Title of the Paper

The Public Benefits of Private Technology Adoption

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1 Introduction

The recent acceleration of climate change due to global warming has been linked to erratic and extreme weather patterns around the globe. India's drought in 2012 was its fourth in the previous 12 years, and the United Nations World Meteorological Society projects the frequency, intensity and duration of these to increase. Moreover, future monsoon rains–on which Indian agriculture relies–are expected to be heavier but shorter in duration, reducing the amount of water table recharge. Among the most vulnerable to the fallout from these climate changes are the poorest farmers who have the fewest opportunities to adapt through alternative livelihoods or adopting conservation agriculture techniques. Much has been written about possible reasons for low uptake of high return agricultural practices, such as the higher risk, lack of information, liquidity constraints, and credit and insurance market failures.

This paper builds on recent analyses of farmer demand and private returns to resource conserving technology in India by evaluating total benefits inclusive of those accruing to nonadopters. In particular, it aims to measure the public benefits to small Indian farmers of private water-conserving agricultural technology adoption in their village. We study the agricultural land preparation technology laser land leveling (LLL), which has been shown to decrease water usage by 26% on flood-irrigated staple-crop lands. Private benefits to this technology are captured by reduced expenditures on diesel needed to fuel pumping. We measure additional public benefit on pumping costs to nonadopters stemming from the changes in water table depth caused by the adopters.

We estimate public impacts by building hydro-economic models that capture how water tables may be affected by private adoption. This can either happen broadly through aquifer-wide withdrawal and recharge of water tables or more locally around water wells, where the size and duration of temporary cones of depression formed during pumping can interact with neighboring pumps and affect the withdrawal process. In this analysis, we specify a model that allows for both of these channels in generating spillover effects from adopters to nonadopters. The model we develop here resembles some of the modeling in Madani and Dinar (2012), which focuses on numerical analyses of groundwater management systems to see how altering private incentives can lead to improved public water use.

In terms of common pool resources, whether one can expect an impact from adopters to nonadopters through either of these channels depends on the nonexcludability and subtractability of the resource (Ostrom, 1995). In terms of LLL, both water table extraction and digging water wells that lead to interacting cones of depression are nonexcludable: anybody can access the water underground and anybody can set up a pump if they are financially able. However, while cones of depression within a close enough radius are subtractable, it is not clear that extraction from water tables necessarily affects their neighbor's hydraulic head, even if hydraulic conductivity rates are low. We do not try to completely measure impacts through water table extraction but instead adjust the weight that each of these channels receive in our model in generating spillover effects. Methodologically, these two channels involve several overlapping explanatory variables, such as soil type, rainfall, geographical positioning, and technology use.

Results from this research have the potential to impact agricultural development policy in India, where overextraction is becoming a more severe problem in a country that already has the highest share of public water going to agriculture (see Figure 1). The diffusion of resource-conserving technologies not only has an immediate impact on the poverty of individual farmers but also on farmers unable to adopt both now and in the future. The determinants of agricultural technology adoption have been studied extensively in recent years, along with the determinants of technology diffusion, particularly in small farm areas of developing countries. Credit and insurance constraints, lack of information, and changing unskilled rural labor markets have all been discussed as issues affecting private adoption, whereas social networks and learning have been shown to be an underlying cause of diffusion. This research builds on upon both of these areas of research by reinforcing key determinants of private adoption, such as information and access, while bringing into the mix potential physical resource spillovers for non-adopters over time.

There are at least two policy implications stemming from this research. First, rural development programs that target agriculture may be able to factor in a multiplier effect into their benefit estimates for agricultural technologies that conserve subtractable and nonexcludable common pool resources, such as water. In light of rising concerns over the vulnerability of developing countries to rapidly accelerating climate change, long-run reductions in poverty that are linked to natural resource availability can be aided with the dissemination or subsidization of key resource-conserving technologies. Second, the private equilibrium quantity of some resource-conserving technologies may not reach their social optimum due to market failure. Better information on public benefits could increase adoption rates and potentially lead to Pareto-improving cooperative cost-sharing strategies in some village economies.

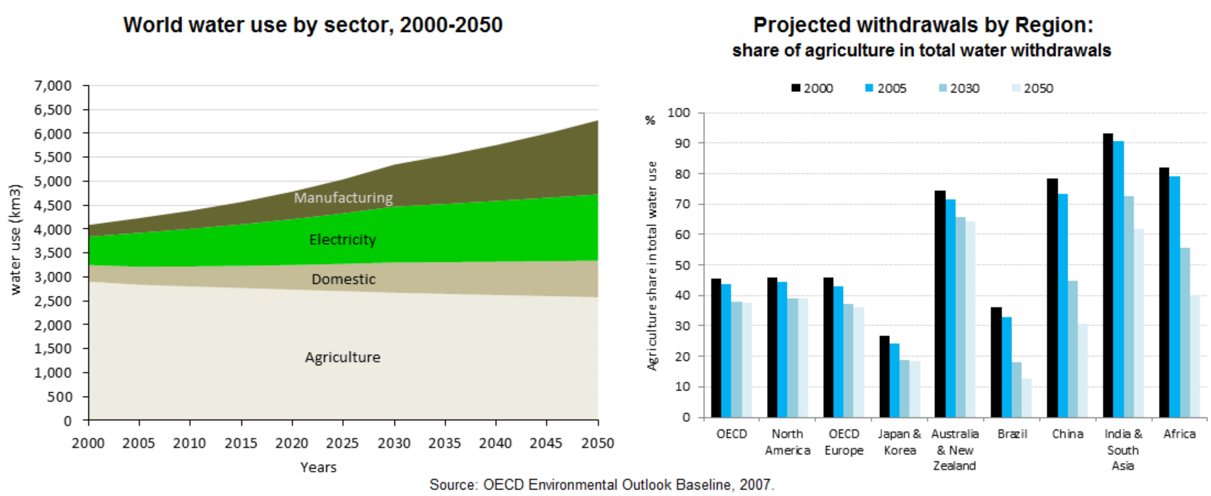

Figure 1: Agriculture dominates world water use (left) while India & South Asia use more water for agriculture than any other region in the world (right).

2 Background

All of India's major rivers originate either from the Himalayas, Vindhya and Satpura ranges in the middle of the country, or the Sahyadri or Western Ghats along the western coast. Most of India's seven main rivers and their tributaries pour into the Bay of Bengal to the east, though some go west into the Arabian Sea and others have inland drainage from Ladakh through the Aravali mountain range and deserts of Rajasthan.

In Uttar Pradesh, the rivers flow west to east mostly from the Himalayas. The two main rivers are the Ganges (or Ganga) and the Ghaghra. The Ganga flows through the heart of the state–from northwest to southeast–until it merges with the Yamuna in Allahabad, then absorbs the Gomti River near Varanasi, and finally leaves the state for Bihar at Patna just south of Deoria district in eastern U.P. The Ghaghra River starts in southwestern Nepal and flows into the Ganges in Bihar but not before converging with the Rapti River, which flows along the southwestern border of Deoria starting near Rudrapur, at Barhai and flowing along the southern border of Deoria for roughly 50 kilometers. The Gandaki River also starts in Nepal and flows on the northeastern border of Maharajganj. The smaller Rapti River flows within the southwestern portion of Maharajganj.

Figure 2: River flow through sample area. Source: Wikimedia Commons

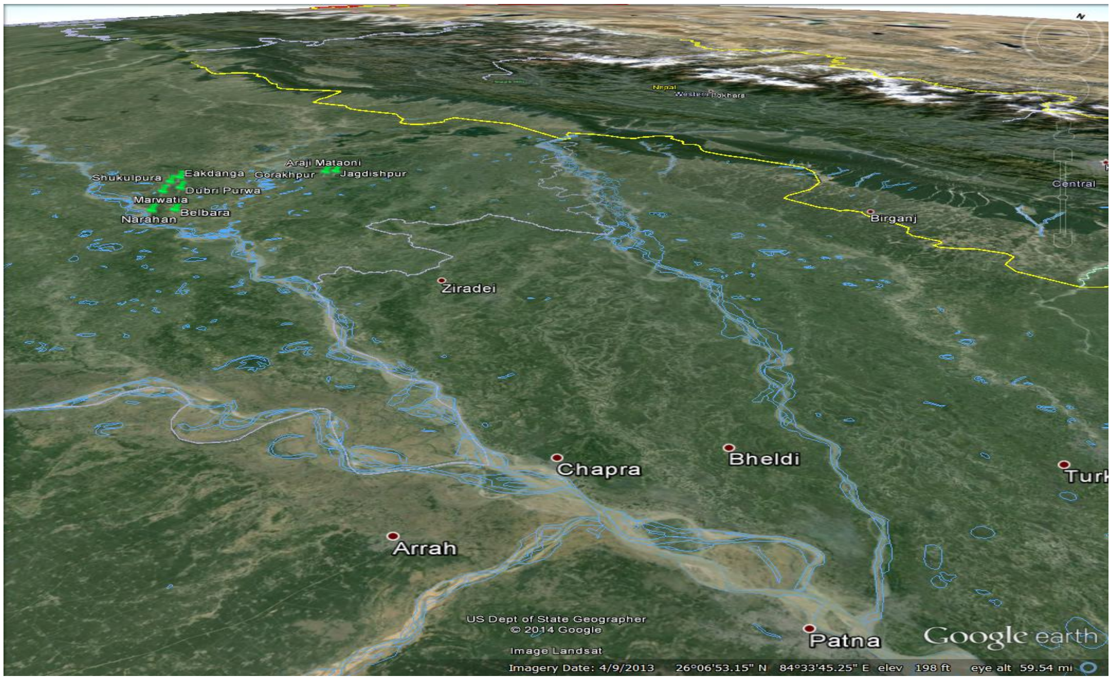

Figure 3: GPS locations of Gorakhpur sample households between Ghaghra and Gandak Rivers, with Chapra and Patna of Bihar in the foreground.

Figure 2 shows the two major rivers and several smaller rivers flowing through the three districts in our sample. The Ghaghara (or Sarayu or Karnali) River originates in Tibet at a roughly 18,000-foot elevation and creates roughly 50 kilometers of southern border for the district of Deoria before flowing into the Ganga in Chhapra (Bihar), while the Gandaki River starts in Nepal at 25,000 feet and brushes up against the northeast corner of Maharajganj before dropping into Bihar and meeting the Ganga east of Chhapra in Patna. The West Rapti River flows through the southwest portion of Maharajganj, through the middle of Gorakhpur and then along the southwest border of Deoria before flowing into the Ghaghara at Barhai. One of its left tributaries, the Rohini River, begins in Nepal, goes nearby Maharajganj town at the Padki Forest and meets it within five kilometers of the town of Gorakhpur. The Little Gandak River flows just west of the Gandak into the northeast quadrant of Maharajganj, then forms the eastern border of the district before flowing straight down through Deoria into the Ghaghara at Lar.

High river flows stem from monsoonal precipitation, with the maximum rainfall usually occurring in July region-wide. This leads to maximum river flows between July and October. This seasonal distribution of flows is similar for all the river basins in the region. The snowmelt contributes to the flow in the snow-fed rivers considerably both during dry and pre-monsoon seasons when there is less rainfall but higher temperature conditions. Although river flow is highly correlated with annual precipitation, monthly flows are not as tightly correlated due to lags in runoff time, site-specific rainfall amounts, and the indirect relationship between rainfall input and catchment runoff output due to hydrological storage.

Uttar Pradesh is the most populated state in India, partially because of the fertile Indo-Gangetic Plains (IGP) that make up much of the area. Our sample districts are in the middle of the the IGP. Figure 5 shows our sample area, which is located in the eastern part of the state, just south of the Nepal border and west of Bihar. Figure 5 shows how our sample villages (eight per district) are spaced within each district and Figure 3 shows the exact GPS coordinates of many of our sample households across all three districts.

Figure 4: Location of eastern Uttar Pradesh districts and spacing of sample villages within districts.

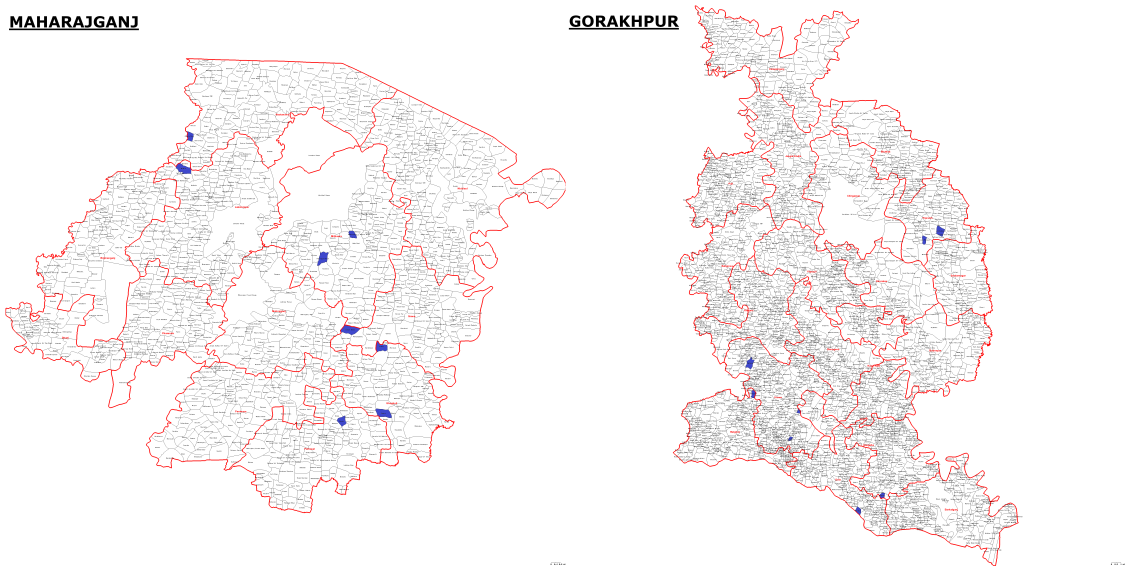

Figure 5: Location of eastern Uttar Pradesh districts and spacing of sample villages within districts.

The physiographic region from the Himalayas to the IGP can be divided into: 1) High Mountain Region, 2) Middle Mountain Region, 3) Siwaliks Region, 4) Terai Region (Nepal), and 5) Gangetic Plains (India). The physiography of the region is highly dominated by altitudinal variation from one place to another. The High Mountain Region includes permanently glaciated areas of the Himalayas. The Middle Mountain Region lies in the south of the High Mountain Region. Elevation in this region ranges from about 200 m to 400 m in the valleys to about 3000 m at the peaks and settlements are sparse with very few villages are found. The Midlands, with an elevation of 200 to 2000 m above sea level, not only provide an agreeable climate for inhabitants but also favor farming and agriculture. Dense forests cover most of the region. The Siwalik Region features small mountains rising straight out of the Terai plain in Nepal. This is geologically the youngest region, fragile and susceptible to erosion and hence major source of sediments in the rivers. Primeval forest covers the rugged landscape in this region, and the Terai Region is a relatively flat area with elevation between 67-300m and a dense population. The capitols of Gorakhpur, Maharajganj and Deoria all have elevations of just under 70m, right where the Terai region of Nepal gives way to the IGP of India.

There is a connection between forest cover and water availability in these latter regions. In the Terai and hill areas, forests decreased at an annual rate of 1.3% between 1978 and 1979, and 2.3% between 1990 and 1991. As the Terai is increasingly deforested, drained and brought under cultivation, an evolving permeable mixture of gravel, boulders, and sand enables the water table to sink deeper. On the other hand, where the Terai zone is composed of less permeable layers of clay and fine sediments, groundwater rises to the surface in springs and wetlands, causing heavy sediment load to fall out of suspension. This enables the frequent massive floods in the greater region as monsoon-swollen rivers overflow their low banks and and rich sediment is washed away. The 2008 Bihar flood was an example of this.

Broadly, the IGP itself can be divided into two drainage basins by the Delhi Ridge; the western part consists of the Punjab Plain and the Haryana Plain, and the eastern part consists of the Ganga–Bramaputra drainage systems. This divide is only 300 meters above sea level, causing the perception that the IGP appears to be continuous between the two drainage basins. The middle Ganga plain extends from the Yamuna River in the west to the state of West Bengal in the east. The lower Ganges plain and the Assam Valley are more verdant than the middle Ganga plain. The lower Ganga is centered in West Bengal, from which it flows into Bangladesh. Some geographers subdivide the Indo-Gangetic Plain into more parts based on regional availability of water. These include the Indus Valley Plain, the Punjab Plain, the Haryana Plain, and the middle and lower Ganges Plains.

U.P.'s climate is primarily defined as humid subtropical with dry winter, though parts of eastern U.P. are classified as semi-arid. Though the IGP gives a predominantly single climatic pattern, U.P. has a climate of extremes with temperatures fluctuating between 0 °C to 50 °C in several parts of the state and cyclical droughts and floods due to unpredictable rains. The region is dependent on the southwest monsoon, with rains varying from an annual average of 1700mm in hilly areas to 840mm in Western U.P. Because most of this rainfall comes within those four months, excess rain can lead to floods and shortages can lead to droughts, causing these two situations to happen frequently in the state, especially as weather patterns become more erratic.

The population densities in the Uttar Pradesh and Bihar portions of the IGP are 415 and 760 persons/km^2, respectively. The main occupation is agriculture, since the entire catchment is cultivable with *rabi* crops dominating the agricultural pattern. The area is practically devoid of any mineral resources except limestone, which are found in the form of marls in the Unnaw and Barabanki districts of Uttar Pradesh. There is little industry in the area, though a few small-scale industries are based on agriculture or forest produce.

3 Model

3.1 Impact through groundwater recharge

One of the most prominent equations relating plot characteristics to water table recharge is Darcy's Law. The viscosity of fluid and pressure drop over a given distance determine the fluid's discharge rate through a porous medium. The porosity of the medium is determined by its permeability and the area over which the fluid flows. In the most general form,

$$Q = \frac{-kA(P_b - P_a)}{\mu L}, \tag{1}$$

where Q is the total fluid discharge ($^{m^3}/_{s}$), k is the intrinsic permeability of the medium (m^2), A is the cross-sectional area to flow (m^2), $(P_b - P_a)$ is change in pressure drop of the area in question (in pascals), μ is the fluid viscosity (in pascal-seconds), and L measures the length over which the pressure drop is taking place (m).

To capture the flow of groundwater in and out of an aquifer, the medium properties of the above law are normally assumed to be constant for small volumes. However, in agriculture, the medium can be quite varied, especially when it comes to soil types, plot elevation and how level the land is. For example, the more level a plot is, the better retention of water it will have for plant uptake during the flood irrigation process. But it may also have higher rates of evapotranspiration because flooded water sits more exposed for longer periods of time before it has a chance to seep back into water tables. An unlevel field may indeed expedite the discharge of fluid back into the ground, but this will have impacts on under-watered plants or increases in water pumped.

To account for this variability in porosity, we take the standard diffusion equation generated from equation 1 over time:

$$\frac{\partial h}{\partial t} = S^{-1}(-\nabla \cdot q - G), \tag{2}$$

where h is the hydraulic head, or depth to pumped water, S is specific storage that characterizes the capacity of an aquifer to release groundwater, q is the volume flux from Darcy's Law in units of ($^{m}/_{s}$) after dividing equation (1) by A, and G captures rainfall, access to rivers, and other aquifer sources/sinks. This equation uses the standard assumptions that water can be considered incompressible (density does not depend on pressure) and q can be defined as the negative product of hydraulic connectivity, K, and the change in hydraulic head, ∇h.

At this point it is often assumed that K, the hydraulic connectivity, or property of plants, soils and rocks that describes the ease with which a fluid can move through pore spaces or fractures, is spatially uniform, and the equation above is further reduced to obtain the groundwater flow equation. However, we make K a function of key variables we believe account for spatial variation: soil type (s) and whether a plot is upland or lowland (u) so that $K = K(s,u)$. This yields our final theoretical village-level groundwater recharge equation:

$$\frac{\partial h}{\partial t} = S^{-1}(-\nabla \cdot (-K(s,u)\nabla h) - G) \tag{3}$$

3.2 Impact through cones of depression

The likelihood that leveling affects water table depths through hydraulic conductivity appears to be less than the chance that it is channeled through a well's cone of depression. Figure 6 illustrates how this channel works. Consider two wells nearby each other as in the top panel of the figure. Each well pumping on its own depresses the water table in a cone-shape fashion as it pumps, which causes the groundwater around it to flow into the well. However, if the two wells have cones of depression that overlap, then this reduces the amount of water available to each well, thereby lowering the effective water table from which the well is drawing.

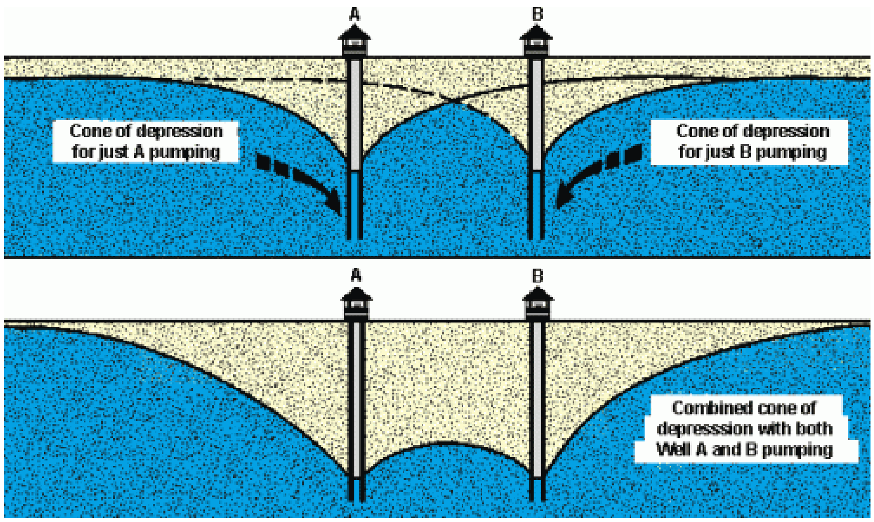

Figure 6: If the cones of depression for two or more wells overlap, there is said to be well interference.This interference reduces the water available to each of the wells. Source: http://wellwater.oregonstate.edu/groundwater/html/GroundwaterWells.htm

The size of the cones during pumping depends both on the soil above the water table and the amount of pumping undertaken. Clay soils are very dense, which means that the radius of the cones are less mutable during pumping. Thus, the cones tend to not expand as much but have a duration that lasts longer on a per-meter basis. Sandy soils, on the other hand, affect their neighbors' water table depths more during pumping because they radially expand much faster. However, after pumping, they return to form faster, as well.

If it's the case that neighboring plots pump their water at roughly the same time due to prevailing weather conditions common to the area, then the duration of the depression is less important than the size of the cone radius. On the other hand, if farmers stagger their pumping as much as possible to account for this, then the duration of the depression may matter more. In our sample area, farmers appeared heavily reliant on the timing of rains, especially in low rainfall months, when planning their pumping at the individual level.

Groundwater flow can also depend on surface water. The proximity of rivers and streams can induce recharge that brings flowing surface water into the groundwater aquifer within the well's cone of depression. Proximity to stream or river may counter the negative impacts of a nearby well's cone of depression on that plot's water table depth. Rainfall may also shorten the duration of depression if farmers pump with the rainfall window but this is not likely to happen since farmers tend to pump more precisely when rainfall is not abundant.

In sum, using a cone of depression framework, we model *effective* water table depth–that is, the depth that a farmer pumps due to cones of depression and not the hydraulic head of an aquifer–as follows:

$$h = f(soil, nsoil, pdist, L, simul, river), \tag{4}$$

where *soil* indicates soil type and, thus, the extent and duration of its cone of depression, *pdist* measures proximity of other pumps, *nsoil* is the type of soil on nearby plots, *L* captures land leveled within a radius of the plot, *simul* is a binary variable indicating whether farmers simultaneously pump with neighbors, and *river* captures distance to river or stream if it is within a quarter-mile of the plot.

4 Methodology

In order to estimate the impact of laser leveling on water table depths using equations (3) and (4), we rely heavily on data collected in eastern Uttar Pradesh on soil types, leveling intensity, water table depths, rainfall, water use, and changes in irrigation patterns due to leveling. For hydrological parameters, we calculate values based on the current state of knowledge, then experiment with ranges of these.

The outcome of interest is the monetary savings for nonadopters of LLL. To calculate this, we combine the change in effective water table depth for a non-adopting farmer with the share of water obtained from the ground (versus the surface) and the diesel cost of pumping per meter of water table depth. The following equation captures the nature of these relationships:

$$y_i = |\triangle w_i|\, p_i cost_i, \tag{5}$$

where y is the monetary savings by non-adopter i as a function of their change in their effective water table depth, $\triangle w_i$, percent of irrigation water obtained from pumping versus surface, p_i, and the cost of pumping per meter of water table depth.

Effective water table depth is related to the amount of nearby leveling and the two main hydrological processes described above: groundwater recharge and cones of depression. We express these as additively separable, starting with the village water table depth, w_v, as the intercept:

$$\begin{aligned} w_i^{NL} &= w_v - (rain_v + river_v)K_i + pump_v/K_i + gdvol_r/rdist_i^2 \\ &\quad + \sum_{j \neq i} 1_j[(r_i pump_i + r_j pump_j)/pdist_j^e + (dur_i pump_i + dur_j pump_j)/pdist_j^e], \end{aligned} \tag{6}$$

where w_i^{NL} is the effective water table depth for plot i, with no leveling. This number falls with rainfall (*rain*) and riverflow (*river*), especially as a plot's hydraulic conductivity, K_i, goes up. The water table depth increases with village-level pumping,[1] $pump_v$, but this effect is mitigated if K_i is high, allowing pumped water on fields to pass into the aquifers below.

The remaining terms in equation (6) capture the potential impacts on water table depth via cones of depression. Absent leveling, actual water table depths will be altered if cones of depression interact between two farmers' pumps, as in figure (6), or if a plot's pump is by a nearby river. Distance to river, $rdist$, affects how much the volume of river flow enters a plot's cone of depression underground, $gdvol$. If the cones of two plots interact simultaneously (indicated by 1 if plot j pumps at the same time as plot i), then the effect of another farmer's pumping on my effective water table depth depends on how big the cones get (radius, r) on each plot and how long they remain depressed (duration, dur). These effects diminish exponentially with $e > 1$ as pump j gets farther away from plot i, denoted by $pdist_j$.

[1] Here, we assume an aquifer is village-wide.

Three terms in equation (6) need to be further defined. Hydraulic conductivity, K, depends primarily on soil type. The cone radius depends on K and amount pumped, while the duration of the cone depends on K, the amount pumped, and nonlinearly on the radius of the cone[2]. This leads to the functions $K = K(soil)$, $r = r(pump, K)$, and $dur = dur(pump, r, K)$, where *soil* is inversely related to K and r and positively correlated with duration. In other words, more clay in the soil reduces the hydraulic conductivity in the soil, while increasing the duration of a depression and reducing the size of the radius. Pumping increases both the cone's radius and duration.

Now we introduce leveling in our equation. Leveling impacts water tables via hydraulic conductivity in the same way as pumping. That is, it will have more of an impact the lower is K. Thus, the second term in equation (7) interacts acres of leveling in village v with K in the same way as pumping in equation (6). Leveling also affects water savings through its direct impacts on water pumped, β, number of irrigations, γ, and duration of irrigations, δ, for all plots j that are leveled around farmer i. Thus, with leveling effective water table depth is modeled as

$$w_i^L = w_i^{NL} - L_v/K_i - \gamma \sum_{j \neq i} 1[(r_i pump_i + r_j \beta pump_j)/pdist_j^e + (dur_i pump_i + \delta dur_j \beta pump_j)/pdist_j^e], \tag{7}$$

where γ reduces the chance that plots level simultaneously through its reduced number of irrigations, β reduces the amount pumped on those plots and δ impacts the duration of cones due to leveling. The difference between equations (7) and (6) is

$$\Delta w_i = -L_v/K_i - \gamma \sum_{j \neq i} 1[(r_i pump_i + r_j \beta pump_j)/pdist_j^e + (dur_i pump_i + \delta dur_j \beta pump_j)/pdist_j^e]. \tag{8}$$

This is ultimately the equation for the change in effective water table depth that is part of the calculation of monetary savings to nonadopters in equation (5).

[2]Cones expand rapidly initially and then more slowly as equal marginal volumes of water are pumped. The reduction of the cone takes the opposite pattern, diminishing slowly at first and then more rapidly. Thus, the duration of the cone depends nonlinearly on radius of the cone, lasting increasingly longer for each additional meter of expansion.

5 Data

Water in eastern Uttar Pradesh is overwhelmingly obtained from the ground. Surface water sources, such as rivers, gravity irrigation and ponds make up less than 1% of all plots' primary water source, while 8% rely on canals[3]. Over 90% of all plots primarily use groundwater via diesel pumps (86% of plots). Only 5% rely on electric pumps, while treadle pumps account for less than half a percent of all plots' main water source. Using the data in the upper half of Table 1, we obtain $p = 0.91$ for equation 5.

Water table depth data was collected at the village level in each of the 24 villages by convening a small group of progressive farmers. Within the group, they were able to create a consensus on the current depth to water in the village and whether and by how much it has changed in the last 10 years. It is interesting to note the variety here within the sample area. While the water tables of the Indo-Gangetic Plains are often thought to be flat, homogenous and stable over time, our data show a more nuanced story. Almost half of the villages (42%) experienced a change in water table depth from five years ago. On average, this was a 22-foot drop or 54% reduction in depth from the 32 ft. average water table for those 10 villages five years before. Fewer villages (17%) had any change during the 5 years before that. Of those, the change in water table depth was smaller and even increased in a few cases. However, magnitudes of those increases were quite small. Overall, the data in the bottom half of Table 1 show that, in the period ten years before the survey, roughly 2001-2006, water tables were relatively steady. This is reflected in studies using data from around this period. However, between 2006-2011, significant reductions in water table depths occurred. These figures are spread evenly in the three districts we sample, although Gorakhpur has deeper water tables than the other two districts. We calculate a $cost_i$ of 14.62 Rupees per meter (Rs/m)[4] by using total water pumped and water table depths and report this at the bottom of the table.

[3]There is some recharge that happens to groundwater that comes from surface water

[4]This is probably an underestimate as it does not account for fixed costs of pumping. This is calculated by multiplying farmer-reported liters of diesel used on a weekly basis times average diesel prices per season.

Variable	Mean	SD	Min	Max	N
Irrigation Pumps					
Primarily use surface water (canal)	0.08	0.27	0	1	1170
Primarily use groundwater (pump)	0.91	0.29	0	1	1170
Diesel pump	0.86	0.35	0	1	1170
Electric pump	0.05	0.22	0	1	1170
Diesel pumps					
Size of tube opening (in.)	6.94	3.35	0	50.24	1171
Horsepower**	7.19	2.55	0	65	1171
Kharif					
Rice irrigations	2.38	1.68	0	20	1169
2011 post-season***	3.11	3.00	0	31	1294
Hours per irrigation	6.19	10.21	0	150	1169
2011 post-season***	1.32	2.18	0	26	1294
Total hours irrigated	21.18	96.71	0	2250	1169
Price of diesel (Rs./liter)	38.43	1.97	34	42	1169
Estimated water pumped	1126.36	5007.70	0	117561.6	1168
Rabi					
Wheat irrigations	2.49	0.74	0	6	1171
2011 post-season***	1.51	1.48	0	10.5	1294
Hours per irrigation	5.93	7.01	0	90	1171
2011 post-season***	3.35	4.89	0	50	1294
Total hours irrigated	15.71	22.67	0	375	1171
Price of diesel (Rs./liter)	38.77	2.09	32	42	1171
Estimated water pumped	933.06	2445.99	0	58780.8	1170
2011 total irrigations***	4.61	3.64	0	31	1294
2011 average hours***	2.33	3.01	0	27.66667	1294
Estimated total water pumped	2058.75	6939.06	0	176342.4	1168
Water Tables					
Depth to water table (meters)	54.58	29.37	25	150	24
Depth to water table 5 years ago, if change	32.20	35.63955	3	120	10
Depth to water table 10 years ago, if change	13.75	11.08678	5	30	4
% of villages with change from 5 years ago	0.42	0.50	0	1	24
Share with less depth to water table 5 years ago	0.90	0.32	0	1	10
Absolute change from 5 years ago	-22.00	17.55	-60	-5	9
% change from 5 years ago	-0.54	0.34	-0.925	-0.1111111	9
Share with more depth to water table 5 years ago	0.10	0.32	0	1	10
Absolute change from 5 years ago	5.00	.	5	5	1
% change from 5 years ago	0.04	.	0.0434783	0.0434783	1
% of villages with change from 10 years ago	0.17	0.38	0	1	24
Share with less depth to water table 10 years ago	0.50	0.58	0	1	4
Absolute change from 10 years ago	-7.50	3.54	-10	-5	2
% change from 10 years ago	-0.32	0.25	-0.5	-0.1428571	2
Share with more depth to water table 10 years ago	0.50	0.58	0	1	4
Absolute change from 10 years ago	3.00	2.83	1	5	2
% change from 10 years ago	0.63	0.53	0.25	1	2
Water table depth 5 years ago, all	46.54	33.45208	3	150	24
Water table depth 10 years ago, all	46.17	33.64219	3	150	24
Parameter calculation					
Pumping cost per meter of water table depth (Rs)	14.62	107.46	0	1798.04	1173
Hydraulic conductivity (meters per hour)	204.23	166.56	0.0036	360	1163
Radius of cones of depression (meters)	5809.25	4162.35	30	9487	1163
Duration of cones of depression (hours)	41.92	22.67	20	67.1	1163

**Horsepower either measured in torque, 1 unit=550 ft-lbs/sec, or 1 kW = 1.36 hp

***Rice irrigations and durations gathered at follow-up survey at end of *kharif* season. Nonreporting plots were assigned zeroes

Table 1: Summary Statistics - Water

Rainfall during the kharif and rabi seasons of 2010-2011–the year leading up to the household survey–was more erratic than over the 5-year average (see Figure). The dry planting periods of April and May 2010 saw about 24 inches of rain total, compared to an average of nearly 73 inches for those two months between 2008-2012. However, the monsoon period of July-September produced 50% more rain than normal in this area. The rabi season then produced almost no rain, only a sixth of the average.

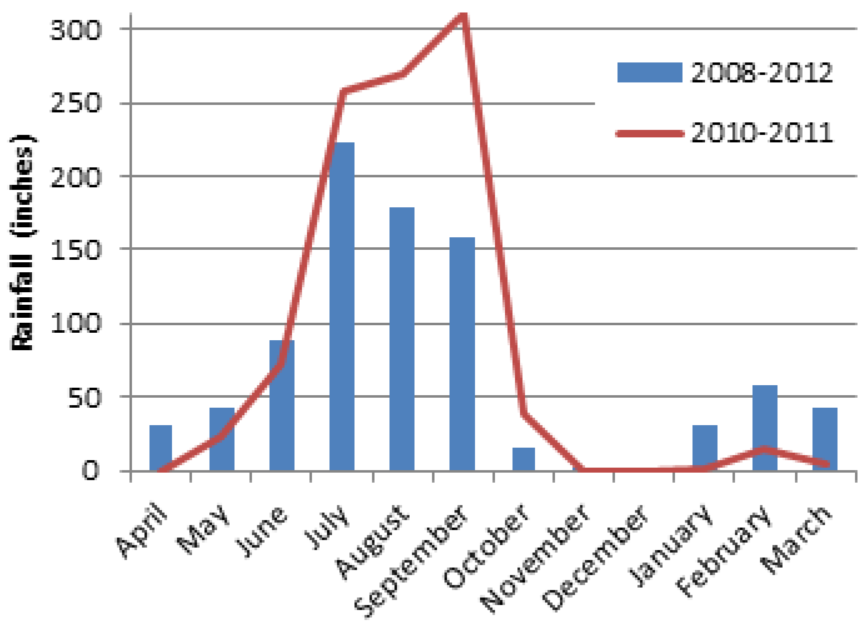

Figure 7: Rainfall during 2010-2011 in eastern UP was erratic compared to the five-year average

Typical ranges of hydraulic conductivity for the different soils found in eastern Uttar Pradesh are between 0.1 and 0.000001 meters per second for the soils in EUP and can go up to 1 x 10^-9 for pure clay elsewhere. Converting to meters per hour produces a range for soils in our sample between 0.0036 to 360 m/hr. The soil types in this area are *Balvi domat* (sandy loam), *Kali* (black), *Chikni domat* (clay loam)*, and Martika* (clay), the first three of which are mostly found in lowland areas and generally have more moisture and clod formation. *Balvi domat*, by contrast, is a light soil that erodes quickly and leads to uneven fields because of continuous need for tillage and puddling in agricultural preparation. There was more demand for laser land leveling on lands for plots with this soil.

Figure (8) shows how the soils in this area of India fall between the most porous, sandy type and the hardest, most dense clay variety. The majority of plots, 51%, consist of *Balvi domat*, which, because of its light consistency, leads to bigger but shorter duration cones of depression, as well as higher rates of hydraulic conductivity. Over a third of plots have either clay or clay loam, as shown in Table 2. Pure clay plots, on which hydraulic conductivity is the lowest and cones of depression the smallest and longest in duration, do not make up much of the sample, at only 7%. The climate of UP suggests that black soils may contain up to 30% sand, more than 40% clay and 15-45% silt (Bhattacharyya et al. 2007). The clay in *kali* soil can be further broken down into a majority coarse clay, as opposed to fine. This places it roughly in the middle of the soil triangle and in the same neighborhood of weight and conductivity of clay loam. We use lower values of K that represent differences in rates of hydraulic conductivity for these soil types and combine all of these in proportion to their share in the sample.

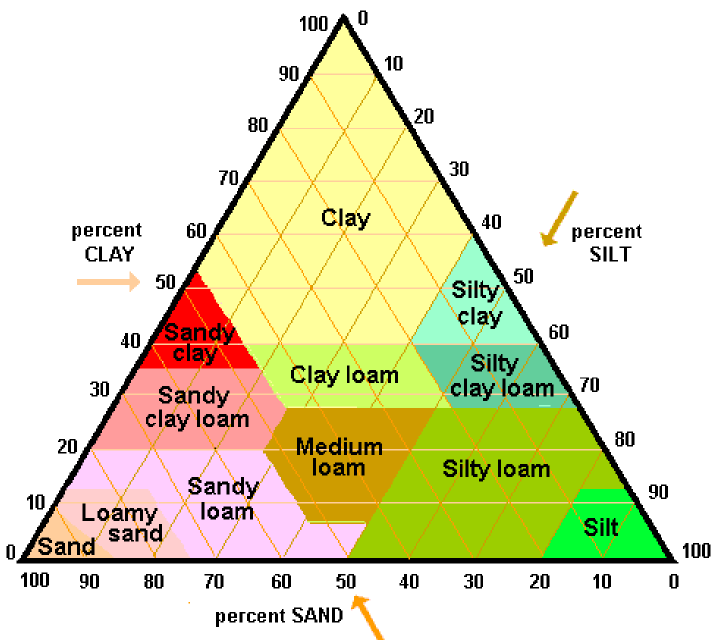

Figure 8: This triangle shows the percentage of clay, silt and sand in various soil types. Sandy loam must be at least half sand and no more than 20% clay and 30% silt. Clay loam is lighter than clay and, thus, leads to larger-radius and shorter-duration cones of depression during pumping. Source: http://www.oneplan.org/Water/soil-triangle.asp

As mentioned earlier, the radius of cones of depression depends on hydraulic conductivity and volume pumped[5]. We obtain values of these for each soil type/hydraulic conductivity combination, as well as for durations of the cones. We generate values of cone duration per meter for each soil type and multiply it by the radius when calculating the duration of cone. Duration per meter will be highest for clay soils but clay soils allow the least amount of radial expansion. Further, it represents only 7% of the sample.

Variable	Mean	SD	Min	Max	N
Farms and Plots					
Landholdings	3.05	7.95	0	100	478
Landholdings cultivable	2.99	7.80	0	90	478
Plots per farmer	2.65	1.64	1	12	478
Area per plot (acres)	0.67	0.98	.01	15	1204
Upland	0.20	0.40	0	1	1170
Soil					
Balvi domat (sandy loam)	0.51	0.50	0	1	1163
Kali (black)	0.12	0.33	0	1	1163
Chikni domat (clay loam)	0.30	0.46	0	1	1163
Martika (clay)	0.07	0.26	0	1	1163
Agricultural Technologies					
Four Wheel Tractor	0.89	0.31	0	1	1265
Thresher	0.82	0.38	0	1	1265
Knapsack Sprayer	0.73	0.44	0	1	1265
Fodder Chopper	0.58	0.49	0	1	1265
Combine	0.52	0.50	0	1	1265
Rotovator	0.50	0.50	0	1	1265
Power Sprayer	0.19	0.39	0	1	1265
Straw Ripper	0.12	0.33	0	1	1265
Turbo Happy Seeder	0.09	0.28	0	1	1265
Seed Drill	0.08	0.28	0	1	1265
Leveling					
Traditional Leveler	0.49	0.50	0	1	1265
Laser Land Leveler*	0.14	0.34	0	1	1265
Acres leveled per adopting farmer*	1.30	1.28	0	6	172
Acres leveled per village*	6.42	3.47	0.8	12.83333	172
Acres leveled*	126.77	0.00	127	126.7654	172
Number of farmers leveling	122.00	0.00	122	122	478
Number of farmers leveling per village	5.08	2.34	0	11	24

*Calculated in the following season

Table 2: Summary Statistics - Farms

[5]This also depends the thickness of the unconfined aquifer with a maximum saturated thickness equal to the minimum depth to water table (Maréchal et al 2011). Thus, when calculating estimated radii, we need use a value of thickness not exceeding the depth to water table.

Because it has been shown that laser land leveling reduces water pumped by 26% (Lybbert et al., 2013), we set $\beta = 26$. Here, we additionally estimate impacts of LLL on number of irrigations and reduced duration of irrigations. The results in Tables 3 and 4 show that laser land leveling additionally reduces the chance that plots level simultaneously through its effect of reducing the duration of irrigations but not on total irrigations. Farmers spend up to 1.8 fewer hours pumping water per year when their field is laser land leveled. Because the actual mean duration of pumping in 2011 was 2.3 hours, this amounts to a 43-77% decrease in pumping duration. Thus, we start with $\delta = -43$ and then consider a range of $\delta \in (-77, -43)$, while setting $\gamma = 1$ so that there is no multiplier effect via number of irrigations.

	Duration of Irrigation											
	OLS			District Controls			Plot Controls			Farmer Controls		
	Rice Hours	Wheat Hours	Total Hours	Rice Hours	Wheat Hours	Total Hours	Rice Hours	Wheat Hours	Total Hours	Rice Hours	Wheat Hours	Total Hours
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Adopt Laser Land Leveling	-0.687	-1.820**	-1.179**	-1.112***	-2.164**	-1.585***	-1.078**	-2.117**	-1.555***	-1.253***	-2.613***	-1.809***
	(0.450)	(0.892)	(0.539)	(0.427)	(0.916)	(0.543)	(0.444)	(0.949)	(0.559)	(0.416)	(0.906)	(0.524)
Gorakphur				2.732***	1.999	2.413***	2.634***	1.725	2.245***	2.160***	0.741	1.679**
				(0.576)	(1.224)	(0.722)	(0.604)	(1.274)	(0.749)	(0.568)	(1.225)	(0.705)
Deoria				-0.463	0.810	0.441	-0.476	0.866	0.478	-0.226	1.379	0.923
				(0.470)	(1.024)	(0.600)	(0.501)	(1.084)	(0.632)	(0.478)	(1.054)	(0.603)
Balvi domat							0.151	-1.384	-0.484	0.111	-2.253	-0.910
							(1.108)	(2.179)	(1.293)	(1.047)	(2.080)	(1.213)
Kali							-0.163	-1.811	-0.659	-0.478	-3.130	-1.316
							(1.167)	(2.333)	(1.386)	(1.089)	(2.215)	(1.291)
Chikni domat							-0.0250	-1.800	-0.657	-0.0736	-2.640	-1.047
							(1.139)	(2.237)	(1.332)	(1.062)	(2.117)	(1.239)
Upland							-0.865	-1.644	-1.313*	-0.460	-0.509	-0.665
							(0.563)	(1.187)	(0.697)	(0.533)	(1.146)	(0.660)
Age										0.00574	0.0776*	0.0396*
										(0.0184)	(0.0395)	(0.0230)
Education										0.122***	0.439***	0.247***
										(0.0387)	(0.0847)	(0.0486)
Experience cultivating plot										-0.00121	-0.0449	-0.0265
										(0.0196)	(0.0427)	(0.0248)
Household size										0.205***	0.125	0.154***
										(0.0377)	(0.0820)	(0.0478)
Constant	2.669***	7.104***	4.706***	2.451***	6.424***	4.133***	2.584**	8.259***	4.924***	-0.130	2.352	0.945
	(0.286)	(0.574)	(0.345)	(0.372)	(0.808)	(0.467)	(1.067)	(2.129)	(1.266)	(1.220)	(2.548)	(1.490)
Observations	206	215	220	206	215	220	201	210	215	194	203	208
R-squared	0.011	0.019	0.021	0.164	0.031	0.074	0.169	0.042	0.086	0.329	0.193	0.254
R2	0.0113	0.0192	0.0215	0.164	0.0314	0.0739	0.169	0.0425	0.0861	0.329	0.193	0.254

Standard errors in parentheses Staple crops only
*** p<0.01, ** p<0.05, * p<0.1

Table 3: Effect of Laser Land Leveling on Duration of Irrigations

	Number of Irrigations											
	OLS			District Controls			Plot Controls			Farmer Controls		
	Rice Times	Wheat Times	Total Times	Rice Times	Wheat Times	Total Times	Rice Times	Wheat Times	Total Times	Rice Times	Wheat Times	Total Times
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Adopt Laser Land Leveling	-0.174	-0.0789	-0.307	0.0473	-0.0742	-0.110	0.0289	-0.0581	-0.130	0.0790	-0.0643	-0.0713
	(0.298)	(0.146)	(0.366)	(0.299)	(0.124)	(0.369)	(0.310)	(0.126)	(0.382)	(0.318)	(0.126)	(0.392)
Gorakphur				-1.302***	0.194	-0.872*	-1.411***	0.122	-0.996*	-1.461***	0.165	-0.908*
				(0.404)	(0.165)	(0.490)	(0.421)	(0.169)	(0.511)	(0.434)	(0.170)	(0.526)
Deoria				-0.796**	-1.111***	-1.421***	-0.848**	-1.191***	-1.488***	-0.933**	-1.226***	-1.599***
				(0.330)	(0.138)	(0.408)	(0.349)	(0.144)	(0.431)	(0.365)	(0.147)	(0.451)
Balvi domat							0.175	0.198	0.646	-0.0161	0.254	0.675
							(0.773)	(0.289)	(0.882)	(0.799)	(0.289)	(0.907)
Kali							-0.375	-0.0970	0.180	-0.570	0.00793	0.219
							(0.813)	(0.309)	(0.945)	(0.831)	(0.308)	(0.965)
Chikni domat							0.132	0.312	0.830	-0.0663	0.386	0.830
							(0.794)	(0.296)	(0.908)	(0.810)	(0.294)	(0.925)
Upland							-0.311	0.110	-0.493	-0.231	0.0294	-0.562
							(0.392)	(0.157)	(0.475)	(0.407)	(0.159)	(0.493)
Age										0.0129	-0.00897	0.00286
										(0.0140)	(0.00549)	(0.0172)
Education										0.0318	-0.0223*	-0.0305
										(0.0295)	(0.0118)	(0.0363)
Experience cultivating plot										-0.0112	0.00988*	-0.0119
										(0.0150)	(0.00594)	(0.0185)
Household size										-0.0304	-0.0115	-0.0565
										(0.0288)	(0.0114)	(0.0357)
Constant	4.813***	2.405***	6.885***	5.364***	2.849***	7.616***	5.423***	2.708***	7.185***	5.263***	3.150***	7.981***
	(0.189)	(0.0938)	(0.234)	(0.261)	(0.109)	(0.317)	(0.744)	(0.282)	(0.863)	(0.931)	(0.354)	(1.113)
Observations	206	215	220	206	215	220	201	210	215	194	203	208
R-squared	0.002	0.001	0.003	0.055	0.325	0.056	0.067	0.346	0.066	0.083	0.376	0.082
R2	0.00167	0.00138	0.00321	0.0547	0.325	0.0563	0.0665	0.346	0.0656	0.0831	0.376	0.0820

Standard errors in parentheses Staple crops only
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Effect of Laser Land Leveling on Number of Irrigations

Finally, the change in water table depth in equation 5 is the difference between equations 6 and 7. For each plot that is leveled, we generate plot-level water pumped, $pump_i$, as the product of tube opening, horsepower of pump and total irrigation hours and report this in Table 1 (2,059 liters on average per year). Total village acres leveled, L_v, is our variable during our simulations, as is the number of farmers leveling as captured by the indicator in equation 7. In eastern Uttar Pradesh, 168 plots initially used LLL after our intervention, resulting in 1.3 acres leveled per leveling household, 6.4 acres per village, 126 acres in the sample, and 122 farmers total. These statistics are shown at the bottom of Table 2.

6 Results

In the first specification, we assume all farmers are identical. They pump the same amount of water on average and generate the same cones of depression in both size and duration. The same distribution of soil within our sample applies uniformly within each village. Water wells are also uniformly spaced 100 meters apart.

Using initial levels of adoption equal to those actually observed in eastern Uttar Pradesh, we generate a ratio of impacts on water table depth between surface and ground of roughly 25:75. To achieve this, we measure hydraulic conductivity in meters per minute and specify $e = 5$ in equation 7. The second term in this equation equals -1.88 meters and the third term -5.1, while the first term cancels out when differencing from equation (6). Thus, the change in effective water table, Δw, equals 7 meters in our sample area, with a diesel cost savings to nonadopters of laser land leveling of Rs. 1865.

We now use this initial equation to measure *changes* from increasing both the acres and number of farmers involved with leveling. Doubling the number of farmers alone works through the indicator function in the third term of the equation. Assuming all other parameters remain constant, this simply doubles the effect on water table depth via cones to -10.2, bringing the total effect to -12.1 and a financial savings of Rs. 3230. Doubling area leveled only without changing the number of farmers only impacts water tables through hydraulic conductivity, resulting in

From a practical perspective, one would more likely intervene at the farmer level in order to increase leveling, not decide on amount of area targeted first. Nevertheless, if this ratio between farmers leveling and area leveled is linear, then doubling the number of farmers adopting within a village also doubles the area. This can simultaneously impact leveling through the surface. This is captured in the additively separable form of equation 7.

Laser land leveling's impact on duration of irrigation impacts water table depths and diesel costs to nonadopters through cones only, specifically, via δ. We use the range of δ estimated earlier and report the remaining results in Table (5).

Simulation Results									
	δ=-43			δ=-60			δ=-77		
	No Action	Double # of Farmers	Double Area Leveled	No Action	Double # of Farmers	Double Area Leveled	No Action	Double # of Farmers	Double Area Leveled
Diesel Cost Savings to Nonadopter (Rs.)[a]	1865	3230	2367	1989	3478	2491	2114	3726	2615
Effective Change in Water Table Depth (m.)	7.0	12.1	8.8	7.4	13.0	9.3	7.9	13.9	9.8

[a] per season

Table 5: Preliminary Simulation Results

We see that as LLL's impact on pumping duration changes from 43% to 77%, so does the diesel cost savings to nonadopters from Rs. 1865 to Rs. 2114 (around $35) per year, even at the relatively low adoption rates and LLL coverage observed in the sample area. Note that these changes in impact are channeled solely through reduced size of cones of depression. As we incorporate increases in area leveled for given a value of δ, diesel cost savings increase because of the impact through groundwater recharge which is a function of area leveled. The most impact in our simulation comes from increasing the number of farmers. Assuming that each farmer pumps from a separate water well, this impact is channeled through smaller and fewer cones of depression throughout the area. Presumably, increases in farmers leveling would necessarily mean increases in area leveled. Since this is also more practical from a policy perspective, aiming to increase the number of farmers leveling would have the highest impact on both water table depths and the diesel costs associated with them.

7 Conclusions and Future Work

The increasing uncertainty and erratic weather patterns linked to climate change are likely to impact poorest countries first. This could be even more problematic for a country like India that depends so heavily on water and uses a higher percentage of it on agriculture than any other part of the world. Further, the poorest farmers in agriculture may be the worst affected. Searching now for the best ways to reduce the severity of water-related impacts on the poor over time is of high importance. This research explores methods of agricultural production at the micro level that could combine with national and international climate policies at a macro level to achieve this.

We find that, in addition to 26% decreases in private water usage due to adoption of laser land leveling, significant public reductions in diesel fuel needed to pump water also accrue to non-adopters. This expands the total number of benefactors to include nonadopters and also produces a secondary environmental benefit to water table depletion rates in the form of less diesel consumed. Estimates produced here are likely to be lower bounds on water savings because increases in effective water table depths can simultaneously increase marginal water usage by decreasing the *de facto* price of pumping, which is a function of water table depth and pump horsepower and specifications. National or state governments interested in reducing poverty and increasing water availability both now and for future generations may want to consider such resource conserving technologies as a policy tool.

Moving forward, improved data on hydrological variables in both in EUP and around India can improve both estimates provided here and their applicability to other hydro-ecological systems. And improved precision in converting hydrological parameters into economic results can help bridge the gap between the specifics of the land on which so many poor farmers depend and the economic prosperity and opportunities that have been sorely lacking in many of these villages in the past.

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