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Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation

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[1] The excessive exploitation of groundwater aquifers is emerging as a worldwide problem, but it is nowhere as dramatic and consequential as it is in India, the world's largest consumer, where hundreds of millions of people depend on it. Usually the problem is framed in terms of a long-term decline in water tables and its consequence for extraction costs, resource depletion, and the sustainability of irrigated agriculture. Here a comparative analysis is provided of coupled groundwater, energy, and irrigation dynamics in two groundwater intensive regions in India that differ in their underlying hydrogeology—the Indian Punjab with its deep alluvial aquifers and the Telangana region in south-central India with its shallow hard rock aquifers. Using a simple modeling framework and piezometric and agricultural time series, we show that in shallow aquifers the sense in which extraction is excessive is different, and is related to the short-term reliability of water supply rather than long-term sustainability. This has important repercussions for irrigated agricultural economies.

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1. Introduction

[2] The excessive exploitation of groundwater aquifers is emerging as a worldwide problem, but it is nowhere as dramatic and consequential as it is in India, the world's largest consumer of groundwater (on the order of 260 km^3 per year), and a country where up to 70% of agricultural production and 50% of the population depend on this vital resource [*The World Bank and Government of India*, 1998; *Shah*, 2008; *Siebert et al.*, 2010]. An understanding of the consequences of groundwater mining for agricultural production is clearly an important research agenda. However, despite the pervasive indications of excessive extraction around the country (R. M. Fishman, unpublished data, 2011), systematic documentation or analysis of the associated impacts on irrigated agriculture are hard to find.

[3] Usually, the problem of excessive groundwater extraction is posed in terms of the implications of falling water tables, resource depletion, quality deterioration, and rising extraction costs for the long-term sustainability of irrigated agriculture [*Moench*, 1992; *Wada et al.*, 2010]. Such persistent declines in water tables are typical in over-exploited aquifers of large storage, such as the alluvial aquifers that cover much of northern and western India, for which dramatic remote sensing evidence was recently discovered [*Rodell et al.*, 2009; *Tiwari et al.*, 2009]. The vast theoretical literature on the exploitation of groundwater aquifers (for a recent review, see *Koundouri* [2004]) has also tended to focus on situations in which extraction costs will stabilize water tables away from the bedrock (for an exception, see *Athanassoglou et al.* [2011]). This paper, however, argues that a different set of considerations apply to the utilization of limited storage (thin) aquifers, and that the nature, dynamics, and implications of over-exploitation of these formations is fundamentally different than it is in large storage aquifers.

[4] A comparative analysis of the differences between human-environment dynamic interactions in "thick" versus "thin" aquifers is provided here. The dynamical analysis couples water tables, precipitation, and water and energy use in irrigation, in a simple model, and its stylized predictions are demonstrated using piezometric and agricultural data from India, where intensive groundwater irrigated agriculture is practiced over a large range of hydrogeological conditions [*World Bank*, 2010]). Much of the peninsular part of South Asia, in particular, overlays hard rock, shallow aquifers of limited storage (Figure 1), and the exploitation of these aquifers has resulted in a boom in irrigation and agriculture [*Shah*, 2008], as well as unregulated and excessive extraction [*World Bank*, 2010] much as it has in northern parts of India. [According to the Central Groundwater Board of India, 45% of the *mandals* (administrative units) in Telangana are no longer *safe*, meaning that more

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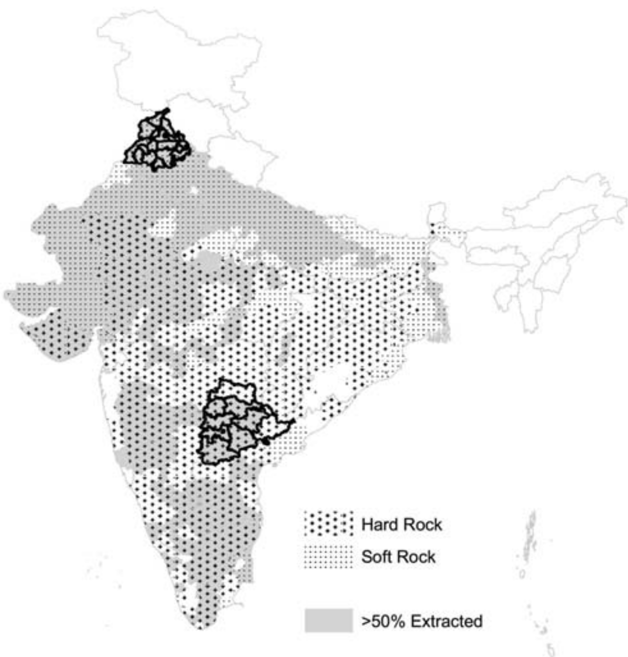

Figure 1. Groundwater hydrogeology and exploitation in India. The underlying geology is classified into the broad types of hard rock and soft rock (data source: Central Groundwater Board). Gray areas indicate districts in which more than half of the renewable recharge is extracted [*Central Ground Water Board*, 2007], usually suggesting a concentration of hotspots of over-exploitation. The districts of two study areas of Punjab (in the northwest) and Telangana are highlighted.

than 70% of their renewable supply of groundwater is extracted, and 17% are over-exploited, meaning that more than 100% of their renewable recharge is extracted, and these ratios are higher in *noncommand* areas which are not served by irrigation canals. In Punjab, only 18% of the *blocks* (administrative units) are *safe*, and 75% are over-exploited (http://cgwb.gov.in/).]

[5] Such an analysis is worthwhile for several reasons. First, it contributes to the general analytical understanding of the groundwater-energy crisis in South Asia (see reviews by *Shah* [2008] and *World Bank* [2010]). Second, it focuses on small storage aquifers, which, while receiving less attention in the literature than large storage aquifers, still support significant parts of India's groundwater irrigated areas and are important water supply sources all over the world [*Shiklomanov*, 2000; *UNDP*, 2006]. Third, it provides a first step in improving our understanding of what it would actually mean for groundwater to "run out" under different water, energy, and land constraints. In other words, observing the consequences of "depletion" in shallow aquifers, like the ones in peninsular India, can provide a hint on where current excessive irrigation from alluvial large storage aquifers might be headed and thus inform the wider policy debate surrounding groundwater mining. Fourth, it highlights the role groundwater aquifers can play as a buffer to climate variability, a role which is particularly important in developing countries [*Ribot et al.*, 1996], and is increasing in importance as a possible adaptation approach to increasing climatic variability under climate change scenarios.

[6] Our approach utilizes available data on water tables, rainfall, and irrigation over two decades from two key regions of intensive groundwater use in South Asia (Figure 1) that represent the two prominent hydrogeological regimes in the country: the "rice bowl" of Punjab [*Kumar et al.*, 2007], which overlies the deep alluvial aquifers of the western Gangetic basin, and the Telangana region in the state of Andhra Pradesh, which overlies shallow, fractured hard rock aquifers with low yields [*Raj*, 2004a, 2006; *Reddy et al.*, 2009], much like those that cover most of peninsular India, and that has nevertheless emerged as another major rice producing area.

[7] An important common characteristic of the two regions, and indeed of the whole country's groundwater irrigation, is that it is powered, to a large degree, by the provision of subsidized electricity by state governments farmers usually pay a flat, low rate, if any (there is currently no fee at all in both our study regions), on electricity use for pumping, and use as much of it as is available, even while lobbying for increases in the daily duration of its supply by public utilities. (In some parts of India, especially in the eastern parts of the Gangetic basin, where rural electricity supply is limited, groundwater irrigation is mostly fueled by diesel for which farmers pay the costs [*Shah et al.*, 2009]. However, in these regions agriculture is, likely as a result, less developed, yields tend to be lower, and concerns over groundwater mining are mostly irrelevant.) While reliable figures are difficult to come by, it is clear that energy use for pumping has increased rapidly over the last few decades [*Morris*, 1996; *Dubash*, 2008]. As an example, Figure 2 documents increases in the numbers of electric pump sets and total electricity use for groundwater pumping in Punjab and Andhra Pradesh (the state in which the Telangana region is located) where the latter has grown 5 to 7 times over the last 30 years. In many states, nowadays, groundwater pumping is estimated to use more than 40% of total electricity consumption and to be responsible for more than 40% of the annual budget deficit [*Briscoe et al.*, 2006].

[8] Under these circumstances, some of the central dimensions of groundwater management theory, such as the role of extraction costs, regulation, and dynamic optimization, are simplified to a great degree, and become less relevant to the understanding of the groundwater crisis in India. We therefore adopted here a modeling approach that is highly stylized along these behavioral dimensions, and instead focuses on dynamical elements associated with the effects of the aquifer's "bottom."

[9] In case of groundwater abundance, e.g., in regions with alluvial aquifers, increases in the use of energy for pumping can make up for the decline in water tables and enable water extraction to be maintained or even increased. This could be one of the reasons for the difficulty of observing the impacts of groundwater depletion on irrigated agriculture. However, in the shallow aquifers of peninsular India, water itself is limited, and increases in the supply of energy may fail to substitute for the depleting resource. This is precisely what our results demonstrate.

[10] The rest of the paper is organized as follows. In section 2 we describe the study regions, present data sources, and introduce a simple coupled human-natural modeling framework of groundwater use. The comparative analysis of the dynamics of water tables and the dynamics of irrigation

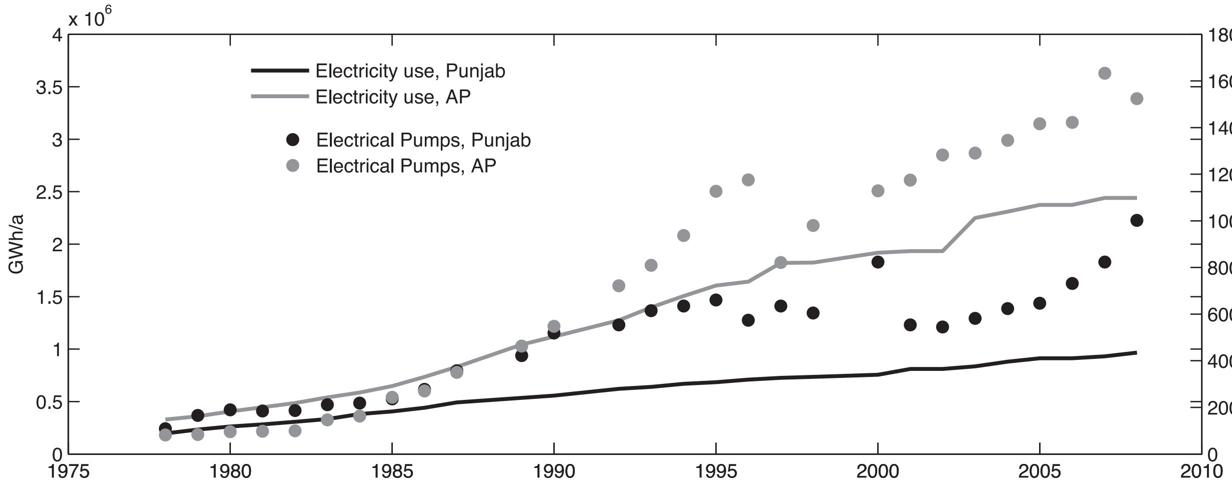

Figure 2. Growth in electricity use for pumping groundwater (solid lines) and number of electrical pumps (dots) in the states of Punjab and Andhra Pradesh. Source: annual editions of *All India Electricity Statistics, General Review.*

water supply in the two regions is presented in section 3. Results are discussed in section 4. Section 5 concludes.

2. Data and Approach

2.1. Comparative Regional Overview

[11] The two study areas, Telangana and Punjab, are semiarid to arid regions that employ a rice dominated, productive but energy intensive irrigation system. In both regions, the intensive groundwater use is resulting in falling water tables and in the deepening and drying up of wells.

[12] In Punjab, quaternary alluvium is the predominant hydrogeological formation. Aquifers are of sandy gravel type, with mixed water quality and aquicludes of clayey loam type interspersed. Groundwater mining is the predominant issue in the central and eastern part of the state, whereas water logging and associated soil salinization due to inadequate drainage pose the biggest problem in the southwestern part of the state (information from Central Groundwater Board, available at http://cgwb.gov.in/gw_profiles/st_Punjab.htm). In Telangana, Archaen rocks (granites and gneisses) and Cretaceous Deccan Trap basalts are the predominant rock types. Since most of these rocks have negligible primary porosity, groundwater reserves are mediocre and aquifers with satisfactory yields only found in weathered, fractured zones throughout the region [*Raj*, 2004a]. Table 1 summarizes key hydrogeological characteristics.

[13] Plots of bi-annual regionally averaged depth to water (drawdown) for Punjab and Telangana are presented in Figure 3. Drawdown is measured in observation wells (which are probably mostly open dug wells) before (June) and after (November) the annual monsoonal recharge season (June–September), during which more than 75% of the total annual rainfall in India is concentrated [*Singh et al.* 2007], and thus follows a see-saw pattern. As shown in Figure 3, Telengana's water tables are dominated by a high degree of inter-annual fluctuations and there is no clear long-term deepening trend as in Punjab, except perhaps in the earlier stages of exploitation in the 1970s. It is also interesting to note that mean precipitation is higher in Telangana, in fact, it is almost sufficient for rice cultivation (of course, a smaller fraction of the total land area is irrigated in Telangana, but on the other hand, only a fraction of precipitation over unirrigated land is actually captured for recharging the aquifer) and it has to be, because there is no large reservoir of old water to tap, which is how Punjabi farmers are able to continue cultivating rice over large parts of their land for many years with the lower available rainfall.

Table 1. Key Irrigation Characteristics in Punjab and Telangana[a]

	Punjab	Telangana
Predominant hydrogeology	alluvial	hard rock
Storativity range (–)	$10^{-4} - 10^{-3}$	$3.13 \times 10^{-2} - 3.38 \times 10^{-2}$
Transmissivity (m^2 day^{-1})	500–1000	2–500
Aquifer depth range (mbgl)	10–500	0–30
Average hours of electricity supply	6.2	6.6
Average pump horsepower	5.4	4.7
Costs of electricity for pumping	free	free
Principal water consuming crop	rice	rice
Percent of area irrigated (from groundwater)	94% (68%)	41% (43%) (AP)
Area irrigated per well (ha), Kharif season	2.6 (rice +)	0.8 (rice +)
Area irrigated per well (ha), Rabi season	2.6 (rice +)	0.5 (rice +)
Average annual precipitation (mm)	680	950

[a]Source: Central Ground Water Board, Min. of Water Resources, Gov. of India, North Western Region and *Raj et al.* [1996]; *Raj* [2004a, 2004b] (lines 1–3). Census of Minor Irrigation Schemes, Min. of Water Resources, Gov. of India.

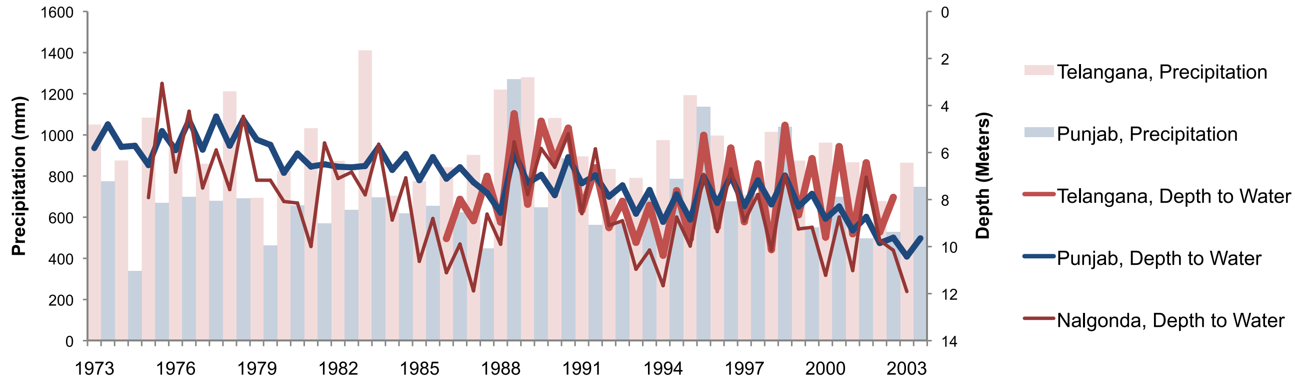

Figure 3. Groundwater levels and precipitation time series for Punjab (alluvial, blue) and Telangana (hard rock, red). Pre- and postmonsoon depth to water are displayed for each year. In Telangana, pre-1986 water table figures is only available in Nalgonda district, a part of Telangana. Post-1986 data is regional average, and pre-1986 data is taken from Nalgonda. Post 1986 comparison suggests good agreement between the two.

[14] The state of Punjab has been a leader in irrigated agriculture in India ever since the green revolution started on its soils in the late 1960s. Today, groundwater irrigation has taken over from the traditional surface irrigation network of the state as the dominant source of irrigation and food production. Despite its relatively small area (1.5% of India's total), Punjab is now the principal provider of cereals (rice and wheat) to the rest of the country (53% in terms of total production), an increase attributed to the expansion of irrigation to cover virtually the entire cropped area of the state. Its seasonal cycle is overwhelmingly dominated by irrigated cultivation of rice during the rainy season, i.e., Kharif from June through October and of wheat during the dry season, i.e., Rabi, from October through March (*Aggarwal et al.* [2009] and references therein). The dry season irrigation is devoted to wheat which, in that region, has an approximately 40% lower irrigation water requirement as compared to wet season irrigation water requirements [*Bandyopadhyay and Mallick*, 2003; *Kang et al.* 2003].

[15] In the region of Telangana, Andhra Pradesh, the cultivation of irrigated crops, predominantly rice and some cotton, was traditionally limited to small areas in which shallow dug wells provided sufficient water yield, or where topographic conditions allowed the constructions of small irrigation tanks. Elsewhere, rain-fed cultivation was dominated by traditional crops with low water requirements such as Bajra (millets), Jowar (Sorghum), and certain pulses. But there too, the introduction of borewells in the 1980s that could tap deeper pockets of groundwater and the spread of rural electrification that could provide more energy for pumping allowed farmers to significantly expand the area under irrigation, from 23% of the net sown area in 1985 to 38% in 2001. Almost this entire increase was due to groundwater irrigation (Figure 4). {Specifically, area irrigated by borewells grew from 0.3% to 10% of net sown area, and area irrigated by shallower dug wells grew from about 8% to about 13% of net sown area [*Vakulabaharanam*, 2004]. Note that while borewell irrigated area has expanded consistently and dramatically, this expansion has been partially eroded by the decline in area irrigated by other sources. The decline in areas served by tanks is noteworthy and is attributed to lack of maintenance and siltation (which is

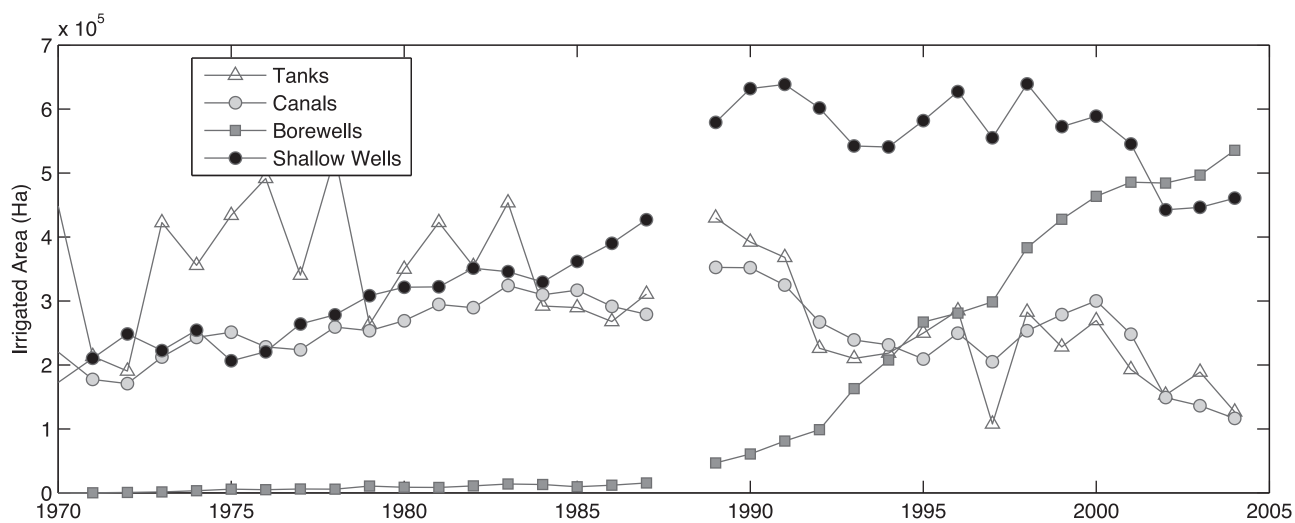

Figure 4. Development of irrigated area (source-wise) in Telangana from 1970 to 2005. Data source: Directorate of Economics and Statistics, Government of Andhra Pradesh.

also possibly related to farmers taking up private wells instead). The decline in areas irrigated by other wells (dug wells and bore cum dug wells, which are borewells drilled at the bottom of open dug wells) is often also attributed to the expansion of deeper tubewells and the resulting lowering of the water table over time. Certain parts of Telangana are also served by surface irrigation canals. See, for example, *Venot et al.* [2007, 2008] for a discussion of some related environmental and social issues.}

[16] The expansion of irrigation is believed to have played a key role in the rapid agricultural growth in the region in the period of 1970–2001 [*Vakulabaharanam*, 2004]. It allowed the cultivation of water-intensive crops like rice and cotton, the use of high yielding varieties, and, above all, a second cropping during the dry Rabi season. By the turn of the century, Telangana rice production began to rival that of the canal-laden coastal regions (Andhra Pradesh is one of the major rice growing regions of India) and Rabi (dry) season production began to rival that of the Kharif (rainy) season.

[17] Table 1 summarizes some basic aspects of the regions' irrigated agricultural economy. Despite the many similarities, the two regions also differ in some important ways. In Punjab, almost the entire cultivated area is irrigated in both seasons (even though wheat, which requires far less water, is grown in the dry season) while in Telangana, a smaller share of the area is irrigated, especially in the dry season. While pumps in the two regions have similar power and hours of electricity supply, a well in Punjab is able to irrigate a larger area, due to higher formation yields there.

[18] This suggests that in Punjab, where aquifers are vast and deep, the real constraint on irrigation is availability of energy and land. In Telangana, where aquifers comprise of a shallow later of weathered granite and scattered pockets and fractures (see *Reddy et al.* [2009]), it seems that the supply of energy has a more limited capacity in overcoming physical water scarcity.

[19] The analysis that follows will further support this hypothesis. It will also relate the difference in hydrogeology to a basic difference in the dynamics of irrigation in the two regions, apparent in Figures 3 and 5, which suggest that in Telangana the dynamics of both irrigated areas and water tables are dominated by a large degree of inter-annual variability, whereas in Punjab they are dominated by secular trends (except perhaps in the earlier stages of exploitation in the 1970s, water tables in Telangana do not display the kind of clear deepening trend as they do in Punjab).

2.2. Data and Sources

[20] In both Telangana and Punjab we use district-level data on irrigated areas, water tables (we will use the terms water table, drawdown, or depth to water interchangeably), and precipitation. Data are available for the nine districts of Telangana, and for eleven districts in Punjab (Table 2 lists all data sets and sources). Annual precipitation figures were obtained from a national gridded data set through a process of weighted spatial averaging (for details see *Siegfried et al.* [2010]). Water table figures were obtained through district-wise averaging of data from a network of monitoring wells (the raw data is not available to us) operated by the state

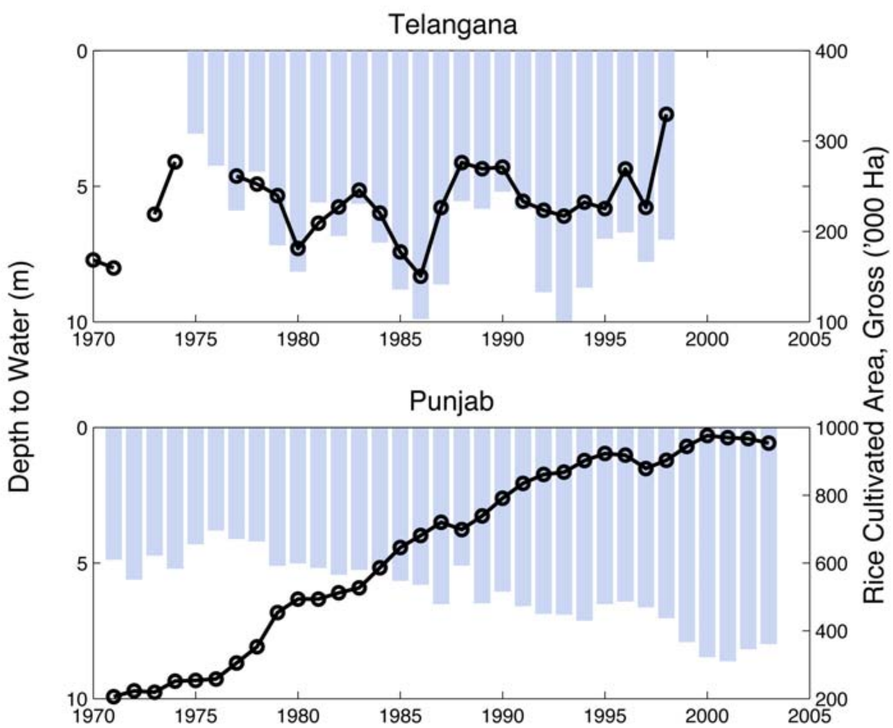

Figure 5. Plots of gross area cultivated with rice (right axis, line) and postmonsoon depth to water (left axis, bars) in Telangana (hard rock aquifer, top) and Punjab (alluvial aquifer, bottom). The correlation between groundwater levels and irrigation is clear in the hard-rock region, but is lacking in the alluvial region, where irrigated areas have been rising even as water tables fall.

Table 2. Data Availability and Sources[a]

	Punjab	Telangana	Source
No. of districts	11	9	
Water tables	1971–2003	1986–2002, 2000–2006	SGWB
Irrigated area (by season)	–	1970–2004	APDES
Irrigated area (by source)	–	1970–2004 (R), 1998–2006 (R + K)	DES
Rice area (by season)	1971–2006	1970–1999	CMIE
Rice yield (by season)	1971–2006	1970–1999	CMIE
Annual precipitation	1971–2003	1971–2003	*Siegfried et al.* [2010]

[a]R: Rabi season, R + K: Rabi and Kharif season. SGWB: Government of Andhra Pradesh, Groundwater Dept.; APDES: Directorate of Economics and Statistics, Government of Andhra Pradesh; CMIE: Center for Monitoring Indian Economy.

groundwater boards of Punjab and Telangana and available on a bi-annual basis (pre- and postmonsoon). In Punjab, data were obtained for the period 1971–2003 and in Telangana, we have data from two separate sets of monitoring wells, one for the period 1986–2002 and another for the period 1998–2006. (It should be noted that water tables reported by monitoring wells tend to be lower than those reported by farmers in their irrigation wells, probably due to local cones of depression around active irrigation wells.) We take these averaged water tables as indicators of fluctuations rather than absolute value of the water tables actually experienced by farmers.

[21] We focus on agricultural seasons in which land is intensively irrigated, mainly for rice cultivation. In Punjab, rice is cultivated only during the rainy season (Kharif). The extent of area devoted to irrigated rice cultivation were obtained from the Indian Harvest Database of the Center for Monitoring Indian Economy. In Telangana, details of areas irrigated during the rainy Kharif season (net irrigated area) and dry Rabi season (area irrigated more than once) were obtained from the Directorate of Economics and Statistics, Government of Andhra Pradesh. In both seasons, a major portion of irrigated areas is devoted to rice cultivation. In Telangana, some figures are also available on the source-wise decomposition of irrigated areas.

2.3. Modeling Approach

[22] Consider the water budget of a simple, single cell aquifer of thickness B (Figure 6). Denote the average depth to water at the beginning of period t by D_t. The volume of water stored in the aquifer at t is $V_t = \rho(B - D_t)$, where ρ is the mean porosity which assumed to be uniform and $B - D_t$ is the saturated thickness at time t. Denote the amount of water extracted for irrigation (net of return flow from excess irrigation) by W_t, and the amount of net natural discharge (including lateral flows) from the aquifer that is irretrievably lost to the downstream by L_t. Finally, denote by P_t the in-period t precipitation, and the aquifer recharge, net evapotranspirative losses by R_t, and assume it to be an increasing function of P_t.

[23] The dynamical evolution of the stored volume follows from the water budget

$$V_{t+1} = V_t - W_t - L_t + R_t. \quad (1)$$

[24] (Additional recharge may occur by leakage from surface irrigation canals, and can change the water balance. See section 4 for a discussion of the role of surface irrigation in our analysis.) We wish to investigate the dependence of water extraction on the aquifer's annual storage (i.e., depth to water). It is reasonable to assume that the depth to water plays a large role in determining this extraction, because the regulatory environment and incentive structure facing farmers encourages them to pump as much groundwater as the energy supply, determined by the state, allows, and this assumption is supported by anecdotal evidence and field interviews. (Recall that farmers face no marginal cost on water or energy, an unreliable power supply, and the "tragedy of the common" groundwater resource.) We also assume that natural losses are an increasing function of the stored volume, i.e., that

$$W = W(V) \leq V, \qquad L = L(V) \leq V \quad (2)$$

so that the water budget can be written as

$$V_{t+1} = V_t - W(V_t) - L(V_t) + R_t. \quad (3)$$

[25] Both our model simulation and regression analysis will estimate a linearized version of this process in which

$$R_t = rP_t, \quad (4)$$

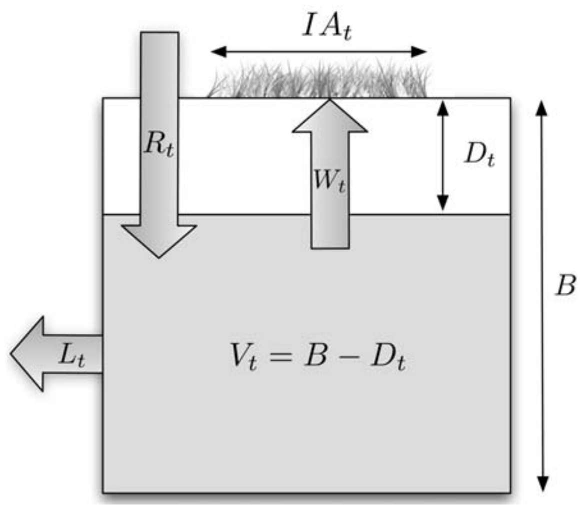

Figure 6. Stylized representation of the modeled groundwater budget for a given district (note: district identifier d is dropped). R_t is net recharge, W_t is pumping, L_t are subsurface losses, D_t is drawdown, and IA_t is irrigated area. V_t is the saturated thickness of an aquifer with mean porosity ρ. The subscript t denotes time-dependent variables.

$$W_t = eV_t = e\rho(B - D_t), \quad (5)$$

$$L_t = n(V_t - W_t) = n(1 - e)V_t, \quad (6)$$

i.e., we assume that (a) recharge is proportional to precipitation $R_t = rP_t$, with r a recharge coefficient; (b) losses are proportional to the stored volume net of extraction with a proportionality factor $n \leq 1$ (a standard modeling assumption in linear reservoir models); and (c) that farmers are able to extract a fixed fraction e of the available storage, a modeling assumption that is common in the natural resources literature (a component of the Gordon-Schaefer model [*Gordon*, 1954]), where the proportionality constant e is referred to as harvesting effort, and in our context can be thought of representing the extraction capacity of farmers, i.e., reflecting the density and power of the irrigation pumps and the duration of the power supply. (This form is also convenient because boundary conditions are automatically satisfied, i.e., the bottom is never "passed.") In the fisheries literature, the assumption that for a given level of effort, e.g., the number of boats, the catch rises with the stock level captures such factors as the greater ease of finding fish when stocks are high. In our context, it captures three factors: first, with a given supply of energy, less water can be pumped to the surface the deeper the water table is, i.e., the lower the stock is. Second, and especially for low storage aquifers, potential extraction can start to approach the actual volume of water stored in the localized pockets and fractures that make up the hard rock aquifers as the water table declines. Third, declines in porosity and conductivity at increasing depths can constrain the extraction rate. The linear form we assume here is but an analytically convenient approximation of all of these factors, as it is in the fisheries literature as well, and should not be relied upon for precise quantitative predictions.

[26] The "effort" level in our model is implicitly assumed to be time independent for the purposes of the statistical estimation below, which means that the density and power of pumps has not changed as rapidly, in intensive (per unit area) terms, as did water tables and irrigated areas. (The geographical expansion of irrigation to new areas does not contradict this assumption and we control for such an expansion in our empirical analysis.) Note, however, that in our numerical simulations we also investigate the possibility of changing effort levels and verify that the main insights are unaltered.

[27] Under the above assumptions, the dynamics take the form

$$V_{t+1} = xV_t + rP_t, \quad (7)$$

$$W_{t+1} = xW_t + reP_t, \quad (8)$$

$$D_{t+1} = xD_t - \frac{r}{\rho}P_t + c, \quad (9)$$

where

$$x = 1 - [e + n(1 - e)] \quad (10)$$

and $c = [e + n(1 - e)]B$ is a constant. Precipitation, and therefore recharge, fluctuates stochastically in time, so that equation (3) describes a stochastic dynamical process. We will assume, for simplicity, that P_t are a sequence of independent and identically distributed random variables.

[28] In section 3 we will statistically estimate the parameters of the model in equations (8) and (9) by regressing the postseason depth to water and the in-season water extraction on the preseason depth to water. To increase sample size we will pool together the entire panel of district-year observations in each region.

[29] Using annual, district-wise water table data, we will first estimate the model in equation (9) by regressing

$$D_{d,t+1} = xD_{d,t} - \frac{r}{\rho}P_{d,t} + c + \epsilon_{d,t}, \quad (11)$$

where d is a district index, and $\epsilon_{d,t}$ are unobserved error terms. Because of the high degree of correlation of rainfall and water tables across districts, we allow the errors $\epsilon_{d,t}$ to be spatially correlated (clustered by year). The regression analysis will provide us with estimates of (the product of) the recharge factor and the porosity, the magnitude of water extraction and losses in relation to the aquifer's storage, and the degree to which the dynamics converge to or are near a steady state or have already reached it.

[30] We also use the available data on irrigation to estimate the model presented in equation (8), i.e., to directly test the degree to which water extraction W_t is dependent on the depth to water (i.e., stored volume) at a season's start, and the degree to which water table fluctuations explain the variability in irrigation. Since direct measurements of water use in Indian agriculture are virtually nonexistent, we use available data on areas cultivated with rice, as well as (in Telangana) total irrigated areas, which we argue are a good proxy for water use.

[31] First, land use is determined through cropping choices that are mostly made in the beginning of the agricultural season and therefore should reflect limits on water supply, as perceived by farmers, especially when it comes to rice, a crop with very high water requirements. (Note however that it is possible that some of the area is abandoned during the season due to either insufficient rainfall, flooding or other factors like pests.) (In contrast, the yield of irrigated crops is subject to numerous stochastic influences, including the distribution of precipitation, pest outbreaks, and solar radiation, to name a few, and would thus be a poorer proxy of water availability. Below, we will actually see that rice yields are less sensitive to water tables and rainfall than are rice areas.) Second, we found no evidence to suggest that water use efficiency, the use of energy per well, the irrigated crop mix, or irrigation practices change as much as land use does to reflect changing conditions, especially in the case of rice cultivation. We therefore assume that the rates of water use per unit area cultivated with rice and per unit of total irrigated area are not as sensitive to the preseason water table as is the spatial extent of rice cultivation and irrigation. Anecdotal evidence and farmers' interviews in the regions supported these hypotheses. (For example, in Punjab, while the number of electrical pumps has increased at an average rate of about 5% per year between 1980 and 2010, the consumption of electricity per pump has only increased at a rate of about 2%. In Andhra Pradesh, the figures are 7% and 4%, respectively.)

[32] We therefore estimate the model (9) by regressing annual time series of irrigated areas on preseason depth to water. Again, we pool together the entire panel of district-year observations and regress

$$\log(IA_{d,t}) = -\alpha D_{d,t} + \beta P_{d,t} + \gamma_d t + \log(IA_d) + \epsilon_{d,t}, \qquad (12)$$

where d is a district index, t is a year index, $IA_{d,t}$ is irrigated area, $D_{d,t}$ is depth to water, $P_{d,t}$ is annual (monsoon) rainfall which is included because it can affect changes in the cropping choices within the rainy season, A_d are unknown district specific scales of irrigation (fixed effects), and γ_d are district specific time trends. The main coefficient of interest is α as its estimated value will indicate the presence/absence of a water constraint on irrigation in each of the regions.

[33] We choose to estimate this logarithmic form because it is natural to expect changes in intensive variables like water tables and precipitation to affect irrigated areas proportionally to some district specific scale. We include time trends because irrigated areas expand over time to new areas, and we need to isolate the fluctuations on the intensive margin, in which we are interested, from the expansion of rice cultivation and irrigation coverage (the extensive margin) through the expansion and connection of the electrical grid to pump sets. For example, the rise of irrigated areas in Punjab coincides with the steady decline in water tables and the associated rise in the amount of energy required to lift a given amount of water. Neglecting to include these time trends would lead to the false conclusion that increases in the depth to water lead to higher water extraction per well. Conversely, with the inclusion of these time trends, we can interpret the estimated coefficients as describing the effect of short-term fluctuations in water tables on changes in irrigated areas which occur locally and independently of the expansion of infrastructure, i.e., on the intensive margin. We check the robustness of the results to the inclusion of quadratic time trends, to the clustering of errors across districts, and to AR(1) serial correlation.

3. Results

3.1. Dynamical Model Analysis

[34] The dynamical model in equations (7)–(9) is a highly simplified model and is intended to explain stylized facts about groundwater irrigation dynamics rather than to produce realistic quantitative predictions. Taken in that light, however, the model can describe the irrigation dynamics of both the deep alluvial aquifers of Punjab as well as the shallow aquifers of Telangana by varying the parameter B. Both regions have roughly similar water requirements per area (same cropping pattern, mainly rice), and comparable water tables D, but they differ in aquifer thickness B(Punjab) $\gg B$(Telangana) implying that e(Punjab) $\ll e$(Telangana). [Also note also that in this linear model we have to first order $W_{t+1}/W_t \approx 1 + \Delta D/B$, so regressing the logarithm of water extraction on water tables yields an estimate that can be interpreted as the inverse of some effective thickness of the aquifer. The estimates we will get below for the two study areas (Table 4) and for different sources of irrigation (Table 5) will be broadly consistent with this interpretation.]

[35] Given a constant level of effort, the stochastic dynamics converge to a steady state probability distribution of water tables and water extraction. This probability distribution is invariant under the dynamics, and if the process is ergodic, it describes the long-term distribution of water tables over time (see, for example, *Feller* [1966]). However, the time it would take to converge to the steady state depends on the parameters of the model, and in particular, on the thickness B.

[36] As an illustration, Figure 7 displays a simulation of the model, over a range of 50 years, for two parameterizations that roughly capture the attributes of the two study regions. Initial effort levels are chosen to enable the irrigation of a single rice crop (assumed to require 1 m of irrigation water) in Punjab and 1.5 crops in Telangana. The top panels in Figure 7 display the simulation results when effort is kept constant at its initial levels. It is clear that Telangana's thin aquifer (small B) reaches its (highly variable) steady state faster than Punjab's deep aquifer, as is also suggested by Figure 3. The steady state is not, as of yet, an appropriate description of the dynamics of Punjab's groundwater irrigation, if only by the fact that it is still able to consistently support extraction in excess of natural recharge and the water table keep declining.

[37] In reality, effort need not be constant. However, it is likely to be increasing with time, because the regulatory environment does not support the closing down of wells, and the political climate makes it unlikely that the power supply be decreased. Increasing effort levels may compensate for a decline in water tables in a thick aquifer, and enable water use to be maintained for a longer time. However,

Figure 7. Illustrative, sample model run of the dynamic model presented in equations (7)–(9) for one particular precipitation realization. Aquifer depth in Punjab is assumed to be $B = 100$ m as compared to the Telangana region where we set $B = 15$ m. Water requirement are set to those a single rice crop in Punjab and 1.5 (cropping intensity) in Telangana, which are achieved initially by initial effort levels set to $e = [0.02, 0.4]$ for Punjab and Telangana, respectively. Further parameter values used: $r = [1, 1]$ (–), $\rho = [0.5, 0.25]$ (–) (these values are consistent with the results of the regressions in Table 4), and $n = [0, 0]$ ($1/a$). Stochastic precipitation series generated with $\mu_R = [0.5, 0.8]$ (m) and $\sigma_R = [0.1, 0.2]$ (m). (a) Sample precipitation realizations for the two regions, (b) depth to water over time, and (c) individual in-period water extraction. Notice that steady state fluctuations (around the mean of 0.8) are reached rapidly in Telangana, whereas after 30 years, water extraction is still far from the steady state value of 0.5 in Punjab, but is remarkably steady. (d), (e), and (f) display simulation results when effort (d) is increased in order to try and maintain water extraction at initial levels. In Punjab, (e) water tables decline faster, but (f) the increase in effort is able to keep water extraction constant. In Telangana, however, (e) water tables reach the steady state as rapidly, and (f) water extraction decreases to its even more variable steady state rapidly after just a few years of unsustainably high water extraction.

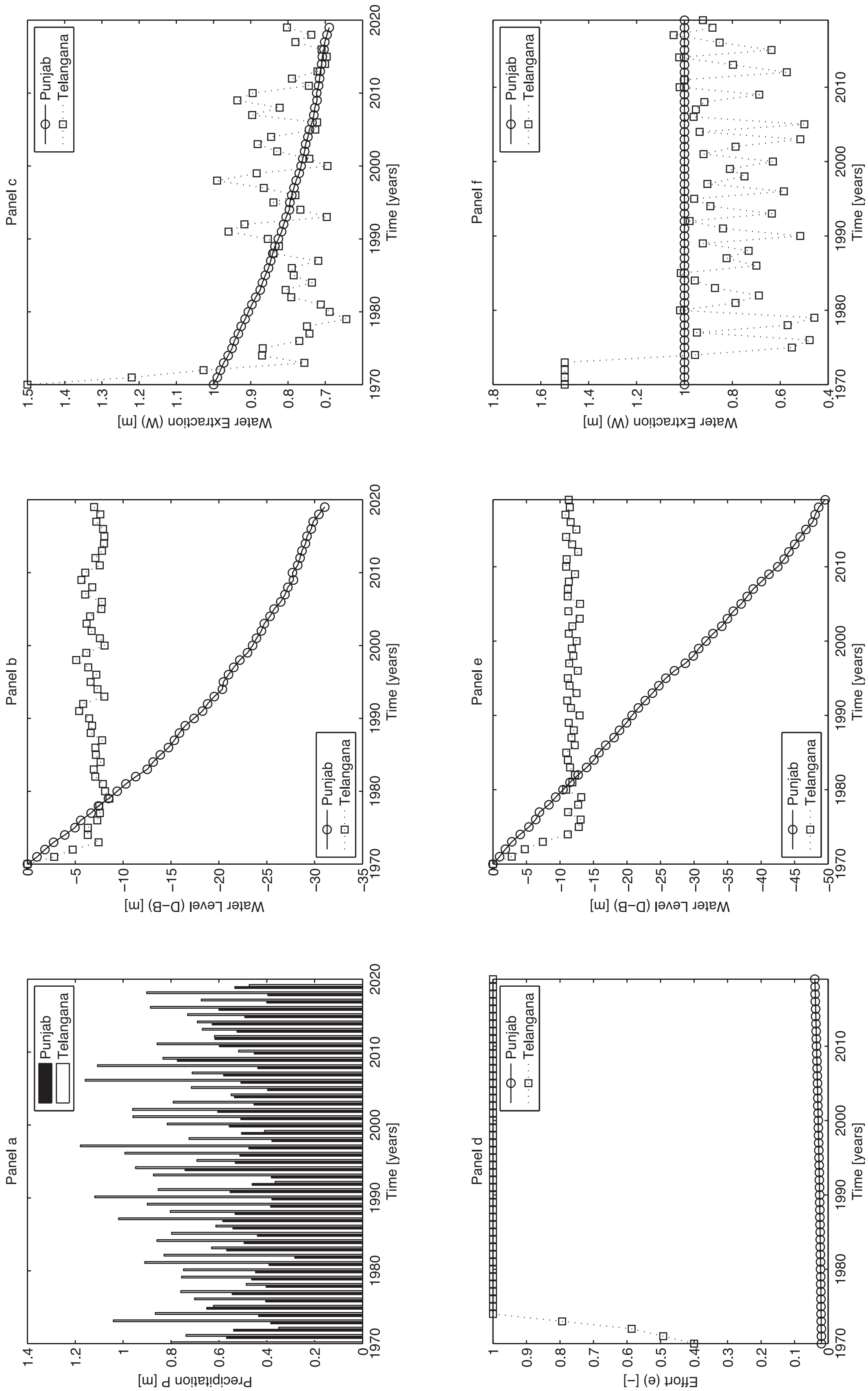
Panel a
Precipitation P [m]
Time [years]
Punjab
Telangana
Panel b
Water Level (D−B) [m]
Panel c
Water Extraction (W) [m]
Panel d
Effort (e) [−]
Panel e
Panel f

Figure 7

in the thin aquifer, increases in effort may only maintain water use for a shorter period, and ultimately result in higher variability.

[38] The bottom panels of Figure 7 display the results of the same simulation if effort is allowed to increase in order to maintain a steady level of water extraction, even as water tables decline. In Punjab, this strategy is effective even after 50 years, but in Telangana the effect is short lived and its only long-term legacy is a higher degree of variability. (The ability to maintain the same water use in Punjab over 50 years should not be taken as a realistic prediction. In this stylized extraction model, the energetic requirements for pumping from deeper depths is underestimated since our model does not take into account the additional lift requirements due to cones of depressions around wells. Thus, the required increase in effort may not be realistic to achieve in reality.)

[39] In this linear model it is easy to actually calculate the first two moments of the steady state distribution of water extraction corresponding to a given effort level e, which we denote by $\mu_W(e) = \mathbb{E}(W)$ and $\sigma^2_W(e) = \mathbb{V}(W)$. Taking the expectation and variance of equation (8) in the infinite time limit, and by observing that recharge from rainfall is independent of preseason water table, we find

$$\mu_W = \frac{re\mu_P}{e + n(1-e)}, \tag{13}$$

$$\sigma^2_W = \frac{\sigma^2_P r^2 e^2}{1 - [e + n(1-e)]^2}, \tag{14}$$

where we denote by $\mu_P(e) = \mathbb{E}(P)$ and $\sigma^2_P(e) = \mathbb{V}(P)$ the mean and variance of the local precipitation. [It should be noted that in this approximation the model does not prevent the aquifer from *spilling over* which implies that negative values of D might occur artificially. Hence, e must be at least high enough to guarantee that $E(D) > 0$ for the model to be physically meaningful, i.e., that $Be(e+n) > R$, so that natural losses plus extraction exceed mean recharge. Lower values of e lead to rising water tables, i.e., a regime that is far removed from the realities of both of our regions.]

[40] From these expressions it can be readily shown that both the expectation and variance of water extraction increase in effort level. This is intuitive. A higher extraction capacity enables one to capture more of the annual recharge from rainfall and lose less to natural discharge. The expected value of water extraction therefore increases in e (unless $n = 0$). The increase in variability with effort level captures the fact that high extraction efforts allow the near emptying of the aquifer even after a relatively abundant recharge, which leave no buffer in the aquifer in case a dry year follows. The reduction in buffering results in higher variability. In the limit, as effort increases and $e \to 1$, all buffering capacity of the aquifer is lost: water extraction is exactly equal to recharge, and is as variable as rainfall.

[41] Since the steady state level of water extraction is just the sustainable yield, in which extraction balances mean recharge and losses, starting by extracting a higher amount from a relatively saturated aquifer, with little uncertainty, and projecting forward, we would expect mean extraction to decline (as in Figure 7b) and its variance to increase toward the steady state levels. This explains why in the simulation of Figure 7c, water extraction is much more variable in Telangana. There, the aquifer rapidly converges to a steady state, and since $e(\text{Telangana}) \gg e(\text{Punjab})$, this steady state variability is higher than Punjab's eventual steady state variability. Moreover, since Punjab is still away from steady state, its current variability is even lower than its ultimate steady state value.

[42] Figure 8 shows a plot of the mean and the standard deviation of the long-term water extraction for two values of n. The benchmark case $n = 0$ (no natural discharge losses) is instructive, and is probably a reasonable approximation in Telangana's aquifers. In this limit, expected water extraction μ_W remains constant at the value of average rainfall recharge μ_R, even as the variability σ_W keeps increasing. This simply reflects the fact that long-term extraction must equal long-term recharge (note that the mean depth does increase with e, but these two balance each other in terms of water extraction). (Of course, the initial volume of water stored in the aquifer can help avoid this long-term mass balance for a while, and for quite a *long* while in a deep aquifer where this initial storage can be very large.) At this limit it obviously makes no economic sense to increase extraction effort, even if it were costless to do so, because it only increases the variability without improving the mean.

3.2. Statistical Analysis of Water Table Dynamics

[43] We estimate the statistical model in equation (11) by using water table data from the two regions, available twice a year (pre- and postmonsoon).

[44] Table 3 displays regression estimates for Telangana (columns 1 and 2) and Punjab (column 3) for premonsoon (May) water tables. (Note that regressions for postmonsoon water tables (not shown) produce similar results.) Regressions for Telangana are separated into the two time periods for which the two (independently measured) sets of water table observations are available.

[45] The estimation suggests, first, that every additional mm of rainfall raises the water table by about 3–4 mm in Telangana and by about 1.2 mm in Punjab. In terms of physical properties, the difference is consistent with the higher porosity and the higher expected runoff coefficients of Punjab's aquifers and soils. (The estimated values have to be interpreted as regional averages and are thus hard to directly compare with in situ site measurements.)

[46] Second, as shown in Table 3, estimated coefficients on preseason water tables, corresponding to the parameter x in equation (10), are not significantly different from $x = 1$ in Punjab. This suggests that in that region neither extraction nor natural discharge are sensitive to the preseason depth to water, and that both are small in relation to the aquifer's storage. In the thin aquifers of Telangana, in contrast, the coefficients are both estimated to be smaller than 1, i.e., $0 < x < 1$ with large probability. This indicates that annual declines in water tables are lower when the starting depth to water is deeper, and that extraction and losses are both comparable in magnitude to the aquifer's storage and sensitive to the preseason water table.

3.3. Statistical Analysis of Irrigation Dynamics

[47] We start by estimating equation (12) for rice cultivated areas in Telangana and Punjab, the principal user of irrigation water in both regions. Regression results are

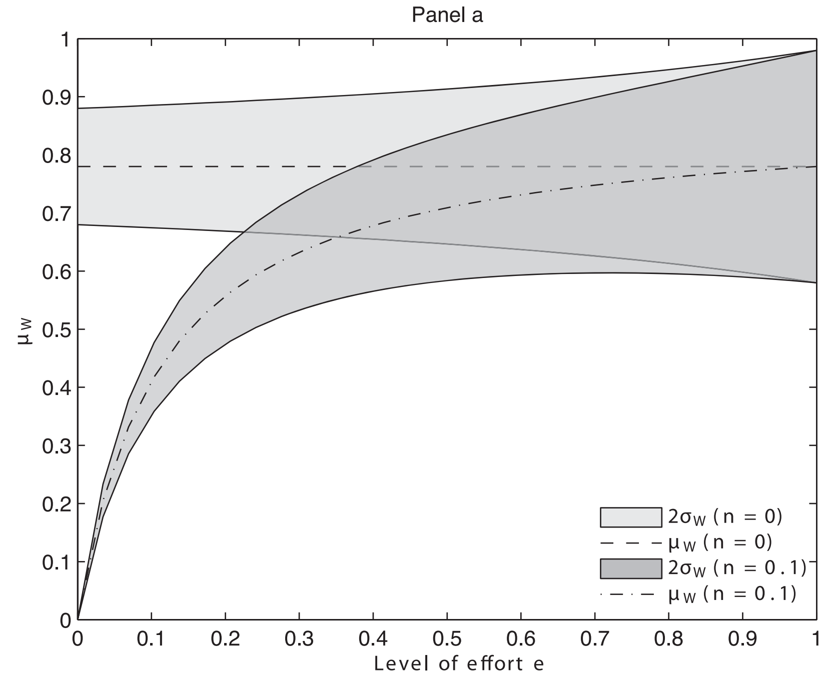

Figure 8. Steady state mean (dotted line) and spread (standard deviation, shaded area) of groundwater supply as a function of extraction effort levels e (see equations (13) and (14)) for the Telangana region are shown, using the parameterization of Figure 7. Two different parameter values for n are shown. $n = 0$ is the case where net water losses L to the downstream are negligible.

displayed in the odd-numbered columns of Table 4. In Telangana, data is available only after 1986 (recall rice is cultivated there during both seasons). In Punjab, data is available since 1971, but we run the regressions there separately over the pre-1986 and post-1986 periods for the sake of a proper comparison.

[48] In Telangana, in a year in which the depth to water in May is lower by 100 mm, the rice cultivated area in the rainy season tends to be lower by 8% with high statistical significance. When the depth to water in November is lower by 100 mm, rice cultivated area in the dry season tends to be lower by 14%, again with high statistical significance. Over the same time period there are no significant effects of either water tables or precipitation on rice cultivated areas in Punjab. However, during the prior period (1971–1986), in which groundwater irrigation and the power supply for pumping were not yet highly developed, Punjab's rice irrigation is significantly and strongly responsive to the water table (unfortunately, parallel data is not available for the Telangana region over the same time period).

Table 3. Premonsoon Water Table Regressions[a]

	Telangana	Telangana	Punjab
	1986–2002	2000–2003	1972–2003
Coefficient (variable name)			
$\times$ (lagged depth to water)[b] (m)	0.528	0.772	1.017
	(0.059)	(0.064)	(0.040)
$-r/\rho$ (precipitation) (mm)	-0.003	-0.004	-0.0012
	(0.000)	(0.001)	(0.0003)
No. of observations	140	36	429
Adjusted R^2	0.696	0.875	0.872

[a]Dependent variable: depth to water. Regression estimates are presented for the coefficients of the variables on the left most column, with reference to the notation in equation (11). Regressions are run separately with the two water table data sets available in Telangana (hard rock region, columns 1 and 2) and in Punjab (alluvial aquifers, column 3).

[b]Standard errors in parentheses. Errors are clustered by year.

[49] We also use data on rice yields (production per unit area) to estimate the parallel regressions

$$\log(Y_{d,t}) = -\alpha D_{d,t} + \beta P_{d,t} + \gamma_d t + \log(Y_d) + \epsilon_{d,t}, \tag{15}$$

where $Y_{d,t}$ is rice yield in year t in district d.

[50] Regression results are displayed in the even columns of Table 4. Rice yields are generally less responsive to both water tables and precipitation than are the cultivated areas, in terms of magnitude, statistical significance (except for rainfall during the rainy season in Telangana), and explanatory power. This lends support to our use of irrigated areas as a proxy for water use. It indicates that farmers respond to water scarcity more by changing the area of cultivation rather than the rate of water use per unit area (and this might actually be inefficient in terms of maximizing production), but also reflects the fact that yields are affected by many other unpredictable factors other than water availability, such as pests. Interestingly, in Punjab, rainfall actually has a negative effect on yields after 1986, which is probably attributable to flooding and water logging, pointing again to the absence of water limitations in this region.

[51] In Telangana, data is also available on total irrigated area (all crops), by source, for which we again estimate equation (12). Since data exists for the rainy (Kharif) and dry (Rabi) season separately, we run the regressions for

Table 4. Regressions of Rice Yields and Cropped Areas[a]

Region	Telangana				Punjab			
Period	1986–2002		1986–2002		1986–2004		Pre-1986	
Season	Dry		Rainy		Rainy		Rainy	
	Area	Yield	Area	Yield	Area	Yield	Area	Yield
Coefficient (Variable Name)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$-\alpha$ (preseason depth to water)[b] (m)	−0.139	−0.041	−0.084	−0.010	−0.014	0.022	−0.155	0.019
	(0.018)	(0.009)	(0.023)	(0.13)	(0.018)	(0.016)	(0.063)	0.044
β (precipitation) (100 mm)	0.059	0.005	0.031	0.028	0.002	−0.017	0.000	0.008
	(0.018)	(0.007)	(0.016)	(0.010)	(0.002)	(0.004)	(0.011)	(0.025)
Observations	122	122	124	124	145	116	112	111
Adjusted R^2	0.923	0.549	0.864	0.650	0.990	0.767	0.973	0.493

[a]Dependent variable: (log) area cultivated with rice, rice yields. Regression estimates are presented for the coefficients of the variables on the left most column, with reference to the notation in equation (12). All regressions contain district specific linear time trends and a global quadratic time trend. Regressions are estimated separately for the two rice growing reasons in Telangana, Kharif (rainy season, columns 1 and 2) and Rabi (dry season, columns 3 and 4) and the single rice growing season in Punjab (rainy season, Kharif, columns 5 and 6).
[b]Standard errors in parentheses. Errors are clustered by year.

both seasons, separately over the two periods 1986–2002 and 1998–2006, for which two independent sets of water table observations are available.

[52] Regressions estimates are displayed in the first four columns of Table 5. The effect of the preseason depth to water has a clear and strong effect in both seasons. A 1 m decline in depth to water leads to a 13% reduction in irrigated areas in the dry season (consistently across both periods, columns 1 and 3) and a 4.5% reduction in the rainy season (column 2), which is consistent with the estimates we obtained above for rice cultivated areas.

[53] Columns 5–7 in Table 5 decompose the regression estimates into source-wise irrigation, available only for the rainy season irrigated areas, including the deeper bore wells, which tap fractures and pockets of groundwater, the shallow open dug wells, and tanks, which shallow surface structures that capture rainfall. All source specific areas respond negatively to increased depth to water and positively to rainfall, but the only statistically significant responses is by shallow well irrigation to the water tables and by tanks to rain. This is consistent with the ranking of these sources in terms of their storage. Tanks have little storage (and high losses to evaporation), and therefore offer little buffering. Shallow wells tap the limited storage of the thin weathered later, and thus offer limited buffering which is contingent on the depth to water in this shallow aquifer. The deeper borewells tap deeper pockets of groundwater, so water extraction from them is not as well correlated with the depth to water in the shallow aquifer, and, at least for now, offer a more effective buffer from variable precipitation.

4. Discussion

[54] The results of the statistical analysis broadly support the predictions of the model's numerical simulation. First, the results of the water table regressions (the estimates of the coefficient x in Table 3) suggest that in Telangana's thin aquifers, annual reductions in storage (including extraction

Table 5. Regressions of Irrigated Areas, Telangana[a]

Period	1986–2002[b]		2000–2006[c]		1986–2002[b]	1986–2002[b]	1986–2002[b]
Season	Dry	Rainy	Dry	Rainy	Rainy	Rainy	Rainy
Source	All	All	All	All	Borewells	Dug Wells	Tanks
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$-\alpha$ (preseason depth to water)[d] (m)	−0.13	−0.045	−0.123	−0.006	−0.04	−0.05	−0.08
	(0.016)	(0.014)	(0.01)	(0.023)	(0.06)	(0.01)	(0.06)
β (precipitation) (100 mm)	−0.014	0.035			0.03	0.02	0.13
	(0.025)	(0.009)			(0.03)	(0.01)	(0.03)
Observations	133	142	63	63	141	142	142
Adjusted R^2	0.918	0.927	0.833	0.884	0.911	0.973	0.723

[a]Dependent variable: (log) irrigated area. Regression estimates are presented for the coefficients of the variables on the left most column, with reference to the notation in equation (12). Regressions are run for Kharif (rainy season) and Rabi (dry season) separately, using the two water table data sets from 1986 to 2002 (columns 1 and 2) and 2000 to 2006 (columns 3 and 4). Columns 5–7 report regression estimates for source-wise irrigated areas, available only for the Kahrif (rainy season).
[b]Regressions contain district specific linear time trends and a global quadratic time trend.
[c]Regressions contain district specific constants and a global linear time trend.
[d]Standard errors in parentheses. Errors are clustered by year.

by human and lateral flows) are negatively correlated with the beginning storage level (i.e., $x < 1$), but not in thick aquifers (i.e., $x \approx 1$). Indeed, this is what we would expect to see from the presence of a shallow bottom that would not allow large declines to occur when the water table starts off near this bottom. This is also directly related to steady state convergence. The dynamics (9) only converge to a steady state if $x < 1$, which supports the interpretation of Telangana's irrigation dynamics as being near or in a steady state, and Punjab's dynamics as being far from it.

[55] The results of the irrigated area regressions (Tables 5 and 4) directly confirm that in Telangana's thin aquifers, irrigated areas are indeed reduced when preseason depth to water is low. Moreover, water table fluctuations explain a significant part of the large annual variability in irrigated or rice cultivated areas. Over the same time period, there is no evidence of a similar pattern in Punjab's thick aquifers.

[56] Field interviews we conducted in Telangana suggest that farmers gauge preseason water tables and take them into account in deciding how much area to sow with paddy rice, especially in the dry season, when groundwater is the sole source of irrigation water. In the rainy season, the decision is more complicated because farmers need to also take into account an uncertain in-season water supply from rainfall, but the same basic logic applies (the effect of in-season rain on irrigated areas is probably a result of abandonment of some irrigation when rain is scarcer than expected in order to apply additional water per unit area). This explains why deeper preseason water tables lead to reduced cultivation of rice and other irrigated crops. Because our data consists of water tables averaged over large spatial areas, it does not allow us, given the heterogenous nature and relatively low transmissivity of Telangana's hard rock geology, to determine whether all farmers irrigate less of their land, or whether some wells simply dry out, forcing their owners to completely forgo irrigation in certain years. Farm level data would be required to settle this important question.

[57] In Punjab, in contrast, groundwater is still abundant. Fluctuations in the water table can probably be compensated for by the use of additional energy for pumping alongside the periodical deepening of their wells in order to ensure these fluctuations do not render their wells dry. Even though the electricity supply for pumping is capped at a certain amount (the duration of daily power supply for pumping is limited), farmers in Punjab are known to supplement it by the use of diesel pumps. While diesel is expensive, it may well be cost effective to use it in limited amounts in order to secure the rice crop. However, ample electricity was not always available in Punjab. The data show that in the period 1971–1986, when pumps were not as dense and the energy supply was lower, rice cultivation was not as well buffered as it is today, and was strongly dependent on annual water table fluctuations.

[58] Our analysis also reveals the role played by groundwater storage in buffering agriculture from annual rainfall fluctuations. In the absence of this storage, annual cultivation would depend on that year's rainfall alone and suffer from its inter-annual irregularities. In Telangana, the presence of a significant dependence of irrigation on both water tables and that year's rainfall means that deficiencies in monsoon rainfall can be compensated for if the water table is shallow. In this sense, groundwater does provide a buffer, but it is limited: if the water table is deep, groundwater extraction will not be able to make up for poor rainfall. In Punjab, the absence of any significant dependence (either statistically or in magnitude) on neither rainfall nor on groundwater tables indicates a very effective buffering capacity.

[59] Note also that in Telangana, in the rainy season, precipitation has a direct significant effect on irrigation, whereas in the dry season, it does not (columns 1 and 2 of Table 5). This is perfectly sensible and lends further consistency to our interpretation. In the rainy season precipitation has its own direct and independent effect on cultivation, alongside the preseason storage in aquifers. In the dry season which follows it, the amount of rainy season precipitation can only act through its recharging effect on the water table, so once this water table is controlled for it should not have a statistically significant effect on irrigation.

[60] In summary, the anecdotal evidence, our numerical simulation, and the statistical analysis all paint a consistent picture of the important role of physical water scarcity as a limiting factor in Telangana and its absence in Punjab, where agriculture has now become constrained by land rather than water. In Telangana, irrigated areas vary annually much more than they do in Punjab (around the increasing trend), and even despite the limitations of our coarse data set, we are able to explain a large portion of this variation in a statistically significant and intuitive manner through stochastic changes in water tables. In the dry season annual fluctuations are largely driven by preseason water tables, and in the rainy season by rainfall. In the deep aquifers of Punjab, in contrast, such short-term fluctuations do not seem to impact irrigation much.

[61] Our approach suffers from several limitations. First, our model is a highly stylized single cell model with linear dynamics and a simplistic extraction equation. However, the purpose of the model is to demonstrate some simple key attributes of the dynamics of irrigation and water tables, rather than to provide quantitative predictions, and we therefore chose to pursue the simplest possible modeling approach.

[62] Second, groundwater irrigation is the principal source of irrigation in both regions, and is the focus of our analysis, but surface irrigation is prevalent in Punjab and in certain parts of Telangana. The water balance (equation (1)) may be affected by leakage from irrigation canals and if this leakage is correlated with local precipitation in these regions, this may bias our porosity estimates in Table 3 upward. (While the results are not shown, we have actually found a clear cross-district correlation between the explanatory power of precipitation for water tables in a particular district and the extent of surface irrigation in that district. This indicates that surface irrigation does play a role in the water budget, but its effects has a significant part which is uncorrelated with local precipitation.) However, we do not believe the presence of surface irrigation should otherwise affect our main line of analysis and our conclusions. We find it hard to imagine that surface, rather than groundwater irrigation is driving the effect of groundwater tables on rice cultivation found for Telangana in Table 4, especially since the regressions in Table 5 find the same effect for areas irrigated by groundwater alone.

[63] Third, while our data set suffers from a low sample size and spatial and temporal resolution, which reduce the scope and accuracy of our statistical estimates, we interpret

the appearance of statistically significant results as an indication for the strength of our main conclusions. Nevertheless, the dynamics of water tables and irrigation should be further investigated using larger data sets that cover additional parts of India and have finer spatial resolution, in order for our results to be verified and extended. In particular, such an analysis may help shed more light on the precise mechanisms at work behind our results, especially if conducted on the individual farmer level.

[64] Finally, reliable time series data on electricity use and electricity supply for pumping would enable us to verify its role in the dynamics of irrigation, a role which we can only hypothesize in our model. Unfortunately, because of the conditions of India's electricity sector with regard to pumping, such data is not available, as far as we are aware.

5. Conclusion

[65] Discussions of the social impacts of excessive groundwater extraction, in India and generally, usually revolve around the long-term threats to the sustainability of agricultural production and incomes as a result of falling water tables. In section 3.2 we showed that over-extraction of deep alluvial aquifers in northwestern India has indeed led to consistent declines in water tables over several decades. However, intensive energy use managed to compensate for this decline, indicating that agriculture there is constrained by energy (and land), and not, strictly speaking, water.

[66] In contrast, we have also showed that in a prominent area of central India, the Telangana region, which overlies shallow hard rock aquifers, a declining trend does not subsist over the long term. Of course, this is a natural consequence of the limited storage of such aquifers. Extraction cannot actually exceed renewable supply consistently in the long run, because of the low initial storage, and water tables cannot, by definition, keep declining, because they relatively rapidly approach the bottom, and also, because they are rapidly recovered by abundant rainfall. In such regions, agriculture really is water constrained.

[67] The classification of such aquifers as over-extracted should therefore be interpreted with caution. In what sense is their extraction excessive? In addition to the possibility that pumping costs exceed the benefits, this paper draws attention to another social cost that may be associated with intensive extraction. We documented here the high degree inter-annual variability in irrigated areas in such a region and showed that it is largely driven by corresponding fluctuations in the water table. Our model suggested that some of this variability may be a result of high levels of extraction "effort," i.e., energy use.

[68] Thus, whereas in thick aquifers excessive exploitation (i.e., excessive energy usage) is an issue of long-term sustainability, we have argued here that in thinner aquifers it is primarily an issue of short-term reliability.

[69] Whereas we have seen that in Punjab the intensification of energy use successfully buffered irrigated cultivation from annual fluctuations in water tables, our model suggests that in regions like Telangana, such an increase may not only raise energy costs, but may actually increase inter-annual variability in agricultural production and its negative impacts on rural development and on food security. This could be an important policy implication, especially in India, where the supply of pumping energy is determined by the state, but further research and more detailed data is required in order to confirm and better quantify our results.

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