1t}, p_{2t}), the amount of land available (A_i) and the parameters of the production function. Demand for groundwater also depends on the private future opportunity cost of groundwater extraction and the scarcity rent. However, our assumptions that groundwater is an open-access resource and of profit maximization imply that $\lambda_t = 0$ and $\beta \frac{\partial v_{t+1}}{\partial x_{t+1}} = 0$.

In moving from the theory to the empirics, we next sum groundwater extraction across all N identical farmers in a district. Linearizing the conditional demand for groundwater in district i and year t, we can characterize demand as,

$$W_{it} = \beta_0 + \beta_1 D_i^{Amin} p^E_{jt} + \beta_2 x_{it} p^E_{jt} + \beta_3 s_{it} + \lambda_{jt} + \gamma_i + u_{it} \tag{6}$$

where W_{it} denotes groundwater consumption in million cubic meters (mcm); D_i^{Amin} denotes the minimum distance to the aquifer; and s_{it} denotes rainfall and serves as a proxy for the annual supply of surface water, a substitute good. State-year dummies, λ_{jt}, flexibly control for any annual state shock in groundwater extraction including variation in crop prices.[14] The error structure includes γ_i, a district fixed effect, and u_{it}, an idiosyncratic error term.[15]

As shown in equation (6), demand for groundwater depends on the annual stock of groundwater. However, the groundwater stock is by construction a function of lagged groundwater demand and because of this will likely be correlated with lagged error terms that also influence extraction. To address this concern, we use a proxy variables approach to measure the stock of groundwater, where the proxy variable used is the maximum aquifer depth.

[14] Our analysis assumes that variation in crop prices occur at the state-year level. We examine the validity of this assumption by evaluating the response of district level crop prices to changes in electricity prices. We find that district level crop prices are not systematically correlated with electricity prices.

[15] The land endowment, A_i, does not vary over time, so it is absorbed in the district fixed effect.

4.2 Simple model

Before estimating equation (6), we estimate a simple OLS model to test whether the quantity of groundwater extraction rises with a decrease in the price of electricity,

$$W_{it} = \alpha_0 + \alpha_1 p^E_{jt} + \alpha_2 s_{it} + \lambda_t + \gamma_i + u_{it} \tag{7}$$

In this specification, the price of groundwater extraction is simply p^E_{jt}, the price of electricity in state j year t. We include year dummies since identification of α_1 comes from variation in electricity prices across state-years. Standard errors are clustered at the district.

Specification (7) also allows us to test the role that generation, and transmission and distribution (T&D) losses play in determining groundwater extraction. These variables may be correlated with electricity prices and may impact extraction in two ways. First, electricity is often rationed in India so that, at any given price, the quantity of electricity supplied may fall below quantity demanded. Because of this, the available supply rather than the price may be driving groundwater extraction. Prices will be correlated with generation since, with low electricity prices, generation constraints are more likely to bind. Second, in addition to manipulating electricity prices, state governments may also alter electricity provision through other channels, such as turning a blind eye to electricity theft in strategic areas. For these two reasons, the coefficient estimate on price may partly reflect supply side factors. To examine whether the effect of electricity prices on groundwater demand is robust to the inclusion of these factors, we estimate equation (7) conditional on generation, and T&D losses. Due to potential omitted variables bias, we view the inclusion of supply constraints in the estimating equation simply as a robustness test.[16]

[16] Identification of the effect of these electricity measures on district groundwater demand comes from state-year variation controlling for time-invariant district unobservables and year shocks. Since all districts in a state face the same electricity prices, electricity prices will not differ across districts within a state. The same may not hold true for the other electricity measures. Electricity outages and T&D losses in particular may differ across districts within a state if politicians or the state electricity boards selectively turn a blind eye to theft or disrupt service in certain districts. Unfortunately we do not have district data on these variables.

4.3 Incorporating hydrology

In India, state electricity prices may reflect the political party in power, the importance of the state's agricultural economy or state expenditure on other agricultural policies. We also anticipate that demand for groundwater will depend on these factors. Because of potential omitted variables bias, the estimated effect of electricity prices on groundwater demand (α_1 in estimating equation (7)) may be inconsistent. To identify the effect of electricity subsidies on groundwater extraction, we turn to the water resources literature to construct a measure for the effective price of groundwater.

The water resources literature uses the interaction of electricity prices and minimum well depth to measure the price of groundwater extraction (Domenico et al. 1968, Miller and Archer 1971).[17] We use a similar variable - the interaction of the minimum aquifer depth and electricity prices - to measure the price of groundwater extraction. In our analysis, minimum aquifer depth, D^{Amin}, is a fixed hydrogeological characteristic that describes the minimum depth one would need to drill a tube well or bore hole to reach a confined, leaky or semi-confined aquifer. A confined aquifer is one that is sandwiched between two impervious formations (Heath 2004). As such the minimum aquifer depth is the depth one would need to drill to reach this confined geologic surface (i.e. clay, sand or other rock type).[18,19] Similarly, we use the interaction of electricity prices and maximum (confined) aquifer depth to capture the effect of the groundwater stock on groundwater extraction. When combined with the minimum aquifer depth, the maximum aquifer depth (D^{Amax}) measures the size of the aquifer or the volume of water that the aquifer can hold.

In our preferred specification, we estimate

$$W_{it} = \beta_0 + \beta_1 D_i^{Amin} p_{jt}^E + \beta_2 D_i^{AMax} p_{jt}^E + \beta_3 s_{it} + \lambda_{jt} + \gamma_i + u_{it} \tag{8}$$

The coefficient of interest, β_1, captures the differential effect of a change in electricity prices on two districts with different minimum aquifer depths, controlling for fixed district characteristics

[17] In Domenico et al. (1968), the marginal cost is defined as the cost to lift one acre-foot of water one foot.

[18] The minimum depth of unconfined aquifers, which are suitable for the construction of dug wells, is defined as the water table. In unconfined aquifers, the water table varies seasonally with the monsoon.

[19] It should be noted that the water level in confined wells is at a height above the aquifer depth (Heath 2004).

and annual shocks to the state. This identification strategy assumes that the interaction term will be uncorrelated with district unobservables that vary over time, such as development assistance programs. To test the plausibility of this assumption, in a separate specification we control for annual district expenditure on rural development programs. Standard errors are clustered at the state-year.

4.4 Agricultural output

We now turn to test our theoretical predictions about agricultural output, namely that both overall output and the composition of crops change in response to electricity subsidies. We estimate the following regression,

$$V_{it} = \beta_0 + \beta_1 D^{Amin} p^E_{jt} + \beta_2 D^{AMax} p^E_{jt} + \beta_3 s_{it} + \lambda_{jt} + \gamma_i + u_{it} \tag{9}$$

in which the dependent variable V_{it} measures the value agricultural output in a district-year. Agricultural output is measured as the sum of total output from cotton, rice, sugar, wheat, maize, sorghum and millet. To test if output of water intensive crops increases disproportionately, we estimate equation (9) separately for water intensive and non-intensive crops. In these specifications, we control for price changes by holding prices fixed at 1995 levels and including state-year fixed effects.

We next explore the drivers behind the change in agricultural production. To test the impact of electricity prices on the share of water devoted to each crop, we estimate equation (9), where the dependent variable is now individual crop yields.[20] To evaluate the impact of electricity subsidies on the allocation of land across crops, we estimate equation (9) except now the dependent variable denotes the area of land devoted to crop c.

[20] Ideally, we would isolate the effect of subsidies on the share of water used by each crop but we do not observe this. Instead, we examine crop specific yields.

4.5 Measurement of Electricity Prices

In our study, the electricity price is measured as the average tariff in a state-year and is calculated as total agricultural electricity revenues divided by total kWh of electricity sold. This measure assumes all agricultural users in a state face a single rate per kWh. However, in practice electricity supplied for irrigation purposes is billed using a fixed fee format, where the structure of the fixed fee varies across states.

The use of fixed fees rather than volumetric rates for agricultural users occurs, at least in part, because monthly electricity usage is determined by pump capacity. This feature of agricultural electricity consumption provides the regulator with an estimate of monthly usage, and allows him to set fixed fees that achieve an implicit volumetric rate. In 2004, for most states, we observe a price structure such that the implied volumetric rate is flat across pump size. In others, the tiered fee structure is such that the implicit price per kWh varies based on pump capacity. In these states, the average electricity tariff is given by $p_{jt}^E = \frac{\sum_b p_{bjt}^E E_{bjt}}{\sum_b E_{bjt}}$, where b refers to the electricity bundle (tier) and E measures electricity sales by bundle.

Using these price data has implications for the interpretation of our results. First, let us assume that all agricultural users in a state pay the same implicit rate for electricity, regardless of pump size. In this case, a change in our measure of price captures on average a change in the implicit volumetric rate. In contrast, if a tiered structure is in place and the implicit volumetric rate varies by pump size, a change in our measure of price may reflect a shift across usage tiers or bundles. For example, if a change in the price of pumps results in some users shifting across pump categories, this would be wrongly reflected as a change in the electricity price. To ensure that our results are driven by variation in electricity prices, in a robustness test we exclude states with a tiered rate structure from our sample.

5 Data and Descriptive Results

We use three main sources of data: district groundwater data collected by the Central Groundwater Board, annual state electricity data collected by the Power and Energy Division of the Planning

Commission and annual district agricultural data compiled by the Directorate of Economics and Statistics within the Indian Ministry of Agriculture.

5.1 Groundwater Data

District groundwater data on extraction, one of our dependent variables, is available for 965 district-years in 15 states. We form an unbalanced panel of groundwater data for 344 districts using data from 1995, 1997, 1998, 2002 and 2004. Summary statistics on groundwater demand and recharge are provided in Table 1; Panel A reports these statistics for the entire sample and Panel B reports them for the balanced panel by year for 1995, 2002 and 2004. On average groundwater extraction amounts to 57 percent of recharge. However, this statistic masks the variation in extraction both across districts and over time. In the balanced panel, groundwater extraction increased between 1995 and 2004 by 125 mcm or 18.5 percent, though recharge increased as well. Groundwater over-exploitation also increased. Between 1995 and 2005, the number of over-exploited districts grew by 18 percent or 3 percentage points.

In our preferred specification, the price of groundwater extraction is measured as the interaction of the minimum aquifer depth in a district and the agricultural retail price of electricity in a state-year. Data on minimum (as well as maximum) aquifer depth are available for the states of Andhra Pradesh, Bihar, Karnataka, Uttar Pradesh, Madhya Pradesh, Maharashtra, Orissa and Tamil Nadu.[21] Figure 1 illustrates the geographic variation in aquifer depth for Tamil Nadu, where district boundaries are outlined in black. It is clear that there is substantial variation in minimum aquifer depth across districts within a state. Panel A of Table 2 summarizes groundwater characteristics in each state and further highlights the within state variation in aquifer depth.

5.2 Electricity data

Data on states' electricity prices, measured in 1995 paise per kilowatt hour (paise/kWh), were collected between 1995 and 2004.[22] Since our identification strategy exploits variation in electricity

[21] Ideally, hydrogeological data would be provided for all districts in India; however the CGWB will only provide these data on a state by state basis, where we must limit our yearly data request to 3 to 5 states.

[22] Electricity data were gathered from three primary sources: "The Annual Report on the Working of State Electricity Boards and Electricity Departments" published by the Power and Energy Division of the Planning

prices within a state over time, we explore variation in state electricity prices in 1995, 2002 and 2004, the years for which we have groundwater extraction data; Panel B of Table 2 provides descriptive statistics. We observe variation across states and within a state over time. In 2002 alone, electricity prices range between 1 and 88 paise, with Tamil Nadu providing agricultural electricity almost free of charge and Uttar Pradesh charging nearly 90 paise per kilowatt hour. Between 1995 and 2004, there was an upward trend in electricity prices, though this increase varied across states.

Panel B of Table 2 also reports summary statistics on the average cost to supply electricity, our measure of the marginal cost.[23] Between 1995 and 2002 (data are not available for 2004) the unit cost of electricity increased by 20 to 110 percent, with the exception of Orissa. A comparison of the difference between unit costs and agricultural retail prices, our measure of the subsidy, highlights both the magnitude of these subsidies as well as their increase over time. On average, electricity subsidies have increased by almost 45 percent, and as of 2002 the agricultural retail price amounted to 11% of the unit cost.

5.3 Agricultural production data

Annual district data between 2000 and 2004 on the value of crop output and crop acreage are reported in Table 1.[24] In our analysis, we restrict our sample of agricultural production data to post-2000 since the pre and post-2000 data come from 2 different sources and the pre-2000 data may suffer from measurement issues.[25]

Total agricultural production is measured as the sum of revenues from wheat, rice, cotton, sugar, maize, sorghum and pearl millet, weighted by the 1995 price for each crop. These crops

Commission between 1992 and 2002, multiple volumes of "Average Electric Rates and Duties in India" published by the Central Electricity Authority and multiple volumes of "Energy", a publication by the Center for Monitoring the Indian Economy in India.

[23]The average unit cost of electricity provision is calculated as the total cost of electricity (revenue expenditure plus depreciation and interest due) divided by total electricity sold.

[24]Data on production come from the District Agricultural Statistics Portal from the Ministry of Agriculture. Data on output prices were taken from"Agricultural Prices in India".

[25]During interviews with the head of data collection at the Indian Ministry of Agriculture, she raised multiple concerns with agricultural statistics collected in the mid to late 1990s. This period was one of substantial economic and government reform, with reductions in the allocation of expenditure to statistics and the bifurcation of multiple states.

were chosen because they are prevalent in India, vary substantially in their water intensity and data were available during the period of study. We hold prices fixed at 1995 levels to decouple the effect of price changes from output changes. Water intensive output is measured as the weighted sum of the value of production in sugar, rice and cotton and water non-intensive output is comprised of sorghum and water millet. A crop was labeled as more or less water intensive based on its relative level of water inputs, as defined by Hoekstra and Chapagain (2007). Since water intensity is defined on a continuous scale, we also examine disaggregated results. In this analysis, we also include maize and wheat, two crops that are considered neither intensive nor non-intensive. As reported in Table 1 water intensive crops account for most of agricultural production, generating 55 percent of annual output. Rice and wheat are the dominant crops in terms of value as well as area cultivated.

6 Results

6.1 Groundwater

We find that electricity subsidies increased groundwater extraction and may have long-run environmental consequences in the form of groundwater over-extraction. Column 1 of Table 3 reports results from the estimation of equation (7), an OLS model of demand for groundwater in which we exploit variation in state electricity prices over time, controlling for fixed district characteristics. We find that district demand for groundwater decreases by 1.84 million cubic meters on average with a 1 paise increase in the price of electricity. This implies that a 25 percent increase in the agricultural price of electricity, where the mean price is 36 paise/kWh, would reduce extraction by 11.1 mcm or 2.1 percent on average. Framed differently, if electricity subsidies were reduced by 10%, where the average subsidy over the duration of the study amounted to 203 paise/kWh, water demand would decrease by 6.8 percent. The implied short-run elasticity of demand for groundwater is approximately -0.13. This fits within the range of elasticities, -0.002 to -1.97, and is close to median value of -0.22 reported in a meta-analysis of irrigation water demand elasticities (Scheierling, Loomis and Young 2006).

We next explore the importance of generation and T&D losses, and test the robustness of our results to their inclusion. As shown in column 3 of Table 3, an increase in T&D losses leads to a significant decrease in groundwater extraction, perhaps because losses further constrain the available supply of electricity. In column 4, we present results from the estimation of equation (7), except now we condition on T&D losses and generation. The estimated effect of electricity prices, both in magnitude and significance, mirrors that reported in column 1, suggesting that our results are not driven by supply side factors. Knowing this, we now focus on isolating the effect of electricity prices on groundwater extraction.

Results from the estimation of equation (8), a district fixed effects model in which we interact groundwater characteristics with agricultural electricity prices and control for state-year shocks are reported in the final column of Table 3. We find evidence to support the prediction that an increase in electricity prices reduces groundwater extraction relatively more in districts with deeper wells (higher priced groundwater sources). For a district with the mean aquifer depth (57.5 m), the implied price elasticity is -0.13 suggesting that a 10 percent reduction in the subsidy would decrease extraction by 6.7 percent. This result is robust to the inclusion of annual district expenditure on rural development programs, suggesting that other district agricultural policies are not confounding the primary treatment effect.

Finally, we evaluate whether or not these subsidies impact the probability of groundwater over-exploitation, a potential environmental cost attributable to them. We use a logistic specification to estimate the effect of electricity prices on the probability of crossing three over-exploitation thresholds: critical, where annual groundwater usage is 75% of annual recharge; over-exploited, where usage is greater than supply; and very over-exploited, where usage is over 125% of recharge. Within the period examined, 25% of districts move from normal to critical status, 14% to over-exploited and 8% to very over-exploited. We are unable to estimate our preferred district fixed effects specification due to a limited sample size; instead we exploit variation in electricity prices across states and include year dummies. The results reported in Table 4 suggest that electricity prices are negatively correlated with groundwater over-exploitation, where a 1 paise increase in the electricity price is associated with a 1.6 percent reduction in the probability of over-exploitation.

Due to limited controls, these results should be viewed as indicative rather than causal.

6.2 Agricultural production

Columns 1-3 of Table 5 report the effect of these subsidies on total, water intensive and non-intensive agricultural output, respectively. Statistically, electricity prices only meaningfully impacted the output of water intensive crops. The implied price elasticity of intensive output is -0.058, implying that a 10% reduction in the subsidy would increase output by 3 percent.

To examine which crops are driving the outuput response, we disaggregate output by crop in Panel A of Table 6, where crops decrease in water intensity from left to right. Rice (a water intensive crop) is the only crop whose output is statistically responsive to electricity prices. It is also the most responsive in magnitude, with an estimated price elasticity of -0.08. Sugarcane exhibits an economically meaningful response, with over 85% confidence, a point to which return to later. Panels B and C of Table 6 explore two reasons behind the response or lack thereof of crop output, investigating changes in yields (Panel B) and the area cultivated (Panel C).

We do not find yields of water intensive crops to be more responsive to price changes. In fact, our results suggest that yields are for the most part insensitive to them. The one exception is sorghum, a water non-intensive crop, where yields weakly increase as the price of electricity decreases. Interestingly, the yields of other crops, both water intensive and non-intensive, also increase with price increases, though we cannot statistically distinguish the estimates from zero.

Our results suggest that farmers are responding to electricity subsidies through the area cultivated, particularly for water intensive crops. Columns 4-6 of Table 5 indicate that farmers are expanding the area on which water intensive crops are grown, where the estimated price elasticity is -0.06. Panel C of Table 6 further disaggregates cultivated area by crop type and suggests that cultivated area of both water intensive (sugar and rice) and non-intensive (sorghum) crops is increasing in the size of electricity subsidies.

One potential reason for the insensitivity of average sugar and sorghum output (two crops that demonstrate an acreage response) is that farmers may not display cultivation responses for these crops in all districts. For example, farmers may display greater area and output responses in districts where agro-climatic conditions are suited to the cultivation of a given crop or alternatively they could respond to electricity prices by cultivating more marginal land. In Table 7, we restrict the sample to districts either suited or not suited to the cultivation of crop c and present results for the output and acreage response for sugar and sorghum. For each district we calculate the fraction of cultivated area allocated to a crop, and define a district as well-suited to the production of that crop if this fraction is above the sample mean. In districts suited to the cultivation of sugar and sorghum, we find both an output and acreage response. This suggests that the lack of an output response cannot simply be explained by a shift in cultivation to less productive lands, though we cannot rule of this hypothesis. It also highlights that electricity subsidies expanded acreage and output on land that is relatively well-suited to the cultivation of sugar and sorghum.

6.3 Demand for Other Inputs

Our measure of agricultural output captures changes in production gross of other inputs, such as labor and fertilizer. Electricity subsidies may also affect demand for and the equilibrium prices of these inputs, if prices are determined locally, which in turn may affect agricultural output. Knowing the impact of electricity prices on other agricultural inputs will provide insight into the extent to which electricity subsidies affect the value of agricultural production through channels aside from irrigation. It will also inform us about the yield response; if farmers do not pair the increase in land cultivated with an increase in demand for other agricultural inputs, this may explain the insensitivity of yields to price changes. To test for these, we examine the extent to which electricity subsidies influence the equilibrium price of labor and demand for fertilizer.

Columns 1 and 2 of Table 8 present results from the estimation of equation (8), except now the dependent variable is the average yearly male and female wage (cols. 1 and 2). We find that wages of both female and male workers increase with electricity prices.[26] While we provide evidence that electricity subsidies impact the equilibrium price of labor, the direction of the effect would

[26] This result is surprising given earlier work that shows a positive correlation between wages and the demand for labor in the agricultural sector in India (Jayachandran 2006). Our results are consistent with a framework in which water and labor are substitutes, rather than complements, in production. An alternative explanation is that the observed shift in crop production (in response to changes in electricity prices) moves production towards less labor intensive crops, thereby reducing the demand for labor.

attenuate the estimated effect of electricity subsidies on agricultural output. It also suggests that the increase in land cultivated is not being coupled with a proportional increase in labor, which may explain the lack of a yields response to electricity prices.

The remainder of Table 8 reports results from a regression of fertilizer use on electricity prices. Regardless of our measure of fertilizer - all, nitrogen, phosphate or potassium - electricity subsidies do not appear to influence the quantity of fertilizer used, suggesting that the previously reported changes in agricultural production are not capturing a change in fertilizer use. It also provides evidence to support the hypothesis that the lack of a yields response may occur because other agricultural inputs remain fixed.

6.3.1 Measurement and Interpretation of electricity prices

The robustness of these results hinges on our measure of electricity prices. Recall that electricity prices take the form of either an implicit flat or tiered rate, where the latter is tiered based on pump size. In states with a tiered rate structure, a change in the average tariff faced by consumers may reflect a shift in users across tiers rather than a change in the price.

To ensure that our results are driven by variation in the actual prices faced by users, we restrict our sample to states in which there is a single flat fee and test the robustness of our results. To do this we collected data on electricity prices by tier for 2004, the only year in our panel for which these disaggregated data are available from the Central Electricity Authority.[27] In Figure 2 we illustrate by state the average tariff charged per tier in 2004. There are four electricity tiers: 400 kWh/month (based on the pumping capacity of a 2 HP pump), 600 kWh/month (3 HP), 1000 kWh/month (5 HP) and 2000 kWh/ month (10 HP). The figure highlights that 11 of the 15 states for which we have disaggregated data charge a single flat rate.

Table 9 reports results using the restricted sample, where the dependent variables are groundwater extraction (cols. 1 and 2), agricultural output (cols. 3 to 5), and area cultivated (cols. 6 to 8). In all specifications, the relationship between the dependent variable and electricity prices

[27] Disaggregated prices were reportedly published for other years by the Central Electricity Authority. Despite multiple meetings and visits to the publications unit, library and price department of the authority, we were unable to acquire these data.

remains almost unchanged, suggesting that electricity subsidies indeed impacted groundwater extraction, and the quantity and composition of agricultural output.

7 Welfare Effects

We now examine the welfare costs of this policy. We specify derived demand for electricity and a long-run marginal cost curve, and then estimate the reduced deadweight loss from a 10 percent reduction in agricultural electricity subsidies. Our estimates of the efficiency costs are coarse and provide a back of the envelope measure; nonetheless they serve as a starting point to think about the policy's welfare costs.

7.1 Electricity demand

In equation (8) we specified derived demand for groundwater, recognizing that farmers value groundwater for the agricultural production it provides. Ideally, we would use this to quantify the deadweight loss from electricity subsidies. However the price for a unit of groundwater, given by the interaction of electricity prices and minimum aquifer depth, is in units of meter-dollars. A consequence of this is that the estimated deadweight loss does not have a monetary interpretation. To convert aquifer depth into a price, we would need to specify a relationship between aquifer depth, electricity usage and groundwater extraction. Instead of doing this, we rely on the derived demand for electricity to quantify the deadweight loss.

Suppose farmers have a log-linear derived demand for electricity, $(E|\lambda_{jt}, \gamma_i) = \alpha_0(D_i^{AMin} * p_{jt}^E, D_i^{AMax} * p_{jt}^E|\lambda_{jt}, \gamma_i)^{\alpha_k}$ where $k = 1, 2$ and we condition on district and state-year unobservables. Derived agricultural demand for electricity in district i and year t is estimated as

$$lnE_{it} = \alpha_0 + \alpha_1 lnp_{jt}^E + \lambda_t + \gamma_i + u_{it} \tag{10}$$

where D_i^{Amin} and D_i^{Amax} are absorbed in the district fixed effect. The quantity of electricity consumed, E_{it} is measured as annual electricity sales in million kWh for agriculture; p_{jt}^E measures the natural log of the price of agricultural electricity; λ_t captures year shocks and γ_j denotes district fixed effects. Due to data limitations on district electricity sales we also estimate demand for electricity using annual state data.[28]

Table 10 reports results. In column 1, the unit of analysis is the district-year and we rely on district level data collected from 4 states between 1998 and 2004. In columns 2 and 3, the unit of analysis is the state-year and the data comprise information from 15 states between 1986 and 2005. In column 3, we also control for state trends. As expected, demand for electricity is responsive to state electricity prices, though inelastic in the short-run. In the district fixed effects model, our results suggest that a 10 percent increase in electricity prices reduces demand by 1.66 percent. Electricity is more price inelastic when we look at state electricity consumption. In the state fixed effects model with state trends, a 10 percent increase in electricity prices reduces demand by 1.14 percent. The price inelasticity of demand is unsurprising given the magnitude of the subsidies and the short-run nature of the analysis.

7.2 Back of the Envelope Calculation: Deadweight Loss

To measure the deadweight loss from the subsidy, we perform a simple counterfactual in which we measure the efficiency gains from a 10 percent reduction in the subsidy. We do not measure the deadweight loss of switching from a policy in which electricity is priced at the marginal cost to one in which it is priced at the status-quo due to concerns about out of sample predictions. In this sample, the average per unit cost of electricity is 283 paise per kWh, though farmers on average only pay 39 paise per kWh. Furthermore there are no observations in which the retail price equals or even approaches the unit cost. By contrast, if we reduce the subsidy by 10%, the overlap between the "counterfactual" and observed price is substantial.

In measuring the deadweight loss, we assume that the long-run marginal cost of electricity is equal to the average cost of electricity in a state-year, and that the electricity supply is infinitely elastic. This latter assumption implies that there is no change in producer surplus from the subsidy, thereby leading us to calculate an upper bound estimate of the deadweight loss.

When agricultural users face a retail price equal to p^e, the efficiency gain from a 10 percent

[28]We do not control for hydrogeological characteristics since these variables are not available for all the states used in the sample.

reduction in the state level subsidy is calculated as,

$$p^o(E(p^e) - E(p^o)) - \int_{E(p^o)}^{E(p^e)} p(E)dE \tag{11}$$

where p^o is defined as a 10% reduction in the current electricity subsidy and $E()$ denotes annual state electricity sales at price p.

Given the price inelasticity in the short-run, the efficiency loss from this subsidy is small. When relying on results using district-year data, we find that for every rupee spent on electricity subsidies roughly 88 paise are passed along to agricultural producers. The efficiency costs are even lower when we make use of state-year data. Our estimates suggest that in 2000 on average 94 paise of every rupee spent was passed along to consumers. There is however substantial variation across states in the efficiency loss. Of the states in our sample, the subsidy in Tamil Nadu generates the largest efficiency cost with only 77 percent of expenditure being passed along to consumers, whereas in Himachal Pradesh and Kerala 98 percent was passed on. From an efficiency standpoint these subsidies are relatively effective at transferring surplus to agricultural consumers of electricity, though it remains to be seen which agricultural producers benefited from them.

One limitation of the analysis is that we only capture the welfare effects of the subsidy on agricultural producers. These subsidies will likely have welfare implications for consumers of agricultural products and the agricultural labor market.

8 Conclusion

Despite the magnitude of agricultural electricity subsidies in India, both in absolute and relative terms, and the controversy surrounding them, little is known about their causal impact on groundwater resources and agriculture. This study aims to inform this discussion by isolating their impact on groundwater extraction and over-exploitation, and agricultural output. Using detailed district panel data we find that this policy increased groundwater extraction and the probability of over-exploitation, and had meaningful agricultural implications both in terms of the value of agricultural output and crop composition. Our results suggest that a 10 percent reduction in the average subsidy generates a 6.7 percent decrease in groundwater extraction, and may have long-run environmental implications in the form of groundwater over-extraction. A 10 percent reduction would also reduce the value of water intensive agricultural output by 3 percent, where this result is largely driven by changes in the value of rice. Decomposing output into the yields and acreage response makes clear that farmers are responding along the extensive margin, increasing the cultivated acreage of water intensive crops and some non-intensive crops.

Our study provides evidence that these subsidies may come at an environmental cost. There is well-founded and substantial concern in India over the over-exploitation of groundwater and the sustainability of India's current extraction patterns. Our results suggest that electricity subsidies have contributed to groundwater over-exploitation, increased groundwater extraction and shifted cropping patterns towards more water intensive agricultural production. These impacts of electricity subsidies are likely to have potentially negative dynamic implications as the over-exploitation of groundwater reduces the amount of groundwater available for future agricultural use.

While these subsidies may in fact come at the cost of the environment and future agricultural production, we find that they are relatively efficient at transferring government expenditure to agricultural consumers of electricity. On average 88% of government expenditure on these subsidies is transferred to farmers.

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Table 1: Summary Statistics: Groundwater and agricultural output

Panel A: Mean characteristics

District variable	Mean	Std. Dev.	Min	Max	Obs
GW extraction	558	484	7.9	4070	965
GW recharge	979	572	31	2976	965
Value agriculture	3,192	2,287	127	12,361	594
Value H20 intense	1,733	1,881	1.62	10,142	594
Value non-H20 intense	233	359.7	0.016	2,044	594
Cotton value	131	226	0.002	1,384	348
Sugar value	703	1,243	0.000	9,446	582
Rice value	972	1,311	0.035	8,484	591
Wheat value	1,284	1,282	0.022	5,806	498
Maize value	156	284	0.004	2,609	569
Sorghum value	162	291	0.012	1,640	576
Pearl Millet value	720	188	0.004	1,916	512
Cotton area	51.1	90.6	0.002	447	348
Sugar area	19.5	34.9	0.008	219	582
Rice area	99.6	110.9	0.001	735	591
Wheat area	98.9	78.9	0.008	308	498
Maize area	19.6	29.1	0.003	177	569
Sorghum area	51.1	105	0.005	714	576
Pearl Millet area	24.1	52.1	0.002	361	512

Panel B: Trends in groundwater and output

	1995		2002		2004	
District variable	Mean	Obs	Mean	Obs	Mean	Obs
GW extraction	522	330	544	243	624	341
GW recharge	873	330	1019	243	1097	341
Value agriculture			3,184	154	2,985	154
Value H20 intense			1,802	154	1,537	154
Value non-H20 intense			208	154	199	154
Cotton value			125	94	138	83
Sugar value			692	151	541	151
Rice value			1,053	153	944	152
Wheat value			1,218	130	1,342	125
Maize value			162	138	164	150
Sorghum value			152	150	123	140
Pearl Millet value			72.0	130	95.7	128
Cotton area			49.0	94	44.9	83
Sugar area			18.9	151	17.7	151
Rice area			110	153	98.2	152
Wheat area			94.1	130	100.6	125
Maize area			19.5	138	19.8	150
Sorghum area			48.3	150	44.5	149
Pearl Millet area			21.5	130	23.0	128

Notes: Panel A presents summary statistics for groundwater and agricultural output across all years and districts. Panel B presents these variables by year. Area is given in 1000 hectares and agricultural value is reported in million 1995 Rupees.

Table 2: Summary Statistics: Cost of groundwater extraction

Panel A: Aquifer depth

	Min Depth				Max Depth				
State	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	Obs
Andhra Pradesh	61.5	21.7	40	123	146	41.8	71	243	52
Bihar	62.2	26.4	20	150	183	33.1	114	250	60
Karnataka	45	8.12	30	50	135	8.12	130	150	26
Madhya Pradesh	50.3	22.1	30	98	152	28.3	88.3	200	105
Maharashtra	58	2.71	50.6	60	184	27.4	115	225	80
Orissa	49.7	0.456	48.8	50	202	16.5	185	249	31
Tamil Nadu	76.4	29.2	30.8	176	172.4	87.3	74.2	402	45
Uttar Pradesh	57.3	74.4	30	578	333	231	100	1800	152

Panel B: Electricity

	1995				2002				2004			
State	Price	Gen	T&D	Cost	Price	Gen	T&D	Cost	Price	Gen	T&D	Cost
Andhra Pradesh	5.3	21141	18.9	129	10.4	35327	32.9	268	10.1	32914	27.7	-
Bihar	15.2	2683	24	233	9.93	2212	26	280	25.6	-	36.66	-
Karnataka	1.8	15171	18.9	121	28.8	19214	35.9	278	35.1	18032	30.8	-
Madhya Pradesh	3.7	15090	19	167	5.35	22147	30	241	80.7	15802	41.4	-
Maharashtra	18.2	46561	15.3	162	61.1	62357	27	266	63.2	66991	34.1	-
Orissa	53.1	4130	23.8	185	-	8934	53	131	70.2	9119	57.09	-
Tamil Nadu	0	19917	16.9	152	1.00	25562	16.3	230	0	24114	17.16	-
Uttar Pradesh	43.1	20029	1776	74.0	88.4	23103	38.7	285	91.6	22836	22.6	-

Notes: Panel A presents district data on minimum and maximum aquifer depth by state. Panel B reports electricity data by state for three years. The variable T&D describes transmission and distribution losses. - indicates that the data are not available.

Table 3: OLS models of demand for groundwater

Demand Groundwater	(1)	(2)	(3)	(4)	(5)
Electricity Price	-1.838**			-1.669*	
	(0.837)			(0.876)	
Generation		-0.00445		-0.00462	
		(0.00403)		(0.00380)	
T&D losses			-6.330***	-3.620	
			(1.992)	(2.208)	
Elec price *Min aquifer					-0.0334**
					(0.0139)
Fixed effects	district	district	district	district	district
	year	year	year	year	state-year
Observations	965	936	965	936	550
R-squared	0.792	0.794	0.792	0.799	0.797

Notes: The dependent variable is the quantity in million cubic meters of groundwater extracted in a district-year. Columns 1-5 report results from an OLS model with standard errors clustered at the district (cols. 1-4) and state-year (col. 5) in parentheses. Regression includes log rainfall and a dummy for rain reported. Column 5 also includes max aquifer depth*electricity price.
Asterisks denote significance; *** p<0.01, ** p<0.05, * p<0.1

Table 4: Logistic model of groundwater exploitation

Exploitation Level	Critical (75%)	Exploited (100%)	Very Exploited (125%)
Electricity Price	-0.00875***	-0.0161***	-0.0159***
	(0.0031)	(0.034)	(0.0042)
Fixed effects	year	year	year
Observations	974	974	974

Notes: The dependent variable is an indicator variable set equal to 1 if annual groundwater extraction is 75%, 100% or 125% of the annual groundwater recharge. Results reported are the marginal effects from a logit model with standard errors clustered at the district in parentheses. The regression includes the log of rainfall and a dummy for rain reported. *** p<0.01, ** p<0.05, * p<0.1.

Table 5: OLS model of agricultural production

	(1)	(2)	(3)	(4)	(5)	(6)
	Agricultural Output			Area		
	Total	More Water Intensive	Less Water Intensive	Total	More Water Intensive	Less Water Intensive
Elec price*Min aquifer	-2.05e-05	-2.76e-05**	-2.08e-05	-2.07e-05	-2.72e-05***	-2.79e-05
	(2.30e-05)	(1.01e-05)	(3.40e-05)	(1.62e-05)	(6.74e-06)	(2.49e-05)
Fixed effects	district	district	district	district	district	district
	state*year	state*year	state*year	state*year	state*year	state*year
Observations	594	594	594	594	594	594
R-squared	0.946	0.976	0.964	0.972	0.977	0.975

Notes: The dependent variable is the log of agricultural output in cols.1-3 and the log of hectares of land cultivated in cols. 4-6. Columns 1-6 report results from an OLS model with standard errors clustered at the state-year. Regression includes log of rainfall, a dummy for rain reported and avg max aquifer depth*electricity price. Asterisks denote significance; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 6: OLS model of agricultural production, yields and area

	Panel A: Output						
	More Water Intensive					Less Water Intensive	
	Cotton	Sugar	Rice	Wheat	Maize	Sorghum	Pearl Millet
Elec price*	2.71e-05	-1.60e-05	-3.96e-05***	-2.66e-05	3.11e-05	-3.21e-05	1.38e-05
Min aquifer	(6.42e-05)	(1.12e-05)	(1.34e-05)	(3.20e-05)	(3.45e-05)	(2.83e-05)	(4.85e-05)
Fixed effects	district	district	district	district	district	district	district
	state*year	state*year	state*year	state*year	state*year	state*year	state*year
Observations	348	582	591	498	569	576	512
R-squared	0.986	0.962	0.975	0.989	0.971	0.965	0.966
	Panel B: Yields						
	Cotton	Sugar	Rice	Wheat	Maize	Sorghum	Pearl Millet
Elec price*	-1.42e-05	7.54e-06	-7.49e-06	4.67e-06	7.41e-06	2.61e-05*	-4.79e-06
Min aquifer	(3.23e-05)	(9.85e-06)	(1.05e-05)	(9.01e-06)	(1.66e-05)	(1.39e-05)	(1.79e-05)
Fixed effects	district	district	district	district	district	district	district
	state*year	state*year	state*year	state*year	state*year	state*year	state*year
Observations	348	582	591	498	569	576	512
R-squared	0.841	0.661	0.930	0.951	0.820	0.742	0.804
	Panel C: Area on which crops grown						
	Cotton	Sugar	Rice	Wheat	Maize	Sorghum	Pearl Millet
Elec price*	4.13e-05	-2.35e-05**	-3.21e-05***	-3.12e-05	2.37e-05	-5.83e-05***	1.86e-05
Min aquifer	(5.36e-05)	(8.74e-06)	(9.88e-06)	(2.49e-05)	(2.23e-05)	(1.76e-05)	(4.22e-05)
Fixed effects	district	district	district	district	district	district	district
	state*year	state*year	state*year	state*year	state*year	state*year	state*year
Observations	348	582	591	498	569	576	512
R-squared	0.991	0.987	0.976	0.991	0.979	0.976	0.975

Notes: The dependent variable is the natural log of crop-specific output, yields or area cultivated in a district year. Columns 1-8 report results from an OLS model with standard errors clustered at the state-year. Regression includes the log of rainfall, a dummy for rain reported and avg max aquifer depth*electricity price. Asterisks denote significance; *** p<0.01, ** p<0.05, * p<0.1

Table 7: OLS model of output and area by land suitability

	Sugar Area		Sorghum Area		Sugar Output		Sorghum Output	
	Not Suitable	Suitable	Not Suitable	Suitable	Not Suitable	Suitable	Not Suitable	Suitable
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Elec price	3.38e-05*	-3.14e-05***	-4.08e-05**	-0.000118***	-1.63e-05	-1.63e-05*	-1.74e-05	-9.94e-05**
*Min aquifer	(1.96e-05)	(1.01e-05)	(1.55e-05)	(2.14e-05)	(4.28e-05)	(7.91e-06)	(1.99e-05)	(4.71e-05)
Fixed effects	district	district	district	district	district	district	district	
	state*year	state*year	state*year	state*year	state*year	state*year	state*year	
Observations	313	269	274	302	313	269	274	302
R^2	0.982	0.994	0.983	0.971	0.991	0.979	0.975	0.976

Notes: The dependent variable is the natural log of area cultivated (cols. 1-4) and output.(cols. 5-8) in a district-year.
Columns 1-8 report results from an OLS model with standard errors clustered at the state-year.
A district is defined as suitable if the fraction of cultivated area allocated to crop c is above the mean in our sample.
Regression includes the log of rainfall, a dummy for rain, max aquifer depth*electricity price. *** p<0.01, ** p<0.05, * p<0.1

Table 8: Robustness Checks: Labor and Fertilizer Inputs

	(1) Male Wage	(2) Female Wage	(3) All Fertilizer	(4) Nitrogen	(5) Phosphate	(6) Potassium
Elec price*Min aquifer	5.77e-06**	6.00e-06***	1.15e-05	2.69e-05	-7.55e-06	4.00e-05
	(2.12e-06)	(1.55e-06)	(2.90e-05)	(3.17e-05)	(2.11e-05)	(5.43e-05)
Fixed effects	district	district	district	district	district	district
	state*year	state*year	state*year	state*year	state*year	state*year
Observations	357	312	429	429	429	429
R-squared	0.764	0.773	0.878	0.874	0.884	0.916

Notes: The dependent variable is the log of wages (cols. 1-2) or fertilizer use (cols. 3-6) in a district-year. Standard errors are clustered at the state-year. Regression includes log of rainfall, a dummy for rain reported and max aquifer depth *electricity price in parentheses. Asterisks denote significance; *** p<0.01, ** p<0.05, * p<0.1

Table 9: Robustness test: Exclusion of states with tiered rate structure

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Restricted Sample	Groundwater Extraction		Agricultural Output			Area		
			Total	More Water Intensive	Less Water Intensive	Total	More Water Intensive	Less Water Intensive
Electricity Price	-1.848**							
	(0.887)							
Elec price*Min aquifer		-0.0336**	-1.96e-05	-2.67e-05**	-2.07e-05	-2.02e-05	-2.67e-05***	-2.75e-05
		(0.0139)	(2.29e-05)	(1.02e-05)	(3.40e-05)	(1.62e-05)	(6.75e-06)	(2.50e-05)
Fixed effects	district	district	district	district	district	district	district	district
	state	state*year	state*year	state*year	state*yea	state*year	state*year	state*yearr
Observations	799	492	515	515	515	515	515	515
R-squared	0.798	0.805	0.946	0.973	0.968	0.971	0.974	0.977

Notes: The dependent variable is mcm of groundwater extraction in cols. 1 and 2, and the log of agricultural product and area in cols. 3-5. and 6-8, respectively. The sample is restricted to states in which there is a single flat electricity rate for all agricutural users. Standard errors are clustered at the district in col. 1 and state-year in cols. 2-8. Regression includes log of rainfall, a dummy for rain reported and, in columns 2-8 avg max aquifer depth*electricity price. Asterisks denote significance; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 10: Demand for electricity

Ag Elec Sales	(1)	(2)	(3)
ln(Ag electricity price)	-0.166**	-0.136*	-0.114**
	(0.0735)	(0.0691)	(0.0383)
Fixed effects	district year	state year	state year
Observations	209	227	227
R-squared	0.991	0.793	0.907
Number of states	4	15	15

Notes: The dependent variable is the natural log of electricity sales in millions of kWh in a district year (col. 1) or state-year (cols 2-3). Standard errors are clustered at the district level in column 1 and the state in columns 2-3. State-year trends are included in column 3. Asterisks denote significance; *** p<0.01, ** p<0.05, *p<0.1

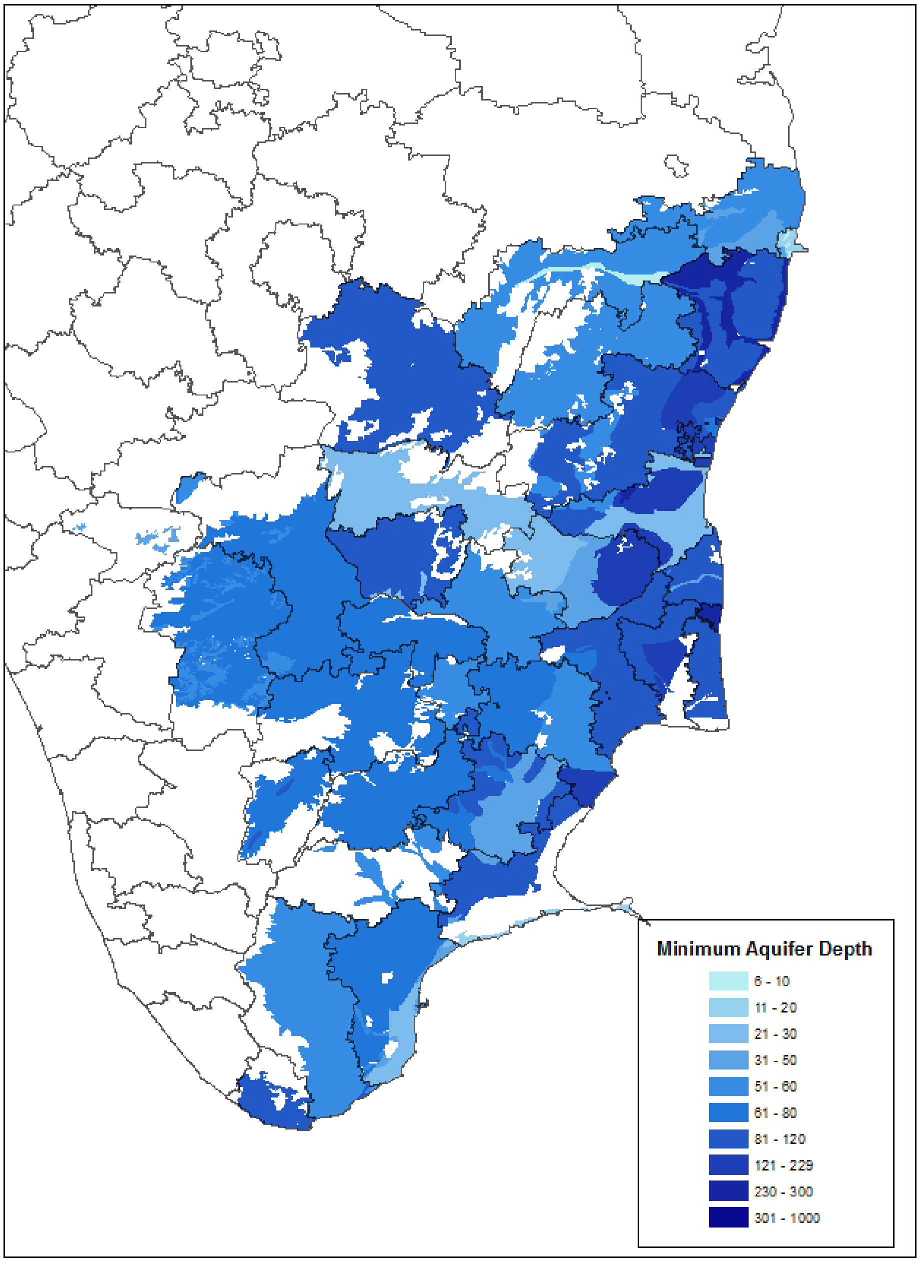

Figure 1: Spatial distribution of minimum aquifer depth in Tamil Nadu

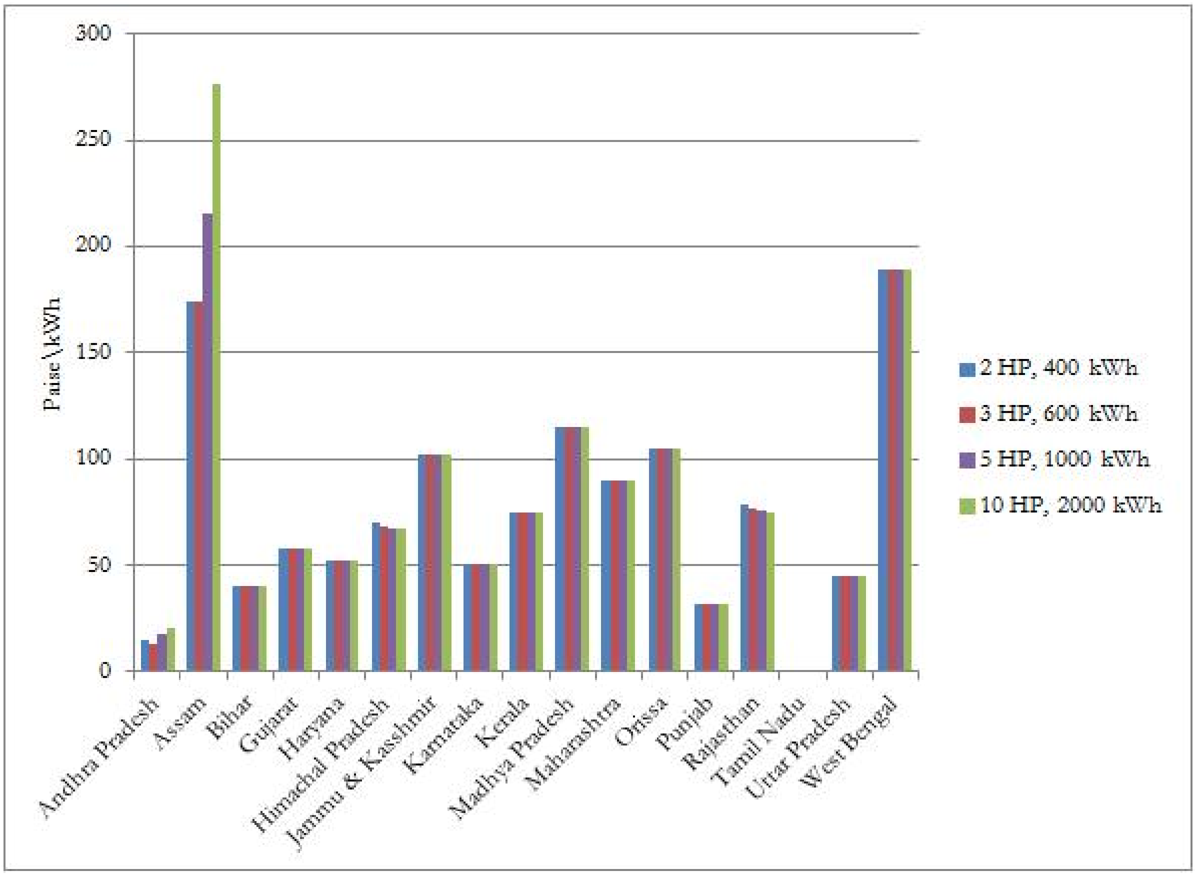

Figure 2: Agricultural electricity prices by tier and state in India 2004