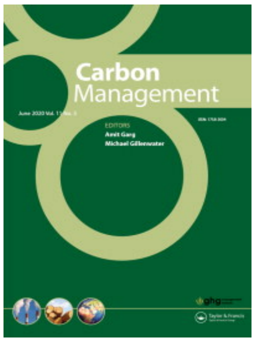

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Carbon footprint of India’s groundwater irrigation

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ABSTRACT

India has an intricate nexus of groundwater irrigation, energy and climate. Subsidized electricity supply has led to unregulated groundwater pumping, causing a decrease in groundwater level and increase in carbon emissions. This complex nexus necessitates estimation of carbon emissions from groundwater irrigation. The study uses actual pumping data on 20.5 million groundwater structures from the Fifth Minor Irrigation Census (reference year 2013–14) to estimate carbon emissions. The estimates show that groundwater irrigation emits 45.3–62.3 MMT of carbon annually, contributing 8–11% of India’s total carbon emission. This analysis shows deep tubewells have a huge carbon footprint, and their growing number is a serious environmental concern. Spatial analysis reveals India’s western and peninsular region, which houses 85% of the country’s over-exploited groundwater blocks, contributes most to carbon emission. Moreover, this region hosts 27 districts which are groundwater–energy–climate nexus hotspots, together accounting for 34% of carbon emissions from groundwater irrigation. Comparison with the previous estimate reveals that carbon emission from groundwater irrigation nearly doubled between 2000 and 2013. Findings of this study are vital to the discourse on the increasing environmental costs of groundwater pumping in the country and will contribute to carbon emission mitigation strategies.

KEYWORDS
Water–energy–climate nexus; GHG accounting; carbon emission

Introduction

India has witnessed the most explosive growth of groundwater withdrawals in the last five decades compared with other prominent groundwater-using countries (see Figure 1). Currently, the country accounts for one fourth of the global groundwater extraction (i.e. 251 km^3/year) and uses 90% of the abstracted groundwater for irrigation [2]. Groundwater serves irrigation to around 40–45 million hectares of cultivated land – around 60% of the total irrigated area [3]. Until the 1950s, the areas irrigated by groundwater and surface water were uniformly balanced (Figure 2). However, post-1970, there was a steep rise in groundwater irrigation. The drivers of India’s silent groundwater revolution have been the atomistic response of millions of smallholders to the mounting population pressure on farmlands and to the demand for a year-round, on-demand water supply to maximize their land productivity [4]. These drivers, coupled with factors like technological advancements in water extraction mechanisms and subsidized electricity for pumping, have spurred the groundwater irrigation boom in the country [5].

India’s atomized pumping revolution has been central to its agrarian growth and poverty alleviation. It has benefited millions of small and marginal farmers by providing year-round water control, which has led to improved agricultural productivity and cropping intensity [1,4]. However, this rapid unregulated groundwater boom has also created negative externalities for the country’s hydrology and environment. Excess groundwater abstraction vis-à-vis recharge in the arid/semi-arid parts has stressed aquifer systems, causing a secular decline in groundwater levels in the region [7]. Several studies have underscored the role of electricity subsidies in unregulated groundwater pumping [5,7,8]. Along with stressing the groundwater reserves, intensive groundwater pumping results in higher energy consumption, sourced from electricity or fossil fuels, resulting in higher carbon emission [9, 10].

The objectives of this article are (a) to estimate the carbon emission associated with groundwater irrigation in India; (b) to analyze the spatial variations in estimated carbon emissions; and (c) to discuss the main factors contributing to increasing the carbon emissions and mitigation strategies to counter them. The study has the advantage of

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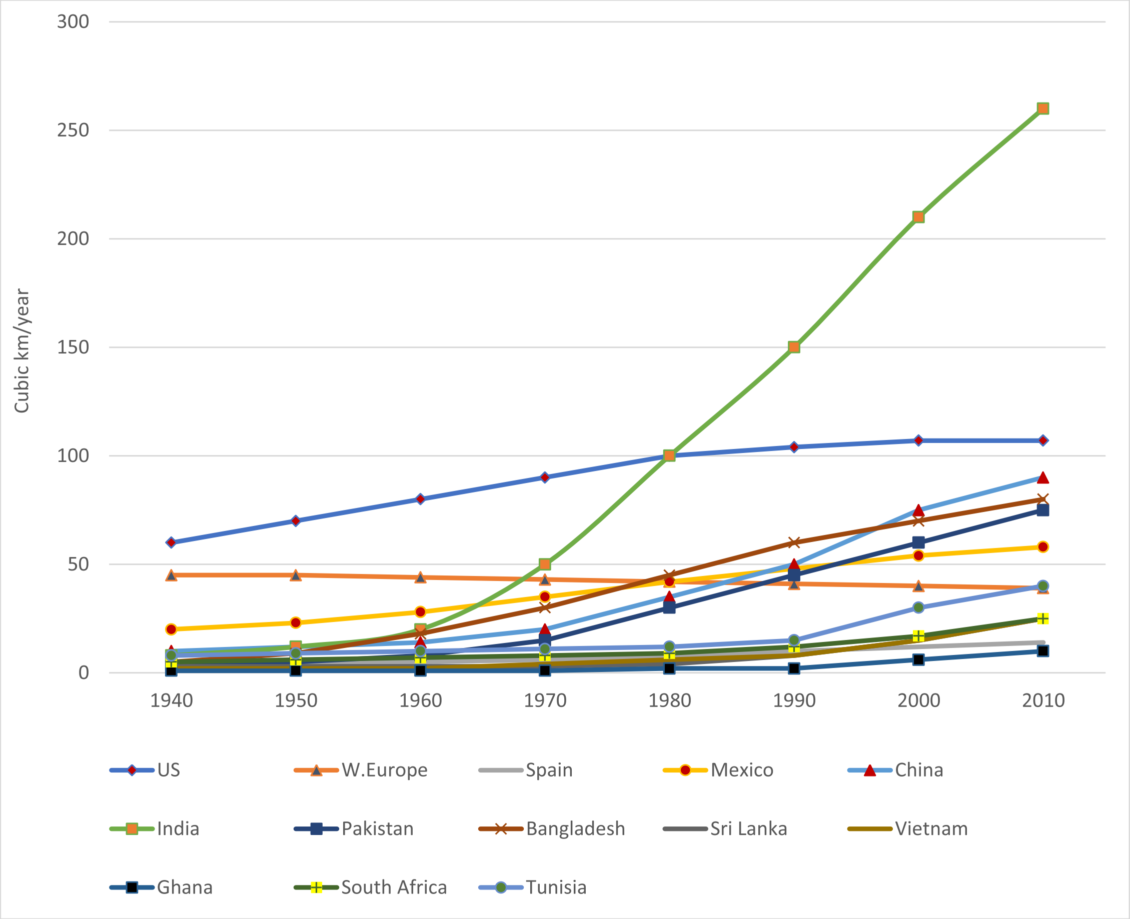
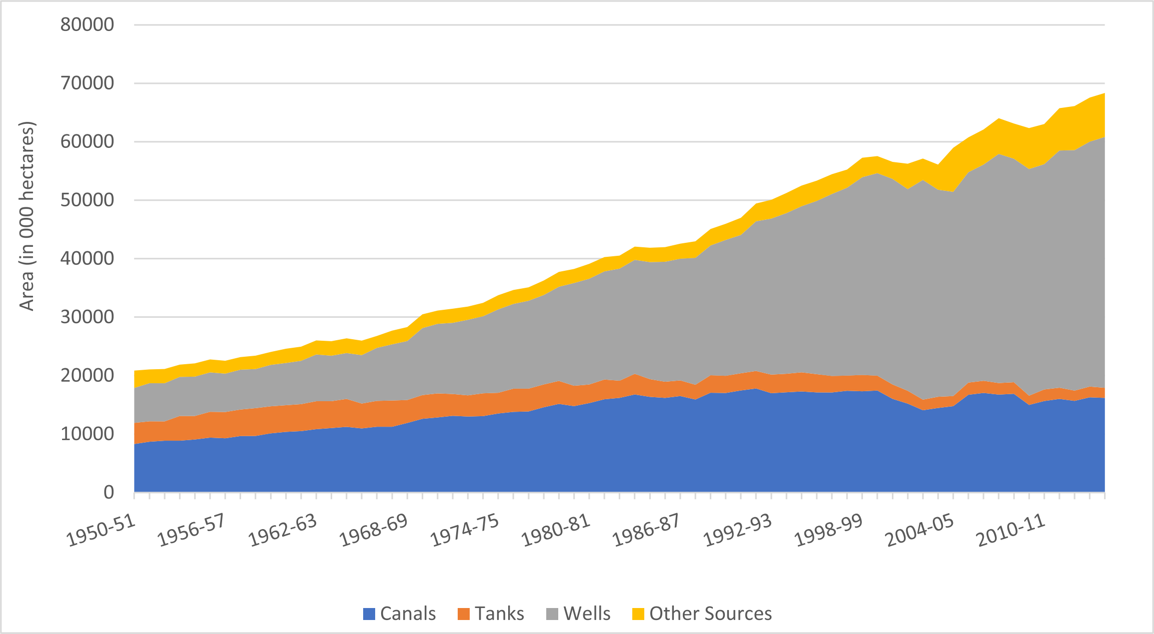


Figure 1. Groundwater extraction by country, 1940–2010. Source: [1].



Note: Other sources include ponds, springs, river streams etc.

Figure 2. Source-wise irrigation of India, 1950–2015. Source: [6].
Note: Other sources include ponds, springs, river streams, etc.

using individual well-level data on 20.5 million irrigators from the recent Fifth Minor Irrigation Census (MIC), which makes the estimation more recent and more accurate compared to previous studies on carbon emissions from India's groundwater pumping.

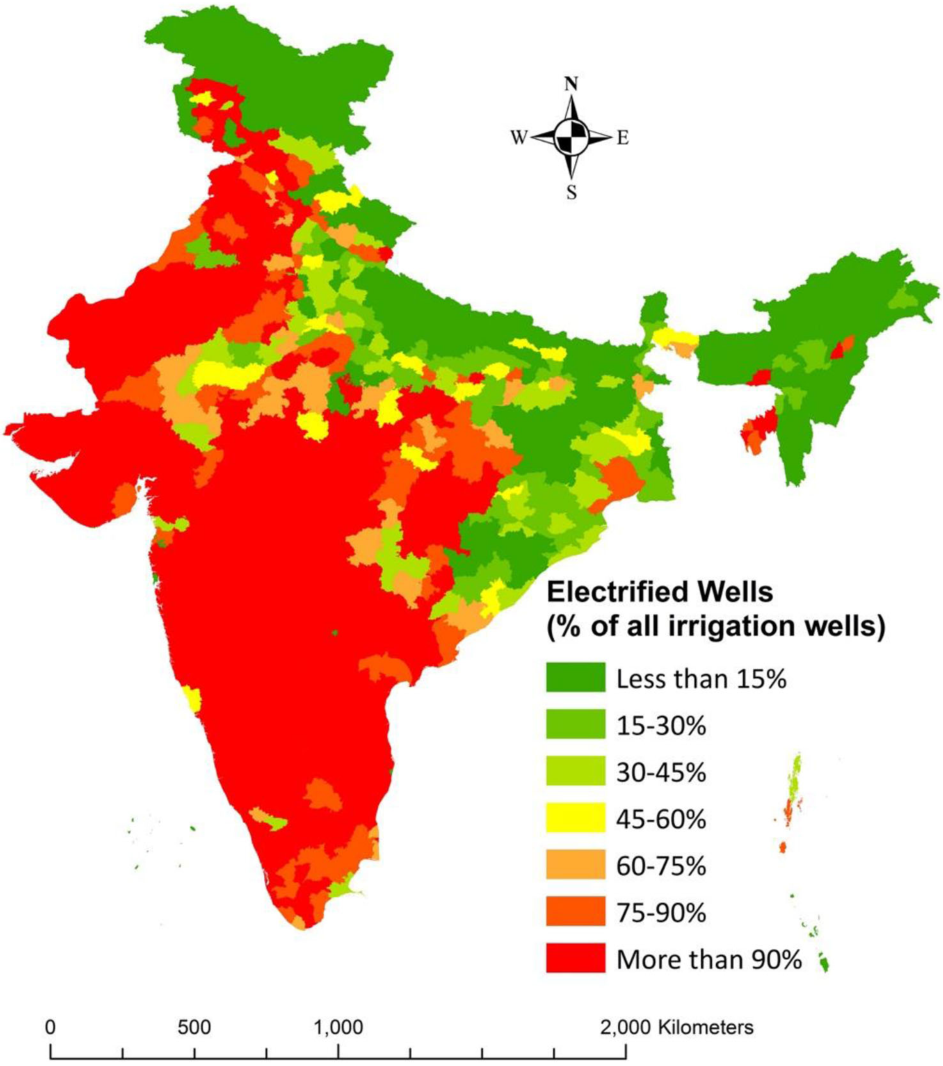


Figure 3. **Energy divide in India according to the Fifth Minor Irrigation Census (2013–14). Source: Government of India [12].**

Electricity–irrigation nexus in India

From less than 0.39 million in the 1960s, the number of groundwater structures (GWSs) in India soared to 20.5 million in 2013–14 [11, 12]. Of these, around 14.6 million are powered by electricity, 5.1 million by diesel oil and 0.3 million by other sources. The predominance of electricity as an energy source for groundwater pumping has historical underpinnings.

In the early 1960s, the Indian government stressed the importance of rural electrification in improving agricultural production to curb food shortage and drought situations in the country [13]. Government policies encouraged farmers to adopt electric pump sets for irrigation by providing them electricity at low tariffs [4]. With the ushering-in of Green Revolution in the same period (the late 1960s), pump irrigation took off rapidly in the country [4, 7, 14]. Following the 1970s, as the number of grid-connected wells increased, the transaction cost of serving these metered wells, scattered in remote locations, also increased [4, 7, 14, 15]. In response to the high and rising transaction cost of metered power supply, various state governments stopped recording actual electricity consumption and started providing electricity at flat tariffs [4, 14, 15]. This gave a tremendous boost to the expansion of electric pumps and their utilization in the country [4, 14]. Flat tariffs accelerated groundwater use, catalyzed irrigation markets and were considered pro-poor. Eventually, farm power prices became part of populist vote-bank politics and began to be used as a potential tool to win the votes of farming communities [7, 14]. As a result, the flat tariff was converted to free power in some states, and in many other states, flat tariffs remained unrevised for decades [7, 14]. Gulati *et al.* reported that electricity tariffs for farmers in India covered 10–12% of the cost of supply [15]. Power utilities of India passed electricity subsidies worth Rs. 369 billion (∼US$7 billion) for pump irrigation in 2012 [15].

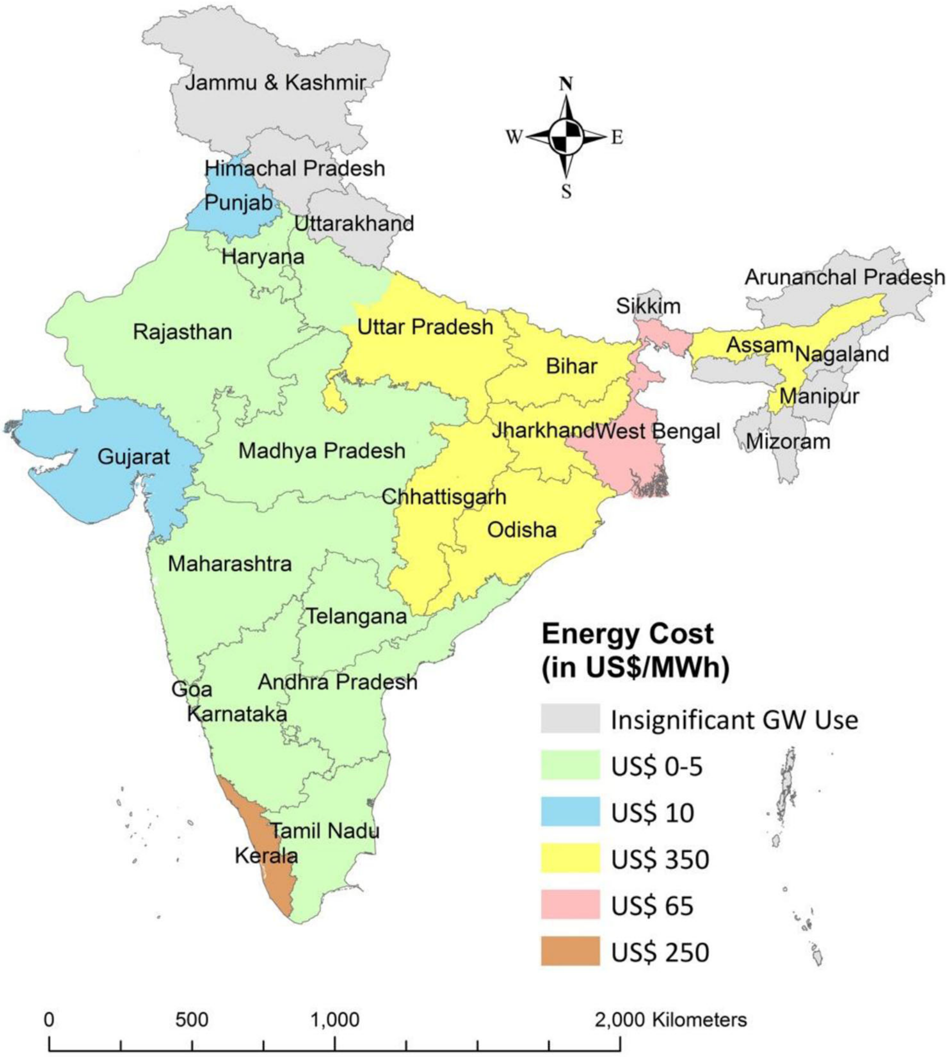


Figure 4. **Energy cost of pumping groundwater (GW) in states of India. Source: [16].**

Electricity subsidy acted as a strong driver for groundwater irrigation, especially in India's western and peninsular[1] parts [4, 5]. Figure 3 depicts the large concentration of electric pumps in western and peninsular India, which receive free or subsidized power. This region houses more than 75% of India's total electric pumps, around 11 million [12], and all of them receive unmetered and highly subsidized electricity. The energy costs of pumping in this region vary from US$0–10 per MWh[2] (see Figure 4). One of the major implications of this free or highly subsidized electricity supply has been excessive pumping. Studies have blamed unregulated and excessive pumping for the groundwater over-extraction and declining water level in the country [5, 15]. A comparison of Figures 3 and 5 shows that groundwater stress is maximum in areas where electric pumps dominate. As per India's Central Groundwater Board (CGWB),[3] 1562 (around 80%) of the 1963 semi-critical, critical and over-exploited blocks are concentrated in the states of Andhra Pradesh, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab Telangana and Tamil Nadu [17]. A Planning Commission report concluded that if the ongoing electricity–groundwater nexus continues, it is expected that 60% of India's blocks will be declared over-exploited by 2025, which will have an irreversible impact on groundwater resources [18]. The continued inefficient pumping practice acts as a twin threat to the environment: it causes the groundwater levels to decline which increases the amount of energy needed to draw the same volume of water, causing higher carbon emission [19].

Carbon accounting of India's groundwater irrigation

The contribution of groundwater pumping to carbon emissions is significant in countries such as India, US, China, Pakistan, etc., which extract large volumes of groundwater annually. Estimates from China, which is the second-largest carbon contributor globally, showed that groundwater pumping emitted 24–33 million metric tons (MMT) of

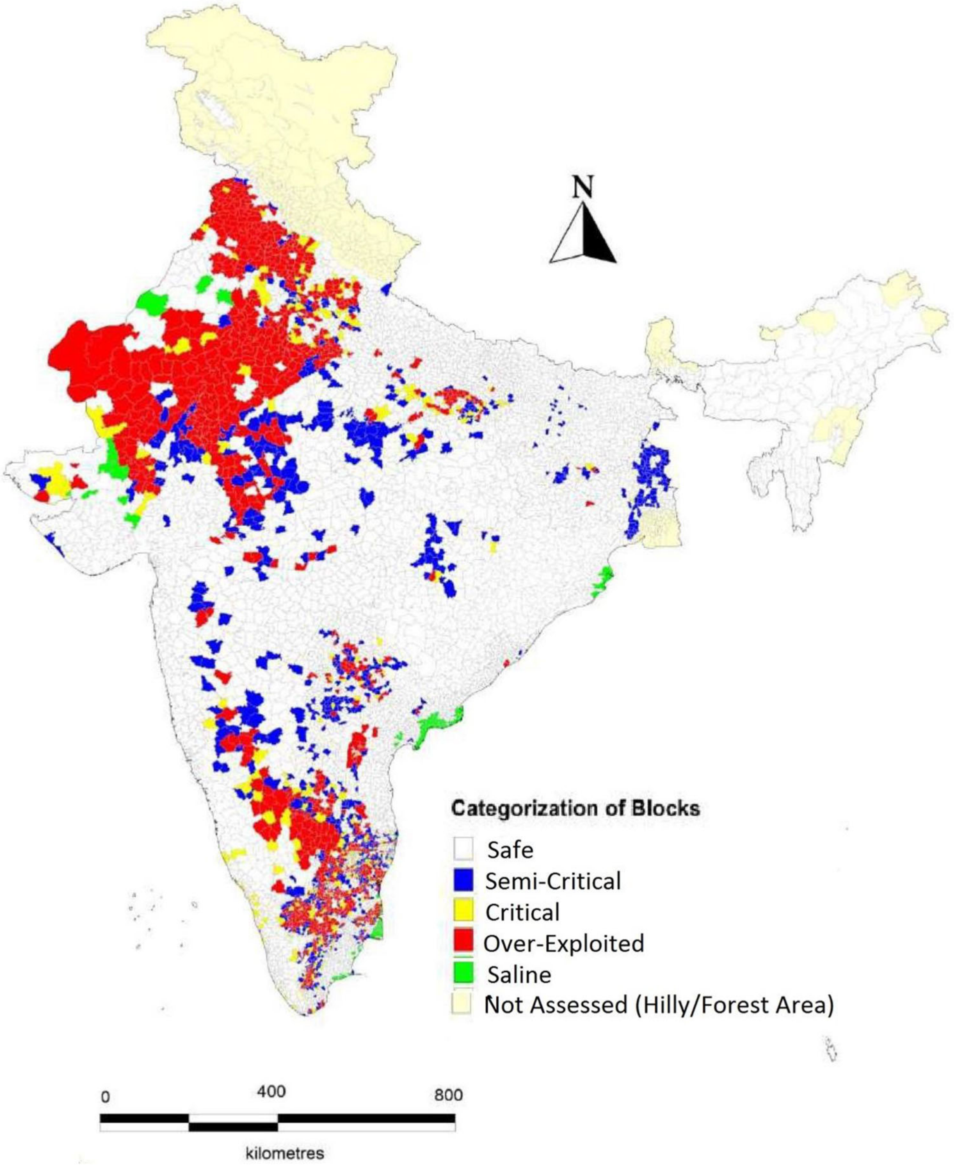


Figure 5. **Categorization of groundwater blocks. Source: [17].**

CO_2 per year (6.5–9 MMT of carbon) annually [20]. Other studies, from Iran, Mexico and Pakistan, reported respective emissions of 4.95, 4.7 and 3.8 MMT of carbon per year from groundwater irrigation. Groundwater irrigation accounted for 6% of total carbon emissions in Iran, 3.6% in Mexico and 2.2% in Pakistan [21–23]. While there has been a great deal of discussion on the water–energy nexus in India's groundwater economy [5,7,8, 14, 15], climatic concerns due to unrestricted and poorly managed groundwater pumping in the country have recently started to garner attention. Some studies have conducted national-level assessments of carbon emission from groundwater pumping, while others have focused on area- and crop-specific assessment of GHG emission from groundwater irrigation [9, 24, 25]. Nelson *et al.* [19], Shah [10] and Mishra *et al.* [26] estimated national-level carbon emissions from groundwater pumping in India. Their findings have significantly contributed to the discourse on the water–energy–climate nexus in the Indian context. However, these three studies used divergent data sources and methods to compute the carbon footprint of groundwater irrigation.

Nelson *et al.* [19] estimated that groundwater irrigation in India yielded 16 MMT of carbon per year, in 2000–01. The study used the number of GWSs and amount of irrigated area from the Third MIC (reference year 2000–01), volumetric estimates of water pumped using these GWSs from International Food Policy Research Institute's (IFPRI) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), and a variety of assumptions to assess the carbon emissions from groundwater irrigation. A study by Shah [10] estimated that India's groundwater irrigation emitted 25.17 MMT of carbon per year in 2000–01. This study first estimated the energy use from groundwater irrigation by computing the

Table 1. **Difference in average annual hours of pumping between Shah [10] and the Third Minor Irrigation Census [27].**

	Shah [10]	Third Minor Irrigation Census*
Average annual hours of pumping of Deep Tubewells	1600 hours	708 hours
Average annual hours of pumping of Shallow Tubewells – electric	900 hours	595 hours
Average annual hours of pumping of Shallow Tubewells – diesel	600 hours	
Average annual hours of pumping of Dug Wells – electric	600 hours	400 hours
Average annual hours of pumping of Dug Wells – diesel	600 hours	

Note: Third Minor Irrigation Census data available in the public domain does not have separate annual pumping hour data for electric and diesel-operated wells for each groundwater type.

product of the number of GWSs, the national average pump size in horsepower (HP) and the national average of annual pumping hours, and then converted energy use to carbon emissions using carbon emission factors from Nelson *et al.* [19]. Mishra *et al.* [26] estimated that the annual carbon emission from groundwater withdrawal varies from 8.53 to 35.73 MMT per year in the country. The study estimated carbon emissions using state-level groundwater withdrawal figures from CGWB for the year 2015 and state-level figures of GWSs from the Fourth MIC (reference year 2006–07).

The major limitation of all these studies was the various assumptions made to determine the amount of groundwater pumped, which did not reflect the variations in actual pumping behavior at different groundwater levels across the country. The main caveat of Nelson *et al.* [19] was that they only estimated water pumped from deep tubewells (DTWs) and shallow tubewells (STWs) for estimation of emissions from groundwater pumping, and did not take dugwells (DWs) into account. DWs accounted for 52% of total GWSs in the country in the year 2000–01 [27]. The study also assumed one fixed pumping depth for all DTWs and STWs in the country. Mishra *et al.* [26] improvised on Nelson *et al.*'s computing approach by using distributed pumping depths for each category of GWSs for every state, but their study did not capture the actual pumping depth of every GWS. Moreover, the latter study assumed that all GWSs in the country operate on electricity. In actuality, there were around 6.3 million diesel-operated GWSs in the country in 2006–07 [28].

Shah [10] used a single average value for HP size and annual hours of pumping for all GWSs of a similar type for carbon estimation. The study did not take into account the geographical variations in pumping hours for different cultivated crops and groundwater levels across the country. Also, on comparing average annual hours of operation used by Shah [10] with Third MIC data, the assumed values of Shah [10] were found to be quite high. The study assumed the average annual hours of operation to be 1600 hours for DTWs, whereas the average annual hours of operation of DTWs was around 700 hours as per the Third MIC in 2000–01 [27] (Table 1).

All these studies used data from the Third and Fourth MICs, conducted in 2000–01 and 2006–07 respectively, to compute carbon emissions. India's groundwater irrigation has evolved in terms of types of wells, installed pump capacity in HP, hours of operation, energy source, etc. over the last decade [29]. Changes in any of these parameters would impact the energy use and carbon emissions from groundwater pumping. This study attempts to bridge this gap by using the actual data on energy source, pump size in HP and annual hours of pumping for each of the 20.5 million GWSs in the country, from the latest Fifth MIC dataset (reference year 2013–14) for the national-level estimation of carbon emission from groundwater irrigation.

Data and methods

This section documents the data sources and methods used for the estimation of carbon emissions from groundwater irrigation. The study estimates the country-level carbon emission from groundwater pumping using the latest (Fifth MIC) dataset (reference year 2013–14) [12]. The MIC is conducted quinquennially by the Government of India, capturing information on all GWSs and surface minor schemes having a culturable command area of less than 2000 hectares. The MIC broadly classifies GWSs into three types: (a) dugwell (DW), (b) shallow tubewell (STW) and (c) deep tubewell (DTW).[4] The Fifth MIC[5] provides detailed information about the features and utilization of each of the 20.5 million GWSs for the year 2013–14. Parameters such as type of GWS, energy source (i.e. electric or diesel), HP size and annual hours of operation were obtained from the Fifth MIC for the computation of energy use and carbon emissions.

Estimation technique

The study first estimates the annual energy consumption of every electric-powered pump and diesel-operated pump separately and then aggregates them for national-level estimation of energy consumed (see Equations 1 and 2). Estimated energy use is further multiplied with carbon emission factors to obtain carbon emission from groundwater irrigation (Equation 3).

$$\text{Energy Use-e (in kWh)} = [\textstyle\sum (Pe^*He)^* 0.746]/(\eta_1{}^*T) \quad (1)$$

$$\text{Energy Use-d (in kWh)} = [\textstyle\sum(Pd^*Hd)^*0.746]/\eta_2 \quad (2)$$

$$\text{Carbon Emissions (in kg)} = \beta_e{}^* \text{ Energy Use-e} + \beta_d{}^* \text{ Energy Use-d} \quad (3)$$

Where:
Energy Use-e = Energy use from electric pumps,
P_e = Electric pump size in HP,
H_e = Hours of operation of electric pumps,
Energy Use-d = Energy use from diesel pumps,
P_d = Diesel pump size in HP,
H_d = Hours of operation of diesel pumps,
η_1 = Pump efficiency of electric pumps (30%, 40%),
η_2 = Pump efficiency of diesel pumps (20%, 30%),
T = Transmission loss (20%),
β_e = Emission factor for electric pumps (0.278 kg C per kWh), and
β_d = Emission factor for diesel pumps (0.0732 kg C per kWh).

A conversion factor of 0.746 was used to convert HP into kilowatts.

Pump efficiency and transmission loss

The Fifth MIC does not include any information on the pumping efficiency of individual pumps. Efficiencies were selected from the available information in several studies. Values for the pump efficiency of electric pumps in Indian conditions mostly vary between 30% and 40% across the studies [10, 19, 24, 26]. Rajan and Verma [29] reported that the estimates for on-farm energy consumption by electric pumps were closest to the electricity supplied to agriculture at 40% pump efficiency. Diesel pumps are considered to be less efficient than electric pumps [10, 19], and their efficiency level varied between 20% and 30% [10, 19, 30].

For this study, instead of using a deterministic approach, a range of values were considered for pump efficiency because of the high sensitivity of C emission estimates to pump efficiency [19]. Energy use and carbon emissions were computed at an efficiency of 30% and 40% for electric pumps, and at an efficiency of 20% and 30% for diesel pumps. In electric pumps, the efficiency is further reduced by transmission and distribution (T&D) losses in delivering power to pumps [10]. The T&D losses were assumed to be 20%, based on a recent estimation by the Government of India [31].

Carbon emission factor

Energy use is converted to carbon emission using emission factors. Nelson *et al.* [19] used an emission factor of 0.0732 kg C per kWh for diesel pumps and 0.4062 kg C per kWh for electric pumps. The study explained that 1 L of diesel fuel contains 0.732 kg of carbon and an energy content of approximately 10.01 kWh. So the ratio of carbon emissions to energy content for a diesel pump is 0.0732 kg C per kWh. Shah [10] and Patle *et al.* [24] used the same emission factor of 0.0732 kg C per kWh for diesel pumps. In this study, the emission factor of 0.0732 kg C per kWh is used for diesel pumps.

For electric pumps, the carbon emission factor depends on the power source used in electricity generation. Nelson *et al.* [19] and Shah [10] used all-India average carbon emissions from Indian power plants using the Carbon Monitoring for Action (CARMA) dataset, which has emission reports for all individual power plants in India. Patle *et al.* [24] used a grid emission factor of 0.2563 kg C per kWh estimated by the Central Electricity Authority (CEA), Goverment of India. The grid emission factor is the carbon emission associated with the generation of each unit of electricity. CEA estimates the values of grid emission factors annually in accordance with the CDM supervised by the UNFCCC. In this study, the average emission factor of 0.273 Kg C per kWh (~1 Kg CO_2 per kWh) reported by the CEA for the Indian grid in 2013–14 is used for the emission factor [32].

Key findings

Carbon footprint of India's groundwater irrigation

This study estimates groundwater irrigation in India to consume 198–272 billion kWh of energy annually, releasing 45.3–62.3 MMT of carbon in 2013–14 (see Table 2). Of this estimated energy consumption, electric pumps alone consume 155–206 billion kWh, equivalent to 75% of the total energy consumed in groundwater irrigation. The estimates of electricity consumption in this study are close to the CEA's figure of 152 billion

Table 2. Carbon emission from different types of Ground Water Structures in 2013–14.

		Carbon emission (in Million metric tons)
Electric – 40%	Dug Wells	11.5
Diesel – 30%	Shallow Tubewells	18.2
	Deep Tubewells	15.5
	Total Ground Water Structures	45.3
Electric – 40%	Dug Wells	12.0
Diesel – 20%	Shallow Tubewells	20.0
	Deep Tubewells	16.0
	Total Ground Water Structures	48.0
Electric – 30%	Dug Wells	15.6
Diesel – 30%	Shallow Tubewells	23.9
	Deep Tubewells	21.1
	Total Ground Water Structures	60.6
Electric – 30%	Dug Wells	15.8
Diesel – 20%	Shallow Tubewells	25.3
	Deep Tubewells	21.2
	Total Ground Water Structures	62.3

Table 3. Carbon emission from groundwater pumping by electric and diesel Ground Water Structures in 2013–14.

Pump efficiency	Carbon emission by electric Ground Water Structures (in Million metric tons)	Pump efficiency	Carbon emission by diesel Ground Water Structures (in Million metric tons)
40%	43.1	30%	3.2
30%	57.5	20%	4.8

kWh of electricity consumed by the agriculture sector in 2013–14 [33].

Tables 2 and 3 show the estimated energy consumption and carbon emission at different pump efficiencies for different types of GWSs and for GWSs using different energy sources. Some major inferences from Tables 2 and 3 are:

- Of the different types of GWSs, the annual carbon emissions range between 11.5 and 15.8 MMT for DWs, 15.5 and 21.2 MMT for DTWs, and 18.2 and 25.3MMT for STWs (Table 2). STWs, which account for 44% of total GWSs, contribute the largest amount (41%) to carbon emission from groundwater irrigation. However, the major concern is the disproportionate emission figures of DTWs, which contribute 34–35% of the total carbon emission from groundwater pumping although their share in total GWSs is only 13%. DTWs lift water from depths greater than an STW or DW, therefore consuming more energy than an STW or DW, and consequently emitting more carbon [10, 19].
- Of the total carbon emissions from groundwater pumping, roughly 95% comes from 15 million electric pumps and 5% comes from 5 million diesel pumps (Table 3). The contribution of electric pumps to carbon emission is not commensurate with their share in total GWSs. One of the reasons behind the excessive emission of electric pumps is their higher emission factor compared to diesel pumps. According to the emission factors used in this study, *ceteris paribus*, lifting water using electricity emits 3 times more carbon than using diesel oil does. The bulk of the electricity used for pumping is generated from coal, which is the dirtiest among all the energy sources used for electricity generation. Another reason behind the excessive emission is electrified DTWs, which have a high carbon footprint; 97% of DTWs run on electricity because lifting water from greater depths using diesel oil is not economically viable [34]. The nexus of electricity subsidies, depleting groundwater resources and high GHG emissions from DTWs will be discussed in detail in the section *"Declining GW levels, persistent electricity subsidies and high carbon emissions"*.
- Carbon emission numbers are highly sensitive to pump efficiency levels. Nielsen *et al.* [19] concluded that

> *'Pump efficiency has the most dramatic effect on our estimates of carbon emissions. If pumps are only 20 percent efficient instead of the 30 percent assumption of the baseline, carbon emissions increase by 50 percent over the baseline'.*

The present results corroborate the findings of Nelson et al. Table 2 shows that changing the pump efficiency value from 40% to 30% for electric pumps increases the total carbon emission from GWSs by around 33%. However, a change in the pump efficiency of diesel pumps has a lower impact on the total carbon emissions because of their lower share in GWSs. Changing pump efficiency from 30% to 20% for diesel pumps increases total carbon emissions by only 6%. If the emission figures are separated based on electric- and diesel-powered sources, a change in the pump efficiency level of diesel pumps from 30% to 20% enhances the emission from diesel-powered structures from 3.2 MMT to 4.8 MMT, a sharp increase of nearly 50% (see Table 3).

Spatial variations in India's carbon emissions from groundwater irrigation

Spatial analysis shows the bulk of India's carbon emissions from groundwater irrigation comes from the western and peninsular India (see Figures 6 and 7). The states of Punjab, Rajasthan, Telangana, Maharashtra, Andhra Pradesh and Tamil Nadu are the prime perpetrators. Together these states emit 28.9 MMT of carbon,[6] which accounts for 65% of the country's carbon emissions from groundwater pumping. States of the Himalayan region and the

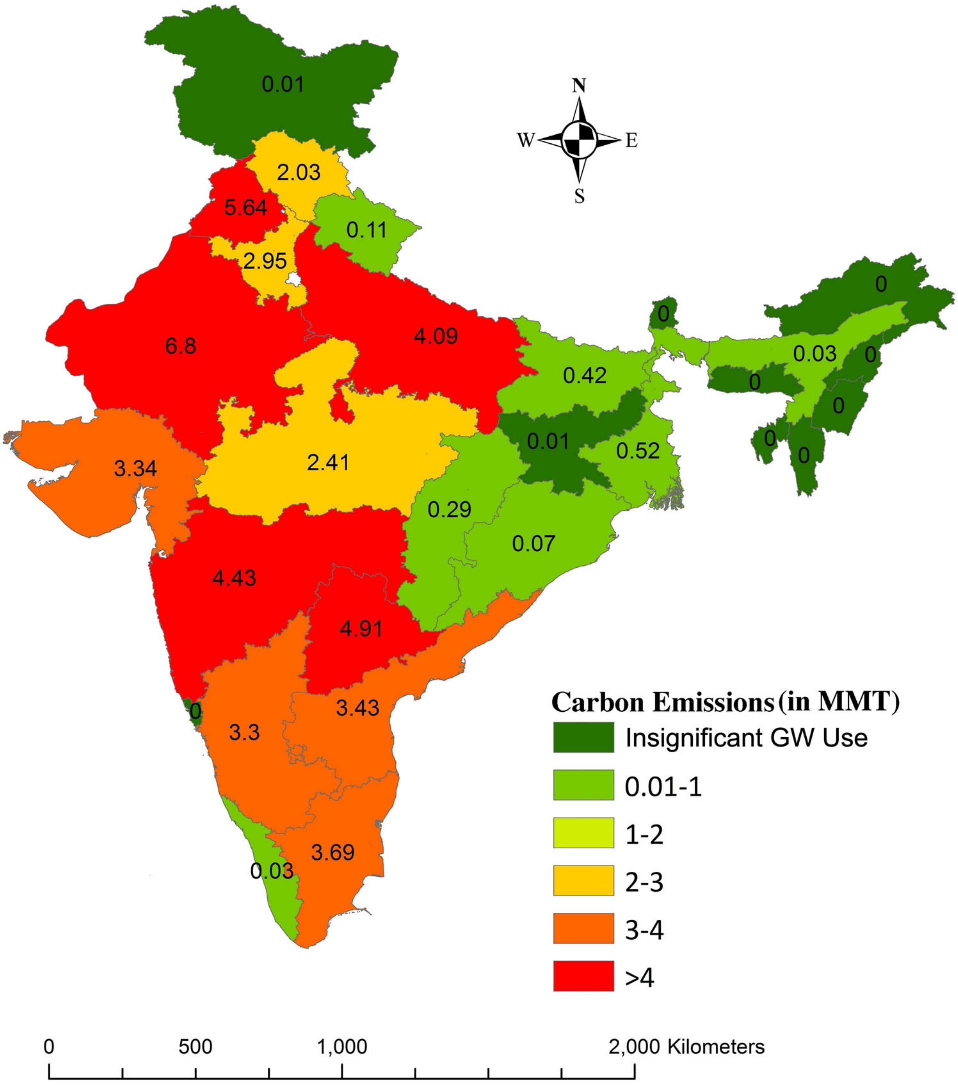


Figure 6. **Estimated state-wise carbon emission from groundwater (GW) irrigation.**

eastern region[7] are the lowest carbon emitters because of their low utilization of groundwater resources (see Figure 6). The Himalayan region's agro-ecosystem is largely dependent on rainfall, and the region fulfills its irrigation requirements from springs and traditional water management practices, not from groundwater [35]. The Eastern region has alluvial aquifers with shallow groundwater levels. Also, it is dominated by diesel pumps, and withdraws less groundwater because of the high cost of pumping using diesel [16, 35, 36].

In the spatial analysis of the carbon emissions from groundwater irrigation, 27 districts stood out as hotspots of the groundwater–energy–climate nexus in India. The hotspots in these districts result from an overlap of excess carbon emission and stressed groundwater conditions. Each of these districts consumes more than 1 billion kWh of energy and emits more than 0.3 MMT of carbon annually. It is all the more distressing that groundwater situation is precarious in these districts. Nineteen[8] of these 27 districts are in the over-exploited stage of groundwater development and eight[9] are in semi-critical and critical stages as per the CGWB report [17]. All 27 districts are located in the western and peninsular region of India (see Figure 7). These 27 districts together emit 15.5 MMT of carbon annually, which is approximately 34% of India's total emission from groundwater pumping across the 674 districts in the country. The share of these districts in total carbon emissions is not in keeping with their share in terms of groundwater-irrigated area or GWSs. These 27 districts account for only 12% of the total groundwater-irrigated area and 14% of the total GWSs in the country.

Discussion

The changing carbon footprint of India's groundwater irrigation

To map the temporal changes in carbon emissions from groundwater irrigation, estimates from this study were compared with Shah's carbon

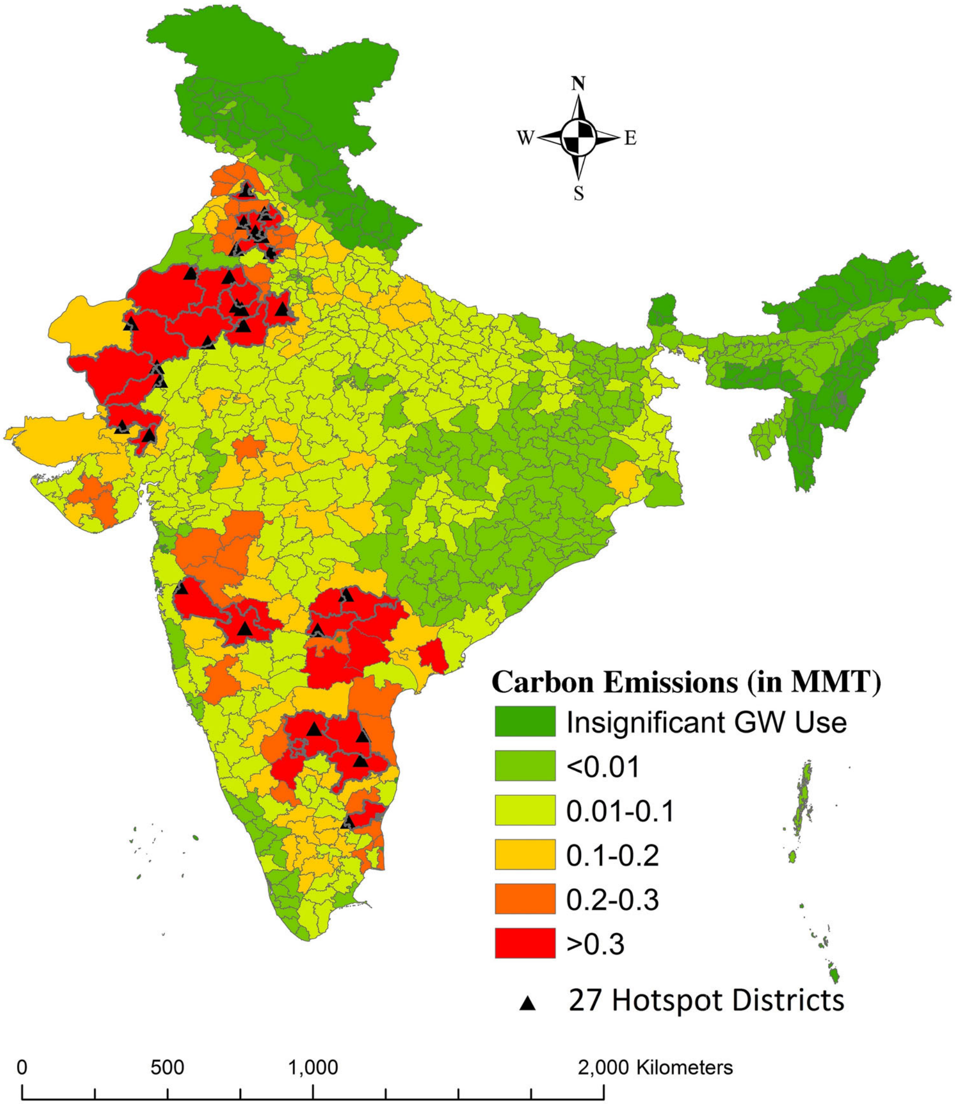


Figure 7. **Estimated district-wise carbon emission from groundwater irrigation.**

Table 4. **Comparison of carbon emission from groundwater wells between 2000 and 2013.**

	2000		2013	
	Number (in millions)	Carbon emission (in Million metric tons)	Number (in millions)	Carbon emission (in Million metric tons)
Electric – Deep Tubewells (a)	0.53	3.39	2.54	15.35
Electric – Shallow Tubewells (b)	3.26	8.00	4.90	16.10
Electric – Dug Wells (c)	6.15	10.60	7.78	11.00
Total electric Ground Water Structures (d) (a + b+c)	9.94	21.99	15.22	42.45
Diesel – Deep Tubewells (d)	–	–	0.08	0.15
Diesel – Shallow Tubewells (e)	4.37	2.40	4.10	2.20
Diesel – Dug Wells (f)	1.99	0.78	1.10	0.50
Total diesel Ground Water Structures (d + e+f)	6.36	3.18	5.28	2.85
Total Ground Water Structures (a + b+c + d+e + f)	16.3	25.20	20.5	45.3

Source: Data for the year 2000 has been sourced from Shah [9]. Data for C emission in 2013 has been estimated using the Fifth Minor Irrigation Census.

estimates [10]. Unlike Nelson *et al.* [19] and Mishra [26], Shah [10] used a technique similar to the method followed in this study, making these two studies fairly comparable. Comparing their estimates at the same pump efficiency shows that carbon emission from groundwater pumping has almost doubled in 13 years – from 25.2 MMT in 2000 to 45.3 MMT in 2013 (see Table 4). The quantum of increase in carbon emissions is still conservative because the emission factor for electric pumps used in this study is 33% less than that of Shah [10]. While the volume of groundwater use in irrigation increased by 20% – from 190 to 230 km^3 between 2000 and 2013 – the carbon emission from groundwater pumping has almost doubled in the same period. This disproportionate increase in carbon emission may be a result of the combined effects of factors such as the increasing number of DTWs due to declining groundwater levels, the increase in pumping hours and average pump capacity, and a shift from diesel to electric pumps. One conspicuous change in this period has been the staggering increase in the number of electrified DTWs – from 0.5 million in 2000 to 2.5 million in 2013. According to Shah [10], 0.5 million electrified DTWs emitted 3.4 MMT of carbon in 2000 (13% of total carbon emission), whereas in 2013, 2.5 million electrified DTWs emitted ~16 MMT of carbon (~35% of total carbon emissions). This increase in the number of electrified DTWs has contributed significantly to India's ballooning carbon emissions over the period.

Beyond electrified DTWs, there was an overall increase in the adoption of electric pumps between 2000 and 2013 due to the continued availability of free or subsidized power. While the total number of GWSs increased by 4.2 million between 2000 and 2013 (see Table 4), the number of electric-powered GWSs increased by 5.2 million – from 10 million in 2000 to 15.2 million in 2013. This means that, even assuming all 4.2 million newly added GWSs are electrified, around 1 million GWSs shifted their energy source from diesel oil to electricity in the period. Both the addition of new electric GWSs and the replacement of diesel pumps with electric pumps contributed to the increase in emission numbers, as electric pumps emit 3 times more carbon than diesel pumps do.

Shah [10], Nelson *et al*. [19] and Mishra [26] stated that groundwater irrigation contributed 6%, 4%, and 2–7%, respectively, of India's total carbon emissions from all sources. As per the present study's estimates, groundwater irrigation accounted for roughly 8–11% of country's total carbon emissions (i.e. 573 MMT of carbon) in 2013–14 [37]. The growing share of groundwater irrigation in the country's total carbon emissions is a concern, and it calls for attention toward controlling the energy used in pumping and over-extraction of groundwater to limit carbon emissions.

Comparison with other major groundwater-using countries

National-level estimates of carbon emission from groundwater irrigation, to the authors' knowledge, are available for only China, Pakistan, Iran and Mexico [20–23]. The average carbon emitted per cubic meter of groundwater extracted in Pakistan, Iran and China was 80, 100.9 and 110–150 g, respectively, in 2010 [21, 23, 24]. India emitted 45.3–62.3 MMT of carbon to withdraw around 230 km^3 of groundwater for irrigation in 2013–14, which means every cubic meter of groundwater lifted for irrigation emitted 200–271 g of carbon, on average. The average carbon emission of India is much higher than that of Iran, Pakistan or China. This difference could be partly due to methodological differences in estimation and partly due to factors like the high presence of electric-powered GWSs, unregulated pumping due to the supply of highly subsidized electricity, and declining groundwater levels. For instance, the wide difference in average carbon emission per cubic meter between India and Iran is largely due to a difference in the emission factors used for electric pumps. Karimi [28] used an emission factor of 0.17 kg C per kWh for electric pumps, which is almost 40% lower than that used for India (0.278 kg C per kWh). In a scenario for Iran using the same emission factor as India, Iran's average carbon emission would increase to 150 g per cubic meter.

The main factor behind Pakistan's lower average carbon emission compared to India is the dominance of diesel pumps for groundwater irrigation in the country: 80% of pumps in Pakistan operate on diesel oil. Poor penetration of electricity in rural areas and the absence of free or subsidized electricity for irrigation has made groundwater irrigation in Pakistan dependent on high-cost diesel pumping [30]. This dependence on diesel pumps for groundwater extraction impacts carbon emissions in two ways: first, the high cost of lifting water inhibits unregulated pumping, which keeps the energy consumption and carbon emission low; second, a diesel pump pollutes less than does an electric pump, as the emission factor for a diesel pump is one fourth that of an electric pump. In China, pumping is more dependent on electric pumps [20]. The supply of electricity for irrigation is metered and there are no or marginal subsidies on electricity supply to agriculture [20]. The average energy cost of groundwater pumping is US $250 per MWh in Pakistan [22] and US $87–91 per MWh in China [7, 38, 39].[10] In contrast, groundwater pumping in the majority of India is, on average, free or nearly free (i.e. US $0–10) [22]. There is a strong possibility that the high environmental cost of abstracting groundwater prevalent in India is deeply rooted in its subsidized, unmetered supply of electricity to agriculture.

Declining GW levels, persistent electricity subsidies and high carbon emissions

The rate of groundwater depletion in India is the highest in the world [40]. CGWB reported that

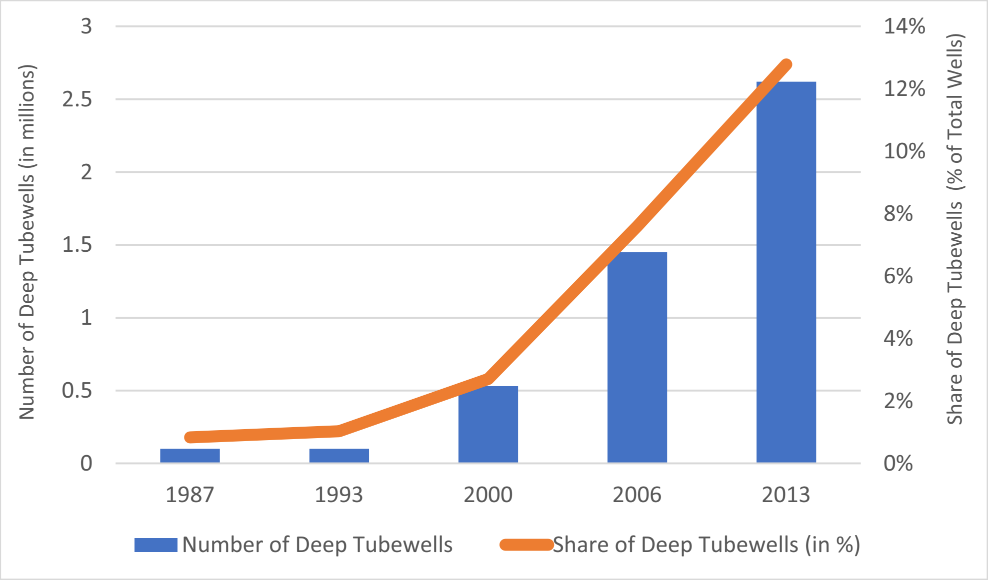


Figure 8. **Increasing number of Deep Tubewells between 1987 and 2013. Source: [29].**

8785 (around 61%) of the total 14,394 monitoring wells in the country recorded a decline in groundwater levels between 2007 and 2017 [41]. The report noted that the greatest decline in groundwater level was observed in the states of Rajasthan, Punjab, Haryana, Gujarat, Telangana and Maharashtra. Rodell and Velcogn [42] reported rapid groundwater depletion in the northwestern Indian states of Punjab, Rajasthan and Haryana.

Excess abstraction of groundwater for irrigation has been proposed as the main reason for the depletion of groundwater [5, 41]. Electricity subsidies are suspected to play a central role in the over-extraction and depletion of groundwater [5, 15]. A World Bank study reported that free or highly subsidized power has allowed farmers to persistently deplete groundwater by operating their wells at far too low groundwater levels [43]. The meteoric rise in the number of DTWs in the country has been in response to lowering water tables and has been incentivized by the energy subsidies [34, 44]. Figure 8 shows the increasing number of DTWs in the last three decades and their spread across the region. As per the Fifth MIC, 98% of the 2.6 million DTWs are operating on subsidized electricity, and around 94% of them are operating in the western and peninsular states, where the maximum decline in groundwater has taken place according to the CGWB (see Figure 9).

Deeper wells require more energy to pump the same volume of water and eventually cause greater carbon emissions [15, 25]. Empirical evidence from Haryana and Andhra Pradesh shows that each meter of increased well depth increased GHG emissions from pumping by 4.37% and 6% in the states of Haryana and Andhra Pradesh, respectively [45]. The findings of this study show the large contribution of DTWs to carbon emission. According to the present estimates, one electric-powered DTW emits on average 6.3–8.5 metric tonnes of carbon per year, which is twice the carbon emitted by an electric-powered STW, and 4 times the carbon emitted by an electric-powered DW at 40% pump efficiency. Even in the 27 districts that are hotspots of the groundwater–energy–climate nexus, DTWs are pivotal to groundwater irrigation. The number of DTWs is exceptionally high in these districts: 0.9 million, which is 30% of their total GWSs. Together these 27 districts account for 36% of the total DTWs in the country. Over-exploited aquifers and a supply of subsidized electricity are the reasons for the mushrooming of DTWs in these districts.

Mitigating carbon emissions from groundwater irrigation

Taming the groundwater–energy nexus is key to reducing carbon emissions from Indian irrigation [10]. Metering each GWS and charging farmers the actual cost of electricity consumed appears to be the best solution to unlock this nexus. However, the socio-political repercussions of imposing any such policy will be a formidable challenge [7, 14]. Previous studies have suggested several other measures such as rationing the electricity supply, adopting micro-irrigation technologies, improving pump efficiency, improving on-farm irrigation efficiency by leveling and proper irrigation scheduling, and artificially managing the aquifer recharge, to make groundwater

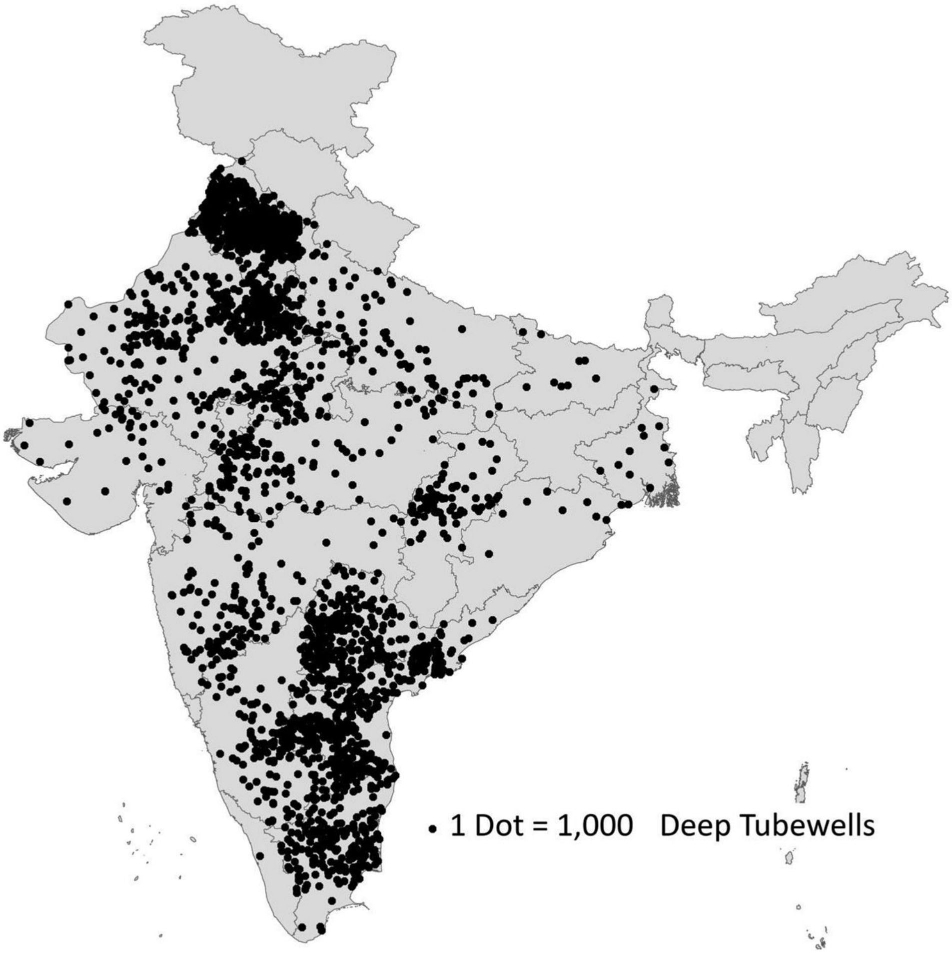


Figure 9. **Distribution of Deep Tube wells in India, Source: [12].**

irrigation more energy and carbon efficient [10, 19, 21, 23, 24, 26]. Solar-powered irrigation systems are another clean and nearly zero-emission solution to India's woes of growing carbon emissions [16]. However, the access to free solar power during daytime might accelerate groundwater use and further deepen the groundwater crisis. Shah *et al.* [16] argued that solar irrigation pumps should be carefully promoted using models that simultaneously provide green irrigation solutions and regulate the groundwater demand. The Government of India announced a new solar irrigation policy – *Kisan Urja Suraksha evam Utthan Mahabhiyan* (KUSUM) – to promote solar-powered irrigation in 2018. One component of KUSUM is a plan to solarize one million grid-connected irrigation pumps and give farmers the option to sell any surplus solar power to utilities. This power-buyback option under KUSUM incentivizes farmers to economize their energy–groundwater consumption and reduce the carbon footprint of India's groundwater irrigation.

From this study, two keys to curb emissions from groundwater pumping can be inferred: first, by improving the efficiency level of pumps; and, second, by arresting the declining trend of groundwater levels.

Carbon emission is highly sensitive to pump efficiency. As per the present study's estimation, for every 1% increase in pump efficiency, carbon emission declines by 1 MMT annually. Studies have suggested that improving pump efficiency can significantly reduce energy consumption and thereby the carbon emissions from groundwater irrigation [19, 21]. A plausible way to reduce the energy consumed for pumping would be the introduction of new, efficient pumps, and replacing the conventional pumps with highly efficient pumps. The Ministry of Power, under its Agriculture Demand Side Management (AgDSM), launched the National Energy Efficient Agriculture Pumps Programme (NEEAPP) in 2016 to replace 0.2 million older generation agricultural pumps with next-generation energy-efficient pumps by 2019, which is projected to save 50 billion kWh of energy every year [46]. Scaling up this program in future could be a potential tool to curtail carbon emissions.

Arresting the declining groundwater levels will require a proactive mix of groundwater supply and demand management strategies. Groundwater demand management measures such as rationing the agricultural power supply could curtail energy and groundwater usage. Gujarat has demonstrated rationing of the agricultural power supply with considerable success, forcing farmers to use energy and groundwater efficiently [7, 10]. However, standalone demand management practices are not sufficient. Reversing this trend by increasing aquifer recharge is one of the possible ways to stop farmers from chasing the water levels [10, 47]. Shah [10] suggested that

> *If a fraction of the resources and energies that India expends on building new surface reservoirs and canal systems is directed to promoting large-scale groundwater recharge in her groundwater hotspot areas of western and peninsular India, the country can not only greatly reduce its GHG emissions from pumping but also restore the resilience of its aquifers to protect agriculture from heightened hydro-climatic variability.*

Adoption of aquifer recharge strategies through farmer-driven decentralized movements has proved effective in enhancing aquifer storage and bringing up the declining groundwater levels in hard-rock regions of Saurashtra [48]. Aquifer recharge through community participation has been identified as an intervention for sustainable groundwater management under the recently launched groundwater management scheme of the Government of India – *Atal Bhujal Yojana* – in over-exploited western and peninsular India [49]. Considering the inexorable groundwater stress in the country, *Atal Bhujal Yojana* will be a major step taken to improve the situation of declining groundwater levels. The scheme envisages strengthening participatory groundwater management and bringing about behavioral changes at the community level for sustainable groundwater resource management in 78 groundwater-critical districts of western and southern India. Reversing the trend of declining groundwater levels could halt the increasing carbon footprint of growing groundwater irrigation. Nonetheless, this study recommends that any strategy (KUSUM, NEEAPP or *Atal Bhujal Yojana*) focusing on uncoupling the groundwater–energy–climate nexus should prioritize its interventions in the 27 districts identified by this study as hotbeds of carbon emission from groundwater pumping.

Conclusion

In summary, this study estimated that groundwater irrigation emits 45.3–62.3 MMT of carbon annually. Of this amount, 35% is contributed by the 2.6 million DTWs, which is disproportionately high considering their 13% share in total GWSs. The study revealed that carbon emission from groundwater irrigation almost doubled between 2000 and 2013. The increasing number of electrified DTWs are largely to blame for the soaring carbon emissions from groundwater irrigation, whose number grew at a Compound Annual Growth Rate of 14% in the same period. With groundwater levels steadily declining, if the count of DTWs continues to increase even at half the present rate (CAGR of ∼7%), then in another 10 years the resultant carbon emissions from DTWs will be doubled (30–40 MMT of C per year). This is a conservative estimate but the emission figures are, nevertheless, alarming.

The notable share of groundwater irrigation in India's carbon emissions is a warning bell to indicate the necessity for groundwater management that addresses not just groundwater sustainability but the complete water–energy–climate nexus. A combination of policies to optimize energy and water use in agriculture is required to respond to this hydro-climatic challenge. Findings of the study revealed that improving the overall pumping efficiency by using more efficient pumps and arresting the growth of DTWs through concerted efforts to reverse groundwater levels could be two main ways to curb carbon emissions.

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Notes

1. Western and Peninsular India includes the states of Punjab, Haryana, Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Telangana, Andhra Pradesh, Karnataka, Kerala, Tamil Nadu and Goa and parts of Western Uttar Pradesh.
2. Energy costs of groundwater pumping in major states of India have been sourced from Shah *et al.* [2018] [15]. The study sourced farm power tariffs from the different state electricity distribution companies and newspaper articles for the year 2017. It estimated cost of diesel pumping using the diesel prices in May 2018.
3. India's Central Groundwater Board monitors groundwater fluctuation through more than 50,000 observation wells. CGWB assesses groundwater resources in units (i.e. blocks). These blocks are categorized in terms of

groundwater development as safe, semi-critical, critical and over-exploited.

4. A DW is an open well that operates at a depth of less than 20 m. An STW is a bore hole drilled into the ground, the depth of which does not exceed 70 m. A DTW extends to a depth of 70 m or more.
5. The Ministry of Water Resources (MoWR), of the Government of India shared the (provisional) data with International Water Management Institute (IWMI). IWMI-Tata Program (ITP) researchers used the data to prepare an analytical report and shared it with MoWR (ITP 2017). The official report of the Fifth MIC was published on the MoWR website in December 2017.
6. For spatial analysis, carbon emission has been conservatively estimated at maximum pump efficiency (electric pump = 40% and diesel pump = 30%).
7. The Himalayan region consists of the hilly and mountainous states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Manipur, Mizoram, Nagaland, Tripura and Arunachal Pradesh. The eastern region comprises the states of Bihar, Odisha, Assam, West Bengal, Jharkhand and Chhattisgarh.
8. The 19 groundwater-overexploited districts are Fatehgarh Sahib, Barnala, Jalandhar, Patiala and Sangrur in Punjab; Banaskantha and Mehsana in Gujarat; Fatehabad and Jind in Haryana; and Alwar, Bikaner, Barmer, Churu, Jalor, Jaipur, Jhunjhunu, Jodhpur, Nagaur and Sikar in Rajasthan.
9. Of these eight districts, two (Villupuram in Tamil Nadu and Anantapur in Andhra Pradesh) are in the semi-critical stage and six (Chittoor and Kadapa in Andhra Pradesh; Karimnagar and Medak in Telanagana; Pune and Solapur in Maharashtra) are in the critical groundwater stage.
10. Shah *et al.* [6] mentioned that farmers paid electricity prices of US $87.5 per MWh in Hanan province of China. Chen *et al.* [37] estimated the total energy consumption for groundwater pumping in North China to be 13.67 billion kWh in 2014, and Qiu *et al.* [38] estimated the energy cost of groundwater pumping in the North China Plain to be US $1.25 billion in 2013. Using these figures, the approximate energy cost of pumping in North China comes out at US $91 per MWh.

Disclosure statement

No potential conflict of interest was reported by the authors.

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