Groundwater depletion and associated CO₂ emissions in India

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Key Points:

- The total estimated groundwater depletion in India is in the range of 122 to 199 billion m³
- The CO₂ emissions due to bicarbonate is ~ 0.72 million tons per year
- The environmental problem of groundwater depletion in India is much more serious than the associated CO₂ emissions
Abstract

India, the world’s largest groundwater user, withdraws about 230 billion m$^3$ groundwater annually for irrigation. Excessive groundwater pumping in India leads to rapid groundwater depletion and $CO_2$ emissions. Here, using multiple data sources (observation wells and GRACE) to estimate groundwater depletion in India, as well as the associated chemistry and the pumping energy requirements, we provide the first estimate of the potential $CO_2$ emissions due to bicarbonate extraction ($CO_2$ release due to lowering of groundwater table) and groundwater pumping. We show that combined annual $CO_2$ release due to bicarbonate extraction and pumping in India is approximately 32.01-131.74 million tons (31.29-131.02 million tons for pumping and 0.72 million tons for bicarbonate). The total estimated groundwater depletion in India is in the range of 122 to 199 billion m$^3$ from the observation wells (1996-2016) and GRACE (2002-2016). The $CO_2$ emissions due to bicarbonate (~0.72 million tons per year) are dominated by those due to groundwater pumping (31.29-131.02 million tons/year) in India. However, the total (pumping and bicarbonate) estimated annual $CO_2$ emission from groundwater is less than 2-7% of the total (annual) $CO_2$ emission from India. Based on our unique dataset collected from more than 500 farmers in Punjab, we show that a low-cost intervention for irrigation scheduling based on soil moisture information can provide a sustainable solution by reducing groundwater pumping and $CO_2$ emissions. The environmental problem of groundwater depletion in India is much more serious than the associated $CO_2$ emissions and hence there is an urgent need for a regulation of groundwater use.

1 Introduction

Groundwater is a lifeline for food and water security for millions of people in India (Kulkarni et al., 2015), the largest consumer of groundwater in the world (Aeschbach-Hertig & Gleeson, 2012; Shah, 2009). About 88% of the total groundwater withdrawal in India is used for irrigation (IDFC Foundation 2013). Groundwater pumping for irrigation (Rodell et al., 2009; Tiwari et al., 2009) combined with the weakening of the Indian summer monsoon (Asoka et al., 2017) has resulted in widespread groundwater depletion in India in the last 20 years. The rate of abstraction in many regions is higher than groundwater recharge (Siebert et al., 2010), causing a recurrent water stress (Hanasaki et al., 2008), persistent groundwater depletion (Gleeson et al., 2010) and long-lasting impacts on streamflow, lakes, and wetlands (Wada et al., 2010). The Indo-Gangetic plain and northwest India have experienced a severe decline in groundwater storage (Asoka et al., 2017; Rodell et al., 2009; Tiwari et al., 2009) and corresponds to one of the largest groundwater footprints in the world (Gleeson et al., 2012).

After the green revolution in the 1970s, the net irrigated area in India expanded from 31 to 60 million hectares between 1970 and 2007, out of which nearly 80% was contributed by groundwater (Shankar et al., 2011). About 60% of irrigation in India was sourced from groundwater during 2000-2007 (Shankar et al., 2011). The expansion of groundwater-based irrigation in India is due in part to the Central government procuring wheat and rice from arid regions and the governments in those states providing highly subsidized electricity for agricultural pumping systems. The result is a rapid depletion in groundwater in India (Shah et al., 2012). While the impacts of unsustainable groundwater consumption on food and fresh water security are well documented (Shah, 2009; Shankar et al., 2011), the role of groundwater depletion in India on $CO_2$ emissions due to bicarbonate and pumping remains unrecognized. Moreover, approaches to managing groundwater sustainably in India are not well established (R. M. Fishman et al., 2011). Here using the observational and satellite-based datasets, we first identify the spatiotemporal extent of groundwater depletion during 1996-
2016. We use a well-distributed record of groundwater related measures (e.g., specific yield, bicarbonate concentration, electric pumps) to estimate $CO_2$ emissions due to due to bicarbonate and pumping in India. Using a unique field survey dataset, we show that water savings in irrigation can be a prominent driver of sustainable management of groundwater in India.

2 Materials and Methods

We collected groundwater well data from Central Ground Water Board (CGWB), which monitors groundwater table four times in a year (January, May, August, and November) at more than 24000 locations. Groundwater well observations were obtained from 1996 to 2016 from the India-Water Resources Information System (India-WRIS). The below ground level (bgl) well observations are available for January, May, August and November. We apply Grubbs test (Grubbs, 1969) to detect outliers in monthly groundwater level observations. After removing outliers, we selected 5875 well observations which are having at least 16 years of observation out of total 21 years.

Additionally, we obtained terrestrial water storage (TWS) from the Gravity Recovery Climate Experiment (GRACE). Groundwater anomalies (GWA) at 1° resolution were derived after removing surface water storage (sum of surface water, soil moisture, and canopy storage) from GRACE TWS anomaly for 2002-2016. Monthly TWS anomaly was obtained from the Centre for Space Research (CSR) at the University of Texas, Austin, NASA’s Jet Propulsion Laboratory (JPL), and from Deutsches GeoForschungsZentrum (GFZ). We applied a 300 km Gaussian filter to reduce the random errors in the data while scaling factors were applied to minimize the attenuation caused due to sampling and post-processing. To estimate surface water storage (canopy water+ soil moisture + snow water equivalent), we used monthly surface water storage data from the four land surface models (VIC, Noah, CLM, and MOSAIC) that are part of the Global land data assimilation system (GLDAS). The ensemble of groundwater anomalies was estimated using the three products from GRACE (JPL, CSR, and GFZ) and four (VIC, Noah, CLM, and MOSAIC) GLDAS products.

We obtained the bicarbonate ions ($HCO_3^-$) concentration data in mg/l from CGWB groundwater year-book of states for 2013-2015 (http://cgwb.gov.in/GW-Year-Book-State.html). The CGWB monitors groundwater quality in the pre-monsoon season when the concentrations of the ions are maximum. We aggregated the $HCO_3^-$ ion concentration to mean district level observations. Downward percolated and infiltrated water is enriched in $CO_2$, which can act as a weathering agent. Several factors like frequency of rainfall can influence the chemical composition of groundwater. Before reaching the saturated zone, water is charged with oxygen and carbon dioxide and slowly frees $CO_2$ associated with water gets released (Eq 1):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

(1)

As most of the aquifers contain sand, gravel, clay, and calcite ($CaCO_3$), the $H^+$ ion reacts with calcite and creates bicarbonate and calcium (Wood & Hyndman, 2017) ($Ca^{2+}$).

$$H^+ + CaCO_3 \rightarrow HCO_3^- + Ca^{2+}$$

(2)

When groundwater is exposed to the atmosphere, $CO_2$ will be released to atmosphere while calcite is precipitated. The atmospheric contribution due to groundwater depletion can be estimated as described in Wood and Hyndman (2017):
Atmospheric $CO_2$ contribution = depletion in groundwater X equivalent concentration of $CO_2$ in groundwater

The detailed methodology of $CO_2$ release due to groundwater depletion can be found in Wood and Hyndman (2017). To estimate $CO_2$ release from groundwater depletion, we used district-level bicarbonate data, groundwater well data, and specific yield data. Specific yield (%) for major aquifers in India was obtained from CGWB (Asoka et al., 2017). Using groundwater table data, we first estimated the trend in groundwater anomalies for each well located within a district boundary. We performed trend analysis using a non-parametric Mann-Kendall (Mann, 1945)) and Sen's slope method (Sen, 1968). After estimating the change in groundwater level between 1996 and 2016 for each well, we estimated the median change in groundwater level for each district using all the observational wells within a district. Then, the median change in groundwater level was multiplied by average specific yield for each district to obtain an effective change in groundwater. Finally, we multiplied the area of each district with the groundwater change to estimate the change in groundwater volume. Since our aim was to provide a conservative estimate of $CO_2$ emission due to groundwater depletion in India, we mainly focused on the regions where groundwater has depleted. Therefore, we selected only the districts that experienced groundwater depletion for the analysis.

We used mean bicarbonate concentration for each district, which was converted into equivalent $CO_2$ concentration by using the following equation:

$$Ca(HCO_3)_2 \rightarrow CO_2 + H_2O + CaCO_3 \quad (3)$$

The above equation can be finally simplified as:

Equivalent $CO_2$ concentration = $(HCO_3^- \text{ (mg/L)}) \times 44)/61$

As mentioned in Wood and Hyndman (2017), we assumed that only half of the bicarbonate is converted to $CO_2$ after reentry of the groundwater to the surface. Using the depleted volume of groundwater and mean bicarbonate concentration, the total amount of $CO_2$ released to the atmosphere was estimated. Our method provides a distributed assessment of $CO_2$ release to the atmosphere as we use bicarbonate values for each district, while Wood and Hyndman (2017) estimated the total release of $CO_2$ based on a single estimate of 190mg/L for the entire United States.

To check the robustness of our results estimated using the groundwater well observations, we used the groundwater anomaly data from the GRACE. For each 1º grid, we estimated the volume of groundwater depletion after estimating changes in groundwater anomalies. For each grid, area-weighted bicarbonate concentration was determined using the district level CGWB data. Similar to groundwater well data, we calculated $CO_2$ emission due to groundwater depletion utilizing the GRACE datasets.

Apart from $CO_2$ emission due to bicarbonate extraction, we also estimated emission due to pumping of groundwater considering the volume of water pumped and the groundwater depth. The distribution on pumps, which are predominantly used for irrigation, for each state at different depths was obtained from the census of minor irrigation. Finally, energy required for groundwater pumping can be calculated as:

$$Energy(kWh) = \frac{9.8 \times \text{lift(m)} \times \text{mass(kg)}}{3.6 \times 10^6 \times \rho}$$
Where $\rho$ is pumping efficiency, $CO_2$ emission to lift 1000 m$^3$ water to 1 m lift with pumping efficiency of 30% can be estimated by multiplying an emission factor (kgCO$_2$/kWh).

4 Results

4.1 Estimates of groundwater depletion

We begin our analysis by highlighting the factors that contribute to groundwater depletion in India (Fig. 1). A large part of India has more than 60% of the total area irrigated with groundwater resources (Fig. 1a). Areas that receive intensive groundwater based irrigation are located in the Indo-Gangetic Plain, northwestern, central, and western parts of India (Fig. 1). More remarkably, a few regions (western India and Indo-Gangetic Plain) have more than 90% of their area irrigated with groundwater resources. The net irrigated area from different sources, mainly tube wells, has increased (except for tanks) between 1950 and 2010 (Fig. 1b). We use the data from the census of minor irrigation (http://micensus.gov.in/) to estimate the distribution of energy sources for groundwater withdrawal in India. We find that electric pumps cover about 70% of the total available pumping energy sources in India (Fig 1c). An exception is the Gangetic plain, which is dominated by the presence of diesel pumps (Fig. 1c). Electric pumps for groundwater irrigation are prominent in central, western, and southern India (Table S1). India withdraws about 230 billion m$^3$ groundwater to irrigate 45 million ha gross cropped area (Shah et al., 2012).

We estimate the spatial distribution of groundwater depletion using well data from more than 24,000 wells located across India. Most of these are shallow wells (less than 30 m below ground level), and they don't account for groundwater pumping from deeper aquifers. After a rigorous quality check, we finally used 5875 wells to estimate changes in groundwater storage in India (Fig. 2, Fig. S1). Over the last 21 years (1996-2016), a majority of districts experienced a decline in annual groundwater levels in India (Fig. 2a). The districts with prominent decreases are located in the Indo-Gangetic Plain, northwest, and central (Maharashtra) regions (Fig. 2a). A few districts located in Punjab experienced a substantial decline in groundwater table from 1996 to 2016. Groundwater depletion has been occurring at much faster rates (91 cm/year) in Punjab due to groundwater withdrawal from deeper wells (Singh et al., 2011). Districts with an increase in groundwater levels are scattered mostly in western India, east coast, and peninsular India (Fig. 2a).

Overall, we find that a majority of districts in India experienced a substantial depletion in groundwater storage in the last 21 years (Fig. 2, Fig. S1d) and these findings are well supported with our observational and GRACE-based estimates (Fig. 2). However, we find that the GRACE-based estimates show a rapid decline in groundwater storage (Fig. 2c) in comparison to well estimates which may be because most of the CGWB monitored wells are shallow and do not account for the pumping for irrigation in deep wells (Kaur & Vatta, 2015; Singh et al., 2011). We find that the regions with the substantial decline in groundwater storage (Indo-Gangetic Plain and northwestern India) have a high pump density (number of pumps/km$^2$) (Fig. S2a) and groundwater withdrawal for irrigation (Fig. S2b). In northwestern India, total groundwater withdrawal exceeds total annual groundwater recharge leading to an overdraft of groundwater resources (Fig. S2c). Overdraft of groundwater resources results in a large number of blocks falling in semi-critical, critical, and overexploited category of groundwater resources (Fig. S2d).

4.2 Estimates of CO$_2$ release from Bicarbonates in groundwater
Next, we estimate CO$_2$ emissions in India due to bicarbonate extraction using the well-distributed observations of groundwater and other characteristics (specific yield and bicarbonate ($HCO_3^-$) concentration). Major aquifers located in northern India and in the Indo-Gangetic Plain, which are alluvium, have higher specific yields (5-10%) (Fig. 3a). Other major aquifers located in central and lower part of western India placed in hard rock and basalts have low specific yields. Hard rock and basaltic aquifers are mainly located in peninsular India have more variability in recharge in response to rainfall in comparison to the aquifers located in northern India (Asoka et al., 2017). District level bicarbonate concentration is higher (more than 300 mg/L) in western India and part of the Indo-Gangetic Plain than that in other parts of India (Fig. 3b). We find that in the Indo-Gangetic Plain and western India bicarbonate concentration (~ 300 mg/L) is much higher than median bicarbonate (~190 mg/L) concentration reported for the USA (Wood & Hyndman, 2017).

We estimated CO$_2$ emissions due to bicarbonate extraction using the depleted volume of groundwater during 1996-2016 and equivalent CO$_2$ concentration (Fig 4c, see methods for more details). Most of the districts located in northern India and Indo-Gangetic Plain released higher CO$_2$ due to bicarbonate extraction than other regions (Fig. 3c). Moreover, a few districts located in northwestern India witnessed a significant depletion of groundwater (Asoka et al., 2017; Rodell et al., 2009; Tiwari et al., 2009) also experienced a higher CO$_2$ emission (Fig. 3c). Our estimates of CO$_2$ emissions using GRACE data are consistent with the well observations showing higher emissions from northwestern India and Indo-Gangetic Plain (Fig. 3d). Total CO$_2$ emissions due to bicarbonate extraction (1996-2016) are 15.25 million tons (0.72 million tons/year). Our estimate of annual CO$_2$ emission rate of 0.72 million tons is lower than estimates of 1.7 million tons/year for the USA due to differences in $HCO_3^-$ concentration (Wood & Hyndman, 2017).

4.3 Estimates of CO$_2$ emissions due to pumping energy requirements

Our estimates of CO$_2$ emissions for groundwater withdrawal are based on year 2015 for which CGWB provides state wise groundwater withdrawal for irrigation (Table S2). We use the state-wise distribution of pumps (deep, shallow, and dug wells) from 2006-2007 census of minor irrigation (http://micensus.gov.in/, Table S3-S5). We assume that groundwater was pumped using electric pumps except for a few states (Uttar Pradesh, Bihar) where it is dominated by diesel pumps. We estimated CO$_2$ emissions due to groundwater pumping considering 30 and 40% pumping efficiency (Nelson et al., 2009; Patle et al., 2016; Shah, 2009; Wang et al., 2012). We used four (0.62, 0.95, 1.01, and 1.49 kgCO$_2$/kWh) emission factors in our analysis (Karimi et al., 2012; Nelson et al., 2009; Patle et al., 2016; Shah, 2009; Tyson et al., 2012; Wang et al., 2012). Pumping of 1000 m$^3$ groundwater per 1m lift using an electric pump releases between 4.22 to 13.52kg CO$_2$ considering 30 or 40% pump efficiency of electric pumps and a emission factor between 0.62 to 1.49 kgCO$_2$/kWh assuming electricity from fossil fuel sources (Table S6). Central and western India is dominated by the presence of dug wells while shallow tube wells are predominately located in the Indo-Gangetic Plain and Karnataka. On the other hand, northwestern India is dominated by the presence of deep wells (more than 70 m depth Table S3-S5). We used the distribution of estimated pumping lift (Table S3-S5) to determine CO$_2$ emissions for each state.

Total CO$_2$ emission was estimated for annual groundwater withdrawal of 222.38 billion m$^3$ for the year 2015 (Table S2). We distributed total annual pumped groundwater for each state in the proportion of deep, shallow, and dug wells. Therefore, our approach is different than previously reported (Nelson et al., 2009) by two ways: 1) consideration of distributed depth...
for groundwater pumping, and 2) consideration of dug wells as they are in significant numbers in a few states. In a previous study, Nelson et al (2009) used only shallow and deep wells with a fixed depth for CO₂ emissions. In our first approach, we estimate CO₂ emissions for each state using deep, shallow, and dug wells and actual pumping depth (Table S3–S5) while the second approach is based on the fixed depth of 120, 35, and 40 m for deep, shallow, and dug wells, respectively. To pump 222.38 billion m³ of groundwater, the total CO₂ emission is estimated to be between 31.29 and 100.26 million tons in 2015 considering distributed head (Table S6). Considering the constant depth of 120, 35, and 40 m for deep, shallow, and dug wells respectively, the estimated total CO₂ emissions is between 40.89 and 131.02 million tons (Table S6).

Nelson et al (2009) did not consider the dug wells in their analysis which account for more than 46% of the total number of wells in India. The fraction of shallow and deep tube wells is 46 and 7.3%, respectively. Our estimate of annual CO₂ emissions (31.29-131.02 million tons) is a conservative estimate as diesel pumps (mainly present in Uttar Pradesh and Bihar) cause less CO₂ emission than electric pumps. Our results show that the total annual CO₂ emissions due to groundwater depletion (bicarbonate extraction) and pumping in India is in the range of 32.01-131.74 million tons/year, which is less than 2-7% of the total CO₂ emissions from all the sectors depending upon the combination of pump efficiency and emission factor (Garg et al., 2017).

4.3 Sustainable management of groundwater resources and CO₂ emissions

We use a unique dataset collected at the farm level in Punjab to show a path of sustainable management of groundwater resources and CO₂ emissions (Fig. 4). Groundwater well data collected from Punjab for more than 1750 wells (including deep wells) show that the groundwater table has significantly (p-value < 0.05) lowered after the green revolution in Punjab and more prominently during the recent decades (Fig. 4a). This rate of groundwater depletion is much faster than our estimates based on the Central Groundwater Board’s data for shallow wells. We experimented with sustainable use of groundwater resources in Punjab (supplemental text S1). In five districts of Punjab, we provided tensiometers to about 500 farmers to monitor soil moisture condition in rice crops. We estimated water and energy saved in groundwater pumping for all the framers in the five districts. We find that irrigation based on tensiometer information to farmers results in 19, 30, 19, 10, and 36% of groundwater saving in comparison to the reference case irrigation without the information of soil moisture (Fig. 4b). Additionally, this intervention also results in a significant reduction in the electricity consumption (Fig. 4c). Our findings demonstrate that the decision making based on soil moisture conditions for irrigation has a potential and can be used as a sustainable measure to reduce groundwater pumping as well as CO₂ emission in Punjab. Therefore, for the sustainable management of rapidly depleting groundwater resources and CO₂ emissions, irrigation based on soil moisture information can play a significant role in India.

5 Discussion and Conclusions

While unsustainable depletion of groundwater due to pumping hampers food and freshwater security, it also results in CO₂ emission to the atmosphere. However, we find that combined CO₂ emissions because of bicarbonate extraction, and pumping is less than 2-7% of total annual CO₂ emissions from India. Considering the size of irrigated agriculture and
groundwater pumping in India, annual $CO_2$ emission related to groundwater based irrigation is not a significant contributor to the total emissions (which may or may not have included these emissions accurately). Moreover, we report that bicarbonate extraction causes $CO_2$ emissions about 0.72 million tons per year, which is considerably lower than the estimates for the USA (Wood & Hyndman, 2017). Lower estimates of $CO_2$ emissions in India can be attributed to lower bicarbonate concentrations in comparison to the USA. Therefore, our results do not support the argument that groundwater depletion is a significant unreported source of $CO_2$ emissions as reported in reference (24). $CO_2$ emissions due to annual groundwater withdrawal of more than 222 billion m$^3$ (CGWB, 2014) is about 32.01-131.74 million tons, which is an insignificant fraction of the total $CO_2$ emissions of ~ 2 billion tons from India (http://www.moef.gov.in/sites/default/files/indburl_0.pdf).

$CO_2$ emission due to groundwater pumping can be reduced by using solar and wind power instead of electricity and diesel based pumping systems and also by improving the pumping efficiency (Table S6). However, we notice that the regions (Indo-Gangetic Plain and northwestern India) with the higher groundwater abstraction and depletion have relatively low potential for the use of solar and wind power (Fig. S3) indicating that these states require additional measures to reduce the dependence on electricity and diesel based groundwater pumping. Further, availability of solar and wind energy based pumping will enhance groundwater depletion (Shah & Kishore, 2012), which is a major environmental degradation problem in the country. Reduction in subsidy in electricity prices can be a useful measure to reduce the pumping and encourage farmers for appropriate crop choices (Shah et al., 2012). Electricity cost of pumping groundwater for irrigation varies widely in India from $28/ha in Uttar Pradesh (lowest) to $560/ ha (highest) in Karnataka; therefore, the abolition of subsidies may significantly reduce groundwater pumping and $CO_2$ emission (Shah et al., 2012).

For India, the environmental problem of groundwater depletion is much more serious than the associated $CO_2$ emissions, and hence there is an urgent need for regulation of groundwater use. We demonstrate that technological intervention through agro-extension systems can result in sustainable management of depleting groundwater and $CO_2$ emissions in Punjab. Additionally, all forms of electricity subsidy, including that for the solar need to be curbed and an effective national groundwater monitoring and extraction program is needed. In the regions that are most affected by groundwater depletion (northwestern India and Indo-Gangetic Plain), a poor choice of crops and irrigation technology is the primary reason. For instance, despite the groundwater depletion in Punjab, the total area under rice has increased from 10% in 1975 to 38% in 2010 (Sarkar & Das, 2014), which resulted in a massive withdrawal of groundwater for irrigation leading to an overdraft condition (Fig. S2). Average water requirement for water-intensive crops such as rice (1200 mm) and sugarcane (2000 mm) is far more significant than the other cereal crops (Reddy et al., 2015). The proper choice of crops, especially in northwestern India and Indo-Gangetic Plain can be a useful measure to reduce unsustainable extraction of groundwater. Along with appropriate crop choices, improving irrigation and water use efficiencies can reduce the amount of excessive extraction of groundwater by two-third (R. Fishman et al., 2015). Therefore, technology and policy related decisions are required at multiple levels ensure sustainable management of groundwater resources in India.
Acknowledgments and Data

Authors acknowledge funding from ITRA-Water project. The data used this study are publicly available from GRACE (https://grace.jpl.nasa.gov/) and CGWB (http://cgwb.gov.in/).

References


Figure 1. **Groundwater pumping in India.** (a) Area (%) irrigated with groundwater, (b) Change in the net irrigated area from different sources, (c) State-wise distribution of different energy sources.
Figure 2. Groundwater depletion in India estimated using well and GRACE datasets. (A) mean annual trend in groundwater level (cm/year) during 1996-2016 estimated using well data from Central Ground Water Board (CGWB), (B) trend in mean annual groundwater anomalies (cm/year) estimated using the GRACE satellite data for 2002-2016 period, (C) groundwater storage anomaly aggregated for all the districts that show groundwater depletion based on CGWB well data and ensemble mean of GRACE products (CSR, JPL, and GFZ) for 2002-2016. Stippling in (A,B) shows statistically significant trend at 5% level.
Figure 3. **CO2 emission in India due to groundwater depletion.** (a) Specific yield (%) for major aquifers in India obtained from CGWB, (b) district level mean bicarbonate (mg/L) concentration in groundwater, (c) CO2 emission due to groundwater depletion (release of HCO3) during 1996-2016, and (d) CO2 emission due to groundwater depletion based on the GRACE estimates during 2002-2016. Mean district level bicarbonate was estimated using the CGWB monitoring wells in each district.
Figure 4. Technological intervention in the sustainable management of groundwater and energy consumption in Punjab. (a) change in groundwater level in Punjab during 1973 and 2011 based on more than 1750 wells, (b) savings in water (%) when irrigation decision was based on soil moisture information from tensiometers in five districts in Punjab, (c) electricity saving (Kwh*1000) in groundwater pumping in five districts in Punjab.