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ORIGINAL PAPER

Is shrinking groundwater resources leading to socioeconomic and environmental degradation in Central Ganga Plain, India?

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Abstract In India, agriculture is a source of livelihood for over 64 % of the country's population. Indo-Gangetic Plains of North India support good cultivation and provides livelihood to several hundred million people. The climatic change studies have documented changes in precipitation pattern which can alter the flow pattern discharge to the reservoirs and availability of water for agriculture. The reduction in groundwater recharge through reduced rainfall and irregularity in surface water availability has increased dependence on groundwater resources causing its overexploitation. Consequently, pumping from deeper groundwater conditions need more energy and pump efficiency for abstraction which ultimately requires huge capital investment. Moreover, volatile fuel prices make the agricultural society vulnerable to economic losses. The repercussions of water level decline are likely to disseminate an additional economic burden to the groundwater user community. To cope with higher energy demands, increase in fuel consumption has led to environmental degradation through higher carbon emission. Thus, the groundwater depletion is likely to have far-reaching socioeconomic and environmental impacts which are not confined to the Central Gangetic Plain. In the present study, attempts have been made to analyze the effect of groundwater depletion as a commodity in the social framework of the region.

Keywords Rainfall pattern · Groundwater depletion · Socioeconomic impact · Central Gangetic Plain

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Introduction

Across India, arable lands have already ceased to grow; water resources too have set declining trends in many cultivated regions (Alagh 2003). Government's sympathetic treatment toward groundwater (henceforth as GW) irrigation, which was initially started in 1960s and 1970s, had left the farmers with more and more GW irrigation mindset (Shah 2000). Groundwater has emerged as the primary democratic water source and poverty reduction tool in India's rural areas. The farmers have full control on GW irrigation abstraction. The benefit of groundwater irrigation helps explain the huge jump in agricultural productivity in recent time (IWMI 2002). As a result of shrinking groundwater resources, any perturbation in agriculture production will considerably affect the food systems of the region and increase the vulnerability of resource-poor populations. Therefore, economic scarcity of water is the key water management issue in agriculture (Kumar 2003). Current agricultural practices are neither economically nor environmentally sustainable and India's yields for many agricultural commodities are low (World Bank 2008). The technological improvements in irrigation systems have increased production opportunities but simultaneously aggravated groundwater exploitation.

The general impacts of climate change on water resources indicate an intensification of the global hydrological cycle affecting both ground and surface water supply (IPCC 2007). Changes in the total amount of precipitation, its frequency, and intensity have also been predicted. This necessitates sustainable management of groundwater resources through enhancing artificial GW recharge (IPCC 2007; Sen et al. 2013). The planning commission of India has emphasized GW overexploitation as a critical water sector challenge for India (Planning Commission 2007). The Indo-Gangetic Plains (IGPs) are expected to be particularly vulnerable to the agricultural impacts of climatic change due to its large population density and its dependence on the agriculture sector.

Numerous studies have shown that extensive agricultural activities together with the increasing industrial setup are reported to cause GW overexploitation (Ahmed and Umar 2008, 2009; Umar and Ahmed 2009; Khan et al. 2012), deterioration in its quality (Umar and Ahmed 2007; Umar et al. 2007, 2009; Tyagi et al. 2009; Umar and Alam 2012), and susceptibility to contamination (Umar et al. 2008; Alam et al. 2012). The GW quantity and quality are equally important factors in the context of modern water management (Kumar et al. 2013).

Within IGPs, GW serves as an important commodity for agricultural-based economy. To meet market demands and profitability issues, the agriculture sector requires increased water supplies with or without adequate scientific understanding of GW sustainability and management. Overexploitation of GW resource not only questions its sustainability but also is linked to the socioeconomic factors in the region. As the additional fuel consumption required for deeper GW abstraction imparts an economic burden on successive end-users. The increased fuel energy requirement issue also complies with environmental degradation through increased emission of greenhouse gases (GHGs). The consequences of future changes of GW recharge, resulting from climate and socio-economic change, are to be addressed; hydrogeologists must increasingly work with researchers from other disciplines, such as socioeconomists, agricultural modelers, and soil scientists (Holman 2006).

The present study explains the pros and cons of GW overexploitation; its importance as a socioeconomic commodity while simultaneously harming the resource sustainability and degrading the environment. The study necessitates policy making to address GW sustainability issues.

Material and methods

A detailed study survey was conducted to collect various data pertaining to aquifer geometry, water levels, GW drafts, rainfall, water extraction wells inventoried, water utilization pattern, cropping pattern, mode of irrigation, average farm size survey, etc.

GW abstraction cost model describes the relationships of various parameters like well inventoried, cost of new installation and maintenance, hourly operating cost, and yearly running hours to obtain cost of GW abstraction for irrigation (C_{gw}) in million Rs.;

$$C_{gw} = (0.35T_{Ne}) + (0.2T_{Ee} \times 0.07) + \left\{(T_{Ne} + T_{Ee}) \times H_{\mathrm{e}} \times 10^{-6} \times t_{\mathrm{e}}\right\} + \left\{(0.15T_{Nd}) + (0.2T_{Ed} \times 0.03) + (T_{Nd} + T_{Ed}) \times H_{\mathrm{d}} \times 10^{-6} \times t_{\mathrm{d}}\right\} \tag{1}$$

Total electricity consumption (E_{C}) in GW irrigation for a particular year can be estimated as follows,

$$E_{\mathrm{C}}(kilowatt\ hour) = BHP_{\mathrm{e}} \times 0.735 \times N_{et} \times t_{\mathrm{e}} \tag{2}$$

For total diesel consumption (D_{C}) in GW irrigation, following relationship has been adopted from ASABE Standards (2006, 2009).

$$D_{\mathrm{C}}(liters) = 0.18 \times BHP_{\mathrm{d}} \times t_{\mathrm{d}} \times N_{dt} \tag{3}$$

Carbon dioxide equivalent (CO_2 eq.) emissions are linked with the electricity generation through the following equation

$$CO_2 eq.emissions(kilotonnes) = 1.3 \times E_{\mathrm{C}} \times 10^{-6} \tag{4}$$

CO_2 equivalent emissions generated through diesel-operated irrigation pumps can be estimated as

$$CO_2\, eq.emissions(kilotonnes) = 2.7 \times D_{\mathrm{C}} \times 10^{-6} \tag{5}$$

All the abbreviations used in the above equations are described in Table 1.

Water utilization pattern in the study area

A pilot study area was chosen from highly cultivated tracts of the Central Ganga Plain which represents an agriculture-based economy. The study area is approximately 4,008 km^2. Geographically, the interfluve between two rivers Ganga and Yamuna administratively forms two districts namely Muzaffarnagar and Shamli in the state of Uttar Pradesh, India (Fig. 1). The study area is famous for sugarcane cultivation and is one of the largest jaggery markets in Asia. The agricultural activities remain the mainstay of life occupying almost

Table 1 Analyses of groundwater irrigation data (as in 2009)

Average depth of water level (d)	12.61 m
Average diesel engine capacity (BHP_{d})	6
Average hourly diesel consumption for BHP_{d} (d_{c})	1 l/h
Average electric engine capacity (BHP_{e})	8
Size of outlet pipe (D)	4 in.
Yearly running hours for electric tube wells (t_{e})	1,250
Yearly running hours for diesel tube wells (t_{d})	1,000
Number of existing diesel tube wells (T_{Ed})[a]	55,116
Number of new diesel tube wells (T_{Nd})[a]	124
Number of existing electric tube wells (T_{Ee})[a]	38,132
Number of new electric tube wells (T_{Ne})[a]	50
Average hourly running cost for electric tube well (H_{e})	2 (Rs.)[a]
Average hourly running cost for diesel tube well (H_{d})	35 (Rs.)[a]

[a] As in 2009, 1 Indian National Rupees (INR or Rs.) equals 0.0212 USD

70 % of the regional population. Approximately 78 % of total irrigation water is harnessed through groundwater using modern water extraction machines (WEMs). The surface water constitutes remaining 22 % of irrigation which is done through canals and minors, i.e., irrigation channels (DSR 2008). The Upper Ganga Canal and Eastern Yamuna Canal are the main canals which supply surface water to a network of unlined irrigation channels.

Four distinct groups of aquifers were identified to a depth of approx. 500 m (Bhatnagar et al. 1982; Khan 1992). Due to easy access and low abstraction cost, shallow aquifer (120 m depth) has been exploited extensively (Ahmed and Umar 2008). For most of the shallow aquifers in Central Ganga Plain (CGP), rainfall is the main source of GW recharge. A number of studies using tritium tracer techniques within CGPs have shown that about 20 % of the total rainfall amount forms the GW recharge (Goel 1975; Gupta et al. 1985; Rangarajan 2006). Apart from the rainfall, significant GW recharge also occurs through irrigation return water and canal seepages (Ahmed and Umar 2008; Umar and Ahmed 2009; Khan et al. 2012). For any year, the positive effect of rainfall on the GW system is visible at the end of the monsoon period causing the water level to rise. Perusal of hydrographs indicates that the water level variation is cyclic and sinusoidal as a function of time and show a progressive decline (Fig. 2). The average annual GW decline recorded at 14 locations is 0.89 m/year. Due to less rainfall after the year 2005, the monsoon effect on shallow GW resources diminishes gradually and due to which the post monsoon (month of November) water level does not surpass pre-monsoon (month of June) levels (Fig. 3). Sustainable groundwater development envisages that for one "hydrogeological year" (365 days) water level should rise to the same level of previous year; otherwise, the GW system will be considered as water deficit (Ahmed 2008). Statistical analysis of rainfall (1990–2010) shows that on an average a study area receives 641 mm of annual rainfall. However, 2005 onwards, the study area receives below average rainfall, i.e., 450 mm/year. Thus, ongoing heavy abstraction and the reduction in rainfall magnitude would, in all likelihood, further aggravate GW depletion.

Results and discussions

Groundwater decline—an economic burden

GW irrigation is the lifeline of agricultural sustainability in the region. Planning and design of wells in Indo-Gangetic plains is greatly influenced by the cost of installation, which in turn depends on the drilling technology used, well depth and diameter, and local and market conditions. With declining water tables, submersible pumps are increasingly preferred to non-submersibles, but these are expensive to install. In general private tube wells tap 6 to 40 m depth depending upon water level depths. The average depth of casing is around 4 m below the water level. For the year 2009, GW draft for irrigation was estimated to be 1915 million m^3. The overexploitation has led to water level decline at variable rates and has left many areas

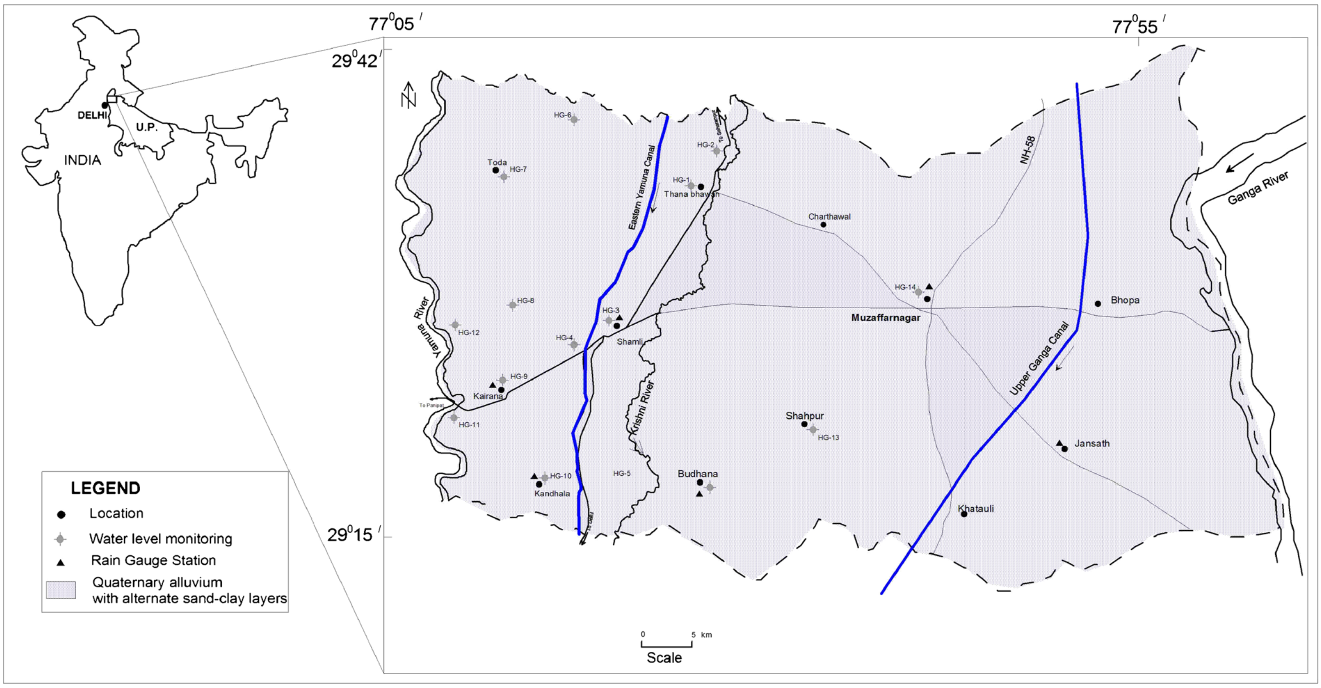

Fig. 1 Base map of the study area

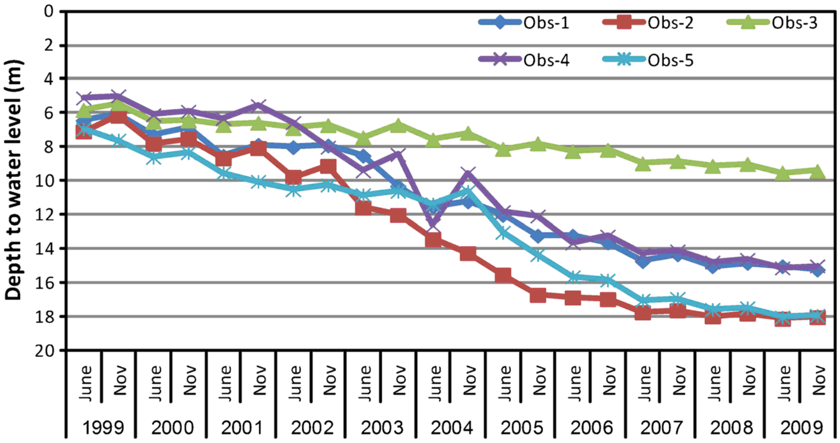

Fig. 2 Long-term water level fluctuation trends at selected observation wells

(*blocks*) under critical and overexploited category of GW abstraction (Ahmed and Umar 2008, 2009; CGWB 2008). Due to rapid GW decline, tube wells with shallow casing depths are more vulnerable to low yield and failure. This demands further deepening of such wells, replacement of old casing and screens, and replacing old with high-efficiency motor. Since, the average depth of casing below the water level is 4 m and ongoing decline rate is approximately 1 m/year; it is more likely that all existing tube wells tend to less discharge or failure in next 4–5 years. Although, the study considers that with the ongoing decline trend, tube well depreciation would be gradual.

For cost estimation purposes, it is assumed that approximately 20 % of the tube wells will need maintenance in terms of well deepening each year. The average annual maintenance cost of the tube wells is set at 20 % of the installation cost. Based on a study survey in 2009, the average installation cost of diesel and electric tube wells was set at 0.15 and 0.35 million Rs. (INR), respectively. The average hourly operational cost for diesel and electric tube wells is about 42 and 2 rupees, respectively. The total expenditure incurred in GW irrigation is estimated through GW abstraction cost model (Eq. 1). The average costs of new installation, maintenance, and operation were fixed after field experimentation, market pricing of usable goods, and negotiations with the farmers. The total yearly expenditure incurred in GW abstraction for irrigation is 2.9 billion Rs. which is approximately 8 % of the total agricultural output cost.

Shrinking field size

The agricultural field (plot) size analysis in the study reveals that a small field (<0.5 ha) constitutes about 48.3 % of the total

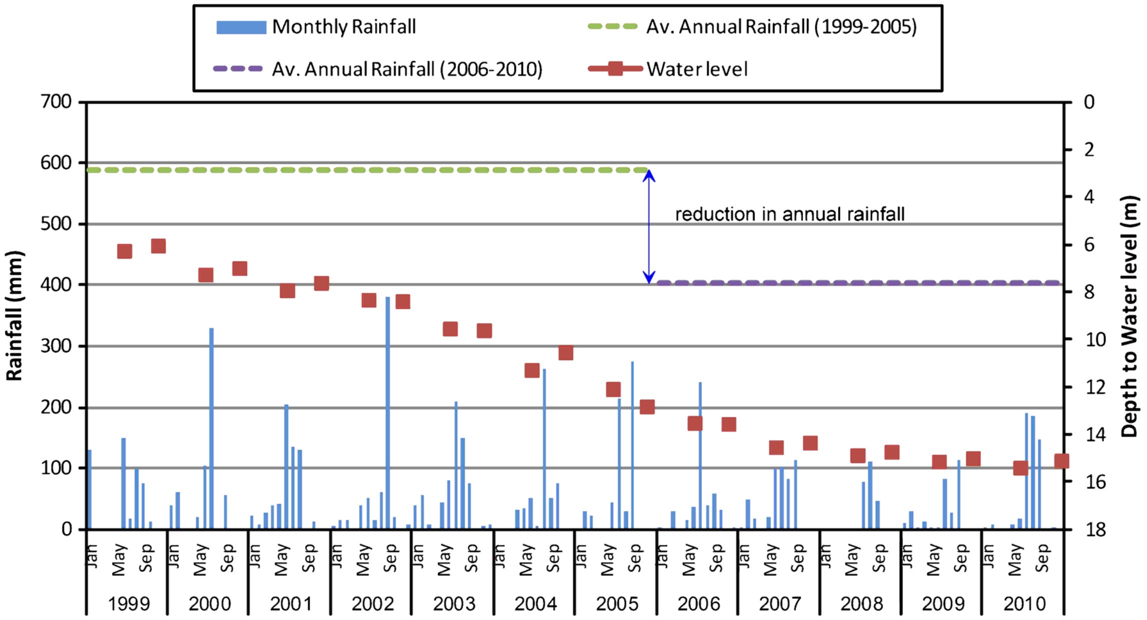

Fig. 3 Temporal variability of rainfall and average water level fluctuation within the study area

plots and area-wise forms about 11 % of the total cultivated land (Table 2). Contrarily, the number of big plots having size >4 ha constitutes only 4.4 % of the total plots, covering an area of 23.8 % of total cultivated land. This uneven distribution of the size of land holdings, apart from historical reason, is attributed to the population increase and family breakups. The concentration of tube well is a crucial issue and to be discussed along with land holding. Ideally, the number of tube wells should proportionate to the number of fields. The overall tube well density of the region is approx 3 tube wells/10 ha while plot-wise tube well density is as low as 3 tube wells/10 plots. The average farm size has a positive effect on tube well density as would be expected where large landowners are more likely to own tube wells. Thus assuming that field size >2 ha have 1 tube well and plot size >10 ha have 2 tube wells, the tube well density for plots sizing <2 ha is 2.3 tube well/10 ha and plot-wise tube well density is as low as 1 tube well per 5 plots. Although considering surface water irrigation (22 %) share in the study area, the tube well density may be slightly more than the estimated. Despite the overall region's high tube well density, many small plots (<0.5 ha) remain without tube well and are irrigated using purchased water from the informal water markets.

Further, the inability of small land holders to own and/or maintain their tube well forces them to buy water from tube well owners. Although the buyer community utilizes paid water more efficiently than the owners (Srivastava et al. 2009), but getting timely and sufficient water supply from owners is a matter of efficiency of these markets. Unavailability or delay in meeting water demand may lead to serious consequences on crop yield and water buyer's community may refrain from cultivating water-intensive yet profitable crops. The sugarcane cropping is more skewed towards field size >2 ha (NABARD 2007). In western Uttar Pradesh, about 50 % of farmers having <0.5 ha of land often lease their plots (Pant 2004) and likely to occupy different profession other than agriculture. Thus, in the absence of a well-defined legislation, GW trading is susceptible to social discrimination among different groups and a cause of feud among water buyers.

Table 2 Statistics of agriculture fields size in the study area

Size (hectare)	Total agricultural fields		Area of field		Tube well (Tw) density	
	Number	Percent	Area (ha)	Percent	(Tw/plot)	(Tw/10 ha)
<0.5	142,442	48.3	34,524	10.5	0.2	8
0.5–1.0	54,651	18.5	39,963	12.2	0.2	2.7
1.0–2.0	51,984	17.6	80,091	24.5	0.2	1.3
2.0–4.0	32,812	11.1	96,783	29.6	1	3.4
4.0–10.0	12,376	4.2	67,919	20.8	1	1.8
>10	479	0.2	7,842	2.4	2	1.2

Effect on cropping pattern

The main crops of the region are sugarcane and food grains (mainly wheat and rice) collectively share 84 % of total agricultural land. Due to high profitability, farmers are more inclined towards growing sugarcane crop and to a lesser extent grow potato, grains (wheat, rice), and oil seeds. This sugarcane belt in western Uttar Pradesh has a water economy where areas share common institutional features (Banerji et al. 2006). Pricing of sugarcane has always remained a hot political issue in this region. A comparison of cost incurred per hectare of land shows that sugarcane is the most profitable crop, generating eight times more money than the second highest profitable crop of potato (Table 3). Sugarcane is the most water-intensive crop, but with a significant profitability as compared to the other crops.

It is expected that shrinking GW resources may cause restrictions particularly to water-intensive crops like sugarcane and rice. The present study documented the reduction in grain crops (wheat, rice, and lentils) but that is attributed to the increase in sugarcane crops on account of its profitability. Due to reduced tube well discharge, during any point of time in summer season corresponding with Rabi crops, owners may not be able to sell water to buyer. This may impart serious economic loss to buyer community first and later to the owners. However, for better validation and to better understand the impact of change in water resources on agriculture and livelihoods, observed climatic data from other stations need to be analyzed (TERI 2005). Another complication in adopting a crop change practice is that since water consumptive crops are associated with higher output cost (Fig. 4), which means more benefits to the farmers, hence they will certainly resist to adopt to crops which are less profitable than the sugarcane. As a part of Ministry of water Resources, India research project, Ahmed and Umar (2009) carried out groundwater flow modeling within a part of the present study area and predicted quick water level decline under reduced rainfall recharges. Projecting ongoing abstraction rate along with decreased rainfall led to drawdown ranging from 6 to 10 m by the year 2015. This tends to increase abstraction cost by several times. The increasing cost of GW abstraction may potentially affect small to marginal farmers. The agriculture profitability of a crop is a subject to gross availability of that crop type and its market condition. For example, market pricing of potato is more volatile than other cash crops. Political shielding of sugarcane price is another factor as why farmer rely more on sugarcane farming.

Energy–environment nexus

Pricing of fuels for WEMs is an important commodity which defines farms income along with agricultural products. Energy cost and availability have remained the top challenges of

Table 3 Total crop area and production in the study area (District Statistical Report 2008–2009)

Crops	Crop area (ha)	Production (1,000 kg/ha)	Rate (Rs./kg)	Av. cost (Rs./ha)	Cost incurred (million)	Water output ratio (Rs./m^3)	Productivity (kg/m^3)
Grains	141,546	3.2	10.8	34,231.7	5,156.9	8.5	0.79
Pulses	4,089	0.6	26.7	15,939.0	69.5	4.5	0.17
Oil seeds	2,641	1.2	35.8	41,290.0	82.9	9.2	0.26
Sugarcane	242,430	65.7	12.5	821,450.0	19,914.4	68.4	5.53
Potato	2,019	22.2	4.6	102,207.0	207.7	20.4	4.44
Cotton	46	0.8	49	39,413.0	1.8	7.8	0.16
Fodder	65,123					–	–

irrigation efficiency (Shah et al. 2007). Electricity price for irrigation are based on subsidized tariffs; one of the most argued issue in GW irrigation. However, due to poor electrification and erratic supply to places, the farmers have no choice but to use diesel pump either as a standby arrangement or full time relying on them. In fact, most of the IGPs rely on diesel pump sets for GW pumping. In the present study, diesel tube well constitutes about 60 % of the total WEMs. Ironically, irrespective of higher diesel pumps, subsidy is more inclined towards the electric tube wells (Malik 2009). Due to large dependence on diesel fuel, hike in diesel prices may cause widespread farm distress (Mukherjee 2007; Shah 2007). A relationship between cost of GW abstraction, diesel prices, and per hectare agricultural output cost incurred was obtained and presented in Fig. 4. A correlation study of parameters of economic importance was performed from 2001 to 2009 (Table 4). This shows a good correlation between the cost of GW abstraction with the GW decline (r^2=0.96) and with diesel price (r^2=0.98). The cost incurred per hectare and diesel price are correlated with r^2=0.82 which could be considered safe. Although, problems may arise if the rise in diesel price or cost of GW abstraction is not concurrently implicated in the cost incurred.

For the present study, total energy consumptions in GW irrigation were estimated using the following empirical relation. Data pertaining to various aspects of GW irrigation, viz pump efficiency (horsepower), running hours per year (hours), water depth (meter), diameter of discharge pipe (inch), and total number of electric and diesel tube wells, were collected from the field study and an average value was set for each aspect (Table 1). The annual electricity consumption in GW irrigation was estimated to be 280.6 million kWh. Total annual diesel consumption comes out to be 59.6 million liters.

Carbon footprints of groundwater irrigation

Carbon footprint may be viewed as a hybrid term deriving from the term *ecological footprint* proposed by Wackernagal and Rees (1996) and conceptually being a global warming potential (GWP) indicator calculated mathematically and is expressed relative to that of CO_2. Therefore, the unit of GWP is carbon dioxide equivalent (CO_2 eq.) emission (Panday et al. 2011). There is little uniformity in the definitions of carbon footprint within the available literature and studies. The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or

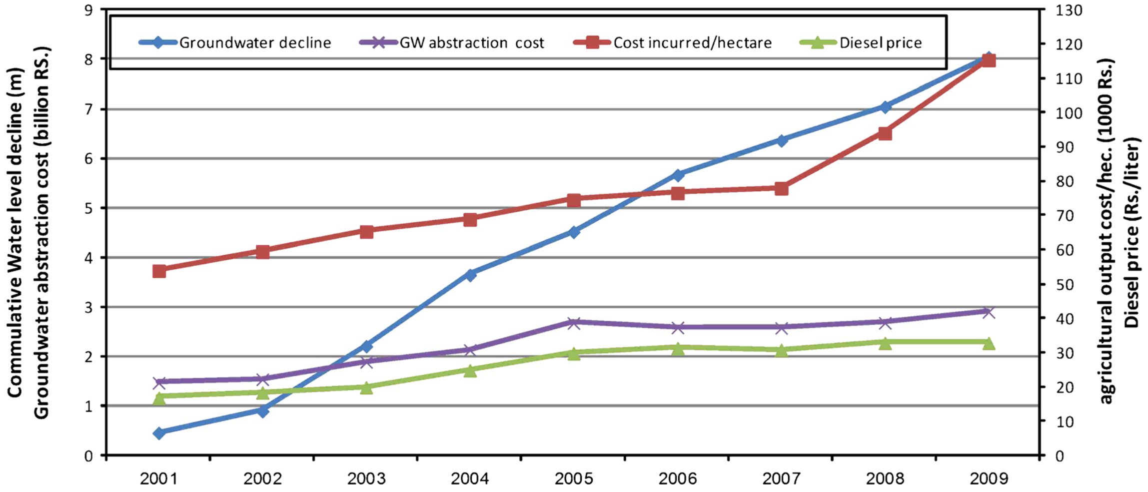

Fig. 4 Relationship between groundwater decline, extraction cost, diesel price, and total agriculture output cost

Table 4 Pearson correlation coefficient for annual data (2001–2009)

Parameters	GW decline	Rainfall	Total prod.	Cost incurred/ha.	GW extraction cost	Diesel price
GW decline	1.00					
Rainfall	−0.70	1.00				
Total prod.	0.70	−0.08	1.00			
Cost incurred/ha	0.91*	−0.57	0.59	1.00		
GW extraction cost	0.96*	−0.55	0.77	0.84**	1.00	
Diesel price	0.97*	−0.67	0.71	0.82**	0.98	1.00

$^*p<0.001$, $^{**}p<0.02$

is accumulated over the life stages of a product (Wiedmann and Minx 2007). Studies and methods followed for carbon footprint calculation suggest including other GHGs as well, apart from only CO_2 (Bokowski et al. 2007; Garg and Dornfeld 2008). However some studies include only CO_2 emissions in carbon footprint calculations (Patel 2006; Craeynest and Streatfeild 2008).

The GW overexploitation, which itself a serious environmental issue, also contributes GHG through increased energy consumption. According to Intergovernmental Panel on Climate Change, agriculture is responsible for over a quarter of total global GHG emissions (IPCC 2007). The vast GW irrigation system of CGP is supported by electric- and diesel-operated tube wells. India's electricity supply is mainly based on thermal power plants using fossil fuels. Coal-generated electricity constitutes about 85 % of total fossil fuels and 55 % among all kinds, i.e., including nuclear and hydropower plants (CEA 2011). Steam power plants using coal with high ash content and low calorific value have long been identified as major contributors of airborne pollution.

In the present study, CO_2 eq. emissions of diesel pumps- and coal-generated electricity used for GW abstraction are considered. There is a lack of uniformity over the selection of direct and embodied emissions. It becomes complex to include all possible emissions, and thus, most studies report only direct or first-order indirect emissions (Wiedmann and Minx 2007; Matthews et al. 2008). The usable energy density of thermal power plant is 1.4 kWh/kg of burned coal (CEA 2011). Since 1 kg of coal is convertible to 1.83 kg of CO_2, thermal power plants produce approx 1.307 kg of CO_2/kWh (EIA 2000). Using this empirical relation, total electric consumption in GW abstraction would produce 366.7 kt CO_2 eq. Similarly, 1 l of diesel produces approximately 2.7 kg of CO_2 eq. Using this empirical relationship, CO_2 emissions from diesel used for annual GW abstraction is estimated around 161.1 kt. Thus, the total carbon footprints of GW abstraction come out to be 527.8 kt of CO_2. Any further increase in the energy consumption would leave the environment with more CO_2 and other GHGs.

Conclusions

Groundwater has become an important economic commodity and farmers' community is using it as a tool to increase agricultural profitability. Nonetheless, with 78 % share in the total irrigated area, the GW has attained a crucial position in defining socioeconomic conditions. The study highlights the linkage between groundwater decline and resultant high cost of GW drafting. The high cost of installation and maintenance of WEMs likely to affect tube well ownership. The small size of land holdings, inadequate rural electrification, and high installation/maintenance cost of tube wells are responsible for low irrigation investment. The installation of new tube wells and high efficiency pump set to tap deeper GW will require significantly high investments, proving an additional financial burden on the society. Due to skewed distribution of tube wells towards the large farmers and on account of huge investment needs, at peak irrigation time small and marginal farmers have to buy water from tube well owners. This categorizes farmer's community into two broad categories of water use: owners and buyers. On account of water requirement and accessibility to water, the water-rationed plots may not get timely and sufficient water supply, resulting in low yield. This trend is also likely to affect the traditional cropping pattern of small and marginal farmers in the region. The buyer community would deprive of sowing water consumptive but profitable crops. The high cost of water lifting affects the cost–benefit ratio, which in turn leads to a rise in the cost of farming products. Thus, the agricultural profitability of small to marginal land holders will be reduced. This compels small farmers particularly with plots less than 0.5 ha to migrate to other occupations for their livelihood.

To meet high energy (electricity and diesel) demands which are inevitable due to deeper groundwater abstraction would be a challenge. The increased energy consumption for GW irrigation will contribute higher GHGs to the environment. The increase in atmospheric concentrations of GHGs would further degrade the earth's atmosphere system. Apart from GW depletion, excessive GW irrigation would increase the concentrations of GHGs emissions; both should be considered as potential threats to environmental sustainability. Thus, extensive agricultural activities in the foothills of the mighty Himalayan range may pose a potential threat to glacier melt. As a matter of fact, groundwater decline issue is directly linked with higher outputs in terms of money and, therefore, farmers would resist to a crop change option. A timely step to prevent further depletion is the key issue which requires strong policy making to ensure GW sustainable agricultural practices. This study recommends that strict policy be adopted by the central/state governments to regulate the GW abstraction.

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