Water in the Balance: The Impact of Water Infrastructure on Agricultural Adaptation to Rainfall Shocks in India

Esha Zaveri, Douglas H. Wrenn, and Karen Fisher-Vanden

Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2

WORK IN PROGRESS. DO NOT CITE

Water in the Balance: The Impact of Water Infrastructure on Agricultural Adaptation to Rainfall Shocks in India

Abstract: Investments in water infrastructure remain key to climate change adaptation plans in many countries, and rank high in adaptation costs for developing countries (Narain et al., 2011). In this paper, we use district-level panel data from 1970-2005 across India's major agricultural states to investigate the role played by subsidized access to electricity, groundwater wells, tank and dam projects in mediating the vulnerabilities associated with monsoonal variation. We focus on wheat, a staple of India's food supply, as it requires irrigation and represents a significant portion of India's total agricultural output. Results show that the impact of negative precipitation shocks is significantly dampened when a particular district has access to a more reliable source of irrigation – e.g., access to tubewells helps to dampen the impact of negative precipitation shocks on irrigation decisions associated with wheat, while upstream dams do not significantly contribute to this dampening effect. In contrast, having access to dugwells exacerbates the impact of a fall in monsoon precipitation curtailing irrigation of wheat. Our results suggest that historical agricultural policies that increased access to tubewells and the subsequent electrification of regions naturally endowed with more groundwater have equipped farmers with the ability to withstand monsoonal shocks and fluctuations.

Keywords: Water infrastructure, Adaptation, Agriculture, Irrigation, Indian Monsoon

JEL Codes: O13, Q15, Q25, Q54, Q56

1. Introduction

Given the broad scientific consensus surrounding climate change, there is a growing concern that increased climatic variability, through its impact on agriculture, is likely to add to the already precarious situation facing many poor households, most of whom are located in developing countries. In India, the south-west monsoon, an atmospheric phenomenon that brings 80 percent of India's yearly rainfall over a four-month period in summer and early fall, plays a key role in providing the water needed to sustain agriculture as it helps to recharge rivers, aquifers, and reservoirs. These rainfall realizations impact water supply, cropping decisions, irrigation decisions, and agricultural profits, thus directly impacting the welfare of around 770 million rural inhabitants who make up the largest share of India's poor (World Bank, 2012). New evidence suggests that anthropogenic forcings have weakened the monsoon since the 1950s making it more erratic (Krishnan et al., 2015). Studies also project future increases in inter-annual and intra-seasonal variability of monsoon rainfall (Menon et al., 2013).

In order to cope with such rainfall variability and smoothen the variability of water supply, investments in water infrastructure remain key to climate change adaptation plans. For many developing countries, water management infrastructure is ranked among the top three categories of estimated adaptation costs (Narain et al., 2011). This is especially salient for India, whose government has for decades promoted investments to expand irrigation as a method for improving agricultural growth, and alleviating rural poverty (Shah, 2010). Previous research has studied the effects of irrigation dams, and groundwater stress on rural welfare, and food production (Duflo and Pande, 2007; Sekhri, 2013). However, there is limited research on the potential mediating effects of different types of water infrastructure in smoothing climate uncertainties, the consequences for irrigation water use decisions, and the spatial distribution of these impacts. Developing such estimates is critical for India since it is the world's most water-stressed nation; it is also the largest agricultural and groundwater user in the world and is thus likely to be particularly vulnerable to future changes in climate (Shah, 2010; Mendelsohn et al., 2006).

In this paper, we use district-level panel data from 1970-2005 across 19 major agricultural states in India to investigate the role played by subsidized access to electricity, groundwater wells, tanks, and dam projects in mediating the vulnerabilities associated with monsoonal variation. Specifically, we focus on the ability of these investments to reduce the uncertainty associated with increased monsoonal variability by increasing access to more reliable, yet largely unstainable sources of groundwater. We focus on wheat, a staple of India's food supply, as it requires irrigation and represents a significant portion of India's total agricultural outcomes. Our preliminary results show that the impact of negative precipitation shocks is significantly dampened when a particular district has access to a more reliable source of irrigation – e.g., access to tubewells helps to dampen the impact of negative precipitation shocks on irrigation decisions associated with wheat, while upstream dams do not significantly contribute to this dampening effect. In contrast, having access to dugwells exacerbates the impact of a fall in monsoon precipitation curtailing irrigation of wheat.

Our results also shed light on the degree to which the introduction of an irrigation-intensive technology (high-yielding varieties of seeds) that triggered the Green Revolution in the mid- 1960s has influenced the evolution of irrigation infrastructure and irrigation decisions in the period we study. Other countries have also been influenced by the evolving impacts of irrigation access, particularly in relation to groundwater. Hornbeck and Keskin (2014) examine how increased access to the Ogallala aquifer in the United States via improved pumps and center pivot irrigation technology initially decreased drought sensitivity but increased drought sensitivity over time because farmers shifted to more water-intensive crops. Given the lack of data over a much longer historical period, we do not explicitly estimate short-run and long-run impacts of groundwater access. However, our results illustrate how historical agricultural policies that increased access to tubewells and the subsequent electrification of regions naturally endowed with more groundwater- as measured by the capacity or thickness of the aquifer- have equipped farmers with the ability to withstand monsoonal shocks and fluctuations. The results also suggest that many of these policies may have increased the use of irrigation sources such as non-renewable groundwater from deep tubewells, which are unlikely to be sustainable in the long run.

Our findings provide a better understanding of how different types of water infrastructure are likely to impact agricultural outcomes under potential water scarcity settings and shed light on the resulting behavior of end-users of water. Such insights can also inform ongoing debates about whether certain types of infrastructure can help with climate change adaptation mechanisms going forward.

The rest of the paper is organized as follows. Section 2 describes the data used in the analysis. Section 3 examines the path dependency of groundwater development in India. Section 4 provides background on the link between different types of groundwater irrigation technology and electricity in India. Section 5 assesses the impact of different types of water infrastructure on irrigation decisions in the dry season. Section 6 concludes.

2. Data

2.1 Aquifers

We use the Water Resources plates (plates 88 to 92) from the 1982 National Atlas of India , which contains hydrological maps of the presence of three categories of aquifer: thickest (aquifer greater than 150 meters), fairly thick (aquifer thickness between 100 and 150 meters) and thick (aquifer thickness up to 100 meters). Figure 2.1 shows the Water Resources plate (plate 88) that was used to construct measures of aquifer thickness for the northern regions of India. We also use the World Bank India Agricultural and Climate data at the district level that reports these variables for 124 districts. The thickness of the aquifer reflects groundwater abundance. It does not measure the water table or annual water depth within the aquifer but captures a long term geological potential (Jain, Agarwal and Singh, 2007).[1] The thickest aquifers are under various districts of Punjab, Haryana, and Tamil Nadu, the Green Revolution states of India, and the fairly thick aquifers underlay Uttar Pradesh and West Bengal, other major food-producing states in the country. Districts that are not under any of these categories have been verified to have sporadic aquifers (Sekhri, 2014) and are not taken into account in the analysis.

2.2 Sources of Irrigation and Electricity

The electricity data comes from the Central Electric Authority's "Public Electricity Supply- All Indian Statistics" published annually between 1950 and 1985. We use the proportion of villages electrified in each state in the year 1965, prior to the period of analysis[2], to allay concerns that electrification during the sample period could also be affecting irrigation decisions. During the 1960s, most of the available electricity was generated within the States, and there was negligible cross-trading of electricity (Rud, 2012). Therefore using this measure also reduces

[1] While subsequent use of available groundwater could be endogenous to irrigation decisions, this measure of groundwater availability at the outset of the period of analysis is exogenous to these decisions over time.

[2] We thank Juan Pablo Rub for making this data available.

concerns that there were spillover effects to other states.

In order to construct source-wise irrigation variables, we use data from the Land Use Statistics Database by the Directorate of Economics & Statistics (DES), Ministry of Agriculture, and the Village Dynamics in South Asia project at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT). All primary statistics related to crop area, production and irrigation are collected using land use surveys by the State governments and consolidated for the country as a whole by the DES. ICRISAT compiles agricultural statistics from various government sources in India including the DES, and is the only long-term publicly available dataset of district- level statistics from 1970 to 2006. Much of the data prior to the mid-1990s is not electronically available and is recovered from books and documents printed by the government. We compared the source-wise irrigation data post 1998 between ICRISAT and the online records of the Land Use Statistics Database[3] to make sure the data are consistent across the two sources.

Our dam data provides information on the number of irrigation dams constructed both within and upstream of a district in a year, and is collected from the World Registry of Large Dams. We draw on the data analyzed by Duflo and Pande (2007)[4] to identify whether a district is downstream or upstream from a dam. Districts that contain a dam do not generally benefit from irrigation, due to soil salinity in surrounding areas and submergence of land immediately surrounding the dam.[5] However, regions that are downstream of a dam or in the command area typically benefit from irrigation access (Duflo and Pande, 2007; Thakkar, 2000). Dam construction is related to state wealth (Duflo and Pande, 2007), but since our analysis is focused on inter-district variation any bias associated with the correlation of state wealth and dam presence will be reduced. Further, we use the presence of an upstream dam or whether a district is downstream from a dam at the beginning of the period of analysis to eliminate concerns that building dams during the sample period could be affecting irrigation decisions, and other issues related to endogenous dam placement.

2.3 Weather Data

---

[3] Land Use Statistics Database's online records begin after 1998.
[4] The dataset is made available by the authors at http://hdl.handle.net/19902.I/IOJHHXOOLZ (Duflo and Pande, 2006)
[5] There could be some beneficial economic activity in the reservoir area, such as fishing, but the agricultural benefits remain limited.

Observed temperature and precipitation data were acquired from the relatively new gauge-based observationally-gridded daily dataset Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) (Yasutomi, Hamada and Yatagai, 2011; Yatagai et al., 2012) compiled by the Research Institute for Humanity and Nature (RIHN) and the Meteorological Research Institute of Japan, Meteorological Agency (MRI/JMA). Precipitation and temperature data are available at a spatial resolution of 0.25° x 0.25° for 1951-2007, and 1961-2007 respectively. We re-scale the gridded weather data to the district level by taking an area-weighted average of grid values in each district, using GIS maps corresponding to 1966 district boundaries.

APHRODITE is the only long-term continent-scale daily product that contains a dense network of daily rain-gauge data for Asia including the Himalayas, South and Southeast Asia, and the mountainous areas in the Middle East (Yatagai et al., 2012).[6] The higher resolution APHRODITE data captures spatial trends in precipitation in greater detail (Duncan et al., 2013), and is also able to effectively account for fluctuations in precipitation driven by changes in local emissions and land use changes (Kharol et al., 2013). APHRODITE compares reasonably well with the 1°x1° gridded rainfall data from the Indian Meteorological Department (IMD)[7] that is predominantly used to study weather-crop relationships in India.

3. Path-dependency of Groundwater Development

The Indian government implements a number of agricultural policies and investments that directly or indirectly affect irrigation. The Green Revolution that introduced a new irrigation-intensive agricultural technology in 1966-67, was one such policy initiative that was a watershed moment in Indian agriculture.[8] Figure 2.2 highlights this moment, and shows the sharp rise in the adoption of high-yielding varieties (HYV) post 1966, with no HYV planting prior to

[6] The dataset is interpolated using station gauge data obtained from a variety of sources: the World Meteorological Organization (WMO) Global Telecommunication System data, pre-compiled datasets, compilation of station data and monthly climatologies (Yatagai et al., 2009).

[7] Both datasets are well correlated (correlation coefficient >0.6) for the entire extent of India (Rajeevan and Bhate, 2009), with some differences. APHRODITE uses recorded observations from 2000 rain-gauge stations - instead of IMD’s use of 2140 - and also underestimates the maximum rainfall along the west coast and in north eastern India. However, the overall differences are mostly within 3 mm/day over the entire country.

[8] The focus on agricultural innovation spearheaded by the Green Revolution was in part a response to the food crisis worsened by the consecutive droughts of the mid 1960s, and the imports of large quantities of grain. The political leadership at that time was also pushing for a reduction in the dependence on food aid from the United States (Evenson and Rosegrant, 1998; Dasgupta, 2014)

1966. This rise was also accompanied by a rapid expansion of wells, particularly tubewells , and a shift from a state- controlled surface water driven irrigation economy to one led by private investments in groundwater infrastructure (Figure 2.3).[9] This coincident rise in groundwater irrigation was in large part because the successful adoption of HYV critically hinged on the intensive, timely and controlled use of irrigation that groundwater sources could provide. Irrigation through wells rose from 28 percent in 1950-51 to 62 percent in 2001-02, largely because the share in tubewell irrigation increased from zero to over 40 percent (Gandhi, and Namboodiri, 2009). Net area irrigated by private tubewells is about double the area irrigated by canals .

Inherent geographical differences that influenced the variation in irrigation capacities across regions was one of the reasons for the widespread spatial variation seen in the diffusion and uptake of HYV seeds during the Green Revolution (Foster and Rosenzweig, 1996). For instance, aquifer thickness, a prehistoric hydrogeological characteristic, which reflects groundwater abundance or water endowment, influenced the variation in the types of groundwater technology that emerged across the country. Regions that were endowed with more groundwater due to the presence of naturally occurring thick aquifers were more suitable for tubewell irrigation and cost-effective utilization of electric pumpsets, and thus HYV crop cultivation (Rud, 2012).

Using this variation in aquifer thickness that is exogenous to irrigation use over time, we estimate the time-varying effects of the introduction of the Green Revolution and spatial variations in groundwater endowments on outcomes Y_{dt} , that include HYV area, tubewell irrigated area and dugwell irrigated area. Following in the spirit of Sekhri (2014) and Rud (2012), we estimate the following:

---

[9]A few government run tubewell programs do exist, like the Indo Dutch Tube Well Program studied by Sekhri (2011). However, in general, researchers have noted that the majority of India's wells and tubewells are owned by individual farmers (Mukherji, Rawat and Shah, 2013). Studies also note that compared to land ownership, the distribution of well ownership is more equitable (Gandhi and Namboodiri, 2009; Mukherji, Rawat and Shah, 2013). Small and marginal farmers with landholdings less than two hectares together owned around 67 percent of the groundwater structures in 2005-06 even though their share of operated land was 40 percent. A majority of these wells are financed by private investments by the farmers themselves, followed by a combination of government subsidies, bank loans and savings. Studies also suggests that average yield on plots irrigated by private wells is much higher than that irrigated by canals, and public tube wells (Gandhi and Namboodiri, 2009).

$$Y_{dt} = \alpha_0 + \alpha_1 Thick_d + \alpha_2 Fairly\, Thick_d + \lambda_t + \sum_t \alpha_{1t}(Thick_d * T_t) + \sum_t \alpha_{2t}(Fairly\, Thick_d * T_t) + \epsilon_{dt} \quad (1)$$

Here, $Thick$ is an indicator that equals one if a district has access to the thickest aquifers, and zero otherwise. Similarly, $Fairly\, Thick$ is an indicator that equals one if a district has access to fairly thick aquifers, and zero otherwise. The excluded group is the thick aquifer category. λ_t are year fixed effects to capture yearly shocks, and standard errors are clustered at the district level. The coefficients of interest are α_{1t} and α_{2t} where positive and significant values indicate that districts with greater access to a particular aquifer category plant more HYV or irrigate more via tubewells or dugwells. Increasing values of α_{1t} and α_{2t} imply that over time the factors responsible for successful HYV adoption also triggered a divergence in HYV adoption, and the type of irrigation used. We estimate the equation and plot the year-by-year coefficients for the districts with the thickest aquifers and fairly thick aquifers relative to those with thick aquifers in Figures 2.4, 2.5, and 2.6.

As seen in the figures, districts with greater groundwater endowments also saw higher HYV cultivation, and higher tubewell irrigation. In contrast, districts with greater groundwater endowments started to see a fall in dugwell irriation. Figure 2.3 shows that growth in dugwell irrigated area remains substantially lower than tubewell irrigated area after the mid-1970s. These patterns highlight that HYV adoption and groundwater infrastructure started to differ in areas with higher initial groundwater endowments after the introduction of the Green Revolution.

Along with the rise in groundwater irrigation, there was a concurrent increase in demand for electricity and electric pumpsets to access irrigation water cheaply, since other alternatives, such as diesel pumps, were relatively more expensive (Rud, 2012). Even prior to the Green Revolution, the State Electricity Boards (SEBs) had already started to introduce flat tariffs for agricultural electricity to spur groundwater irrigation (Badiani, Jessoe and Plant, 2012). In Figure 2.7, we see that there is a rise in the share of villages electrified post 1965. The extent of electrification increased greatly between 1966 and1979; the proportion of electrified villages went up from 13 percent to 43.5 percent, closely following the trend in the ownership of electric pumpsets (Barnes, 1988). By 2008, the Indian government estimated that there were 15 million electrical pumpsets (agricultural consumers) on the grid, (Fishman et al., 2014). We run a similar regression as above where the divergence in electrification is explained by the interaction of aquifer thickness categories with time dummies. Instead of using district-level indicators of aquifer thickness, we use the proportion of state area that is under the thickest or fairly thick aquifer category, since we only have access to electricity data at the state level. Figure 2.8 plots the year-by-year coefficients up to 1976. We see that states with greater groundwater endowments also saw an expansion in electrification.

Overall, these patterns suggest that access to groundwater endowments enabled the adoption of HYV which, in turn, created a demand for tubewells and rural electricity. Over time, these characteristics that determined the successful adoption of HYV triggered a path of divergence in the expansion of tubewell irrigation and electricity in India.

4. Background: Groundwater Technology and Electricity

In the following section, we highlight various characteristics of groundwater irrigation technology that underlie the heterogeneous effects seen in the empirical analysis.

Dubash (2002) notes that there are four dimensions to groundwater irrigation technology: accessing the water, pumping the water to the surface, the vertical location of the pump and the power of the pump. Dugwells are the most common mode of accessing water. They are also the shallowest, ranging in depth from 33-50 feet[10] (Jain, Agarwal and Singh, 2007). Before the time of mechanized irrigation in India, water was pumped to the surface using a traditional lift system dependent on animal power. Later, diesel engines came to be used along with suction pumps. In this type of setup, the engine is installed at the well mouth, and the pump is lowered down the well shaft until it rests within 10 meters of the water level[11] (Dubash, 2002). With the spread of electricity to India's villages, motors started to replace engines. In this setup, the motor is fused together with the pump[12] and placed just above the water level (Dubash, 2002).[13] However, over time, it can become increasingly unviable to adapt to falling water levels with dugwells and suction pumps. For instance, as water levels drop, the entire well floor has to be deepened[14] to remain within the 10 meters range of the suction pump, the equipment has to be raised and the

[10] These depths can increase over time as irrigators deepen wells and lower pumps to keep pace with falling water levels.
[11] Suction pumps are limited by the height air pressure can lift a column of water and so must be located no more than about 10 meters from the water source
[12] In the engineering literature, this is referred to as 'monoblock'
[13] The motor can also be placed on the dry bed of the dugwell, such that water is sucked out using a hand drilled bore. Hence, this type of well is also called dug-cum-bore well). In general, such technology is difficult to maintain since it is located at the bottom of the well.
[14] Dugwell depths can go as deep as 150 feet.

exposed well wall has to be lined to prevent collapse, thus, considerably increasing the extent of repair and maintenance (Dubash, 2002). Moreover, over time, the suction force of the pump limits the extent to which water can be raised from very high depths. This is because 33 feet (or 10 meters) of water exerts a pressure of 1 atmosphere, and is the maximum height as which a pump can suck water (Dubash, 2002; Sekhri, 2011). Since suction cannot create a perfect vacuum, the accepted standard for vertical lift using these pumps is 25 feet (or approximately 8 meters) (Sekhri, 2011). Therefore, if the water level is beyond 25 feet or 8 meters below the ground level, then suction pumps cannot be used to lift water.

Tubewells allow irrigators to circumvent these problems associated with increases in pumping depths. Tubewells comprise a machine drilled tube from the ground level, an electric powered motor and an electric submersible force pump that is lowered into the well shaft until it rests below the water depth. The electric submersible force pump pushes water up without relying on suction, enabling water to be pumped to any height and from far greater depths beyond the capacities of diesel engines or electric suction pumps used in dugwells (Dubash, 2002). [15] Since tubewells, on average, have larger pumps, it is also possible to extract greater yields of water. Shallow tubewells can range in depth from 50-70 feet, and in sedimentary formations can go as deep as 230 feet, providing roughly two to three times the water available from a dug well (Jain, Agarwal and Singh, 2007). Deep tubewells are drilled to depths of 300-500 feet and provide fifteen times the water available from a dug well (Jain, Agarwal and Singh, 2007). Even if water levels fall in tubewells, submersible pumps can be easily lowered to access water.[16] Tubewells are, therefore, technically able to provide assured long-term access to groundwater even in times of drought, and also greater volumes of water.[17]

5. Heterogeneous Effects

In this section, we use the variation in irrigation infrastructure and electricity provision initiated by the Green Revolution as well as natural groundwater endowments to understand their role in diminishing or amplifying the influence of precipitation shocks on crop irrigation

[15] When farmers switch from low cost surface pumps to much more expensive submerged pumps as depths increase, the overall fixed cost of pumping increases at one (or more) discrete point(s) (Sekhri, 2011), even with subsidized electricity.

[16] Over time, however, discharge rates could decrease if the pump is made to extract water from even greater depths

[17] Shah and Kishore (2009) explain that the dugwell irrigated southern regions in India were affected relatively more than the tubewell irrigated northern states during the 2002 drought that followed below normal rainfall in 2000 and 2001.

decisions in the dry season. We focus on wheat since it is the predominant irrigation-intensive crop grown in the dry season.

5.1 Empirical Model and Results

We split the districts into those that fall under thickest, fairly thick and thick aquifers to compare how areas with different factor (water) endowments influence adaptation of agriculture to weather shocks. The sample size is relatively small since we only cover districts that have information about aquifer thickness or initial groundwater endowments. The following model is estimated separately for each sample of districts:

$$\log Y_{d,t} = \gamma_0 + \alpha\, logY_{d,t-1} + \beta\, log\, \boldsymbol{R_{d,t}} + \gamma_1 logGDD + \gamma_2 log\overline{A_{d,t-1,t-6}} + \rho_d + \lambda_t + A_{s,t} + \epsilon_{d,t}$$

As discussed in section 3, factor endowments have played a role in influencing the types of irrigation infrastructure and capacities that have developed in India. Therefore, we expect that precipitation shocks will not impact districts that overlay the thickest aquifers. Results in Table 2.1 show that, as expected, for districts overlaying the thickest aquifers, irrigation in the dry season is completely buffered from monsoon rainfall shocks, and monsoon rainfall no longer impacts wheat irrigation. For districts that overlay fairly thick and thick aquifers, however, the impact of monsoon rainfall is positive and significant, such that the magnitude of the coefficient on monsoon rainfall is significantly lower for regions with access to fairly thick aquifers (100-150 meters) relative to those with access to thick aquifers (≤ 100 meters). These results reflect the differential processes of electrification and tubewell irrigation in places with higher groundwater endowments as illustrated in section 3.

In Table 2.2, we examine whether better access to the benefits of groundwater in districts that experienced a higher process of electrification, can help mediate rainfall shocks. Since electrification enables the use of electric pumps for groundwater extraction, we interact total precipitation with a dummy for states whose share of electrified villages was greater than the national average in 1965 in Column (1) of Table 2.2. We use the share of electrified villages at the outset of the Green Revolution and a little before our sample period to allay the concern that electrification during the sample period could also be affecting irrigation decisions. We find a significant impact of electrification mediating the adverse effects of a negative rainfall shock on wheat irrigated area. In columns (2) and (3), we interact total precipitation with share of electrification as well as a dummy for whether a district overlays the thickest or fairly thick aquifer. The excluded group is the thick aquifer category. As expected, we find that the mediating effect of electrification is even stronger in districts with access to the thickest aquifers (Column (2)).

Next, we examine the impacts of different types of irrigation infrastructure on mitigating or amplifying monsoon rainfall shocks. In Columns (4)-(6) , we interact total monsoon precipitation with dummies identifying districts whose proportions of tubwell, dugwell and tank irrigated area (normalized by district area) are above the national average. Consistent with section 4, we find that tubewells mediate the impact of a fall in monsoon precipitation on wheat irrigation, in contrast to dug wells and tanks. The coefficients on the monsoon precipitation variable and the interaction of monsoon rainfall with the tubewell indicator variable have opposite signs, and remain statistically significant in columns (4) - (6). On the other hand, dugwells amplify the effect of a monsoon rainfall shock. The coefficients on the monsoon precipitation variable and the interaction of monsoon rainfall with the dugwell indicator variable have the same sign, and are statistically significant (Columns (5) and (6)). Overall, the results suggest that access to deep groundwater plays a fundamental role in mediating negative rainfall shocks and supporting irrigation in the dry season.

Even as the Green Revolution provided an impetus to the rise of wells, public investments in dams continued. The Government built 3000 large dams[18] between 1947 and 2001 (Pande, 2008), using 80 percent of its direct irrigation outlays for major and medium irrigation[19] projects towards their construction (Vaidyanathan, 2010; Taraz, 2015). Since dams supply surface water to downstream districts, we identify districts that have upstream dams. Since dam placement is likely endogenous to the extent of irrigation, we use indicator variables to classify downstream districts using information about presence of upstream dams from 1970 or the beginning of our sample period. This prevents concerns about dam presence during the sample period also affecting irrigation coverage. Results are reported in Column (7) of Table 2.2. We see that districts that are downstream are able to mediate the effect of a fall in precipitation since the interaction term between the downstream indicator and monsoon precipitation is

[18] A large dam is defined as a dam having a height of 15 meters from the foundation, or, if the height is between 5 and 15 meters, having a reservoir capacity of more than 3 million cubic meters (Duflo and Pande, 2007)
[19] Major (medium) irrigation projects are defined as those with a command area larger than 10,000 (2000) hectares.

negative; however this effect is not significant.

6. Conclusion

The results of this analysis demonstrate that access to different types of irrigation infrastructure can significantly dampen or exacerbate the role that monsoonal variation plays on irrigation decisions along the extensive margin.

The results also show that policies enacted during the Green Revolution that increased access to more reliable sources of irrigation have been vital in mediating the impact of monsoonal uncertainties – especially for dry-season crops like wheat. For instance, agricultural policies related to tubewell expansion and electrification, have been especially vital in determining the extent to which monsoonal rainfall variation impacts dry- season irrigation.

Our results also suggest that many of these policies may have increased the use of irrigation sources that may not be sustainable in the long run. While groundwater irrigation clearly provides an economic and social benefit via access to a more reliable source of irrigation, the fact that these resources are non-renewable in many regions of the country makes their use as an irrigation resource largely unsustainable in the long run.

References

Badiani R., K.K. Jessoe and S. Plant (2012) Development and the environment: the implications of agricultural electricity subsidies in India, *The Journal of Environment & Development* 21(2): 244-262

Barnes, D. F. (1988) Electric power for rural growth: how electricity affects rural life in developing countries, *Rural Studies Series*

Dasgupta, A. (2014) Why Dominant Parties Decline: Evidence from India's Green Revolution, Working Paper

Dubash, N. K. (2002) *Tubewell capitalism: groundwater development and agrarian change in Gujarat*. Oxford University Press, New Delhi

Duflo, E. and R. Pande (2007) Dams, *Q. J. Econ.*, 122(2):601-646

Evenson, R. E.and M.W. Rosegrant (1998) *Agricultural Research and Productivity Growth in India*. Vol. 109 International Food Policy Research Institute.

Fishman, R. U. Lall, V. Modi and N. Parekh (2014) Can Electricity Pricing Save India's Groundwater? Evidence from Gujarat, Working Paper

Foster, A. D. and M. R. Rosenzweig (1996) Technical change and human-capital returns and investments: evidence from the Green Revolution, *American Economic Review*, 931-953.

Gandhi, V.P. and Namboodiri, N.V. (2009) *Groundwater irrigation in India: Gains, costs, and risks.* Ahmedabad, India: Indian Institute of Management

Hornbeck, R., and P. Keskin (2014) The historically evolving impact of the ogallala aquifer: Agricultural adaptation to groundwater and drought, *American Economic Journal: Applied Economics, 6*(1), 190-219.

Jain, S., P. Agarwal, and V. Singh (2007) *Hydrology and Water Resources of India*, Water Science and Technology Library, Springer

Krishnan, R., T. P. Sabin, R. Vellore, et al. (2015) Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world, *Clim. Dynam.* 1-21

Mendelsohn, R., A. Dinar, and L. Williams (2006). The distributional impact of climate change on rich and poor countries, *Environ. Dev. Econ*, 11(02):159-178

Menon, A., A. Levermann, J. Schewe, J. Lehmann and K. Frieler (2013) Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models. *Earth Sys. Dynam.* 4(2): 287-300

Mukherji, A., S. Rawat, and T. Shah (2013) Major Insights from India's Minor Irrigation Censuses: 1986-87 to 2006-07, Economic & Political Weekly, *48*(26): 115-124.

Narain, U., S. Margulis, and T. Essam (2011) Estimating costs of adapting to climate change, *Clim. Policy*, 11: 1001–1019

Rajeevan, M. and J. Bhate (2009) A high resolution daily gridded rainfall dataset (1971-2005) for mesoscale meteorological studies, *Curr. Sci*, 96, 558-562

Rud, J. P. (2012) Electricity provision and industrial development: Evidence from India, *Journal of development Economics*, *97*(2): 352-367

Sekhri, S. (2011) Public provision and protection of natural resources: Groundwater irrigation in rural India, *American Economic Journal: Applied Economics*, 29-55.

Sekhri, S. (2013) Missing Water: Agricultural Stress and Adaptation Strategies in response to Groundwater Depletion among Farmers in India, Working Paper

Sekhri, S. (2014) Wells, Water, and Welfare: The Impact of Access to Groundwater on Rural Poverty and Conflict. *Am Econ J Appl Econ 6*(3):76-102.

Shah, T. and A. Kishore (2009) Will the Impact of the 2009 Drought Be Different from 2002?" *Economic and Political Weekly*, 11-14.

Shah, T. (2010) *Taming the Anarchy: Groundwater Governance in South Asia*, Resources for the Future Press, Washington DC

Taraz, V. (2015) Adaptation to Climate Change: Historical Evidence from the Indian Monsoon, Yale University Working Paper

Thakkar, H. (2000) *Assessment of Irrigation in India*. World Commission of Dams

Vaidyanathan, A. (2010) *Agricultural Growth in India: The Role of Technology, Incentives, and Institutions*, Oxford University Press India

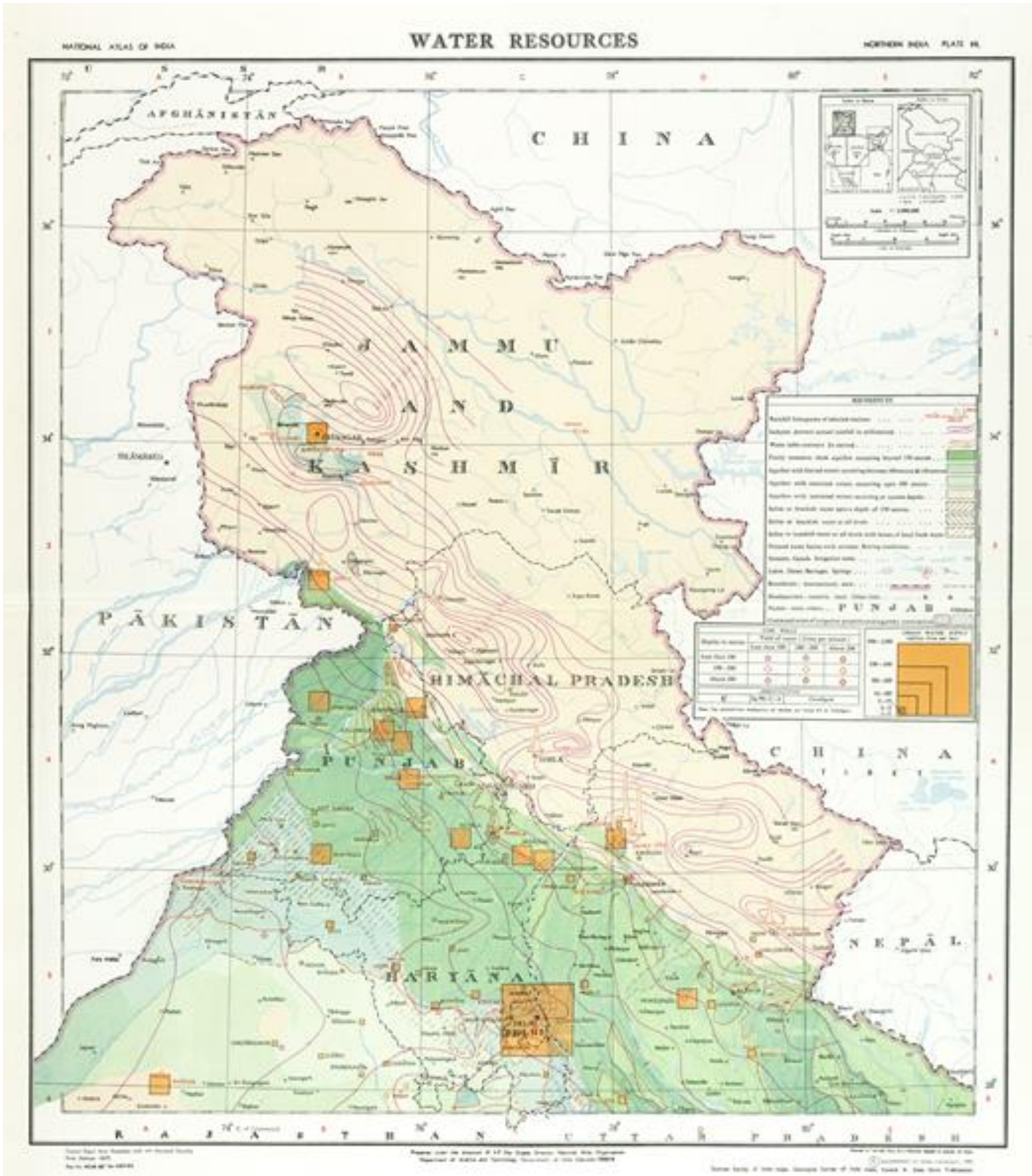
Yasutomi, N., A. Hamada and A. Yatagai (2011) Development of a long-term daily gridded temperature dataset and its application to rain/snow discrimination of daily precipitation, *Global Environmental Research* 15(2):165-172.

Yatagai A., et al. (2012) APHRODITE: Constructing a Long-term Daily Gridded Precipitation Dataset for Asia based on a Dense Network of Rain Gauges, *Bulletin of American Meteorological Society*, 93, 1401-1415, doi:10.1175/BAMS-D-11-00122.1.

World Bank (2012) India: Issues and Priorities for Agriculture, available from: http://www.worldbank.org/en/news/feature/2012/05/17/india-agriculture-issues-priorities

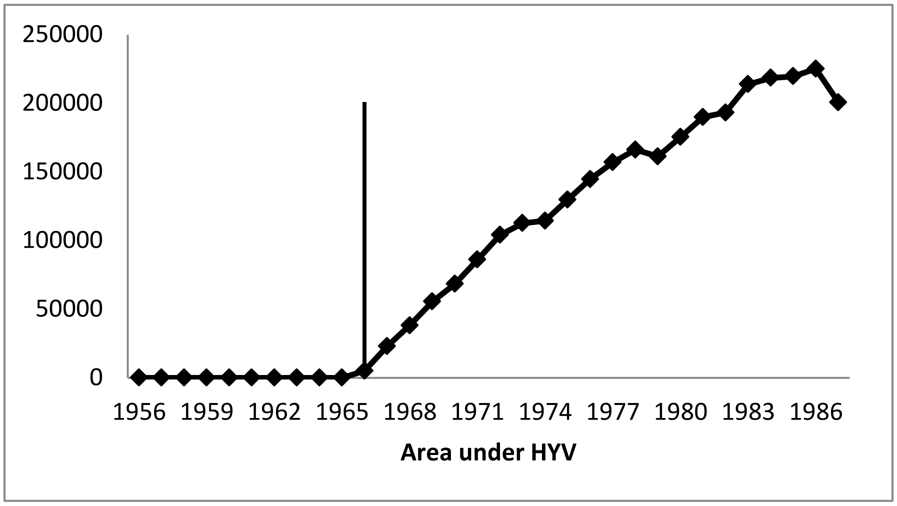
Figures

Fig 2.1 Aquifer capacity in northern India



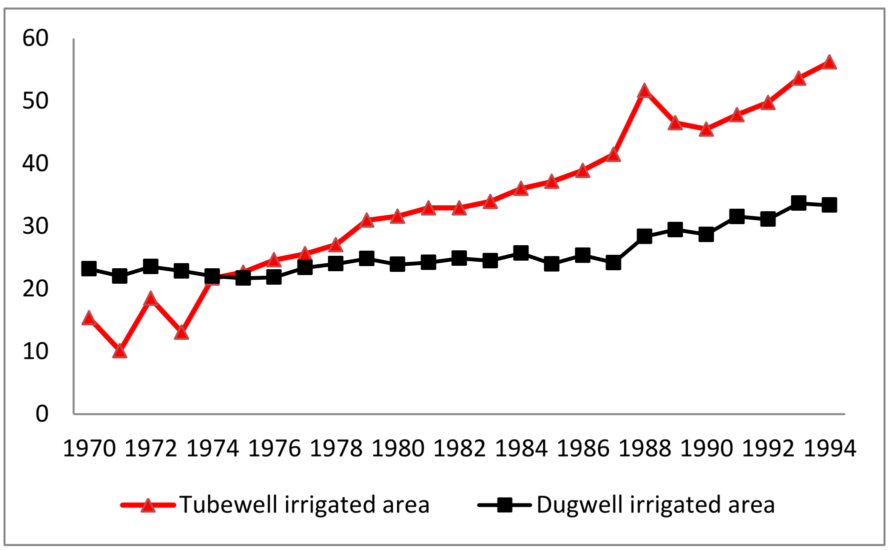
Notes: The map illustrates Plate 88 from the 1982 National Atlas of India

Fig 2.2 Trends in area under High Yielding Varieties (HYV)



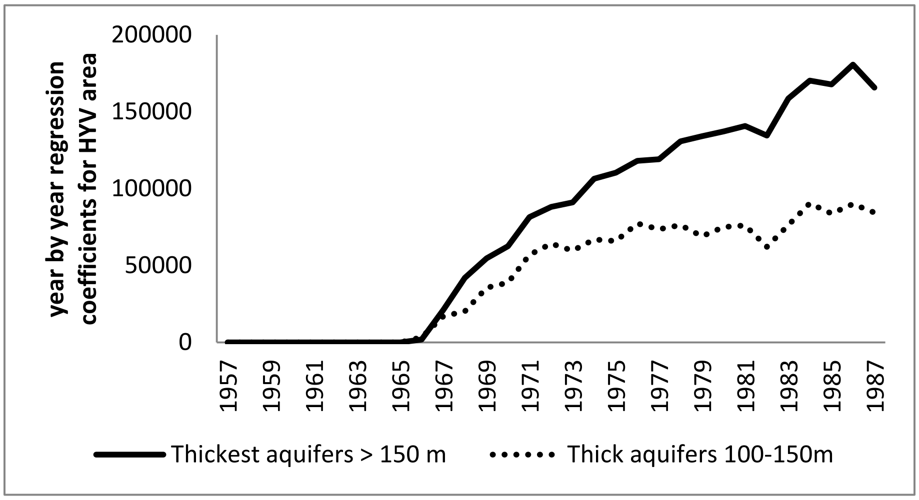
Notes: Area is measured in hectares. Data is from the Indian Agriculture and Climate Dataset, World Bank.

Fig 2.3: Trends in irrigated area by different sources



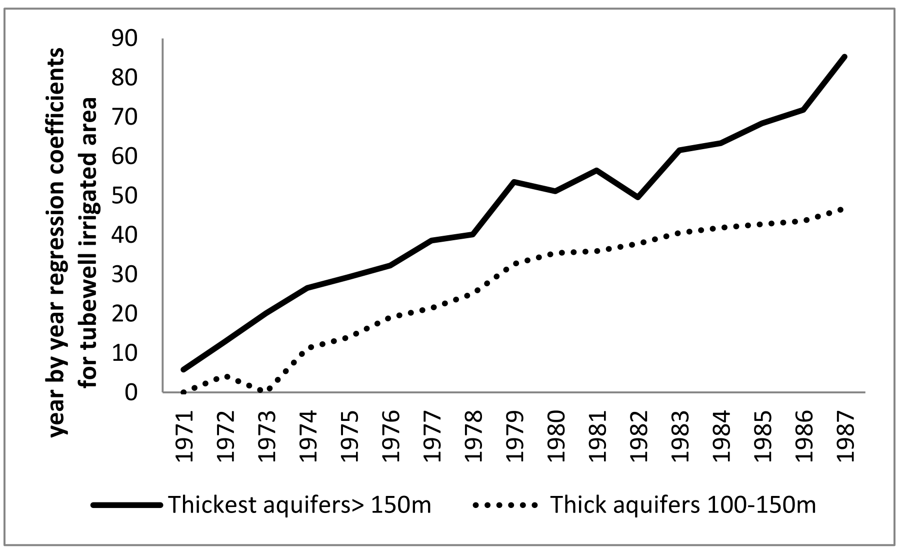
Notes: Area is measures in 1000 hectares. Data is from ICRISAT and Directorates of Economics and Statistics, Ministry of Agriculture.

Fig 2.4: Differential trends in area under High Yielding Varieties (HYV) by aquifer capacity



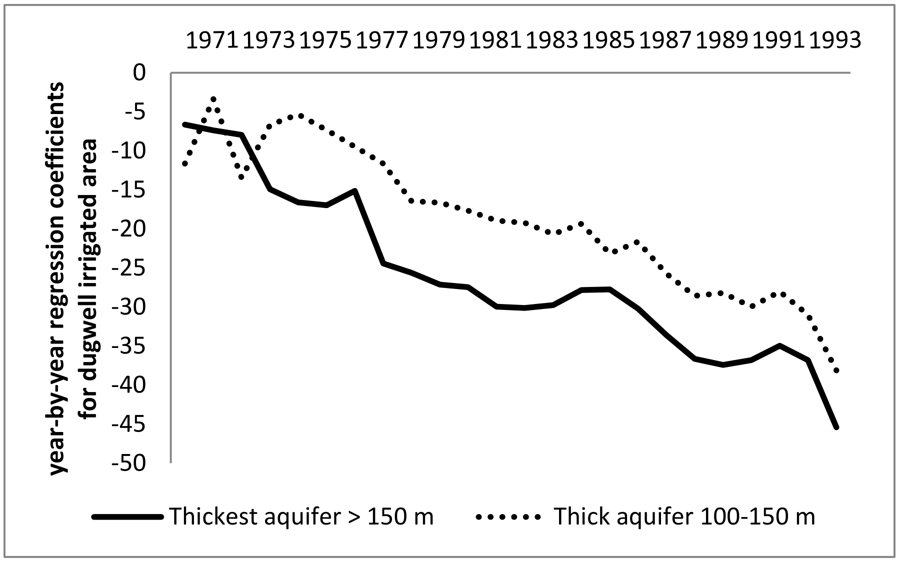
Notes: Area is measures in hectares. Data is from the Indian Agriculture and Climate Dataset World Bank, and National Atlas of India

Fig 2.5: Differential trends in tubewell irrigated area by aquifer capacity



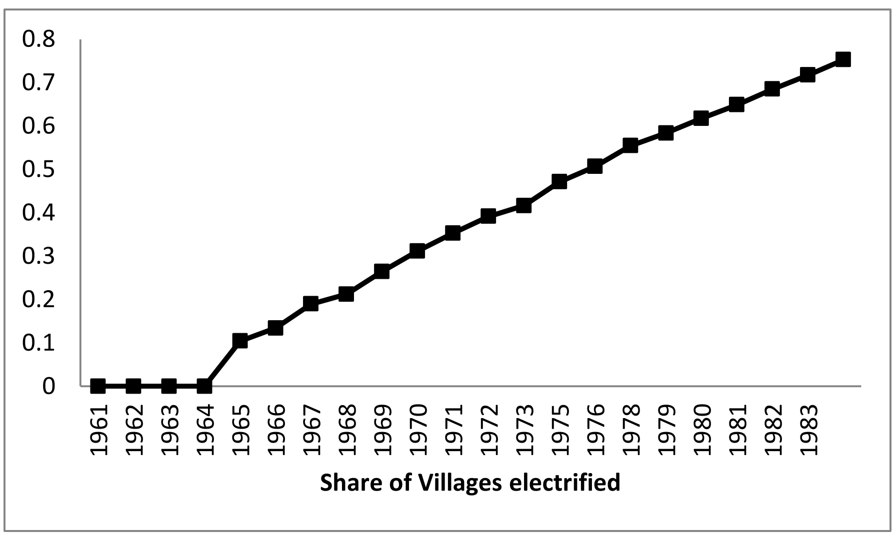
Notes: Area is measures in 1000 hectares. Data is from ICRISAT, Directorates of Economics and Statistics, Ministry of Agriculture, and National Atlas of India.

Fig 2.6: Differential trends in dugwell irrigated area by aquifer capacity



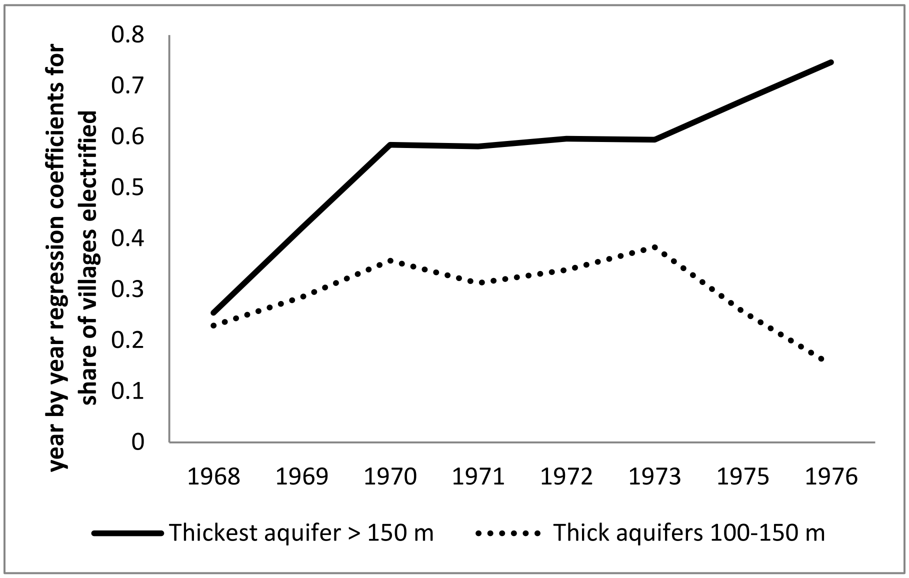
Notes: Area is measures in 1000 hectares. Data is from ICRISAT, Directorates of Economics and Statistics, Ministry of Agriculture, and National Atlas of India.

Fig 2.7: Trends in electrification



Notes: Data is from the Central Electric Authority.

Fig 2.8: Differential trends in electrification by aquifer capacity



Notes: Data is from the Central Electric Authority, and National Atlas of India

Tables

Table 2.1. Log Wheat Irrigated Area: Aquifer Capacity

	Dry Season Wheat		
	(1)	(2)	(3)
	Thickest Aquifer	**Fairly Thick Aquifer**	**Thick Aquifer**
No. of rain days	-0.017	0.029	-0.219*
	(0.063)	(0.057)	(0.099)
Rainfall JJAS	-0.017	0.128***	0.163***
	(0.042)	(0.025)	(0.048)
Kharif degree days	0.022	-0.163	0.319+
	(1.276)	(0.124)	(0.174)
Rabi degree days	0.237	0.044	-0.569+
	(0.233)	(0.233)	(0.342)
Lag log irrigated area	0.440**	0.728***	0.654***
	(0.168)	(0.068)	(0.082)
Log Previous 5 yr avg. crop area	0.259	0.020	0.143*
	(0.180)	(0.045)	(0.069)
Year fixed effects	Yes	Yes	Yes
District fixed effects	Yes	Yes	Yes
State specific trends	Yes	Yes	Yes
N	624	2002	696
Adj.R-sq	0.990	0.990	0.990

Notes: Table 1 reports coefficient estimates and SEs from 3 separate regressions. Each regression includes districts that overlay the thickest (aquifer thickness greater than 150 meters), fairly thick (aquifer thickness between 100 and 150 meters) and thick (aquifer thickness up to 100 meters) aquifers. Dependent variable is log wheat irrigated area. All variables are in logarithmic form. Includes district and year fixed effects, as well as state specific trends. + $p<0.10$ * $p<0.05$ ** $p<0.01$ *** $p<0.001$.

Table 2.2. Log Wheat Irrigated Area: Heterogeneous Effects

	Dry Season Wheat						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
No. of rain days	-0.005	-0.072	-0.064	-0.032	-0.062	-0.055	-0.055
	(0.071)	(0.072)	(0.072)	(0.071)	(0.070)	(0.069)	(0.069)
Rainfall JJAS	0.250***	0.387***	0.344***	0.404***	0.310***	0.294***	0.324***
	(0.034)	(0.049)	(0.040)	(0.043)	(0.040)	(0.046)	(0.055)
Rainfall JJAS x electricity		-0.262***					
		(0.052)					
Rainfall JJAS x electricity x thickest aquifer			-0.359***				
			(0.044)				
Rainfall JJAS x electricity x fairly thick aquifer			-0.282***				
			(0.043)				
Rainfall JJAS x high tubewells				-0.371***	-0.339***	-0.331***	-0.344***
				(0.043)	(0.040)	(0.043)	(0.047)
Rainfall JJAS x high dugwells					0.198***	0.206***	0.211***
					(0.048)	(0.047)	(0.051)
Rainfall JJAS x high tanks						0.057	0.076
						(0.058)	(0.059)
Rainfall JJAS x upstream dam 1970							-0.054
							(0.052)
Kharif degree days	0.089	0.155	0.136	0.096	0.098	0.101	0.101
	(0.069)	(0.105)	(0.104)	(0.104)	(0.103)	(0.103)	(0.103)
Rabi degree days	-0.159	-0.329+	-0.249	-0.172	-0.181	-0.183	-0.186
	(0.099)	(0.185)	(0.184)	(0.180)	(0.177)	(0.177)	(0.178)
Fixed Effects	District, Year, State-Year Time Trends						
N	7460	6847	6812	6847	6847	6847	6847
Adj.R-sq	0.990	0.999	0.999	0.999	0.999	0.999	0.999

Notes: Column (1) reports the baseline model without interactions. Column (2) -(7) include interactions of total rainfall with dummies for states with higher electrification in 1965relative to national average, for districts overlaying thickest and fairly thick aquifers, for districts dominated by tubewells, dug wells, and tanks, for districts that have upstream dams in 1970. Standard errors reported in parentheses are corrected for spatial and serial correlation. Statistical significance is given by + p<0.10 * p<0.05 ** p <0.01 ***p < 0.001.