The Groundwater Constraint: Responses to Falling Water Tables in India

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Abstract

What are the trends in groundwater depletion in India and what are the short term consequences of falling water tables? We document the groundwater depth between 1996 and 2012 and find that overall trends mask important regional and temporal heterogeneity. We identify three phases: (a) in the 1996-2001 phase, water tables were falling rapidly in the northwestern and southern parts of the country; (b) in the 2002-2007 phase, the epicenter shifts eastwards; and (c) a phase of resurgence in 2008-2012 when water tables declines are (relatively) secular. We also analyze the impacts of falling water tables on winter cropped area. Exploiting within-well variation and controlling for local regional trends, we find that a 1 meter fall in groundwater in November reduces the winter cropped area around the well by 0.04-0.07 percentage points. Given that the magnitude of the impact is a third of the average annual gains India has made in irrigation since independence, this implies that the groundwater constraint is strict and binding.

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1 Introduction

The objective of this paper is to examine the groundwater situation in India and study its impact on agriculture. Indian agriculture continues to employ three out of five people in the labour force and its development is crucial for the growth of the entire economy. Efforts to increase the growth rate of agriculture have relied on increasing the intensity of cropping, use of high-yielding variety of seeds, expansion of irrigation facilities and use of fertilizers. The New Agricultural Strategy (NAS) announced by the government in 1965 ushered in a “green revolution” and transformed the country from a food-dependent nation to being self-sufficient in grain production. The NAS advocated a technical package that was complemented with input, credit and marketing subsidy and this resulted in the modern seed-fertilizer-water technology, which catalyzed the entire crop production system, but not without its share of environmental consequences (in terms of ground water depletion)[1].

An open question in policy circles now is whether the groundwater constraint is binding or not, and if it is then what is the impact of falling water tables[2]. While it is true that apart from groundwater, surface irrigation also plays an important role in India, Sekhri (2011) points out that “groundwater irrigation sustains about 60 percent of India’s agriculture. Groundwater irrigation has increased more rapidly than other sources of irrigation, such as tanks and canals, and is called water by demand as it is readily available in times of moisture stress.” Consequently, water tables have fallen drastically and nearly one in four ground wells have been categorized as “unsafe”. Figure 1 compares ground water levels in 2004 and 2009: the situation appears to have had improved in the some parts of the country (eg. south Gujarat, northern Karnataka) but has particularly worsened in the dry and arid parts of northern India.

What are the implications of falling water tables in the short run? Do farmers respond by dig-

[1] Robert Repetto laments: “The Green Revolution has often been called a wheat revolution; it might also be called a tubewell revolution” (Repetto 1994, p. 35 cited in Mukherjee (2007))

[2] The term water table and groundwater will be used interchangeably in this paper.

ging deeper, aggravating the tragedy of commons or do they reduce the area under cultivation? We combine panel data on water tables from monitoring wells with high-resolution spatial data on area under cultivation to empirically examine this question. Exploiting within-well variation and controlling for local regional trends, we find that a 1 meter fall in groundwater in November reduces the winter cropped area around the well by 0.04-0.07 percentage points. The findings complement those of Sekhri (2011) who data from 3 rounds of Indian agricultural census (1995, 2000 and 2005) finds that a "1 meter decline in groundwater in a year reduces food-grain production by 8 percent, water intensive crop production by 9 percent and cash crops by 5 percent". We contribute to the existing literature by improving the unit of analysis, as undertaking the analysis at an extremely fine resolution (in 1 km, 3 km and 5 km radii around a well) allows us to mitigate some of the typical concerns regarding measurement error in previous work.

To put these numbers in perspective, it is important to remember that gains in area under irrigation are notoriously sluggish and that it has taken India more than 60 years to increase gross irrigated area by 20 percentage points (net irrigated area has increased only by 13 percentage points since independence). Figure 2 illustrates the trends in gross and net irrigated area. Given that the slope coefficient on year for net irrigated area is 0.24 (which falls in the range of the coefficients we deduce from our analysis), this implies that Indian farmers do face a strict groundwater constraint and a continued fall in water table levels could have deleterious consequences on Indian agriculture.

The remainder of the paper is structured as follows: in section I we discuss the model that provides the equation we need to estimate. In section II we discuss the data and in section III we discuss the findings before concluding in section IV with the way forward.

2 Model and Empirical Strategy

There are two sets of key results discussed in the paper, those related to: (a) trends in the groundwater depth and (b) impact of groundwater depth on irrigated area.

For the former, we conduct the analysis at the well level and estimate the following equation for each well separately:

$$D_t = \alpha + \beta timeperiod + e_t \tag{1}$$

where D_t is groundwater depth, $timeperiod$ is a $(year, season)$ pair.

In addition to the OLS specification, we also estimate a model which includes seasonal fixed effects:

$$D_t = \alpha + \beta timeperiod + \gamma_s + e_t \tag{2}$$

where γ_s is a dummy for each of the four seasons.

Note that if β is positive it would imply falling water tables (as groundwater depth is increasing over time).

The second set of results are motivated by the modeling approach as described in Fishman et al. (2011). The main equations for the water budget, water extraction and water table are as follows:

$$\begin{aligned} V_{t+1} &= xV_t + rP_t \\ W_{t+1} &= xW_t + reP_t \\ D_{t+1} &= xD_t - \frac{r}{\rho}P_t + c \end{aligned}$$

where, V_t is the volume stored in the aquifer at t, D_t is the draw-down (average depth to water at beginning of period t), W_t is pumping (net natural recharge), P_t is the precipitation in period t, r is the recharge coefficient, e is the fraction that farmers can extract from the ground water, ρ is the mean porosity, $x = 1 - [e + n(1 - e)]$ and $c = [e + n(1 - e)]B$ is just a constant. See Figure **??** for an illustration of the modeled ground water in an aquifer.

The key equation to be estimated is:

$$Area_{ict} = \alpha P_{ict} + \beta D^s_{ict} + \gamma_i + f(t) + \epsilon_{ict} \tag{3}$$

where, $Area_{ict}$ is the irrigated part of the area under cultivation in well i in cluster c at year t, D^s_{ict} is the depth of the water table in season s in well i in cluster c at year t, P_{ict} is the amount of rainfall that well i in cluster c receives at year t, γ_i are time-invariant well fixed effects, $f(t)$ are simply year fixed effects or geography-specific flexible trends like year fixed effects interacted with either state, district or tehsil; and ϵ_{ict} is the idiosyncratic shock. We also estimate the above equation for irrigated area using deviation from the mean depth of groundwater in well i. The shocks to groundwater in season s for well i in year t are calculated as follows:

$$shock^s_{i,t} = \frac{D^s_{i,t} - mean(D^s_i)}{sd(D^s_i)} \tag{4}$$

We expect over-extraction of groundwater i.e. an increase in the depth of the water table to lead to a reduction in area under irrigation and therefore expect β to be negative.

In addition to analyzing the short-run effects of groundwater depletion, we also examine the correlation between area and depth averages at two different points in time using a 'long difference' approach. The estimating equation is as follows:

$$\Delta \bar{y}^k_i = \beta \Delta d\bar{e}pth_i + \gamma \Delta rai\bar{n}fall_i + Z_r + e_i \tag{5}$$

where, $\bar{Q}_i$ refers to the 'long' difference between 2002 and 2013 where $Q \in \{y, depth, rainfall\}$; $\bar{Q}_i$ is the three-year moving average for area/depth/rainfall; Z_r are fixed effects for state, district, tehsil (as in the panel estimation); and e_i is the idiosyncratic error term. Comparing the results from the panel estimating equation (3) with equation (5) allows us to test for adaptation (Zaveri, 2016; Burke and Emerick, 2016).

3 Data

The groundwater data comes from NSRC-WRIS. It is an unbalanced panel of 20,166 wells, a majority of which are monitoring wells, over 1996-2012. Each year, observations are taken from the monitoring well at four points of time in the: post-monsoon rabi season (typically corresponding to January), pre-monsoon season (this could be either April, May or June), monsoon season (generally August) and post-monsoon kharif season (generally November). This panel (which we refer to as WRIS in the paper) has 894,528 observations over 68 time-periods and is used to estimate equation (1) and (2). Spatial attributes are available for 20,157 wells and this allows us to identify the state, district and tehsil a well lies in (we use GADM to identify administrative boundaries[3].

Figure 6 summarizes the depth of groundwater in each well over the entire duration for which data is available. Water tables in the arid regions of Rajasthan and northern Gujarat are the deepest (in the top 1 percentile of depths), followed by Punjab, Haryana in the north, West Bengal in the east and Telangana, Karnataka and Tamil Nadu in the south. Water tables are relatively shallow in eastern Uttar Pradesh, Bihar, Orissa, Chhattisgarh, Jharkhand and the north eastern states. As expected, there are also seasonal fluctuations in the groundwater data: overall mean groundwater depth is lowest at the beginning of the agricultural season/in the monsoon season (6.9mbgl in Aug), slightly higher in the post-monsoon kharif season (7.2mbgl in Nov), followed by 8.2mbgl in rabi/Jan (which is very close to the annual mean) and highest at the end of the agricultural season in Apr at 9.8mbgl. The within component of the standard deviation ranges from 2.5 to 2.8 with the highest variance in Apr and lowest in Aug.

[3] There are 32 states, 539 districts and 2087 tehsils in the GADM data.

Data on winter cropped area comes from Jain et al. (2017) who has developed these measures using remote sensing techniques at a fine spatial resolution. The primary outcome variable is derived using a MODIS Scaling Approach (MSA) and MODIS Enhanced Vegetation Index (EVI) satellite data to map the winter cropped area of smallholder farms across India from 2000–2001 to 2015–2016 (Jain et al., 2017). The data was validated with eleven high-resolution scenes (at a spatial scale of 5 × 5 m2 or finer) and the R^2 was 0.71. An important advantage of this data is that it allows us to identify smallholder cropped area across years at a high resolution spatial scale. The satellite data was used to extract irrigated area in a 1 km, 3 km and and 5 km radii around the well; this measure was then merged with WRIS and to get a panel of 20,166 wells spanning 13 periods/years. In terms of notation, $Area_{ict} \in \{well1km, well3km, well5km\}$ and $s \in \{jan, apr, aug, nov, ann\}$. Note that in contrast to equations (1) and (2) where $timeperiod$ was a season-year pair, in equation (3) time refers to year. The data on irrigated area reveals spatial patterns: the northern states of Punjab, Haryana, Uttar Pradesh and Bihar together have 39 percent of irrigated area; states in the west: Gujarat, Rajasthan, Madhya Pradesh and Maharashtra together have 17 percent irrigated area; southern states of Tamil Nadu, Karnataka, Andhra Pradesh and Kerala have 13 percent irrigated area; and eastern India, comprising of West Bengal, Jharkhand, Chhattisgarh and Orissa have only 3 percent area under irrigation (see Table **??** for disaggregated state figures).

4 Results

4.1 Trends

First, consider trends in groundwater. In the initial years, 1996-2001, the decline in groundwater depth was statistically significant in the north: Punjab and Haryana, in the west: Rajasthan and Gujarat and in parts of Tamil Nadu and Karnataka. In the next six years, 2002-2007, the western states recover but water tables in the north continue to decline; Uttar Pradesh along with West Bengal are the new epicenters of groundwater extraction. In the third phase, 2008-2012, the trend of declining water tables witnesses a resurgence in the areas that improved in the previous phase while also intensifying in the eastern states. Including fixed effects for the seasons, as in equation (2), does not qualitatively change the results.

It is perhaps most instructive to map the magnitude of the trend for each well and Figure 7 illustrates this, albeit only for those wells where the coefficient (in equation (2)) was statistically significant. The differences in the three phases are apparent:

- In the first phase - the period of concentration - groundwater is declining in the north and west (excluding Maharashtra)
- In the second phase - the period of diffusion - there is a remarkable improvement in the second phase as locii of groundwater extraction shifts to east (though in terms of magnitude the problem is not severe)
- In the third phase - the period of resurgence - the erstwhile problem areas from phase 1 make a comeback and the problem intensifies in the new areas that were added in phase 2.

4.2 Impact on irrigated area

Having explored the spatial and temporal nature of groundwater trends, consider now the impact of falling water tables on area under irrigation. Regression results for irrigated area under 1 km, 3 km and 5 km are depicted in Table 1-Table 3. Col (1) presents results from the baseline specification that includes only well and year fixed effects. The coefficient becomes weaker after including stricter fixed effects as in Col (2)-(4), but the results still remain statistically significant. (We control for state-year, district-year and tehsil-year fixed effects). In the model that imposes the most restrictions, a 1 meter decline in groundwater in November reduces irrigated area in 1 km radius by 0.07 percentage points. The decline is smaller (0.05 percentage points) in the 3 km radius (see Table 2 and 0.04 in the 5 km radius around the well (see Table 3). The results are robust if alternative definitions of groundwater depth are used: panel B in Tables 1-3 estimate the same equation using annual groundwater levels and the overall picture doesn't change much.

This impact of falling water tables is heterogeneous across states. Among the big states, Gujarat, Madhya Pradesh, Uttar Pradesh and Rajasthan show a reduction in irrigated area, whereas Bihar and Kerala witness an increase. There is also heterogeneity according to intial conditions: if we were to group wells in four quantiles based on the area irrigated in the first year for which groundwater observation is available then we see that the coefficient is largest for wells in the 50^{th} to 75^{th} percentile group (results not shown).

We also find that differential results by the type of aquifer and source of irrigation. Table 4 shows that the impact of falling water tables is larger in parts of the country which do not have an alluvium aquifer. Table 5 shows that impact is larger in areas that are not irrigated by canals.

Finally, results in Table 6 also find no support for adaption among farmers.

5 Discussion

The findings of the study point to important variations in trends in groundwater extraction. India's dependence on groundwater cannot be understated. "About 85 percent of India's rural domestic water requirements, 50 percent of its urban water requirements and more than 50 percent of its irrigation requirements are being met from ground water resources." (CGWB 2011) We find that farmers face an binding groundwater constraint and that they respond to falling water tables by reducing the area under cultivation. The magnitudes of the impacts are large and have crucial policy implications.

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A Tables

Table 1: Impact of groundwater depletion on cropped area (1 km)

	(1)	(2)	(3)	(4)
Panel A: November				
Groundwater	−0.208***	−0.167***	−0.092***	−0.065***
	(0.021)	(0.018)	(0.013)	(0.014)
N	171,121	171,119	170,976	150,934
Panel B: Annual				
Groundwater	−0.099***	−0.097***	−0.050***	−0.035***
	(0.012)	(0.011)	(0.008)	(0.009)
N	202,103	202,103	202,009	182,021
Fixed effects	Year	State × year	District × year	Sub-district × year

Note: Mean cropped area is 12 percent, depth of water table in November is 7.2 mbgl and annual depth of water table is 8.3 mbgl.

Table 2: Impact of groundwater depletion on cropped area (3 km)

	(1)	(2)	(3)	(4)
Panel A: November				
Groundwater	−0.189***	−0.150***	−0.078***	−0.051***
	(0.019)	(0.016)	(0.010)	(0.010)
N	171,121	171,119	170,976	150,934
Panel B: Annual				
Groundwater	−0.080***	−0.084***	−0.038***	−0.025***
	(0.011)	(0.011)	(0.006)	(0.006)
N	202,103	202,103	202,009	182,021
Fixed effects	Year	State × year	District × year	Sub-district × year

Table 3: Impact of groundwater depletion on cropped area (5 km)

	(1)	(2)	(3)	(4)
Panel A: November				
Groundwater	-0.175^{***}	-0.138^{***}	-0.066^{***}	-0.039^{***}
	(0.018)	(0.016)	(0.009)	(0.008)
N	171,121	171,119	170,976	150,934
Panel B: Annual				
Groundwater	-0.073^{***}	-0.077^{***}	-0.033^{***}	-0.019^{***}
	(0.011)	(0.010)	(0.006)	(0.005)
N	202,103	202,103	202,009	182,021
Fixed effects	Year	State × year	District × year	Sub-district × year

Table 4: Differential effects by type of aquifer

	(1)	(2)
November	-0.076^{***}	-0.054^{***}
	(0.018)	(0.018)
N	99,413	47,496
Aquifer	Non-alluvium	Alluvium

Table 5: Differential effects by source of irrigation

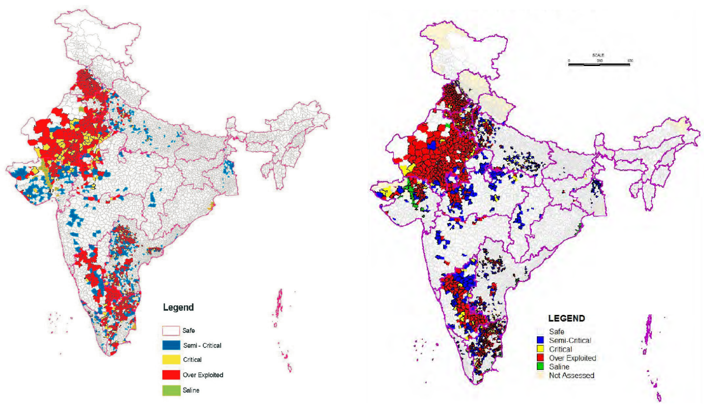
	(1)	(2)
November	-0.078^{***}	-0.047^{***}
	(0.020)	(0.015)
N	67,431	76,751
Irrigation source	Below median canals	Above median canals

Table 6: Comparison of long Difference estimates (3 year window) with panel estimates

	(1)	(2)	(3)	(4)	(5)	(6)
1km radius	-0.256^{***}	-0.167^{***}	-0.120^{***}	-0.092^{***}	-0.087	-0.065^{***}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.107)	(0.000)
3km radius	-0.186^{***}	-0.15^{***}	-0.051	-0.077^{***}	-0.039	-0.051^{***}
	(0.000)	(0.000)	(0.106)	(0.000)	(0.356)	(0.000)
5km radius	-0.172^{***}	-0.138^{***}	-0.042	-0.066^{***}	-0.022	-0.039^{***}
	(0.000)	(0.000)	(0.134)	(0.000)	(0.489)	(0.000)
N	4,571	171,119	4,571	170,976	4,571	150,934
Estimation	Long-diff	Panel	Long-diff	Panel	Long-diff	Panel
Level	State	State	District	District	Sub-district	Sub-district

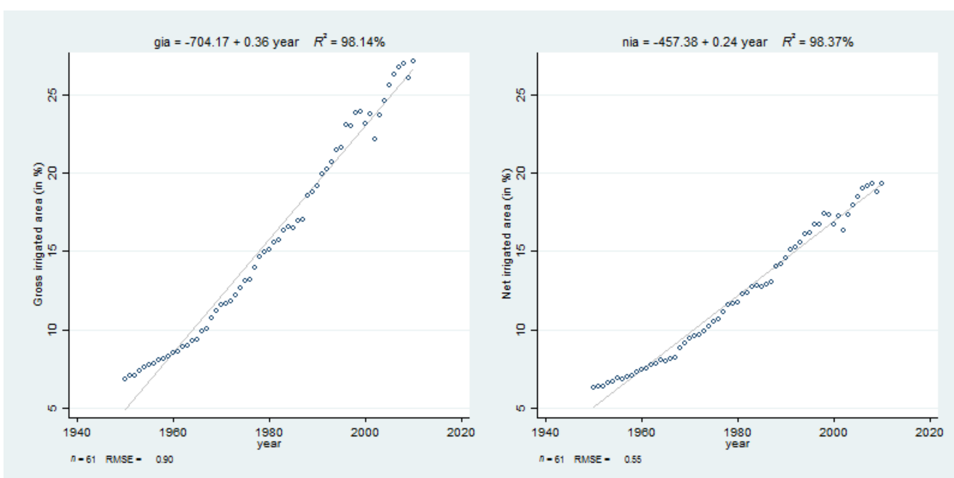
B Figures

Figure 1: Situation of ground water assessments units in 2004 and 2009



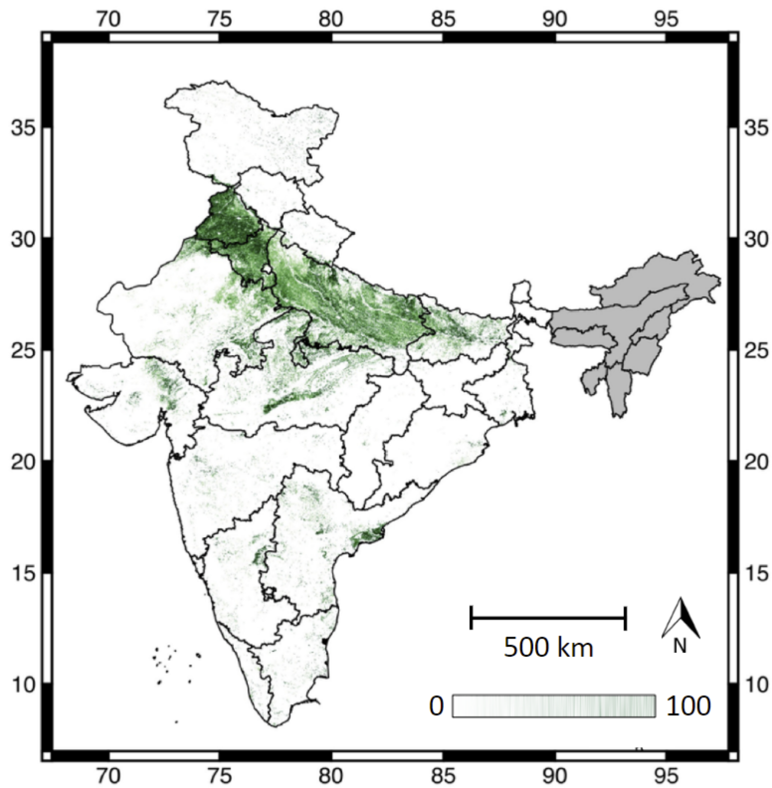
Note: Based on “stage of ground water development” and “significant long term water level decline trend” the government identifies blocks (administrative units at the sub-district level) as either safe, semi-critical, critical or over-exploited. Source: CGWB GOI 2011

Figure 2: Coverage of irrigation in India, 1950-2010



Note: To calculate GIA and NIA, total geographic area in India is assumed to be 328.8 million hectare. Source: IndiaStat `http://www.indiastat.com/table/agriculture/2/irrigation/145/14328/data.aspx`

Figure 3: Crop area for 2000–01, reproduced from Jain et al. (2017)



Note: Pixels classified based on winter growing season phenology and scales the % of cropped area within MODIS pixel based on observed EVI values at peak phenology. R^2 in data validation = 0.71. For details, see Jain et al. (2017).

Figure 4: Correlation between winter crop area and NIA

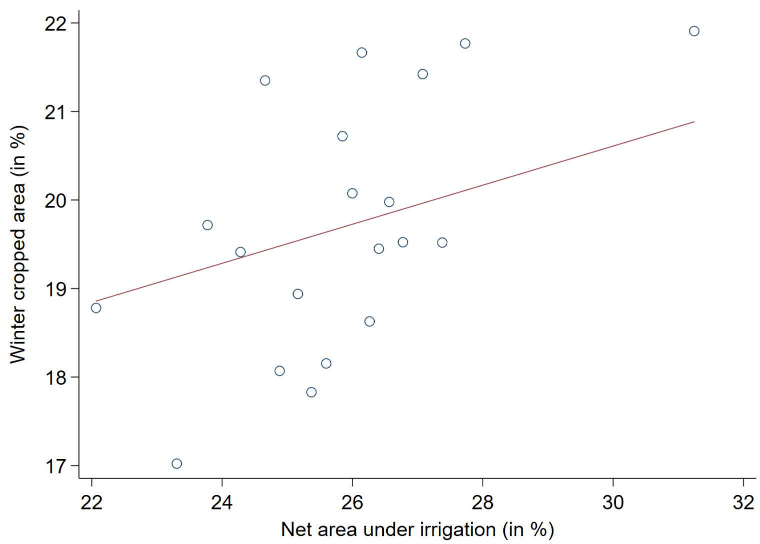
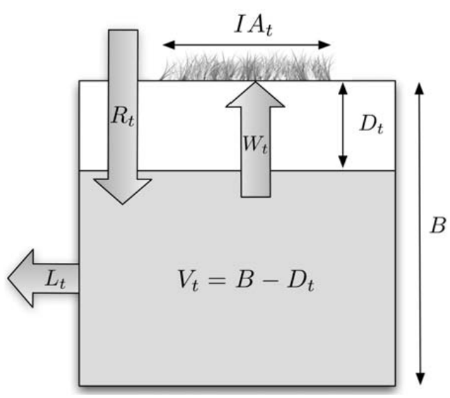
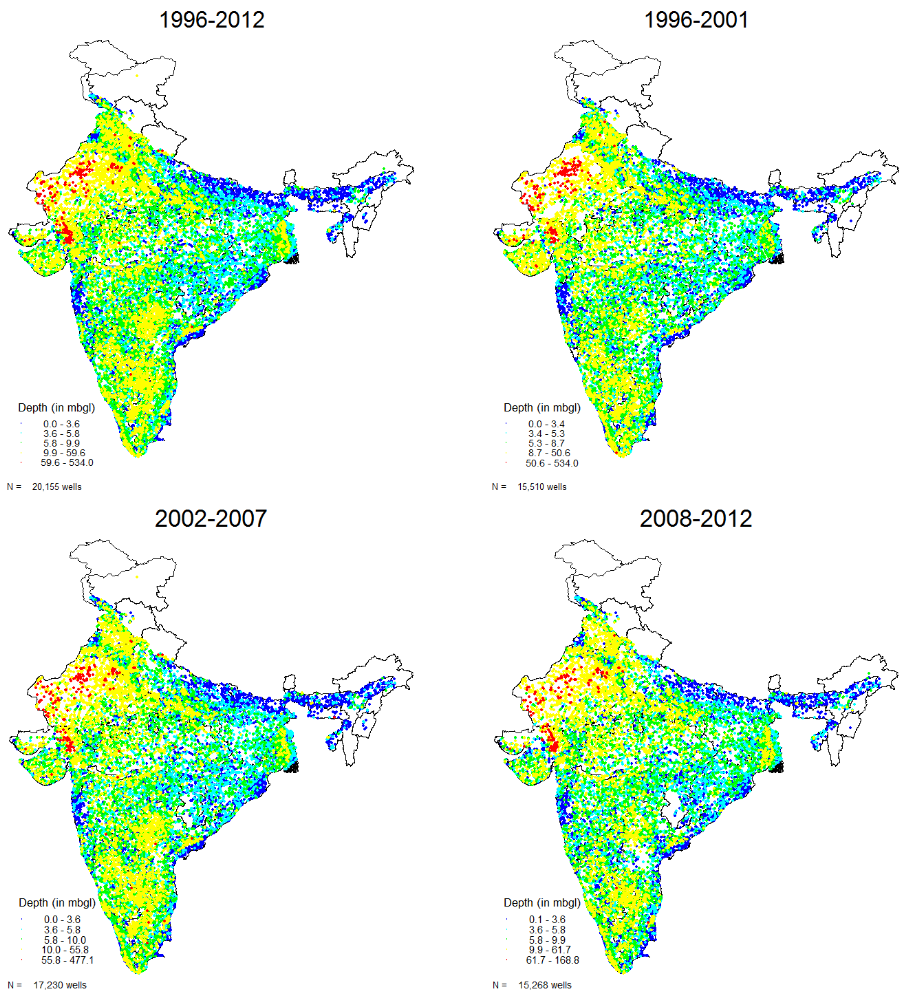


Figure 5: 'Groundwater budget'



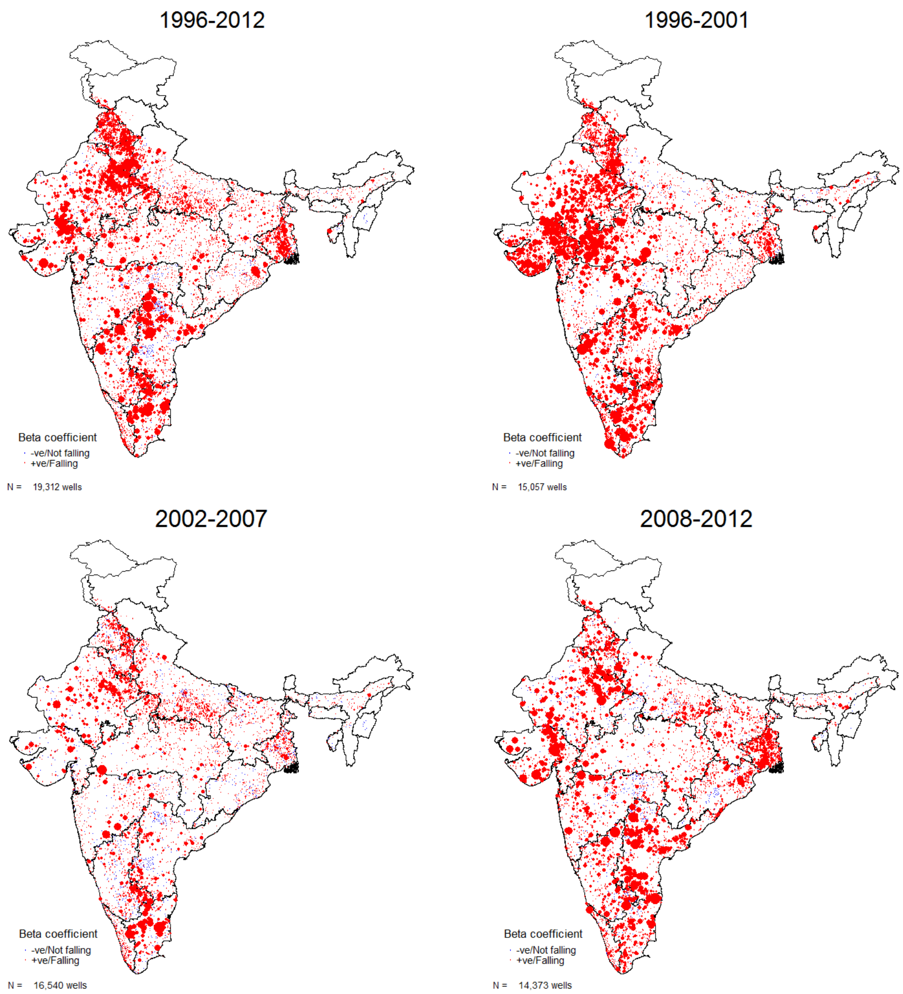
Note: Figure reproduced from Fishman et al. (2011) R_t is net recharge, W_t is pumping, L_t are sub-surface losses, D_t is drawdown, and IA_t is irrigated area. V_t is the saturated thickness of an aquifer with mean porosity ρ.

Figure 6: Groundwater depth, absolute levels



Note: Groundwater depth is measured in meters below ground level (mbgl). The five categories of depth correspond to the following: (a) blue: wells in the lowest 25th percentile, (b) cyan: wells with depths in 25th to 50th percentile, (c) green: wells with depths in 50th to 75th percentile, (d) yellow: wells with depth in 75th to 99th percentile, (c) red: wells with depth in top 1 percentile. Source: WRIS

Figure 7: Groundwater depth, magnitude of statistically significant trends (including seasonal FE)



Note: The map plots magnitude of only those β coefficients that are statistically significant in the following regression: $D_t = \alpha + \beta timeperiod + \gamma_s + e_t$, where $timeperiod$ is a $(year, season)$ tuple and γ_s are seasonal dummies. The regression is run for each well separately and statistical significance was calculated at the 5-percent level. Standard errors are calculated using -_regress- in Stata and not corrected for heteroskedasticity. The size categories correspond to: (a) blue: negative β/water table not falling, and (d) red: positive β/falling water table. The map emphasizes falling watertables. Source: WRIS