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LETTER

Can improved agricultural water use efficiency save India's groundwater?

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Abstract

Irrigated agriculture is placing increasing pressure on finite freshwater resources, especially in developing countries, where water extraction is often unregulated, un-priced and even subsidized. To shift agriculture to a more sustainable use of water without harming the food security and livelihoods of hundreds of millions of smallholders, substantial improvements of water use efficiency will be required. Here, we use detailed hydroclimatic and agricultural data to estimate the potential for the widespread adoption of efficient irrigation technologies to halt the depletion of India's groundwater resources. Even though we find substantial technical potential for reversing water table declines, we show that the impacts are highly sensitive to assumptions about farmers' water use decisions. For example, we find that widespread adoption of proven technologies that include drip and sprinkler irrigation has the potential to reduce the amount of excessive extraction of groundwater by two thirds. However, under more realistic assumptions about farmers' irrigation choices, half of these reductions are lost due to the expansion of irrigated area. Our results suggest that without the introduction of incentives for conservation, much of the potential impact of technology adoption on aquifers may be lost. The analysis provides quantitative input to the debate of incentive versus technology based water policies.

1. Introduction

Irrigated agriculture is the dominant global user of freshwater, accounting for nearly 70% of consumptive use (Gleick *et al* 2014). In many parts of the world, increasing demand for irrigation, as well as extensive subsidies and limited regulation, are placing increasing stress on freshwater resources (Postel *et al* 1996, Vorosmarty *et al* 2000, Haddeland *et al* 2014). To maintain agricultural productivity while reducing pressure on these resources, large increases in water use efficiency (the economic value produced per unit of the resource) will be required (Gleick 2003, Tilman 1999, Rockström *et al* 2007), which, at least theoretically, can be brought about through the use of proven, water efficient cultivation technologies. In developing countries especially, where substantial proportions of the population rely on irrigated agriculture for their livelihoods but water resources are typically unregulated or priced, governments often pursue the widespread adoption of such technologies as a means of achieving sustainable water use.

However, the ultimate impact of technology adoption on water resources depends on farmers' behavior, and not only on the technical potential for conservation. Here, we empirically assess the sensitivity of this impact to assumptions about farmers' decision making, comparing a benchmark 'naive' scenario (based purely on technological potential) and a 'realistic' scenario' (which incorporates farmers' profit maximizing adjustments) that we believe to be more appropriate in the prevailing institutional environments in developing countries.

We develop a general methodology and then empirically apply it to the case of India, whose government is attempting to address severe, rampant groundwater depletion through the subsidization of water efficient irrigation. We begin by using detailed, spatially disaggregated data on groundwater recharge and agriculture to provide novel estimates of the impact of improved efficiency on water table trends. We then test the sensitivity of the results to assumptions about farmers' decisions, and assess the extent to which farmers' behavioral responses may reduce the potential for reversing water table declines, if the dissemination of technologies is not complemented by regulatory reforms that improves economic incentives around water (and energy) use.

1.1. The Indian groundwater crisis

Globally, about 40% of irrigation water is supplied from groundwater, and India is the world's largest user (Aeschbach-Hertig and Gleeson 2012). The common-pool nature of groundwater and the difficulty of observing it directly make this resource difficult to monitor and regulate, especially in developing countries, (Mukherji and Shah 2005). Perhaps as a result, groundwater resources in many parts of the world are being depleted because of unsustainable extraction levels that exceed natural recharge rates (Wada *et al* 2010, Famiglietti 2014, Aeschbach-Hertig and Gleeson 2012). In India, groundwater irrigation covers more than half of the total irrigated area, is responsible for 70% of production and supports some 50% of the population (World Bank 1998, Shah 2010). However, it is now becoming clear that over-extraction of groundwater is depleting aquifers across the country, and water table declines are pervasive (Rodell *et al* 2009, Tiwari *et al* 2009, Livingston 2009, Shah 2009, Fishman 2011, Devineni *et al* 2013, Russo *et al* 2013). In fact, the rates of depletion in India are probably the highest in the world (Aeschbach-Hertig and Gleeson 2012).

Despite growing scarcity, groundwater irrigation in India remains highly inefficient from a technical point of view. For example, India's third Minor Irrigation Census has shown that in 2001, only 3% of India's some 8.5 million tube-well owners used drip or sprinkler irrigation and 88% delivered water to their crops by flooding through open channels[5]. Various government subsidy programs are attempting to boost adoption of more efficient technologies, with varying degree of success. Part of the logic behind this subsidy program is the hope that the adoption of water saving technologies can reduce groundwater extraction and stabilize water tables (Dhawan 2000). However, groundwater is seldom regulated or even priced in India, and even the electricity used for pumping is heavily subsidized and often priced at a flat tariff, if at all (Badiani *et al* 2012, Fishman *et al* 2014). The absence of monetary incentives to save water may therefore potentially undermine the effectiveness of this approach, but this point seems to be absent from discussions of this policy (Narayanamoorthy 2004).

1.2. Relation to previous literature

Recent empirical evidence from domestic (Olmstead 2010) and agricultural (Pfeiffer and Lin 2014) water use in the US shows that adoption of water efficient technologies need not necessarily reduce water use, and can even increase it. Qureshi *et al* (2010) present an empirical study comparing a policy that help finance investments in water efficiency and one that 'buys' water from farmers in the Murray–Darling basin, Australia. They find substantial differences in the impacts on return flows and consumptive use. Similarly, simulations that employ integrated hydrological-economic-agricultural models in several US river basins show that reductions in return-flows and farmers' profit maximizing decisions can reverse the intended consequences of subsidies on water saving technologies, like drip irrigation (Ward and Pulido-Velazquez 2008, Peterson and Ding 2005, Huffaker and Whittlesey 2003, Scheierling *et al* 2006, Huffaker and Whittlesey 2000). This paper complements these studies, but focuses on a single aspect of farmers' water use decisions that we believe to be of central importance in the institutional environment common in developing countries.

In the 'naive' behavioral scenario, farmers utilize a water saving technology to reduce water usage while maintaining irrigated area at its baseline (pre-adoption) levels. This is an implicit assumption underlying common assessments of the water saving potential of these technologies. In the second, 'realistic' behavioral scenario, irrigated area is expanded until the baseline (pre-adoption) level of water extraction is reached, or until the cultivated area is saturated. In this scenario, actual reductions in demand for groundwater occur only if all cultivable area can be irrigated, using the new technology, with less water than is used with pre-existing technologies.

The actual decisions taken by farmers is a subject for empirical analysis that is beyond the scope of this paper. Rather than attempting to simulate these decisions through a optimization model based on multiple assumptions, particularly profit maximization, that are unlikely to be appropriate for smallholder farmers in developing countries, we conduct a transparent comparison of water demand under two natural behavioral scenarios. We believe the 'realistic' scenario is at least equally, if not more plausible in the regulatory environment facing farmers in India and in many other developing countries, than the assumption of dynamic optimization adopted in related studies in developed countries. In particular, lack of marginal pricing of water or the electricity used for pumping it suggest farmers will continue to use as much of it as is available to them, an assumption supported, for example, by evidence from India that water extraction

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[5] See //mowr.gov.in/micensus/mi3census/nt/_level.htm.

increases whenever water tables are shallower (Fishman *et al* 2011). Our analysis estimates the extent to which the impact of water saving technologies on the eventual fate of India's aquifers differs between the two scenarios.

2. Methods

The comparison of the 'naive' and 'realistic' scenarios is conducted for two separate technological mixes. The first deploys an illustrative combination of proven, existing technologies, including drip and sprinkler irrigation (Postel *et al* 2001, Postel 2000, Foley *et al* 2011) and laser land leveling (Jat *et al* 2006, 2009) across areas cultivated with suitable crops across India. While this mix is mainly used to illustrate the methodology, micro-irrigation technologies (drip and sprinkler) are prominently featured in discussions of water conservation and are supported by generous government subsidies (Kumar and Palanisami 2011, Palanisami *et al* 2011), both in India and more broadly.

The second technological mix simulates a theoretical limit of water use efficiency. This limit is estimated by using historical daily precipitation data for over 100 years across India to calculate an annual deficit index—representing the precise amount of water that is needed by various crops to meet their evapotranspiration requirements when precipitation is insufficient (Devineni *et al* 2013). It measures the accumulated water shortage that needs to be provided from non-precipitation sources.

For each technological mix and scenario ($2 \times 2 = 4$ combinations), we estimate spatially disaggregated agricultural groundwater demand across India, and compare it to estimates of local renewable recharge (supply). The analysis is conducted at the level of districts (administrative units), of which there are 454 in our data. A comparison of demand and supply allows us to estimate the extent of unsustainable depletion under each of the two scenarios for farmers' behavior.

All the scenarios we consider maintain the current, localized, irrigated crop mix. While shifts to more water efficient crops have substantial potential for reducing water use, they are fraught with social, economic and political difficulties that may render them difficult to implement. We refer the reader to (Devineni and Perveen 2012) for an analysis of optimal national crop shifting.

2.1. Data sources

Groundwater data. India's Central Groundwater Board (CGWB) estimates net renewable recharge on the basis of simple assumptions on hydro-geological parameters and data on water table changes and precipitation. These estimates are presented in the left panel of figure 2. The CGWB also estimates groundwater extraction on the basis of the number of extraction structures (various types of wells) and uniform assumptions on the extraction of each type of structure (Central Ground Water Board 2005, Chatterjee and Purohit 2009).

Climate data. Gridded daily rainfall data from 1901–2004, available at 1° × 1° spatial resolution from the Indian Meteorological Department (Rajeevan *et al* 2006), and gridded daily temperature data (at 6 hourly time step) from 1948–2000, available at the same spatial resolution from National Center for Environmental Predictions, National Center for Atmospheric Research (Ngo-Duc *et al* 2005), are used in this study. Since the daily temperature data is available only for 53 years we used the daily climatology i.e. the mean daily temperature for the remaining 51 years. The daily climate time series grids were spatially averaged over each district using the geographic information system district boundary layer for India. This resulted in a national district-level time series dataset of daily precipitation and temperature estimates for a period of 104 years. Using daily time series of minimum, mean and maximum temperature data along with extra terrestrial solar radiation, the daily Reference Crop Evapotranspiration (ET_0) is developed based on the method illustrated by (Hargreaves and Samani 1982). The Hargreaves method is used globally to predict ET_0 in regions where data availability is limited to air temperature data (Allen *et al* 1998).

Agricultural data. Estimates of groundwater use for irrigation are based on district-wise data on crop specific net and gross irrigated areas and assumptions about the crop specific rate of water use. We use publicly available data from the directorate of economics and statistics[6] on crop specific net irrigated areas and total net area irrigated by groundwater for the year 2000–1. We use regional agricultural calendars to decompose estimates of irrigated area into the three agricultural seasons (*kharif*, June–September, *rabi*, October–February, and Summer, March–May), as described below.

Assumptions on crop specific irrigation water requirements under flood irrigation (baseline scenario) are based on the experience of Raman (see also Palanisami *et al* 2011). These are presented in the first column of table 1. Most of these crops are almost exclusively grown once a year. The exceptions are rice, which can be grown in both the rainy (kharif) and winter (rabi) seasons, for which we have provided separate estimates, and sorghum (jowar), for which estimated water requirements do not differ markedly between the two seasons, and for which we therefore chose to use a single value for simplicity.

2.2. Methods

Let $IA_{c,d,s}$ and w_c be irrigated area and water use under flood irrigation (baseline scenario) for crop *c*, in a

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[6] http://eands.dacnet.nic.in

Table 1. Assumptions about irrigation water requirements for important crops under existing technologies. Figures for flood, result, incentives for conservationdrip and sprinkler are based on the experience of Raman (see also Palanisami *et al* 2011). Figures for laser land levelling (LLL) are based on percentage saving rates reported in Jat *et al* (2006, 2009).

Crop	Irrigation water use (mm)			
	Flood	Drip	Sprinkler	LLL
Cotton	450	250	—	—
Groundnut	600	350	450	—
Soyabean	670	375	500	—
Wheat	450	—	300	—
Bajra	400	—	300	—
Tur	500	275	—	—
Jowar	400	—	300	—
Gram	240	130	150	—
Tobacco	600	350	450	—
Barley	400	—	300	—
Sugarcane	1600	—	1040	—
Rice (kharif)	1000	—	—	750
Rice (rabi/summer)	1500	—	—	1200
Maize	650	—	450	—

district d in a season s. Let IA_d and $GWIA_d$ be the total (all sources) and groundwater irrigated area in that district. The share of groundwater in irrigated area is[7]

$$g_d = \frac{GWIA_d}{IA_d}. \tag{1}$$

We estimate total groundwater use for irrigation in season s as

$$W_{d,s} = g_d \sum_c IA_{c,d,s} w_c \tag{2}$$

and total annual groundwater use is estimated by summing across seasons $W_d = \sum_s W_{d,s}$. Data limitations require us to make two strong assumptions in this calculation. First, that crop water requirements per unit area do not vary geographically. To the extent that localized climate affects water requirements in similar proportions, which is a weaker assumption, the proportional reduction in water use is unaffected. Second, in the absence of data on crop specific irrigated area from groundwater, this formula effectively assumes that the share of groundwater irrigated area in total irrigated area is uniform across crops.

Our estimates and the CGWB's estimates of groundwater use, both of which are quite rough, are nevertheless reasonably well correlated across districts (figure 1), but our estimates tend to be higher, with total groundwater use estimated at 15% higher than the CGWB's figure (232 versus 203 KCM) and a larger extent of over-extraction (108 versus 59 over-extracted districts) and over-extracted water (60 versus 16 KCM). Both approaches are based on spatially uniform assumptions of water use extraction/rates, and require fine-tuning. However, the main purpose of the analysis is not to precisely quantify water use, but to assess how farmers' adaptations influence the impact of improved water use efficiency.

Water use in the 'proven technologies' mix. Groundwater use in a scenario in which proven technologies are applied to increase efficiency are estimated based on assumptions laid out in columns 3–5 of table 1. In the proven technologies scenario, we assume drip and sprinkler are applied to crops for which they are suitable, and when both are suitable, the more efficient of the two is used. For rice cultivation, for which neither drip nor sprinkler are commonly used, we assume water savings in the range of 20–25% is achieved through the use of laser land levelling (LLL), an increasingly common intervention, choosing a intermediate value in the range reported by Jat *et al* (2006, 2009).

The rest of the calculation follows as above. Letting w_c^T be the water use with the best existing technology for crop c, in a district d in a season s, we have

$$W_{d,s}^T = g_d \sum_c IA_{c,d,s} w_c^T \tag{3}$$

and total annual water use is estimated by summing across seasons $W_d^T = \sum_s W_{d,s}^T$.

Water use in the maximum efficiency scenario. We also estimate crop water use under theoretical efficiency limits, in which the precise evapo-transpirative requirements of the crop are supplied. We estimate this water requirement using district specific and year specific climatic variables (Devineni *et al* 2013) as the accumulated deficit between a crop's daily water requirement and daily precipitation.

The annual crop water deficit is calculated in a simulation framework using the sequent peak algorithm (Lall and Miller 1988, Loucks *et al* 1981). The steps for the computation are presented below. For district d, define the following quantities:

$$\text{Deficit}_{t,d,c} = \max\ \text{Deficit}_{t-1,d,c} + D_{t,d,c} - S_{t,d} \tag{4}$$

(with $\text{Deficit}_{t=0,d,c} = 0$) and

$$w_{c,d,y}^M = \max_{t=1:365, y=1901:2004} \text{Deficit}_{t(y),d,c}, \tag{5}$$

where $\text{Deficit}_{t,d,c}$ refers to the accumulated daily deficit; $D_{t,d,c}$ refers to daily water demand for crop c; $S_{t,d}$ refers to the total daily water supply for district d, and day t; y refers to a calendar or cropping year. We use 1901–2004 as the time period in the analysis. For this 104-year record, intra-annual crop water deficit is evaluated as the maximum cumulative deficit, defined annually as $w_{c,d,y}^M$.

The renewable water supply is estimated as:

$$S_{t,d} = \alpha P_{d,t}, \tag{6}$$

where $P_{d,t}$ is the rainfall for any day t, over a district d, α is the factor that determines the usable fraction of rainfall for irrigation. For this analysis, α is chosen as 0.7 based on the FAO recommendation. This parameter can be varied if needed to assess the sensitivity of the final results to the assumed values.

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[7] we calculate this ratio using net irrigated area because of greater data availability. These shares are not significantly different when gross irrigated areas are used.

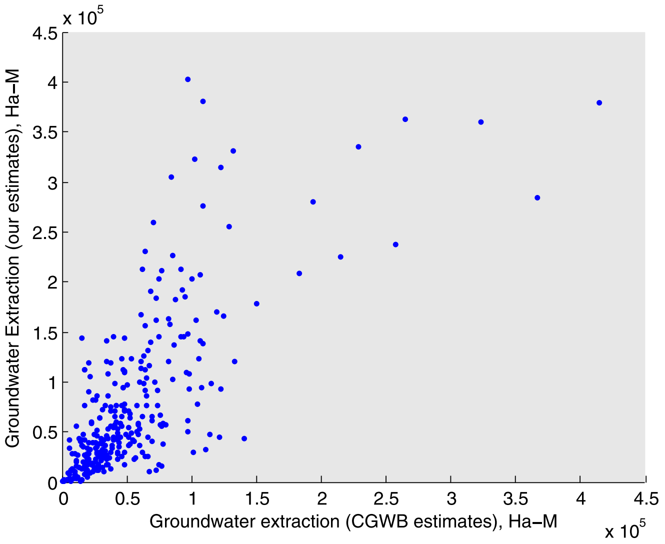

Figure 1. A comparison of our own and CGWB's baseline estimates for groundwater draft for irrigaiton.

Water demand $D_{t,d,c}$ is estimated as:

$$D_{t,d,c} = Kc_{t,c} ET_{0t,d}, \tag{7}$$

where $Kc_{t,c}$ is the crop coefficient for crop c for day t. It is the ratio of actual evapotranspiration of a given crop under non-stressed conditions to reference crop evaporation. It represents crop specific water use at various growth stages of the crop and is typically derived empirically based on local climatic conditions.

The daily crop water deficit is defined as the difference between the daily crop water demand and the daily renewable water supply. The deficits are accumulated (equation (4)) while setting negative accumulations to zero. The maximum accumulated deficit in a given year is the crop water deficit for that year, $w^M_{c,d,y}$, computed as one number for each year using historical daily rainfall data for the district and current daily crop water needs. It measures the maximum cumulated water shortage each year that needs to be provided from additional water resources. The deficit at the beginning of each year is set to 0 for the calculation of the $w^M_{c,d,y}$. The expected value over the years 1901–2004:

$$w^M_{c,d,s} = \frac{1}{104} \sum_{y=1900}^{2004} w^M_{c,d,s,y} \tag{8}$$

is then used to estimate total water use in irrigation as before

$$W^M_{d,s} = g_d \sum_c IA_{c,d} w^M_{c,d,s} \tag{9}$$

Stage of groundwater development. Given CGWB estimates of net renewable recharge R_d (figure 2, left panel) the *stage of groundwater development* is defined as the ratio of usage to recharge, and is calculated in the current, proven and maximal efficiency technological mixes as

$$SD_d = \frac{W_{d,s}}{R_d}, \tag{10}$$

$$SD^T_d = \frac{W^T_{d,s}}{R_d}, \tag{11}$$

$$SD^M_d = \frac{W^M_{d,s}}{R_d}. \tag{12}$$

Whenever the stage of groundwater development exceeds 100%, usage exceeds renewable supply and extraction is un-sustainable.

Irrigation water use in the 'realistic' scenario (expansion of irrigated areas). To estimate the potential for expansion of irrigated area with the current amount of water use (through an improvement in efficiency), we use data on aggregate cropped area for the crops we consider (also available from the directorate of economics and statistics), which we again disaggregate by season into $CA_{d,s}$. We assume irrigated area can be expanded to cover all potentially cultivable area, which we take as $PCA_d = \max_s CA_{d,s}$. Of this area, the un-irrigated (by any source) component in a given season is $PCA_d - IA_d$. The maximum factor of expansion in season s is therefore taken to be

$$f_d = \frac{PCA_d - IA_{d,s} + GWIA_{d,s}}{GWIA_{d,s}}, \tag{13}$$

where groundwater irrigated area is assumed to be, as before, $GWIA_{d,s} = IA_{d,s} g_d$. Under the area expansion assumption, in every season, savings in water from efficiency improvements are used to first increase $GWIA_s$ until there is no more room for expansion or until the current amount of irrigation water is fully used. In this scenario, therefore, the actual water use for irrigation at each season, under the two efficiency scenarios, is

$$\hat{W}^T_{d,s} = \min\left(W_{d,s}, f_d W^T_{d,s}\right) \tag{14}$$

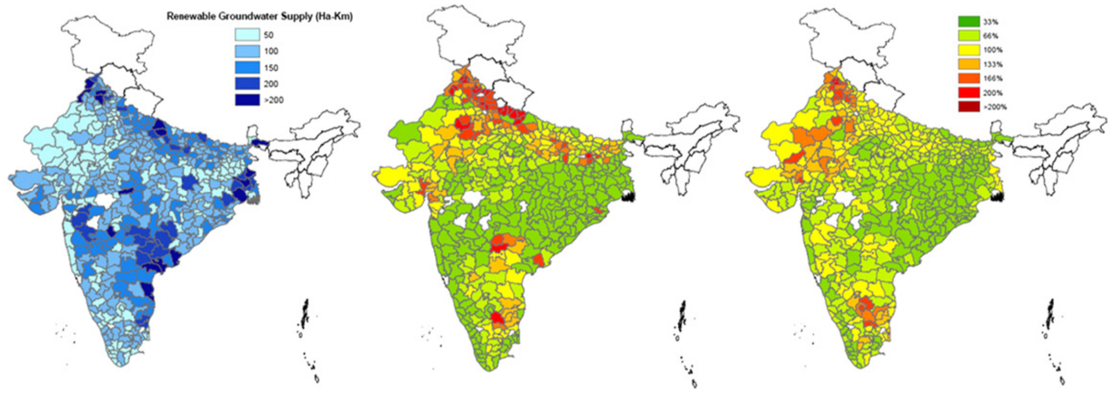

Figure 2. Left: renewable groundwater supply (CGWB estimates). Middle: stage of development (our estimates). Right: stage of development: CGWB estimates.

$$\hat{W}_{d,s}^{M} = \min\left(W_{d,s}, f_d W_{d,s}^{M}\right) \tag{15}$$

and the annual totals are achieved by summing over the three seasons.

3. Results

The left panel of figure 2 displays a map of net renewable groundwater supply, as estimated by CGW) (Central Ground Water Board 2005). The spatial distribution largely follows the broad East–West gradient in rainfall across India. The middle and right panels display the district-wise *stage of groundwater development* under current conditions, defined as the ratio of current groundwater use to renewable supply. Whenever the stage of groundwater development exceeds 100% (yellow, orange and red color), usage exceeds renewable supply and extraction is unsustainable. The right panel displays CGWB's estimates, and the middle panel displays our estimates, based on data on district-wise irrigated area, crop-wise cultivated areas, and estimates of crop specific water application rates using flood irrigation (table 1, see methods section for details). The figures show that groundwater depletion is concentrated in the North–West (and in particular in the Western parts of the Gangetic basin, i.e. the states of Punjab, Haryana, Gujarat and Rajasthan, as well as Western U.P) and in Southern peninsular India (in both Tamil Nadu and the Telangana region of Andhra Pradesh).

In figure 3, we display the district-specific stage of groundwater development calculated for each of the technological-behavior cases we consider. These consist of four combinations of two technological mixes (proven and maximal efficiency) and two behavioral scenarios (naive and realistic).

The top panels displays estimates from a scenario which deploys three proven, existing water-saving technologies—drip, sprinkler and LLL—wherever appropriate, on a crop-specific basis. In general, drip and sprinkler are applied to horticultural crops (and sprinkler for wheat), and LLL is applied to rice cultivation (table 1 displays estimates of water saving potential of each of the three technologies that were used in the analysis). The bottom panels displays results for the theoretical limit of water use efficiency, in which water consumption matches the precise average deficit (in relation to evapo-transpirative needs) crops are facing as a result of precipitation shortages, calculated using 100 years of daily precipitation and temperature data. Within each row of panels, the leftmost panel displays results from the 'naive' scenario that assumes irrigated areas are unchanged following the adoption of the improved technology, whereas the middle panel displays results from the 'realistic' scenario that assumes that irrigated areas are expanded until either current water demand is reached or the cultivated area is saturated. Summaries of India wide impacts on groundwater depletion are presented in table 2.

The naive assumption (irrigated areas are not expanded) obviously leads to higher water savings. This can clearly be seen in the figures and in table 2. For example, in the proven technologies case, the number of over-extracted districts drops from 108 to 63, and the total amount of unsustainable water extraction drops by half from 26% to 13% of total groundwater use in India (column 4). In the 'realistic' scenario, where irrigators may use water savings to expand irrigated area, most of these gains are eroded (column 5). However, the losses from area expansion in the maximum efficiency scenario are considerably more modest. Finally, the right most panel compares the spatial extent of excessive use (numbers of over extracted districts) across the various scenarios. The results show that hot spots of depletion in the North-West are hard to 'save' even when irrigation achieves its theoretical maximum efficiency.

4. Discussion and conclusion

Improved water use efficiency in irrigated agriculture is considered, globally and in India, as a way of meeting

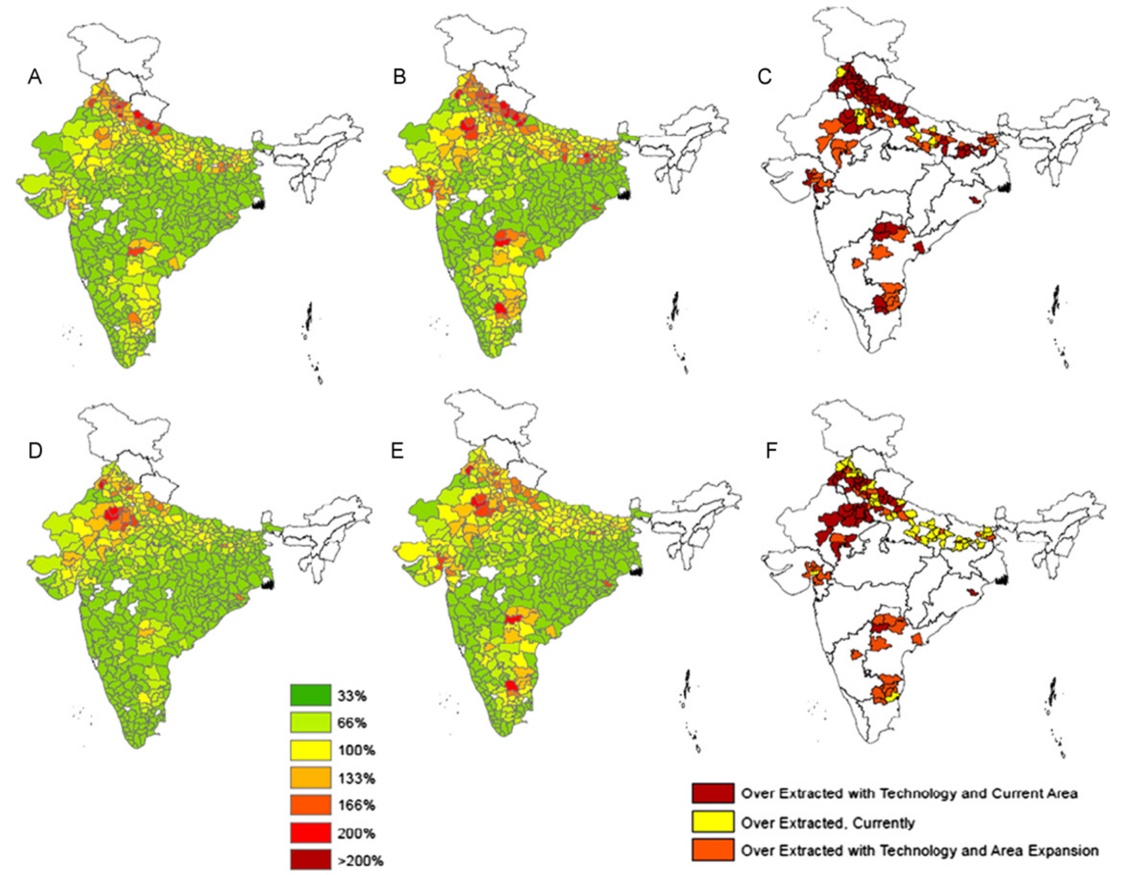

Figure 3. Stage of groundwater development under: existing technologies (top, panels (A)–(C) and theoretical efficiency limits (bottom, panels (D)–(F)). In both rows, the left-most panels display results under the naive scenario (assuming that irrigated area is unchanged), and the middle panels under the realistic scenario (irrigated area may expand). The right hand panels compares the extent of over-extraction (stage of development exceeding 100%) currently (yellow color), and under the naive (efficiency improvement and current area irrigated, brown color) and sophisticated (efficiency improvements and irrigated area expansion, orange color) scenarios. Note that over-extraction in the naive scenario necessarily also implies over-extraction in the sophisticated scenario and the latter necessarily also implies over-extraction in the current situation, so that brown shades 'cover' orange shades and the latter 'cover' yellow shades.

Table 2. Results of calculations for water use, excessive water use and over-extracted districts. (1) Our baseline estimates (2) Proven technologies, naive scenario. (3) Proven technologies, realistic scenario. (4) Maximum efficiency, naive scenario. (5) Maximum efficiency, realistic scenario.

	(1)	(2)	(3)	(4)	(5)
Water extraction (CKM)	232	164	209	124	174
Excessive Extraction (CKM)	60	21	41	7	16
As percentage	26%	13%	19%	6%	9%
Over-extracted Districts	108	63	97	43	66

future food requirements with increasingly scarce water resources. Often, water resources are unpriced and poorly regulated. India, the world's largest user of groundwater, and the country perhaps most dependent on this resource, provides a stark example. Groundwater is unregulated, and even electricity for pumping is highly subsidized, mostly unpriced, and even where it is priced, charges are mostly flat and independent of actual usage (Badiani *et al* 2012, Fishman *et al* 2014). As a result, incentives for conservation and efficiency are lacking.

From an economic theory point of view, the optimal policy instrument to achieve efficient use of groundwater is the marginal pricing of water (and the electricity used to pump it) at a rate that accurately reflect the total social cost of water extraction (Rogers *et al* 2002). Such pricing can be achieved directly through extraction taxes, or through mechanisms such as entitlement trading. With efficient pricing, subsidies for water saving technologies become unnecessary and distortive. In practice, however, the political economy of water resources means that socially efficient pricing can be impractical on technical and political grounds (Johansson *et al* 2002, Schoengold and Zilberman 2007). In developing countries especially, other pervasive market imperfections may justify 'second best' policies (Greenstone and Jack 2015). Public support for the adoption of such technologies may therefore be socially warranted in some situations.

In lieu of direct demand side management, such as pricing, many governments, including in India and the US, resort to promoting the adoption of water saving technologies, with the hope that widespread adoption will reduce pressure of depleting aquifers and stabilize falling water tables. However, as we show here, when sufficient incentives for saving water are largely absent, the effectiveness of such policies can be compromised by farmers' adaptations. In particular, expectations for water savings that are based on naive extrapolation of the technical capacity of proposed technologies may be inflated.

We first assessed the technical potential of both proven and the theoretical limit of water efficiency improvements to reduce the extent of depletion. In both technological scenarios, results show that efficiency improvements have a significant potential to reduce the extent of unsustainable groundwater irrigation. However, in the Western Gangetic basin, and especially in states of Haryana and Punjab, which supply a major share of India's food grains, even the maximal theoretical efficiency can reduce the rate of water table decline, but not reverse it. Hence, in such regions, sustainable water management will require complementary strategies, such shifting the cropping pattern to less water intensive crops, or supply side interventions such as inter-basin transfers.

We have also analyzed the extent to which economically realistic behavior by farmers to use water savings to expand cultivated area, and find that capacity to reduce groundwater depletion is substantially lower. For example, when using proven technologies like drip and sprinkler irrigation, the reductions in unsustainable over-extraction of groundwater are reduced by half. Our results highlight the potential inadequacy of basing water policy on the promotion of water saving technologies *by itself*. While the adoption of these technologies has large potential for water saving, and thus for protection of water resources, this potential may fail to be fully realized if it is not accompanied by the introduction of incentives for conservation of groundwater or the electricity used for pumping it, through the use of marginal pricing (even at rates that are below socially optimal levels) or other mechanisms that can limit the expansion of irrigation.

It is worth mentioning that the opposite may also be true: proactive encouragement of technology adoption may be necessary for incentive programs to realize their own potential for conservation. For example, evidence from Gujarat suggests that the absence of relevant, accessible low-cost technologies may render innovative incentive schemes ineffective (Fishman *et al* 2014). We also note that technology adoption and demand side management is not the only policy instrument for stabilizing water tables. Supply side management through artificial recharge or alternative from surface sources may also be viable in certain situations (Dillon 2005, Sharda *et al* 2006).

Our analysis is based in India, the world's largest user of groundwater, and where hundreds of millions of smallholder farmers critically depend on the resource for their livelihoods, food security, and drinking water needs. However, our methodology and the fundamental trade-off we highlight are even more widely applicable. The Indian situation is extreme from an institutional point of view, but depletion of groundwater resources, and the challenge of finding policies that can facilitate sustainable management are becoming increasingly common globally (Aeschbach-Hertig and Gleeson 2012).

Our analysis has the following caveats. First, data limitations (to be expected in developing countries) limit the accuracy of our simulations. Second, we do not account for all possible water saving technologies, or for all forms of farmers' adaptations following the adoption of these technologies. For example, even when cultivated area is saturated, farmers may choose to sell excess water in informal water markets, increase the frequency of irrigations or the amount of water applied, or to change the crop mix to more water intensive crops. Our analysis is mainly intended to highlight the importance of considering farmers' cultivation choices in assessing effort to halt the depletion of India's groundwater aquifers, and not to accurately simulate the full range of responses accurately. Nevertheless, we believe the main margin of adaptation occurs on the extensive margin (irrigated area), which we account for. Shifts in crop mixes, or in the frequency of irrigations are not observed as frequently by Indian farmers in response to water scarcity (Fishman *et al* 2013).

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