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Article

Watering the Seeds of the Rural Economy: Evidence from Groundwater Irrigation in India

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ABSTRACT

This study explores the impact of private investment in groundwater extraction for irrigation on the spatial and sectoral distribution of rural economic activity in India. Exploiting a kink in access to groundwater, generated from an absolute technological constraint on the operational capacity of irrigation pumps with depth of the water table, there is evidence of a significant improvement in agricultural production accompanied with modest consumption gains. Groundwater extraction causes a substantial increase in population density, but has no effect on the employment rate or labor reallocation between sectors of the economy. Furthermore, irrigated agriculture appears to provide additional employment opportunities for waged labor from surrounding non-irrigated villages.

JEL classification: O12, O33, O53, Q15

Keywords: irrigation, development, agriculture, labor, India

1. Introduction

How a boost to agricultural productivity affects the process of economic growth and development is a long-standing question. First chronicled with reference to the Industrial Revolution in England during the 18th century, scholars argued that it was a thriving agricultural sector which enabled subsequent industrialization (Robinson 1954). Building on this evidence, models of structural transformation have shown that a productive agricultural sector can generate demand and hence production in off-farm sectors spurring a movement of labor towards the manufacturing and service industries (Gollin, Parente, and Rogerson 2002; Ngai and Pissarides 2007). This view has been challenged by indicating that in an open economy having a comparative advantage in farming will in fact lead to the pooling-in of labor into the agricultural sector, hence slowing down the development process (Matsuyama 1992). A resurgence of

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empirical studies have attempted to shed new light on this debate, demonstrating that the movement of labor between sectors may vary with the technological change (Bustos, Caprettini, and Ponticelli 2016) and geographic scale (Blakeslee et al. 2023) considered. This paper investigates how groundwater extraction for irrigation in India has shaped the rural economy.

Irrigation is one of the most conspicuous technologies for stimulating agricultural output. Improved productivity primarily occurs through a direct yield effect, irrigated agriculture is on average at least twice as productive as rainfed (Faurès, Hoogeveen, and Bruinsma 2002). Furthermore, the technology has also been found to (a) minimize inter-annual variability by reducing exposure to rainfall shocks (Sarsons 2015), (b) augment land endowments (Blakeslee, Fishman, and Srinivasan 2020), and (c) complement other key inputs such as high-yielding varieties (Gollin, Hansen, and Wingender 2021). In India, advancements in pumping equipment to extract groundwater revolutionized access to irrigation in the early 1970s. In 2013, approximately half of cultivated land across the country was irrigated. Groundwater, accounting for over 70 percent of this irrigated land, provides the single largest source of irrigation (Jain, Kishore, and Singh 2019), arguably making this technology one of the most recent salient changes to the agricultural sector.

Groundwater is extracted through tube-wells, with an irrigation pump used to move water up the tube to the surface. There are two types of irrigation pump available—centrifugal and submersible. Centrifugal pumps are installed at ground level and generate a pressure differential between the water table and the pumping mechanism. The maximum possible pressure differential at any given altitude is achieved through a perfect vacuum in the pumping mechanism. Under this ideal condition, Bernoulli's principle of fluid dynamics dictates that the maximum depth from which water can be extracted by a centrifugal pump is a constant (Faber 1995). At sea level, this maximum depth is 10.33 meters. Below this threshold, no centrifugal pump will be operational. Extracting water from greater depths requires significantly more expensive submersible pumps which are placed at the bottom of a tube-well and push the water to the surface.

For groundwater depths shallower than the maximum operational threshold, the more cost effective centrifugal pumps are the farmers preferred choice. Hence, if all centrifugal pumps were homogenous in their ability to generate a perfect vacuum, one would expect to see a jump in access to groundwater at this threshold. Evidence from industry standards, however, suggest that centrifugal pumps typically offer a range of efficiencies (Elsey 2020) such that a jump at any given groundwater depth is unlikely. Instead, there exists a pump-efficiency-specific threshold such that as one approaches the maximum operational depth from shallower levels, a subset of lower-efficiency centrifugal pumps will not function. As empirically demonstrated in this study, this generates a *kink* in the mapping of centrifugal pump adoption with groundwater depth at the arbitrarily stipulated maximum operational threshold, accompanied by an incomplete substitution to the more expensive submersible pumps.

This study exploits quasi-random between village variation in access to groundwater, generated by the technological constraint of centrifugal pumps, in a *fuzzy* regression kink (RK) design. This approach allows estimation of the causal impact of groundwater extraction for irrigation on agricultural production and the distribution of economic activity at the local level. Outcome variables were recorded between 2011 and 2013, by which time half the villages in the sample had had access to irrigation for at least 14 years, hence capturing a long-to-medium-run effect.

Existing and newly assembled data compiled for this study at the village level across the country allow employment of methods that leverage spatial variation in groundwater depth at a high resolution across a large geographic area. The assignment variable—groundwater depth—was compiled using data published by the Central Ground Water Board (CGWB). Monitored wells were matched with individual villages using their geographic positioning system (GPS) locations. Irrigation data, including tube-well construction and ownership of irrigation pumps, were obtained from the Minor Irrigation Censuses. This study further draws from remote sensing, administrative micro-data, population and economic censuses to measure the local agricultural production, consumption, sectoral labor allocation, and demographics.

The impact of groundwater extraction for irrigation was estimated as an additional standard deviation unit (≡ 103 L/ha/day) of groundwater on the outcomes of interest. The results indicate that irrigation significantly improves agricultural production by augmenting land productivity in the monsoon/*kharif* season by 8.6 percent, as well as an 18.8 percent expansion in cultivated land area. Gains in agricultural production translate to modest improvements in consumption. This study finds evidence of an increase in the ownership of household assets, especially solid housing, but no effect on consumption per capita or the poverty rate.

Employment in the agricultural sector, as well as the five largest non-agricultural industries, was considered to investigate changes in the sectoral distribution of economic activity at the village level. An agricultural production boost from irrigation does not appear to have transformative effects on the allocation of labor between sectors of the local economy. However, when considering the employment status of residents in the nearest neighboring villages (within 5 km of the main sample villages) that had not adopted groundwater irrigation, the share of agricultural laborers working full time increases by 18.2 percent. This provides suggestive evidence for a pooling-in of farm labor from less agriculturally productive nearby population centers. Finally, in terms of the village demographics, the results show that groundwater extraction causes a large increase in the population density. This appears to be the result of both in-migration, especially by the economically disadvantaged scheduled castes, as well as changes in fertility/mortality.

This paper is linked to a resurging literature providing empirical evidence on the effect of productivity shocks in agriculture on the process of economic development. Investigating the role of the Green Revolution on income growth across the developing world, Gollin, Hansen, and Wingender (2021) found that the spread of high-yielding variety crops significantly increased agricultural productivity, reduced the share of labor in agriculture, thereby initiating the process of industrialization. Similarly, analyzing the effect of an increase in yields from improved fertilizer use in Africa, McArthur and McCord (2017) showed that this generated a 14 percent rise in GDP per capita and led to a 5 percent decline in the share of agricultural labor over a five-year period. In contrast to these studies, this paper exploits high-resolution data with variation at the village level to investigate more localized changes within the rural economy, finding that despite villages being at the root of agricultural productivity gains they do not themselves witness a shift in off-farm opportunities.

At a more micro-level, researchers have attempted to better understand the presence of heterogeneous response to agricultural shocks along different dimensions. In a study exploiting the spread of improved seed varieties in Brazil, Bustos, Caprettini, and Ponticelli (2016) showed that the direction of labor movement between sectors depends on the factor bias of the technological change. The authors found that hybrid maize, which enabled a second harvest, led to a pooling-in of labor to the agricultural sector, consistent with the findings of this study which exploits irrigation as another form of land-augmenting technology. The results are closely related to recent work by Blakeslee et al. (2023) and Asher et al. (2022) leveraging variation in access to canal irrigation in India using the gravity-driven nature of water flow in a spatial regression discontinuity. Both of these papers document a lack of village-level off-farm growth following production gains in the agricultural sector. This study adds to this literature in three main ways. First, most studies have focused on technological change dating back to the 1960s in the case of the Green Revolution and even earlier for canals. In contrast, this paper studies a much more recent period of agricultural change in response to groundwater irrigation. Second, the approach used in this study leverages a direct measure of irrigation water use versus an indirect proxy for access. Finally, unlike in a spatial regression discontinuity design, the method used here can capture spillover effects as the control and treatment groups are not in close proximity.

This work also adds to a strand of causally interpretable evidence on the impact of groundwater irrigation. The scarcity of such research is due in large part to the empirical challenges involved in establishing reliable estimates. The context of this work is most closely related to Sekhri (2014), who found that access to groundwater reduces poverty rates—mediated by augmenting agricultural yields—which significantly reduces water-related conflict in India. This paper also documents a boost to the agricultural sector and asset accumulation, but goes on to focus on shifts in the allocation of labor between different sectors of the rural economy and its implications on village demographics. Other papers in this sphere include that of Blakeslee, Fishman, and Srinivasan (2020) who explored farmer adaptations to the drying up of groundwater for irrigation in India, and Hornbeck and Keskin (2014) who investigated changes in production choices in the United States.

The rest of the paper is structured as follows.The following Background Section provides insight on the use of irrigation in India over time and describes the different technologies available to farmers for groundwater extraction. The data sources are explained in the Data Section and the empirical strategy including graphical evidence is presented in the Section on Empirical Approach. The Results Section reports the results on the impact of irrigation on the rural economy. Finally, the Section Conclusion provides concluding remarks on this paper.

2. Background

In the 1950s, following independence, India invested extensively in public provision of irrigation infrastructure, making canals the dominant source of water for agricultural purposes (Jain, Kishore, and Singh 2019). However, over the years, minimal maintenance of the infrastructure resulted in water supply from these canal networks becoming increasingly unreliable (Mukherji 2016). At the same time, technological advancements in pumping equipment accompanied by government energy subsidies to operate these pumps made extracting groundwater an affordable and appealing option (Shah, Giordano, and Mukherji 2012). Hence, as of the early 1970s, groundwater overtook canals as the largest source of irrigation water. The following decades witnessed a groundwater revolution—by 2013 groundwater accounted for 70 percent of the country's irrigated area (Jain, Kishore, and Singh 2019).

The gradual evolution in groundwater extraction over time is evident among the sample of villages used in this study—the share of villages with tube-wells increased five-fold between 1986 to 2013 (fig. 1). This expansion is also reflected in the intensive margin of technology adoption over this period—on average the number of tube-wells used to extract groundwater for irrigation increased from 3 to 52 per village. This implies that by 2013, which is when the primary outcome variables used in this study were recorded, half of the villages will have had tube-wells for at least 14 years. The study thereby captures the medium-to-long-run impact of private investment in groundwater irrigation, conceivably one of the most salient recent technological innovations aimed at boosting agricultural productivity.

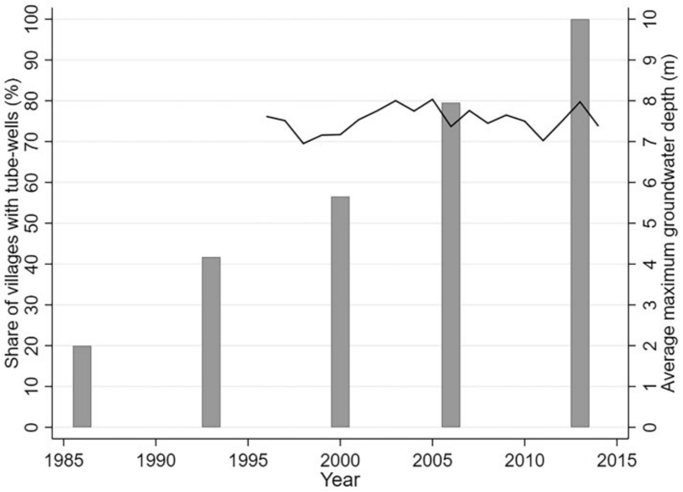
A tube-well consists of a borehole which is drilled into the ground so as to tap groundwater from porous zones in the aquifer. An irrigation pump is then used to move the water up the tube to the surface. There are two main types of irrigation pump available—centrifugal and submersible. The choice of which pumping technology is most suitable for extracting groundwater depends on the depth of the water table at that location.

Centrifugal pumps are installed at ground level and create a vacuum, with water moving up the tube from an area of high pressure at the bottom of the tube-well, to an area of low pressure in the pumping mechanism. The extraction of water from a tube-well using a centrifugal pump can be described by Bernoulli's principle of fluid dynamics (Faber 1995):

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2, \tag{1}$$

where the variables P_i, v_i, and h_i refer respectively to the pressure (kg/m/s^2), velocity (m/s), and height (m), between the pump ($i = 2$) and the water table ($i = 1$). The constants ρ and g are the density of water (997 kg/m^3) and gravitational force (9.81 m/s^2) respectively. Assuming constant flow velocity, one can

Figure 1. Tube-Well Construction and Groundwater Depth over Time



Source: Data on tube-well construction were obtained from the Minor Irrigation Censuses conducted every seven years since 1986. Groundwater depth was compiled from the Central Ground Water Board which has monitored wells across the country since 1996.

Note: The percentage share of villages with tube-wells is represented by the bar graph with its axis on the left. Annual maximum groundwater depth is represented by the line graph with its axis on the right. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point.

rewrite equation (1) in the following form:

$$h_2 - h_1 = \frac{P_1 - P_2}{\rho g}. \tag{2}$$

As can be interpreted from equation (2), the maximum possible pressure differential is achieved through a perfect vacuum ($P_2 = 0\,\mathrm{kg/m/s^2}$) in the pumping mechanism. Under this ideal condition and atmospheric pressure at sea level ($P_1 = 101{,}325\ \mathrm{kg/m/s^2}$), the maximum depth from which water can be extracted—that is, the difference between h_2 and h_1—is 10.33 meters. This represents the maximum operational threshold achievable by a centrifugal pump.

Realistically however, it is unlikely that all centrifugal pumps are able to create a perfect vacuum. Industry standards suggest that centrifugal pumps more typically offer efficiencies ranging from 55 to 93 percent (Elsey 2020).[1] This will reduce the depth from which a centrifugal pump can extract groundwater. For instance, at sea level the depth from which a centrifugal pump can extract water falls from 10.33 to 5.18 meters as pump efficiency falls to half its maximum potential. This naturally leads to the concept of an efficiency-specific threshold, below which a centrifugal pump can no longer be used to access groundwater for irrigation.

In a scenario where a centrifugal pump can no longer operate, submersible pumps can provide an alternative technology for water extraction. Submersible pumps are placed at the bottom of the tube-well and push the water to the surface. Consequently, provided it has sufficient horsepower, a submersible pump could extract water from any depth. Given its additional functionality, a submersible pump is significantly more expensive than a centrifugal pump. Based on an online search among India's top five irrigation pump manufacturers, the starting price of centrifugal pumps was less than half that of submersible pumps.[2] The

[1] Pump efficiencies were verified on the site of numerous irrigation pump suppliers and manufacturers. The information indicated that centrifugal pumps could achieve up to 90 percent efficiency, with most pumps ranging from 50 to 80 percent. See for instance https://www.tapflopumps.co.uk, https://www.rotechpumps.com, and https://www.inoxmim.com.

[2] This information was sourced from providers, including https://www.moglix.com and https://www.indiamart.com.

lowest priced centrifugal was 3,000 rupees (30 GBP) compared to 7,500 rupees (75 GBP) for the lowest priced submersible pump.[3] To put these costs into context, the mean annual per capita consumption in the sample of villages is approximately 18,000 rupees (GBP 180).

The supplementary online appendix provides a simple decision-making framework for the adoption of these different irrigation pumping technologies and demonstrates that it is the subset of farmers that can afford a centrifugal pump but not a submersible that generates a decline in overall centrifugal pump adoption, culminating in zero take-up at the maximum operational threshold. The presence and validity of this relationship is empirically demonstrated in Empirical Approach Section.

3. Data

For this study, observational water-table depth from wells in 2013 are linked with multiple external contemporaneous data sets describing irrigation practices and the rural economy to obtain a village-level cross-section. Importantly for the empirical approach, this data set combines spatial variation in groundwater extraction at a high resolution over a large geographic area.

Data on the assignment variable—groundwater depth—come from the official website of the Central Ground Water Board (CGWB).[4] Wells were monitored four times in the year, capturing both seasonal and inter-annual variation, and covered 511 districts across 21 states. The assignment variable was constructed as the maximum groundwater depth recorded at any point over a three-year period (2010–2013).[5] Wells were matched to villages if they fell within the village boundary.[6,7]

The Minor Irrigation (MI) Census, which has been conducted every seven years since 1986, contains information on irrigation technology and practices.[8] Specific to the needs of this study, the Fifth MI Census (2013) has data on ownership of different pump types, including submersible and centrifugal. Importantly, there also exists information on pump capacity (horsepower) and usage (pumping hours) which was leveraged to calculate water extraction in liters following a standard engineering formula (Manring 2013). This measure enabled us to capture the intensive margin of access to groundwater for irrigation.

Data on agricultural inputs and labor, as well as village demographics, were obtained from the 2011 Population Census of India.[9] The Socioeconomic High-resolution Rural–Urban Geographic Dataset on India (SHRUG, version 1.5) was the source of information on a range of consumption indicators including durable assets, per capita consumption, poverty rate, and night-light intensity.[10,11] Finally, data from the Sixth Economic Census (2013), which enumerates all non-farm village economic establishments, were

[3] When comparing prices for the top three selling centrifugal and submersible pumps, centrifugal pumps ranged from 4,500 to 5,700 rupees (45–57 GBP), while submersible pumps were priced between 10,000 to 12,000 rupees (100–120 GBP). Similar differences were found when comparing prices for pumps with the same features (e.g. horsepower).

[4] Data can be downloaded in excel format from http://cgwb.gov.in.

[5] Taking a three-year horizon enables us to account for some of the temporal fluctuation which may affect groundwater depth.

[6] Shapefiles mapping the whole of India are available from the Socioeconomic Data and Applications Center (SEDAC) of NASA: https://sedac.ciesin.columbia.edu/data/set.

[7] If more than one well was matched to a village, an average of the assignment variable was taken.

[8] Data from the MI Censuses are publicly available in excel format on the Government of India open data platform at http://data.gov.in.

[9] Data from the Population Census of India can be downloaded from https://censusindia.gov.in.

[10] For information on the SHRUG, please refer to Asher et al. (2021). The data set, including codebooks and references, can be found at http://www.devdatalab.org/shrug.

[11] Consumption per capita and poverty rates are predicted from household-level asset and earning data using the small area estimation methodology of Elbers et al. (2003).

utilized to capture industry-sector employment.[12] The analysis focuses on the largest employing industries: livestock, education, manufacturing, services, and forestry, which within the final sample account for over 85 percent of employment. Data on agricultural production based on direct field measurements are not available at the village level in India. Consequently, the Enhanced Vegetation Index (EVI), calculated and compiled by Asher and Novosad (2020) from satellite imagery, was used as an alternative.[13] Specifically, the maximum EVI value (log transformed) in each agricultural season of 2013 was constructed as the preferred outcome variable.

So as to capture the natural geophysical features of the village, altitude and ruggedness, as well as distance to the nearest river and whether the village is in the command of a canal network, were obtained from the SHRUG and the 2011 Village Directory respectively. Data on temperature and rainfall were obtained from high-resolution gridded data sets from the Climate Hazards Centre.[14] Further details of the data and the computation of specific variables used in this study can be found in the supplementary online appendix.

The final sample of villages are those that have (a) non-missing information across all variables, (b) tube-wells built by 2013,[15] and (c) groundwater depth within the bandwidth of 7 meters from the maximum operational threshold of a perfectly efficient centrifugal pump. This leads to a final sample size of 3,227 villages across 415 districts in 19 states of India.

4. Empirical Approach

This study is interested in capturing the effects of access to groundwater for irrigation on agricultural production and local economic activity. Irrigation practices, however, are likely to be endogenous. For instance, one might expect that villages with better access to markets are more likely to adopt tube-wells. Any naive correlation estimates between groundwater extraction for irrigation and economic outcomes will in such a case be biased, partially attributing the effect of irrigation to markets rather than the technology itself. In order to identify exogenous variation in access to groundwater, this study exploit the laws of physics which dictate that there exists an arbitrary maximum groundwater depth from which water can be extracted by a centrifugal pump.

Previous work by Sekhri (2014), evaluating the effect of access to water on poverty and conflict in rural India, also used the physical constraint on the operational capacity of centrifugal pumps with groundwater depth as a source of exogenous variation. The author adopted a *fuzzy* regression discontinuity (RD) design at a threshold of 8 meters, based on expert opinion that achieving a perfect vacuum in the pumping mechanism is in practice unlikely. However, reports from industry standards suggest that centrifugal pumps in fact typically offer efficiencies ranging from 55 to 93 percent (Elsey 2020). Hence a *jump* in access to groundwater, whether at 8 or 10.33 meters or anywhere in between, is unlikely. It is more realistic that pumps are drawn from a distribution of efficiencies, leading to a gradual decline in adoption of the technology, culminating in zero take-up at the maximum operational threshold, hence generating a *kink* in access to groundwater at that point.

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[12] Economic census data are available on the National Data Archive site: http://microdata.gov.in/nada43/index.php/catalog/47.

[13] The paper by Asher and Novosad (2020) and its associated data set is available at https://www.aeaweb.org/articles?id=10.1257/aer.20180268.

[14] See Funk et al. (2014) and Funk et al. (2019) for information on how to use these data sets.

[15] Information on groundwater depth can only be observed by farmers if there exists at least one tube-well for irrigation in the village. This is a critical component to the adoption decision which was exploited in the empirical approach. Furthermore, this condition enabled us to investigate the spatial spillovers between villages having adopted tube-well irrigation and their neighboring villages that did not.

In this section the proposed empirical approach—*fuzzy* regression kink (RK) design—is outlined in detail. Estimated results are presented alongside graphical evidence corroborating the validity of this method.

4.1. Regression Kink Design

Centrifugal pumps provide the most affordable technology to privately access groundwater for irrigation. However, as described inthe Background Section, there exists a maximum operational threshold below which a centrifugal pump can no longer function. Furthermore, as one approaches this threshold from shallower depths, a subset of the lower-efficiency pumps will no longer be viable. This leads to a gradual decline in the use of centrifugal pumps for irrigation, with zero take-up of the technology at the maximum operational threshold. In this context the change in slope of the assignment function, which maps the relationship between groundwater depth and groundwater extracted at the kink point, is unknown and must be estimated based on observed data. Accordingly, a *fuzzy* RK design is employed (Card et al. 2015) wherein the assignment function is specified as

$$G_{vds} = \delta_0 + \delta_1(w-k) + \delta_2(w-k) \cdot D_{vds} + \sigma X_{vds} + \eta_s + \varepsilon_{vds}, \tag{3}$$

where G_{vds} is groundwater extracted from irrigation tube-wells in village v, district d, and state s. The variable w is groundwater depth and k is the kink point, calculated based on Bernoulli's principle of fluid dynamics described in equation (2), assuming 100 percent pump efficiency and atmospheric pressure adjusted for village altitude. The variable D_{vds} is a binary indicator which takes the value 1 if village v has a groundwater depth w below the kink point k; that is $w > k$. One expects to observe a kink in the deterministic relationship between the treatment variable, groundwater extracted, and the assignment variable, groundwater depth, at k. It follows that if groundwater extracted exerts a causal effect on the outcome of interest one should then also expect to see an induced kink in the relationship between the outcome and the assignment variable at k. This outcome function is estimated as

$$Y_{vds} = \gamma_0 + \gamma_1(w-k) + \gamma_2(w-k) \cdot D_{vds} + \nu X_{vds} + \mu_s + \upsilon_{vds}, \tag{4}$$

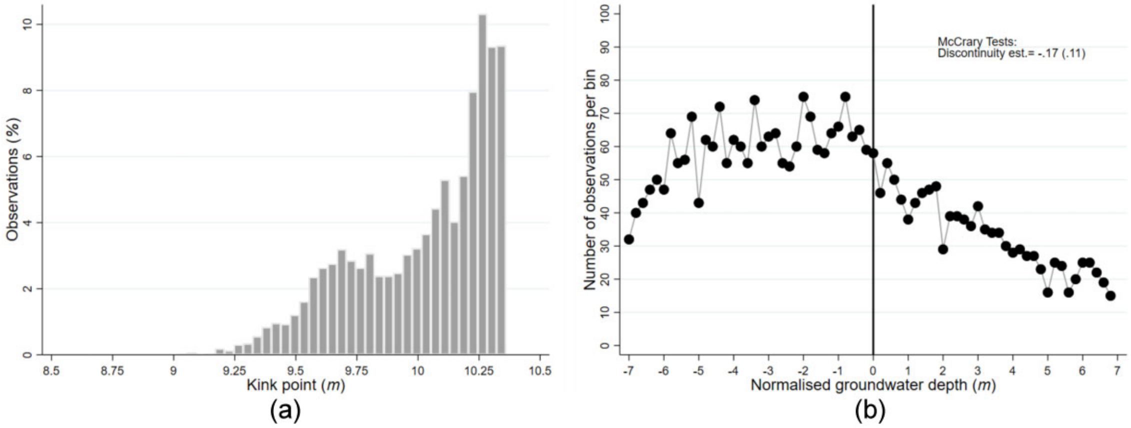
where Y_{vds} is the outcome of interest. The causal impact can then be calculated as the ratio of the coefficients—$\beta = \gamma_2/\delta_2$—and interpreted as the average treatment effect on the treated. Standard errors for β are clustered at the district level and recovered using the delta method. All regressions use a linear functional form with a bandwidth of 7 meters from the kink point. Control variables and fixed effects are not necessary for identification in an RK design, but do improve the efficiency of the estimation (Calonico, Cattaneo, and Titiunik 2014; Imbens and Lemieux 2008). Therefore a vector, X_{vds}, of village geophysical covariates (temperature, rainfall, distance to river, whether the village is in the command area of a canal, altitude, and ruggedness of the terrain) are included as controls in the specified regression. Furthermore, state fixed effects, η_s and μ_s are also included in equations (3) and (4) respectively.

4.2. Impact of Groundwater Depth on Groundwater Extraction

Identification in a *fuzzy* RK design requires three key assumptions (Card et al. 2015): (a) the conditional density of the assignment variable, given the unobserved error in the outcome, is continuously differentiable at the kink point, (b) there is no jump in the direct marginal effect of the assignment variable on the outcome of interest at the kink point, and (c) covariates are continuously differentiable at the kink point.

The first assumption ensures that villages and their inhabitants cannot manipulate the water-table depth to improve their access to groundwater. To rule out this prospect, the probability density function of the assignment variable is plotted to check for bunching at the kink point. First, the exact location of the kink point is village specific as it is adjusted for the local altitude (panel A, fig. 2). Second, the distribution of the assignment variable shows no signs of discontinuity around this point (panel B, fig. 2 presents the number of observations in each bin for groundwater depth normalized at the kink point). This is further

Figure 2. Distribution of the Assignment Variable



Source: Data on groundwater depth were obtained from the Central Ground Water Board (2010–2013).

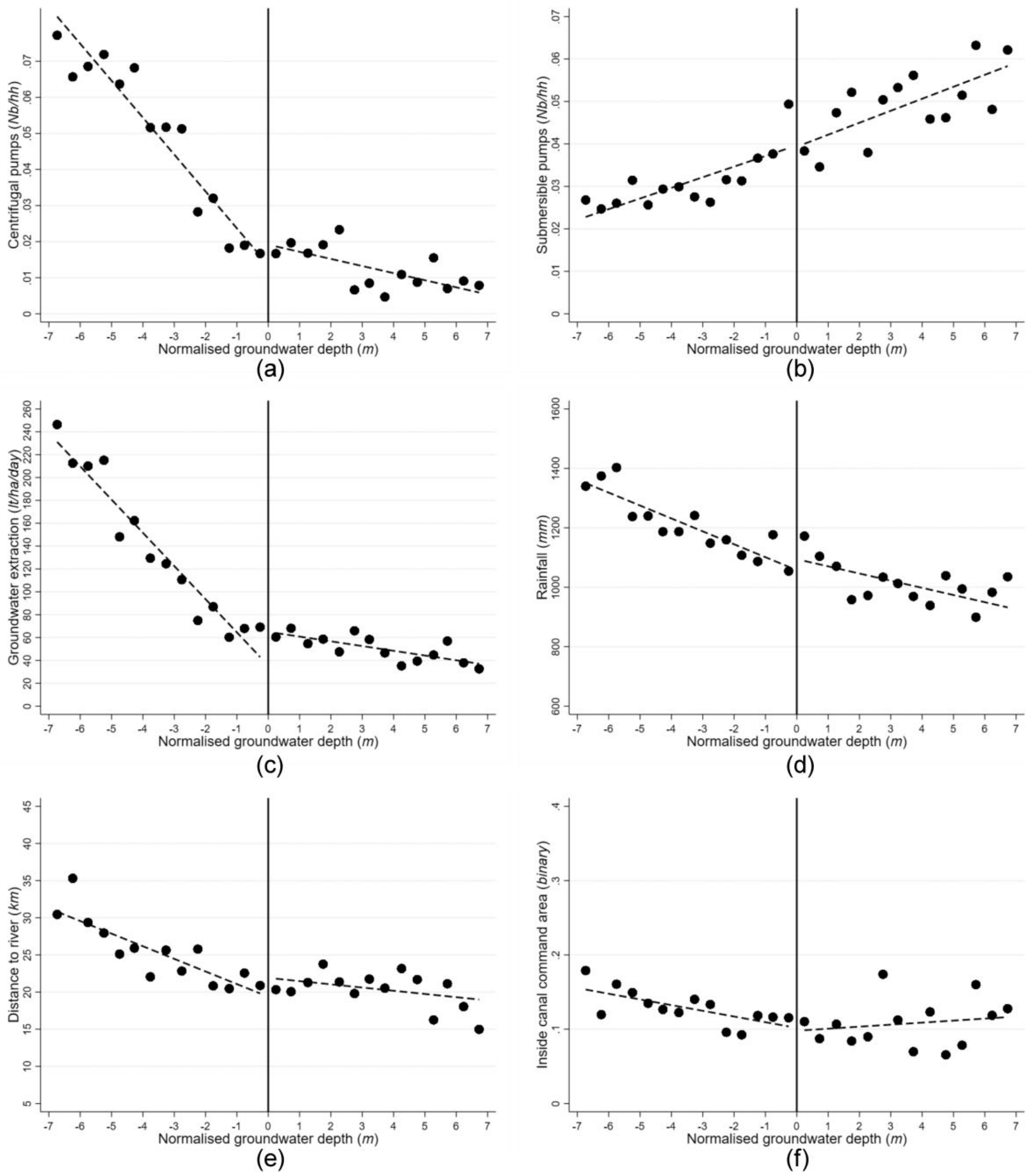
Note: The kink point of a village was calculated using Bernoulli's principle of fluid dynamics assuming 100 percent pump efficiency and atmospheric pressure adjusted for village altitude. Panel A shows the distribution of the kink point for villages in the sample. Panel B plots the number of observations in each bin for groundwater depth normalized at the threshold. A *fuzzy* Regression Kink design requires the conditional density of the assignment variable, given the unobserved error in the outcome, to be continuously differentiable at the kink point. The McCrary test, reported in panel B, provides an additional validation by estimating the log change in height between bins at that point. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point.

supported by the McCrary test, commonly used in the RD literature, which estimates the log change in height between bins at the kink point. Results from this test (displayed directly on the graph) confirm that a significant discontinuity at that point cannot be detected.

The second assumption validates the treatment effect. Corroborating the known technological constraint and the effect of efficiency in limiting the operation of centrifugal pumps with groundwater depth, there exists a clear kink in the slope of the relationship between centrifugal pump adoption and groundwater depth normalized at the kink point (panel A, fig. 3). Specifically, there is a decline in the adoption of centrifugal pumps as groundwater depth increases, followed by a sharp visible switch to a constant near-zero adoption at the kink point ($w > k$). As expected, the price differential of submersible pumps limits the substitution to this alternative technology (panel B, fig. 3). The amount of water extracted from tube-wells for the purpose of irrigation closely follows the same change in slope as centrifugal pump adoption with groundwater depth (panel C, fig. 3). Results on the assignment function further substantiate this graphical evidence, indicating a statistically significant positive change in the slope of centrifugal pump adoption (column 1, table 1) with groundwater depth at the kink point and similarly in the case of water extraction for irrigation (column 3, table 1).

Finally, the third assumption attempts to address the concern that there may be village characteristics which are correlated to the treatment status. This is addressed by testing for a discontinuity in the first derivative of equation (4) with covariates capturing local geophysical factors for which one would not expect there to be an effect from groundwater extraction—temperature, rainfall, distance to river, inside a canal catchment, altitude, and ruggedness. With the exception of altitude, the results of this test confirm that none of the covariates indicate a change in slope with groundwater depth at the kink point (columns 4 to 9, table 1 and for graphical evidence see panels D to F, fig. 3). To alleviate any concerns that the results may be driven by altitude, it is included as a control variable in all regressions, along with the other geophysical features of the village. Furthermore, a balance test was conducted on the key outcome variables—irrigation, agricultural production, poverty, population, and village amenities—prior to having access to groundwater irrigation. To this end the distributions of these variables are observed in 2000 among a subsample of villages that built tube-wells solely after 2000. While there are average differences

Figure 3. Deterministic Relation between Groundwater Depth and Pump Adoption, Groundwater Extraction, and Geophysical Covariates



Source: Data for groundwater depth and extraction were obtained from the Central Ground Water Board (2010–2013), pump adoption from the Fifth Minor Irrigation Census (2013), rainfall from the Climate Hazards Centre (2010–2013), distance to nearest river and whether the village is in a canal catchment area from the Village Directory (2011).

Note: The *x*-axis in each panel represents the assignment variable, groundwater depth. This variable was normalized around the kink point of the village. The kink point was calculated using Bernoulli's principle of fluid dynamics assuming 100 percent pump efficiency and atmospheric pressure adjusted for village altitude. Points to the right of zero correspond to depths deeper than the kink point, while those left of zero are shallower. Each panel reports results on the deterministic relation between the assignment variable and measures of pump adoption (panels A and B), groundwater extraction (panel C), and geophysical covariates (panels D, E, F). Each panel shows the mean values of the variable of interest in each bin of the assignment variable. The bin size is 0.5. The dashed lines display predicted values of the regressions in the linear case allowing for a discontinuous shift at the kink point. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point.

Table 1. Estimated Kink in the Deterministic Relation of Groundwater Depth and Pump Adoption, Groundwater Extraction, and Geophysical Covariates

	Pump adoption		Groundwater	Covariates					
	Centrifugal (nb/ha) (1)	Submersible (nb/ha) (2)	extraction (L/ha/day) (3)	Temperature (Celsius) (4)	Rainfall (mm) (5)	Distance to river (km) (6)	Canal catchment (binary) (7)	Altitude (m) (8)	Ruggedness (index) (9)
δ_2	0.003**	0.001	0.106***	−0.027	6.604	0.596	0.010	−6.015**	−0.005
	(0.001)	(0.001)	(0.016)	(0.030)	(10.883)	(0.530)	(0.006)	(2.967)	(0.006)
Mean	0.035	0.037	−0.000	32.187	1,137.002	23.403	0.119	265.329	0.091
SD	0.077	0.062	1.000	1.731	515.047	25.584	0.324	232.105	0.307
N	3,227	3,227	3,227	3,227	3,227	3,227	3,227	3,227	3,227

Source: Data on pump adoption were obtained from the Fifth Minor Irrigation Census (2013), groundwater extraction from the Central Ground Water Board (2010–2013), temperature and rainfall from the Climate Hazards Centre (2010–2013), distance to nearest river and whether the village is in a canal catchment area from the Village Directory (2011), altitude and ruggedness from the Socioeconomic High-resolution Rural Urban Geographic Dataset on India.

Note: This table presents estimates on the effect of groundwater depth and pump adoption, groundwater extraction, and covariates. The variable δ_2 is the estimated change in slope of the assignment function at the kink point. Pump adoption, calculated as the number of pumps per agricultural land area, is reported for centrifugal (column 1) and submersible (column 2) pumps. Groundwater extraction was calculated as the average capacity over the year, measured in liters per hectare per day and standardized (column 3). Six geophysical covariates are reported in columns 4 to 9 respectively: temperature (measured as a three-year average, 2010–2013, of the maximum monthly temperature recorded in degrees Celsius), rainfall (measured as a three-year average, 2010–2013, of the total annual rainfall recorded in millimeters), distance to the nearest river (in kilometers), a binary indicator for whether the village has tube-wells inside the command area of a canal network, altitude (meters), and ruggedness (measured as the average square difference in elevation between a pixel and its eight neighboring pixels). The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point. Mean and standard deviation are reported for the full sample. Each regression includes state dummies and covariates, with the covariate of interest omitted from the vector of controls. Standard errors are clustered at the district level and reported in parentheses. * significant at 10 percent, ** significant at 5 percent, *** significant at 1 percent.

between villages, there is no statistically significant change in slope at the kink point when using the *fuzzy* RK specification (column 5, table 2).

Robustness: As explained in Landais (2015), the RK method is demanding on bandwidth. Including villages across a 7-meter window either side of the threshold may raise concerns on their comparability. A robustness test demonstrates that the results are in fact consistent to a range of bandwidth down to 3 meters (fig. S1.1). Furthermore, endogeneity in the treatment variable could emerge if villages may over time manipulate groundwater depth. This could come about if more prosperous villages have a history of investing in groundwater irrigation technology, thus lowering the water table as a function of wealth. This concern was addressed by showing that the results are robust to excluding villages where the groundwater depth fell by more than 1.6 meters over the previous decade (2003–2013)—corresponding to the bottom 25th percentile of fluctuations in the maximum groundwater depth (table S1.1). Finally, the results are robust to excluding the geophysical covariates as controls (table S1.2).

5. Results

This section reports and discusses the results on the impact from access to groundwater on agricultural production and the sectoral distribution of rural economic activity. As explained in the Empirical Approach Section, for each outcome variable the beta estimate is reported (with the heteroskedasticity robust standard errors clustered at the district level in brackets) corresponding to the ratio of the coefficients capturing the change in slope of the outcome (equation (4)) and the assignment function (equation (3)) at the kink point. The treatment variable, groundwater extraction, was constructed as water extracted in L/ha/day and standardized such that all results can be interpreted as the effect of a one-standard-deviation (≡ 103 L/ha/day) increase in groundwater extraction.

Table 2. Balance of Outcome Variables Pre-treatment for Villages with Tube-Wells Built post-2000

	Full sample (1)	Deep ($w > k$) (2)	Shallow ($w \leq k$) (3)	RK estimate (4)	p-value on RK estimate (5)
Panel A: Agriculture					
Irrigation by tube-wells (%)	3.256	2.258	3.832	2.055	0.70
Monsoon production (EVI max, ln)	8.943	8.927	8.953	0.040	0.54
Winter production (EVI max, ln)	8.458	8.424	8.478	−0.026	0.74
Land (ln)	5.963	6.090	5.885	0.555	0.35
Panel B: Consumption					
HH income > Rs 250/month (%)	80.462	82.110	79.353	−13.687	0.43
HH own land (%)	56.923	61.000	54.380	−20.783	0.16
Night-light (ln)	1.740	1.808	1.701	0.286	0.29
Panel C: Demographics					
Population (ln)	7.635	7.628	7.640	0.790	0.15
Scheduled caste (%)	17.595	16.733	18.119	14.522	0.10
Panel D: Village amenities					
Primary school (nb)	2.603	2.643	2.578	1.771	0.19
Medical center (binary)	0.659	0.698	0.634	−0.144	0.57
Electricity (binary)	0.664	0.735	0.621	0.121	0.53
Paved road (binary)	0.809	0.847	0.786	0.199	0.40
N	1,403	514	889		

Source: Data on irrigation (share of village area irrigated by tube-wells) were obtained from the Third Minor Irrigation Census (2000), agricultural production (proxied by maximum value of the Enhanced Vegetation Index, EVI, log transformed, in each season) and night-light (average value) from satellite imagery (2000), consumption indicators (share of HHs that earn above Rs 250/month and who own land) from the Below Poverty Line Census (2002), demographics (population and share of the population as scheduled castes) and village amenities (number of primary schools and whether the village has access to a medical center, electrical connection, and paved road) from the Population Census of India (2001).

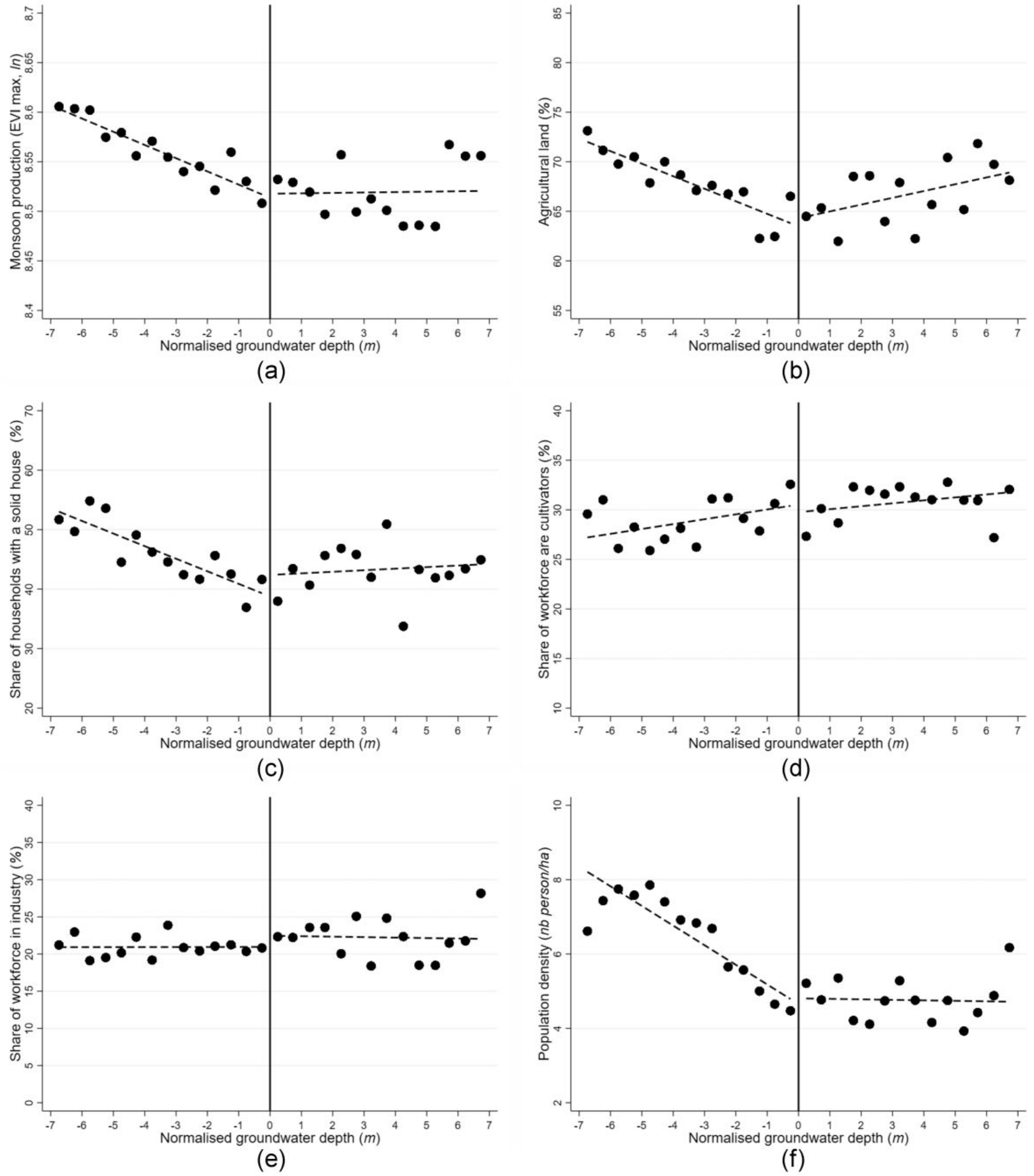
Note: The table presents summary statistics and balance tests pre-treatment for villages with tube-wells built after 2000. Columns 1 to 3 show the unconditional mean for all villages, villages with groundwater depths deeper than the kink point, and villages with groundwater depths shallower than the kink point respectively. Column 4 reports the regression kink (RK) estimates capturing the effect of groundwater extraction on each variable. The specification includes state dummies with standard errors clustered at the district. Finally, column 5 presents the p-value for the regression kink (RK) estimates. The sample consists of villages with tube-wells built after 2000 and groundwater depth within the bandwidth (7 m) of the kink point.

5.1. Agriculture

Before all else, the direct impact of groundwater extraction on agricultural production was evaluated. To this end, the maximum Enhanced Vegetation Index (EVI) value calculated from satellite imagery was used as a proxy for agricultural yields in both the monsoon/*kharif* and winter/*rabi* season of 2013. Having demonstrated a kink in the deterministic relationship between groundwater extraction and groundwater depth at the maximum operational threshold (panel C, fig. 3), it follows that if water extraction has a causal effect on agricultural production one would expect to see an induced kink in the relationship between agricultural production and groundwater depth at that same point. Graphical evidence suggests this to be the case—there exists a sharp decline in monsoon/*kharif* agricultural production with groundwater depth up until the kink point and leveling off at greater depths (panel A, fig. 4). Formal estimates of this causal effect of groundwater in augmenting agricultural production, especially during the monsoon/kharif season, indicates that a one-standard-deviation increase in groundwater significantly boosts agricultural production by 8.6 percent during the monsoon months (column 1, table 3).

Having established the effect of groundwater extraction on agricultural production, this study then analyzes the pathways through which these effects may operate over and above the direct yield impact. Improvements in agricultural output could happen through two main channels: (a) conditional on higher production translating to higher profits, farmers may increase investment in other inputs, and/or (b) farmers may reoptimize their production strategy in response to a reduced exposure to climate risk.

Figure 4. Deterministic Relation between Groundwater Depth and Outcomes



Source: Data on groundwater depth were obtained from the Central Ground Water Board (2010–2013), agricultural production (proxied by the Enhanced Vegetation Index) from satellite imagery (2013), information on village land area cultivated, agricultural employment, and demographics from the Population Census of India (2011), employment in industry from the Sixth Economic Census (2013), and household assets from the Socio Economic Caste Census (2012).

Note: The *x*-axis in each panel represents the assignment variable, groundwater depth. This variable was normalized around the kink point of the village. The kink point was calculated using Bernoulli's principle of fluid dynamics assuming 100 percent pump efficiency and atmospheric pressure adjusted for village altitude. Points to the right of zero correspond to depths deeper than the kink point, while those left of zero are shallower. Each panel reports results on the deterministic relation between the assignment variable and a selection of outcome variables. Each panel shows the mean values of the outcome of interest in each bin of the assignment variable. The bin size is 0.5. The dashed lines display predicted values of the regressions in the linear case allowing for a discontinuous shift at the kink point. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point.

Table 3. Impact of Groundwater Extraction on Agriculture

	Production		Inputs			Crop choice		
	Monsoon (EVI max, ln) (1)	Winter (EVI max, ln) (2)	Agricultural land (%) (3)	Water-saving technology (%) (4)	Mechanized equipment (%) (5)	Water intensive (binary) (6)	Drought tolerant (binary) (7)	Cash (binary) (8)
Groundwater	0.086***	0.005	18.849***	−5.537	−1.506	0.116	−0.138	0.018
(standardized)	(0.033)	(0.031)	(5.567)	(3.560)	(1.766)	(0.086)	(0.101)	(0.087)
Mean	4,604.738	4,872.520	67.149	4.832	5.039	0.686	0.345	0.229
SD	950.872	1043.889	24.420	18.826	8.708	0.464	0.475	0.420
N	3,227	3,227	3,227	3,227	2,296	2,619	2,619	2,619

Source: Groundwater extraction was calculated using data from the Fifth Minor Irrigation Census (2013) and the Central Ground Water Board (2010–2013). Data on agricultural production (proxied by Enhanced Vegetation Index, EVI) were obtained from satellite imagery (2013), water-saving technology from the Fifth Minor Irrigation Census (2013), mechanized equipment from the Socio Economic Caste Census (2012), land and crop choice from the Population Census of India (2011).

Note: This table presents *fuzzy* Regression Kink estimates on the effect of groundwater extraction on agricultural output and production choices. Groundwater extraction was measured in L/ha/day and standardized. The maximum value of the Enhanced Vegetation Index (EVI, log transformed), an index of vegetation cover calculated from satellite imagery, was used to proxy for agricultural production in both the monsoon/kharif (column 1) and the dry winter/rabi season (column 2) of 2013. Columns 3 to 5 report results on the adoption of three inputs respectively: agricultural land (percentage share of village area used for agricultural purposes), water-saving technology (percentage share of tube-wells which are adapted to water-saving mechanisms such as drips and sprinklers), and mechanization (percentage share of households who own mechanized farm equipment such as tractors, harvesters, etc.). Columns 6 to 8 report results on three measures of crop choice respectively: whether a village grows water-intensive crops (sugarcane, cotton, and rice), drought-tolerant crops (millet, sorghum, maize, pigeon pea, and groundnut), and cash crops (sugarcane, oilseed, cotton, and tobacco). The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point. Mean and standard deviation are reported for the full sample, and in the case of production on the level form of the variables. The specification includes state dummies and covariates. Standard errors are clustered at the district level and presented in parentheses. * significant at 10 percent, ** significant at 5 percent, *** significant at 1 percent.

In response to the first channel, investments in a range of inputs including land, water-saving technology, and mechanized equipment was investigated (columns 3 to 5, table 3). Groundwater extraction significantly increased the share of village area used for cultivation. A one-standard-deviation increase in groundwater led to an 18.8 percent rise in the proportion of village land being cultivated (panel B, fig. 4 provides graphical evidence). No direct shifts in the ownership of mechanized equipment or the use of water-saving technology were detected.

With respect to the second channel, shifts in the most common crops grown in the village were evaluated (columns 6 to 8, table 3). Three categories of crops were considered—water intensive, drought tolerant, and cash—all of which are characterized by differing levels of risk. Water intensive crops (e.g. rice) are vulnerable to rainfall shocks. Conversely, drought-tolerant crops (e.g. sorghum) are resistant to semi-arid conditions, and are thereby an effective way of reducing exposure to adverse weather. Finally, cash crops (e.g. sugarcane) which cannot be directly used for household consumption, as they require post-harvest processing, are generally considered to be quite profitable but also more susceptible to price fluctuations. As one may expect, the point estimate on water-intensive crops is positive and that of drought-tolerant crops is negative; however, these are not statistically significant.

5.2. Consumption

A boost to agricultural production from groundwater use may have important welfare implications. To capture this the analysis focused on a range of consumption indicators. No significant shifts in consumption per capita, poverty rate, or night-light activity were detected (columns 1, 2, and 8 respectively, table 4). There was, however, a significant 0.54-standard-deviation increase in the household asset index for durable goods consumption (column 3, table 4). When considering the effect independently on the main items included in this index, the results indicated that this was mostly driven by an increase in solid house construction (column 4, table 4). The share of households that own a solid, brick and mortar, house

Table 4. Impact of Groundwater Extraction on Consumption

	Consumption	Poverty rate	Household assets					Night-light
			Index	Solid house	Refrigerator	Vehicle	Phone	
	(ln)	(share)	(index)	(%)	(%)	(%)	(%)	(ln)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Groundwater	0.024	−0.037	0.541**	21.214***	0.220	3.434	1.056	0.077
(standardized)	(0.037)	(0.027)	(0.242)	(6.856)	(2.322)	(3.229)	(3.845)	(0.097)
Mean	18.659	0.288	0.413	44.597	8.713	21.352	72.952	7.211
SD	4.710	0.176	0.994	28.937	12.995	16.116	22.125	5.042
N	3,227	3,227	2,296	2,296	2,296	2,296	2,296	3,227

Source: Groundwater extraction was calculated using data from the Fifth Minor Irrigation Census (2013) and the Central Ground Water Board (2010–2013). Data on the consumption indicators were obtained from the Socio Economic Caste Census (2012) and night-light from satellite imagery (2013).

Note: This table presents *fuzzy* Regression Kink estimates on the effect of groundwater extraction on consumption. Groundwater extraction was measured in L/ha/day and standardized. Column 1 reports results on the imputed consumption per capita (log transformed). Column 2 shows estimates on the imputed share of the population living below the poverty line (poverty line is set at Rs 31/day). Column 3 shows estimates for the household asset ownership index calculated as the village-level average of the primary component of indicator variables for all household assets captured in the Socio Economic Caste Census of 2012. Columns 4 to 7 report results on four assets—solid house, refrigerator, vehicle, and phone respectively—calculated as the percentage share of households who own that specific asset. Finally, using satellite imagery, column 8 captures the average night-light in 2013. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point. Mean and standard deviation are reported for the full sample, and in the case of night-light and consumption on the level form of the variables. The specification includes state dummies and covariates. Standard errors are clustered at the district level and presented in parentheses; for consumption and poverty we report bootstrapped standard errors. * significant at 10 percent, ** significant at 5 percent, *** significant at 1 percent.

increased by 21.2 percent due to a one-standard-deviation increase in groundwater extraction (panel C, fig. 4 presents graphical evidence).

5.3. Labor

An increase in agricultural production with improved groundwater extraction may simultaneously increase demand for labor in this sector. This effect, however, may be small or even reversed if farmers switch to less labor-intensive crops or replace labor activities with specialist mechanized tools such as transplanters and harvesters. Furthermore, labor supply to agriculture is likely to be influenced by market opportunities in other sectors. On-farm growth may spur production in off-farm sectors, hence increasing demand for labor in those industries. Characterized by these complex interactions, the overall effect of groundwater irrigation on the sectoral allocation of labor is ambiguous.

First, the effect of groundwater use on the employment status of the village population was considered. There appears to be no significant shift in the share of the population employed (panel A, column 1, table 5). Second, the effect of groundwater extraction on the share of the workforce employed within the agricultural sector - the largest employing industry in the sample of villages - was explored. Groundwater use does not appear to have any significant effect on the share of the workforce engaged either as cultivators or manual laborers (panel B, columns 2 to 7, table 5). Third, while there is no evidence of labor movement in or out of this sector, there may be more subtle changes occurring within the labor market. Cultivators may spend longer hours working on their farm or employ manual labor for longer periods as they cultivate more land. In order to test for this, the study analyzes the share of full-time workers (those that work for more than six months of the year) as the outcome of interest (panel C, columns 2 to 7, table 5). An increase of 5.6 percent in the share of full-time cultivators was detected. This indicates some effect from groundwater use on shifts in the intensive margin of agricultural work.

Following the investigation of agricultural sector employment, the effect of groundwater extraction on labor allocation off-farm was considered: specifically, the share of the workforce employed across all village industries, as well as in the five largest employing off-farm industries independently. The regression kink restimates indicate no significant effects on the movement of labor in these sectors (table 6). These

Table 5. Impact of Groundwater Extraction on Aggregate and Agricultural Sector Employment

	Total	Cultivators			Laborers		
	Person (1)	Person (2)	Male (3)	Female (4)	Person (5)	Male (6)	Female (7)
Panel A: Share of population employed (%)							
Groundwater	−2.241	−0.631	0.395	−1.775	0.829	0.603	1.117
(standardized)	(1.374)	(1.617)	(1.965)	(1.593)	(2.071)	(2.097)	(2.399)
Mean	43.855	13.110	18.405	7.546	18.235	19.184	17.174
SD	10.460	9.673	11.334	9.972	11.325	11.061	14.000
Panel B: Share of workforce (%)							
Groundwater	–	0.274	1.735	−1.980	3.469	1.786	7.298
(standardized)	–	(3.380)	(3.496)	(3.450)	(3.950)	(3.654)	(4.891)
Mean	–	29.527	33.204	21.418	40.291	34.600	50.035
SD	–	18.784	19.496	20.596	20.391	19.052	26.032
Panel C: Share of full-time workers (%)							
Groundwater	4.340	5.645∗	2.880	5.115	2.672	1.713	5.852
(standardized)	(3.658)	(3.268)	(2.805)	(5.317)	(5.022)	(4.741)	(5.762)
Mean	75.436	87.009	91.152	69.908	64.644	70.873	54.627
SD	20.393	17.583	15.523	30.749	29.450	28.919	33.791
N	3,227	3,227	3,227	3,227	3,227	3,227	3,227

Source: Groundwater extraction was calculated using data from the Fifth Minor Irrigation Census (2013) and the Central Ground Water Board (2010–2013). Data on aggregate and agricultural sector employment were obtained from the Population Census of India (2011).

Note: This table presents *fuzzy* Regression Kink estimates on the effect of groundwater extraction on aggregate employment, as well as within the agricultural sector. Groundwater extraction was measured in L/ha/day and standardized. Panel A reports results on the percentage share of the population employed, calculated as the ratio of those employed to the total working-age population. Panel B reports results on the percentage share of the workforce, calculated as the ratio of those employed to the total workforce. Panel C reports results on the percentage share of full-time workers (those that work for more than six months of the year), calculated as the ratio of full-time workers to the total workforce. Alongside total employment, two specific occupational categories in agriculture are considered: cultivators are those who cultivate their own land, and laborers are those who work for a daily wage. Furthermore, these categories are disaggregated by gender. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point. Mean and standard deviation are reported for the full sample. The specification includes state dummies and covariates. Standard errors are clustered at the district level and presented in parentheses. ∗ significant at 10 percent, ∗∗ significant at 5 percent, ∗∗∗ significant at 1 percent.

Table 6. Impact of Groundwater Extraction on Industry Sector Employment

	All (1) (%)	Livestock (2) (%)	Education (3) (%)	Manufacture (4) (%)	Services (5) (%)	Forestry (6) (%)
Groundwater	−2.900	0.133	−0.202	−0.793	−0.550	−0.876
(standardized)	(3.354)	(1.955)	(0.420)	(1.302)	(1.482)	(0.593)
Mean	21.425	5.577	2.109	3.755	8.720	0.172
SD	18.903	10.963	2.710	6.743	9.264	2.610
N	3,227	3,227	3,227	3,227	3,227	3,227

Source: Groundwater extraction was calculated using data from the Fifth Minor Irrigation Census (2013) and the Central Ground Water Board (2010–2013). Data on industry sector employment were obtained from the Sixth Economic Census (2013).

Note: This table presents *fuzzy* Regression Kink estimates on the effect of groundwater extraction on employment within village industries. Groundwater extraction was measured in L/ha/day and standardized. Column 1 reports the share of the workforce employed on aggregate across all village industries. Columns 2 to 6 refer to the share of the workforce in the following largest employing sectors respectively: livestock, education, manufacturing, services, and forestry. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point. Mean and standard deviation are reported for the full sample. The specification includes state dummies and covariates. Standard errors are clustered at the district level and presented in parentheses. ∗ significant at 10 percent, ∗∗ significant at 5 percent, ∗∗∗ significant at 1 percent.

Table 7. Impact of Groundwater Extraction on the Spatial Distribution of Aggregate and Agricultural Sector Employment

	Total	Cultivators			Laborers		
	Person (1)	Person (2)	Male (3)	Female (4)	Person (5)	Male (6)	Female (7)
Panel A: Share of population employed (%)							
Groundwater	0.705	−1.578	−0.846	−1.323	2.408	3.008	1.816
(standardized)	(3.344)	(2.883)	(3.381)	(2.785)	(2.777)	(2.934)	(3.181)
Mean	40.308	13.617	18.628	8.361	17.308	18.286	16.251
SD	18.419	12.948	15.273	13.251	14.996	15.375	17.238
Panel B: Share of workforce (%)							
Groundwater	–	−2.918	−1.475	−0.805	5.598	4.331	8.841
(standardized)	–	(5.585)	(5.794)	(5.685)	(5.256)	(5.054)	(6.499)
Mean	–	30.026	33.428	21.693	37.125	32.726	44.024
SD	–	25.018	26.179	25.851	27.238	25.880	32.944
Panel C: Share of full-time workers (%)							
Groundwater	9.125	5.008	3.316	10.208	18.212**	15.555*	25.769***
(standardized)	(7.032)	(7.034)	(6.980)	(8.741)	(8.242)	(8.342)	(8.793)
Mean	65.462	74.056	77.641	55.124	53.805	59.146	44.108
SD	32.867	35.072	35.329	41.463	38.088	39.028	40.069
N	2,211	2,211	2,211	2,211	2,211	2,211	2,211

Source: Groundwater extraction was calculated using data from the Fifth Minor Irrigation Census (2013) and the Central Ground Water Board (2010–2013). Data on aggregate and agricultural sector employment data were obtained from the Population Census of India (2011).

Note: This table presents *fuzzy* Regression Kink estimates on the spatial distribution effect of groundwater extraction on aggregate employment, as well as within the agricultural sector. These effects were captured for the nearest neighboring village without access to groundwater. Groundwater extraction was measured in L/ha/day and standardized. Panel A reports results on the percentage share of the population employed, calculated as the ratio of those employed to the total working age population. Panel B reports results on the percentage share of the workforce, calculated as the ratio of those employed to the total workforce. Panel C reports results on the percentage share of full-time workers (those that work for more than six months of the year), calculated as the ratio of full-time workers to the total workforce. Alongside total employment two specific occupational categories in agriculture are considered: cultivators are those who cultivate their own land, and laborers are those who work for a daily wage. Furthermore, these categories are disaggregated by gender. The sample consists of villages without tube-wells in 2013 that are the nearest neighbor within a 5 km distance from the main sample of villages (villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point). Mean and standard deviation are reported for the nearest neighbor sample. The specification includes state dummies and covariates. Standard errors are clustered at the district level and presented in parentheses. * significant at 10 percent, ** significant at 5 percent, *** significant at 1 percent.

results are corroborated by graphical evidence which demonstrate no discernible change in slope in the mapping between the share of persons employed in industries and groundwater depth at the kink point (panel E, fig. 4). These result is tightly estimated and consistent across bandwidth down to 3 meters either side of the kink point (panel E, fig. S1.1).

Finally, the possibility that groundwater extraction may have implications on the spatial distribution of labor was explored. Investment in tube-wells may provide villages with a comparative advantage in farming, thereby pooling-in labor from neighboring villages, especially those without access to the technology. Using the standard regression kink specification, the impact of groundwater use on the employment status of residents in the nearest neighboring village from the main sample (within a maximum distance of 5 km) that had no tube-wells in 2013 was considered. In response to a one-standard-deviation increase in groundwater extraction in village v, the results indicate that its nearest neighbor without irrigation witnessed a significant increase in its share of full-time agricultural laborers (panel C, columns 5 to 7, table 7). This is especially so among female manual workers—the share of full-time female laborers increases by 25.7 percent. A robustness check demonstrates that groundwater extraction in village v had no effect on the agricultural production in its nearest neighbor without tube-wells (table S1.3), hence suggesting that the estimated shift on full-time labor is indeed a response to higher demand for workers in relatively more agriculturally productive villages.

Table 8. Impact of Groundwater Extraction on Village Demographics

	Persons (1)	Male (2)	Female (3)	Adult (4)	Child (5)
Panel A: Population density (ln)					
Groundwater	0.339∗∗	0.339∗∗	0.339∗∗	0.295∗∗	0.419∗∗∗
(standardized)	(0.140)	(0.139)	(0.141)	(0.146)	(0.137)
Mean	5.802	2.976	2.835	3.783	0.790
SD	5.591	2.897	2.741	3.652	0.843
Panel B: Share of the total population (%)					
Groundwater	–	−0.043	–	–	1.094∗∗
(standardized)	–	(0.306)	–	–	(0.516)
Mean	–	51.141	–	–	13.156
SD	–	2.014	–	–	3.257
Panel C: Share of scheduled caste population (%)					
Groundwater	8.375∗∗∗	8.518∗∗∗	8.221∗∗∗	–	–
(standardized)	(3.053)	(3.067)	(3.047)	–	–
Mean	19.942	19.878	20.006	–	–
SD	16.156	16.158	16.206	–	–
N	3,227	3,227	3,227	3,227	3,227

Source: Groundwater extraction was calculated using data from the Fifth Minor Irrigation Census (2013) and the Central Ground Water Board (2010–2013). Data on village demographics were obtained from the Population Census of India (2011).

Note: This table presents *fuzzy* Regression Kink estimates on the effect of groundwater extraction on village demographics. Groundwater extraction was measured in L/ha/day and standardized. Panel A presents results on population density, calculated as the ratio of the population to village area (log transformed). Column 1 presents estimates for the total population. This is disaggregated by gender (columns 2 and 3 for male and female respectively) and age (columns 4 and 5 for adults, 18+ years, and child, 0–6 years, respectively). Panel B reports results on the percentage share of the male and child population, calculated as the ratio of that population to the total population. Panel C presents results on the percentage share of the scheduled caste population, calculated as the ratio of that population to the total population. The sample consists of villages with tube-wells in 2013 and groundwater depth within the bandwidth (7 m) of the kink point. Mean and standard deviation are reported for the full sample, and in the case of population density on the level form of the variables. The specification includes state dummies and covariates. Standard errors are clustered at the district level and presented in parentheses. ∗ significant at 10 percent, ∗∗ significant at 5 percent, ∗∗∗ significant at 1 percent.

5.4. Demographics

Groundwater extraction appears to cause large changes in village demographics. Specifically, the results indicate a 33.9 percent increase in population density from a one-standard-deviation increase in groundwater (panel A, column 1, table 8). While the magnitude of this estimate may appear surprisingly high, it is in fact comparable to those of Asher et al. (2022) who found a 20 percent increase in population density from being in the catchment of an irrigation canal. The estimates from this study are marginally higher, but captured on the intensive margin of a one-standard-deviation increase in groundwater extraction. This considerable effect on the village population is likely due to two key pathways: (a) a more productive agricultural sector may have spurred in-migration, and/or (b) it provided the food/water supply, and associated increase in income, critical in sustaining a higher fertility and/or reduced mortality.

First, the migration pathway was examined by looking at the male population share. According to the 2011 Population Census, work is the primary reason for which men migrate in India. A pooling-in of labor from outside may increase the proportion of men in the village. The analysis however does not detect any evidence of this shift (panel B, column 2, table 8). Note however that this does not rule out in-migration of working-age men. For instance, in the medium-to-long-run time frame which was considered here, it is possible that men were settling in with their families. Indeed, population density appears to increase equally across gender (panel A, columns 2 and 3, table 8). Another group known to migrate for work are the scheduled caste. Members of these castes are among India's most economically disadvantaged groups and in 2011 represented 16 percent of intra-state migrants. For this group there is evidence that a one-standard-deviation increase in groundwater extraction caused an 8.3 percent increase in their population share, with similar effects for both men and women (panel C, columns 1 to 3, table 8).

Second, the fertility and/or mortality pathway was considered by investigating changes in the share of village population by age group. Increased fertility will lead to a higher proportion of children. Reduced mortality is likely to affect the most vulnerable, such as children and the elderly, thereby increasing their representation in the population. Indeed, the results indicate a significant increase of 1.1 percent in the share of the child (0 to 6 years) population (panel B, column 5, table 8).

6. Conclusion

A substantial literature has documented the process of economic growth across countries, overwhelmingly finding that a boost to agricultural production precedes the reallocation of labor from the agricultural sector towards the manufacturing and service industries, initiating the course for industrialization and development (Herrendorf, Rogerson, and Valentinyi 2014). Recently, this topic has received renewed interest among micro-empirical studies to better understand the catalysts to this process, as well as how it unfolds across space and time.

This paper analyzes the effect of access to groundwater irrigation on agricultural production and the rural labor market in India. Since the 1970s, adoption of tube-wells for groundwater extraction has gradually increased, making it the single largest source of irrigation. This study finds that groundwater extraction significantly improved agricultural production and enabled farmers to reoptimize their production strategies by cultivating more land. This was accompanied with modest consumption gains, mostly with respect to durable goods. Groundwater irrigation also caused a substantial increase in population density, driven by a combination of in-migration and changes to fertility/mortality. However, it did not appear to have brought manufacturing firms and employment opportunities in services to rural communities.

Data Availability Statement

The data used for this study are all available in the public domain. Links to these are included in the Data Section as well as the Supplementary Online Appendix.

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