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ORIGINAL ARTICLE

Understanding energy and groundwater irrigation nexus for sustainability over a highly irrigated ecosystem of north western India

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Abstract
This paper examines various features of energy and groundwater irrigation nexus in a highly irrigated ecosystem of north western India. The study is based both on primary and secondary sources of data. Electric tube-wells account for about 72 percent of the total tube-wells population and consume about 40 percent of the total electricity consumption. Power subsidies account approximately 46 percent of the total subsidies disbursed which stimulate the groundwater development. The area irrigated by means of tube-wells has enlarged from 22 to 58 percent. Rice and sugarcane crops are the key consumers of energy both in terms of average energy consumption as well as per hectare of cultivated land. The average use factor of tube-wells is about 7.5 times high during *kharif* than in *rabi* season. Farmers have yielded high economic productivity under all crops with the exception of rice than other states such as Uttar Pradesh, Bihar and Gujarat.

Keywords Energy · Groundwater · Irrigation · Productivity · Farmers · Perception · India

Introduction

Of late, groundwater irrigation has prospered as a key resource for assured supply of water to farmers. Its smoothness and flexibility in relation to other sources of irrigation has resulted in an increasing groundwater withdrawal (Srinivasan and Kulkarni 2014). About 75 percent of rural population and more than 50 percent of the total population in India, directly or indirectly depend on groundwater for their livelihoods (Sharma et al. 2004). Groundwater irrigation infrastructure contributes over 10 percent of India's gross domestic product and 60 percent of irrigation requirements (Shah 2007; Scott and Sharma 2009). It accounts for about 70–80 percent of the farm value output, which is 1.2–3.0 times higher than those of canal irrigation (Dhawan 1995; Sharma et al. 2004). Surprisingly, only 58 percent of the identified groundwater resources have been developed till now, reflecting much scope for their development in India (Shankar et al. 2011). Groundwater development is modest in eastern region (less than 50 percent), whereas its development is more than 150 percent in the major food grains producing states of Punjab, Haryana and Uttar Pradesh. Currently, 972 out of 6881 blocks (groundwater observation units) in India are overexploited (CGWB 2017). In the north western states, which have been an epicenter of the Green Revolution like Haryana and Punjab, groundwater use exceeds natural recharge by 49 percent and 35 percent, respectively (CGWB 2017). In the state of Haryana, Singh and Kasana (2017) have used the data of 893 monitoring wells and observed a decreasing trend in groundwater level with decline of about 32 cm annuum^{-1}. India's groundwater consumption dramatically increased from 50 in 1970 to 250 km^3 in 2010 (Shah 2014). Of 250 km^3, more than 90 percent is used for irrigation alone. Overall, the groundwater irrigated area increased from 12 million ha to 40 million ha in between 1970 and 2010 (MoSPI 2015). Due to the rapid growth in groundwater irrigated area, there has been a sharp growth in the electricity use in the agriculture sector, especially since the 1980s. The abstraction of groundwater for irrigation is closely coupled with access to subsidized or free electricity in the country (Rajan and Ghosh 2019; Sarkar 2020). Supply of free electricity has led to the

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perverse groundwater energy nexus in the country. Electricity consumption in agriculture has increased approximately 54 times from 1969 to 2016 in India (Dharmadhikari et al. 2018). The running of tube-wells account for about one-third of the India's total electricity consumption, which varies from 27 to 45 percent in different states of India (Sharma et al. 2004; Scott and Shah 2004; Kumar et al. 2013). Currently, there are nearly 20 million operational groundwater wells in India, in which approximately 70 percent are relying on electricity (Dharmadhikari et al. 2018). Accordingly, both energy and groundwater development are inextricably linked because groundwater withdrawal through tube-wells rests directly on energy supply. This association between the two is frequently known as energy groundwater irrigation nexus, which has significantly improved agricultural productivity, livelihoods and food security as well as the social and economic development (Shah et al. 2003; Dubash 2007).

Setting up the argument

Energy use for groundwater withdrawals has been a subject of discussion since the early 1970s. All state electricity boards have been charging their tube-well owners based on meter consumption, but, due to a range of administrative issues (rampant tempering of meters, under-billing and dishonesty at the level of meter readers, maintaining an army of meter readers etc.), this has been changed to a flat tariff in the early 1980s (Shah et al. 2007). These flat tariffs have remained perpetually low over the years on account of an electoral tool of appeasement by many state governments, incurring huge losses to state electricity boards to the tune of Rs. 260 billion (Dubash and Rajan 2001; Sharma et al. 2004). Energy subsidies in farm sector on account of flat tariffs in the country stand at Rs. 45,561 crores (Mukherji and Das 2012). Government generally provides subsidies on electricity for pumping wells used for irrigation but there are huge environmental costs, especially groundwater exploitation (Jessoe and Badiani 2019); Singh et al. 2021). (Barik et al. 2017) has witnessed a negative correlation between groundwater level and energy consumption. Any further subsidies in energy supply for withdrawal of groundwater for crop production would result in its over-exploitation to 30 percent, which will subsequently threaten the groundwater resource sustainability (Kumar 2007; Kondepati 2011). Electricity subsidies have contributed significantly in this as subsidies incentivise increased groundwater extraction and shifting toward more water intensive cropping (Badiani and Jessoe 2013; Sarkar 2020). Likewise, low cost of pumps and massive investment in rural electrification will enhance the energy consumption and use of groundwater (Kumar 2005; Mukherji et al. 2012). Recently, Sidhu et al. (2020) have found that flawed tariff policies, in conjunction with rampant subsidies have caused extensive groundwater pumping leading to rapid decline in groundwater level in different regions as well as causing huge financial losses to governments. Estimated average annual energy use per hectare of groundwater irrigated area has been found as high as 6,997 kWh for Karnataka, 5,863 kWh for Andhra Pradesh, 5,630 kWh for Tamilnadu, and 5,297 kWh for Gujarat (Shah 2009). Tason et al. (2020) have reported similar results with respect to Spanish irrigated agriculture in the period 1950–2017.

Implementation of a flat tariff on energy for groundwater pumping does not reflect the actual unit of consumption. Therefore, it has been universally written off as inefficient, irrational and responsible for wastage of both energy as well as groundwater resources (Saleth 1997; Kumar and Singh 2001; Sharma et al. 2004; Scott and Shah 2004; Mukherji et al. 2009; Kumar et al. 2011). Also, the quality of energy supply in terms of voltage, interruptions, and timing will decline quickly, resulting in higher reparation costs on farmers (World Bank 2001; Monari 2002). At the same time, a low flat tariff with subsidy has been criticized from an equity perspective. It has been frequently alleged that most of subsidy benefits are percolated to large farmers as they have higher share of the tube-wells fitted with electricity (Kumar and Singh 2001; World Bank 2002). The large farmers on an average receive energy subsidy to the tune of Rs. 29,710 per year, which is almost 10 times the subsidy received by a marginal farmer (Howes and Murgai 2003). Conversely, flat tariff has been advocated by farmers on account of higher water pumping rate without tension of billing, no need of pilferage, no need of meter tempering and groundwater selling to neighboring farmers at low rates (Qureshi et al. 2003).

Meanwhile, controlled pricing of energy on pro-rata (metering) basis has been increasingly advocated as a tool of management for energy and overdraft of groundwater (Dubash 2007; Scott and Sharma 2009). The energy consumption is nearly 35 percent below the estimates based on pump metering, thereby improving the quality of power supply (World Bank 2001; Mukherji et al. 2009). A judicious management of energy and groundwater revolves around metering of tube-wells, energy rationing using prepaid meters, denial of energy connections in regions which have experienced groundwater overdraft and restricting the permits for installation of new pumps (Shah et al. 2004a; Shah et al. 2004b; Dubash 2007; Malik 2009; Kondepati 2011; Kumar et al. 2011). An enhancement in energy tariffs on pro-rata basis can be introduced to promote efficiency, equity and sustainability in groundwater use (Saleth 1997; Shah et al. 2003; Kumar et al. 2011). But on the other hand, a complete withdrawal of energy (electricity) subsidy (Fig. 1) and metering on actual consumption basis will destroy the agricultural activities in India (Kumar et al. 2010; Mukherji et al. 2012).

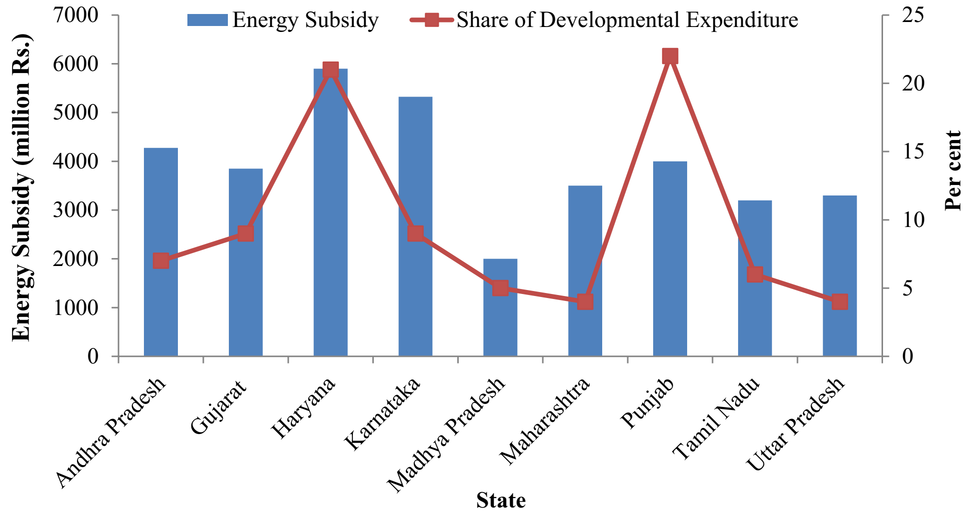

Fig. 1 Energy subsidy to irrigation sector and its percentage share to developmental expenditure in different states of India during 2014–15. Source: Dabadge et al. (2018)

While, the arguments made above are valid for the whole of India, however, the studies pertaining to association among energy and groundwater use in agricultural sector with respect to the state of Haryana are rather scanty. This study, therefore, examines the energy and groundwater irrigation nexus in the state, which enjoys the enormous energy subsidies. The paper also examines the overall impact of changing pricing policy on groundwater development, use factor, physical productivity and net returns from crops and perception of farmers regarding energy supply and its pricing. The results of this study will provide a feedback to energy and groundwater managers in formulation of suitable policies for the judicious energy use and sustainable development of groundwater resources.

Materials and methods

Study area

The state of Haryana, located in north western part of India, lies between 27° 39′ and 30° 55′ N latitudes to 74° 28′ and 77° 36′ E longitudes (Fig. 2). It occupies approximately 44,212 km^2 area (1.4 percent of country's total geographical area). A large proportion of state is irrigated by the two main surface irrigation systems i.e., western Yamuna canal and Bhakra canal systems. In spite of this, area under tube-wells irrigation is comparatively very high than area served by canal systems. Farmers extract huge amount of groundwater through tube-wells to fulfill the needs of irrigation to support its agrarian economy. Therefore, overall groundwater development level in the state is about 133 percent (CGWB 2013). The depth to the groundwater level varies from less than 4 m to as deep as 65 m and about 86 percent of the districts are over-exploited or critical. The long-term average fall of groundwater levels has been witnessed to the tune of 20 cm per year.

The energy and groundwater irrigation nexus are of high importance to Haryana because energy subsidy has been used as a tool to encourage the groundwater development. Irrigation sector uses approximately 40 percent of total energy consumption on account of lowest energy tariffs for its consumers across India. Energy subsidies for irrigation sector nearly amounts to 46 percent of the total subsidies (Sharma et al. 2015). These enormous subsidies have led to a booming of groundwater withdrawals with depleted aquifers and exploitation of energy economy. Given the heavy subsidies on energy, the state electricity board has faced substantial losses, adversely affecting its overall supply and quality of life in rural as well as urban areas. Table 1 summarizes the energy and groundwater irrigation scenario in Haryana and other states of India.

Data sources and methods

The present study is based on both primary and secondary sources of data. Data have been collected in 2015–16 via individual respondent face-to-face interviews using a pre-tested standardized questionnaire in order to evaluate the energy and groundwater irrigation nexus. The respondents (farmers) in this study have been selected using multi-stage sampling techniques as outlined in Table 2. Since all respondents have cooperated and enthusiastically participated in the survey, the response rate has been found extremely high (100 percent). In comparison to postal and other forms of surveys, face-to-face interview surveys yield higher response rates (Bowling 2005). Filling out the questionnaire with each respondent has took about 30 min. Farmers have been interviewed in their fields much of the time. On-the-ground conversations have allowed them to publicly share their thoughts, beliefs, and perspectives

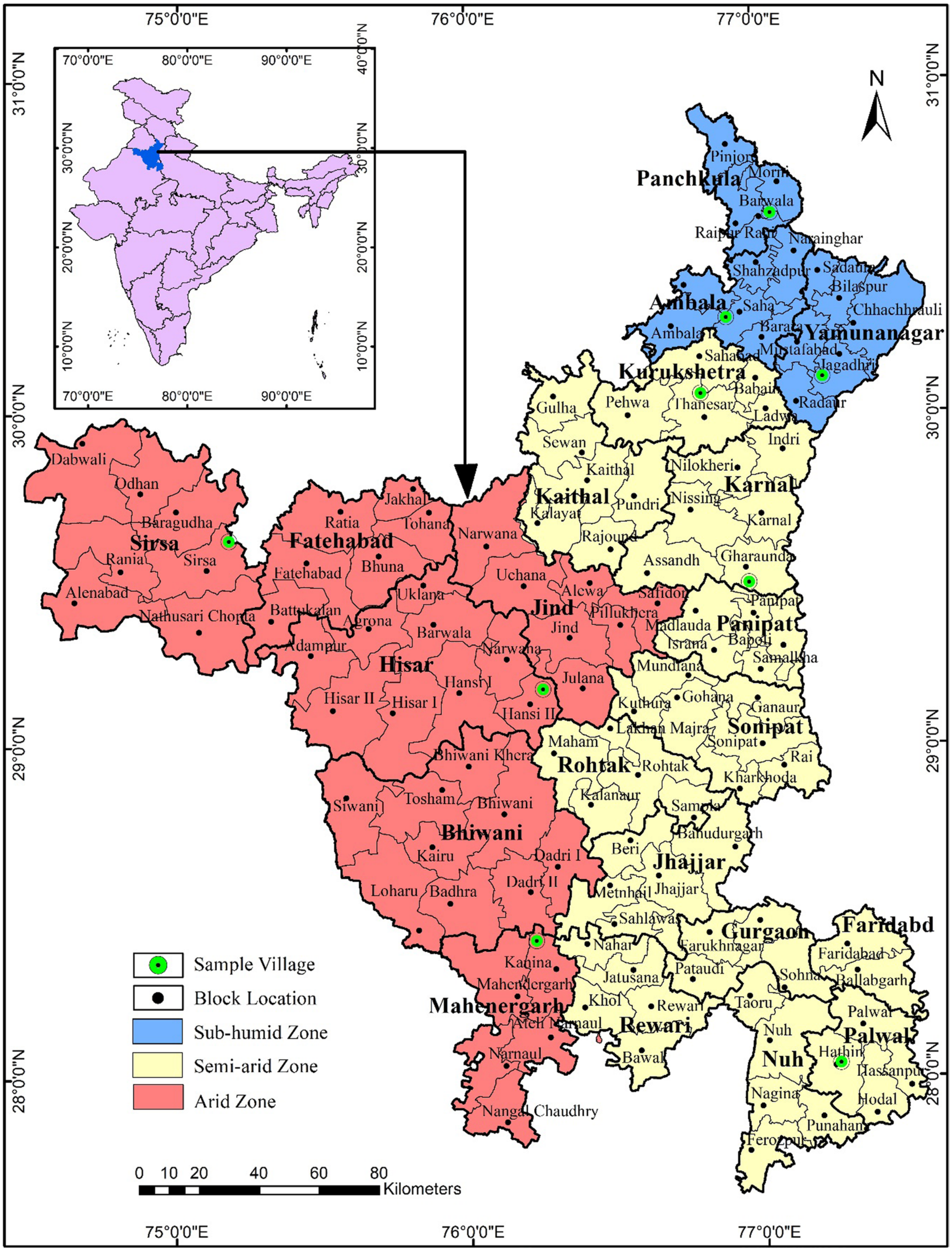

Fig. 2 Location of sample villages, blocks and districts in Haryana, India along with major climatic regions

about the energy-groundwater irrigation nexus, as well as to expand on the specific problems. The questionnaire has been given out in English, but it has been translated and interpreted into the local languages (Hindi and Haryanvi) to bridge the communication gap, explain questions, and obtain more detailed answers. A total of 25 respondents over the age of 25 have been interviewed. These are older ages, reflecting a purposeful sampling bias in favor of

Table 1 Comparison of energy-groundwater irrigation scenario in Haryana and other states of India

Indicators	Andhra Pradesh	Bihar	Gujarat	Haryana	Maharashtra	Punjab	Uttar Pradesh	West Bengal
Level of groundwater development (percent)*	45	44	67	133	53	172	74	40
Over-exploited blocks (number)*	83 (7)	0 (0)	24 (11)	71 (61)	10 (3)	110 (80)	111 (14)	0 (0)
Average annual rainfall (mm)*	575	1030	915	468	705	497	906	1148
Nature of aquifer*	Hard rock	Alluvial	Alluvial and hard rock	Alluvial	Hard rock	Alluvial	Alluvial	Alluvial
Annual per capita energy consumption in agricultural sector (kWh)**	223.9	89.2	226.8	368.8	217.7	367.8	43.1	14.4
Consumption of electricity in agricultural sector (percent of the total electricity consumption)**	29.8	17.8	24.9	39.4	31.87	28.2	20.0	3.9
Transmission and distribution losses (percent)***	15.3	35.0	22.3	22.7	21.6	16.8	24.4	22.3
Percentage of electric tube-wells to total tube-wells****	93.5	NA	54.5	63.1	NA	73.3	NA	8.2
Flat tariff rate (Rs./HP/Year) ****	Free	NA	850	420	NA	Free	NA	1760–2160
Electricity subsidy (percent of fiscal deficit) ****	54	01	56	78	26	38	13	0.8

Figures the parentheses indicate toward percentage

NA: Data not available

Source: CGWB (2013) ** (Mukherji 2007) *** (Raju et al. 2013) **** (Mukherji et al. 2009); (Department of Economic and Statistical Analysis 2012)

older respondents in order to capture the energy-groundwater irrigation nexus.

Apart from this, secondary data on number of electric connections in irrigation sector, consumption, tariffs and subsidy have been collected from published and unpublished records of Haryana Vidyut Prasaran Nigam Limited, Panchkula for the period 1990–2013. Likewise, data pertaining to number, density and irrigated area for the same period have been collected from Statistical Abstract issued by Department of Economic and Statistical Analysis, Haryana. Information regarding depth of irrigation and water productivity under major crops for tube-well and non-tube-well owners for other states has been collected from published research papers.

Several indices such as cropping intensity, operating and use factor of tube-wells and physical and economic productivity of water have been computed from the above collected primary data to highlight the energy and groundwater irrigation nexus. A comprehensive procedure for computing these indices has been discussed by Qureshi et al. (2003), Shah et al. (2003), Shah et al. (2006), Kumar et al. (2008), Kumar et al. (2010) and Kumar et al. (2011). In addition, grouping of respondent farmers based on land holding size has been done as small (0.0–2.0 ha), medium (2.1–4.0 ha) and large (4.1 ha or more) (Singh and Singh 2015). This grouping of respondents by their landholding size shows the land ownership pattern in Haryana. Finally, to summarize quantitative data, descriptive statistics involving frequency distribution, tables and graphs have been prepared. The statistical program MS EXCEL has been used to handle and analyze the data.

Results and discussion

Groundwater economy

Groundwater irrigation has reduced the dependency of farmers on rainfall and other irrigation sources. Irrigated agriculture in Haryana increasingly depends on groundwater use and has a long history of its use. Traditional irrigation sources were important until 1970. Extraction of groundwater through Persian wheels from dug wells accounted for about a quarter of the net irrigated area. Later, during 1970–90, dependence on dug wells have reduced sharply and tube-wells irrigated area has enhanced from 34 to 48 percent, with a growth of 132.4 percent. This remarkable increase in area under tube-well irrigation in the state can be ascribed to the decreasing canals discharges and rising requirement for timely and sufficient quantity of water for crops with the introduction of Package Technology. The Package Technology basically refers to Green Revolution introduced in agriculture. The package that comes with it are High Yielding Variety of seeds, modern equipments of

Table 2 Details of sample design and data collection for energy-groundwater irrigation linkages in Haryana

Districts	Climatic zones*	Rainfall (mm)	Temperature (°C)	Sample districts	Sample block	Category of block	Sample villages	Latitude	Longitude	Altitude (m)	Number of respondents
Ambala, Panchkula, Yamunanagar	Sub-Humid Zone	750–1050	24	Panchkula, Yamunanagar, Ambala	Raipur Rani	Over-exploited	Rampur	30° 60'N	77° 04'E	345	30
					Radaur	Over-exploited	Bhadurpur	30° 05'N	77° 23'E	268	49
					Ambala-II	Critical	Bhilpura	30° 33'N	76° 94'E	280	46
Total											**125**
Faridabad, Gurgaon, Jhajjar, Kaithal, Karnal, Kurukshetra, Mewat, Palwal Panipat, Rewari, Rohtak, Sonipat	Semi-Arid Zone	500–750	26	Karnal, Kurukshetra, Palwal	Gharaunda	Over-exploited	Kohand	29° 49'N	30° 76'E	243	30
					Thanesar	Over-exploited	Dhurala	30° 05'N	76° 80'E	258	40
					Hathin	Critical	Bahin	28° 03'N	77° 32'E	189	30
Total											**100**
Bhiwani, Fatehabad, Hisar, Jind, Mahendergarh, Sirsa	Arid Zone	300–500	27	Sirsa, Mahendergarh, Hisar	Sirsa	Over-exploited	Bhrokhan	29° 61'N	75° 17'E	203	25
					Kanina	Over-exploited	Sehlang	28° 40'N	76° 21'E	243	60
					Hansi-II	Critical	Khanda-Kheri	29° 18'N	76° 22'E	223	50
Total											**135**
Sample Total											**360**

Source: *(Government of India 2011)

The boldface values are showing the average values

tilling the soil, organic fertilizers, pesticides etc. to farmers. This technology aims at yielding maximum benefits in less period of time in agriculture. These characteristics have provoked the farmers to set up their individual tube-wells during the period 1970–90. However, till 2000, tube-well irrigated area has exceeded the canal irrigated area (Fig. 3). Current estimates show that canal irrigated area has declined from 77 to 42 percent, and tube-well irrigated area has increased from 22 to 58 percent during 1966–2013. The consciousness of farmers about groundwater is evident from the increasing use of resource. But on the other hand, this impressive growth in groundwater irrigation during the last five decades has adversely affected the groundwater resources of Haryana.

Recent estimates show that net groundwater available in the State is 9.79 billion cubic meters, while the net groundwater draft is 13.06 billion cubic meters, thus leaving an annual deficit of 3.27 billion cubic meters, which can result a serious groundwater crisis in near future. Figure 4 shows an increasing trend in groundwater exploitation through tube-wells. The major reason for increased tube-well pumpage may be ascribed to low setting up cost of electric tube-wells with high efficiency, subsidized energy supplies and commencement of horse-power rating based flat tariff of the tube-wells after the year 1978. The farming community of the state has favored flat tariff on account of higher pumpage without tension of billing, no need of pilferage and meter tempering and groundwater selling to nearby farmers at economical rates than diesel tube-wells. Other benefits of electric tube-wells include-easy handling, low operating cost, better pumping efficiency and performance for extraction of deep groundwater. An electric tube-well is a downhole pump which is powered by electricity, and used for lifting groundwater from an aquifer.

Table 3 shows the growth in net area sown, number of tube-wells, number of tube-wells per 1000 hectare of net area sown, tube-well irrigated area, area irrigated per tube-well in hectare and annual growth rate of tube-wells in Haryana.

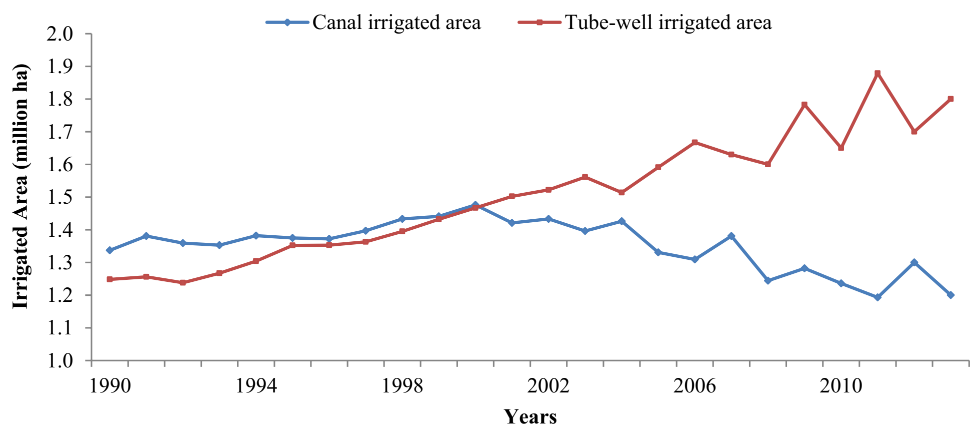

Fig. 3 Growth of irrigated area through canals and tube-wells in Haryana during 1990–2013

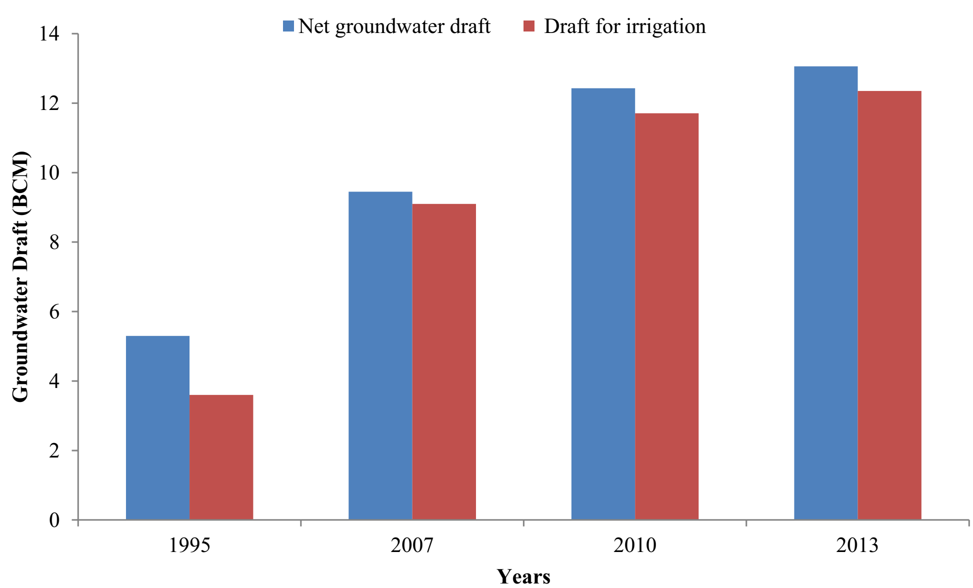

Fig. 4 Trends in groundwater draft in Haryana during 1995–2013

Table 3 Growth in number, density and area irrigated per tube-well in Haryana during 1990–2013

Year	Net area sown (million ha)	Number of tube-wells (million)	Number of tube-wells per 1000 ha of net area sown	Tube-well irrigated area (million ha)	Area irrigated per tube-well (ha)	Annual growth in number of tube-wells (%)
1990	3.58	0.50	139.2	1.24	2.49	8.77
1991	3.51	0.51	145.4	1.26	2.46	2.55
1992	3.49	0.52	149.7	1.24	2.37	2.48
1993	3.51	0.52	148.4	1.27	2.43	-0.28
1994	3.56	0.53	150.2	1.30	2.44	2.51
1995	3.59	0.54	150.7	1.35	2.50	1.08
1996	3.62	0.56	154.3	1.35	2.43	3.20
1997	3.64	0.57	155.8	1.36	2.41	1.59
1998	3.63	0.58	158.6	1.40	2.42	1.59
1999	3.55	0.60	168.6	1.43	2.39	4.08
2000	3.56	0.59	165.6	1.37	2.32	-1.53
2001	3.57	0.60	167.0	1.50	2.52	0.96
2002	3.46	0.60	174.1	1.52	2.53	1.09
2003	3.53	0.59	167.7	1.55	2.62	-1.54
2004	3.53	0.58	165.4	1.51	2.59	-1.56
2005	3.57	0.58	162.5	1.59	2.75	-0.69
2006	3.56	0.63	175.9	1.67	2.66	7.96
2007	3.59	0.66	184.3	1.63	2.46	5.91
2008	3.58	0.68	189.7	1.60	2.36	2.38
2009	3.76	0.67	179.4	1.78	2.65	-0.66
2010	3.68	0.72	196.6	1.65	2.28	7.39
2011	3.52	0.74	209.6	1.88	2.55	1.90
2012	3.51	0.75	214.2	1.76	2.33	2.08
2013	3.50	0.77	220.8	1.77	2.29	2.62

Source: Statistical Abstracts of Haryana (1990–2013)

The tremendous annual growth in number and density of tube-wells (2.3 and 2.4 percent, respectively) exhibits the growing importance of groundwater irrigation in agricultural development of the state. Several factors such as soft loans, subsidies and rural electrification explain the growth in tube-well numbers. The installation of large number of tube-wells has helped the farmers to exploit groundwater resources to add-on their water supplies, which resultantly increased the cropping intensities in the state from 144 in 1970s to 185 in the year 2015. Besides, farmers across the state have adopted high yielding cereal crops, initially wheat and subsequently rice with moderate to high and very high-water demand. At present, rice–wheat is a very common cropping system covering more than 3.75 million ha (approximately 60 percent of total cropped area). This may be a result of combination of high and guaranteed purchasing prices and subsidized inputs for these crops. Additionally, general shift from metering to a flat rate energy tariff for irrigation sector has induced new entrants to the groundwater economy. In contrast, negative annual growth in number of tube-wells during some of the years can be attributed to shifting of shallow tube-wells (centrifugal) to deep tube-wells (submersible) as a result of declines in groundwater levels throughout except the central tracts, where both waterlogging and poor quality impede the development of resource. Also, the area irrigated per tube-well shows that in spite of rise in the number of tube-wells in recent period, the area irrigated per tube-well has not increased, indicating clearly that the groundwater development has crossed its limits and exhibiting scarcity.

Energy economy

Groundwater withdrawals hinges directly on energy delivery and tariffs. During the 'Green Revolution' period (1960s and 1970s), World Bank has showered enormous investments and funds to enhance electricity infrastructure in rural areas to stimulate the groundwater irrigation standings of India in general and of Haryana in particular. Given the importance of groundwater irrigation in agricultural economy, the state government has implemented several policies and programs. Additionally, government has started to offer loans for digging wells, funds for deep tube-wells, concessions on

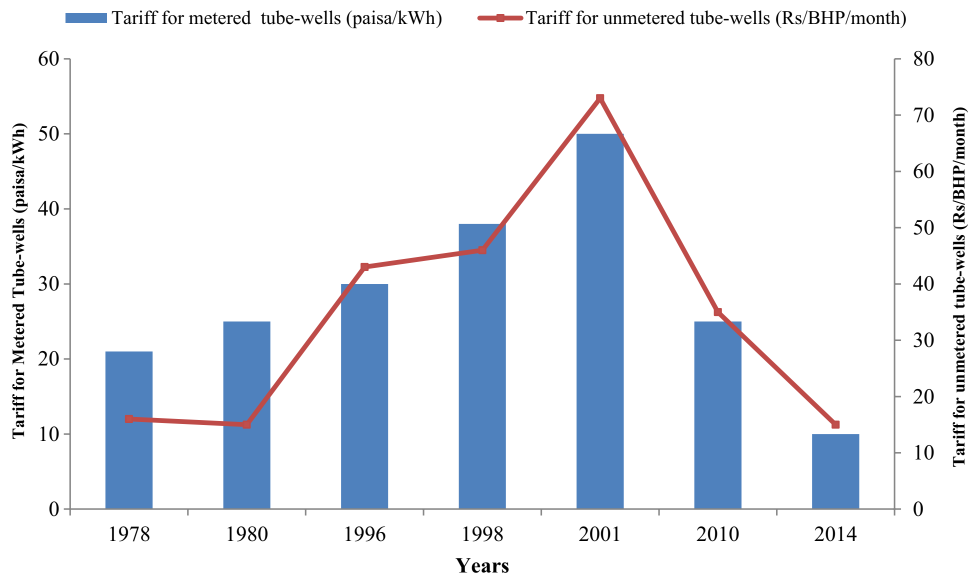

Fig. 5 Change in electricity tariff in Haryana 1978–2014. Source: Various Yearbooks of Haryana Vidyut Prasaran Nigam Limited and Aggregate Revenue Requirements (ARR) filings by Haryana Electricity Regulatory Commission)

pumps and highly subsidized energy tariffs. Figure 5 shows the quantum of electricity tariffs applicable since the beginning of flat tariff rates in the year 1978. The marginal cost of groundwater extraction is nearly zero after switching from a meter-based tariff system to a flat tariff system based on the motor horsepower rating. Moreover, these policy interventions have not only kick-started a massive tube-well irrigation economy leading to depletion of aquifers, but have also contributed toward the increasing subsidized energy bills (Table 4). Cumulative subsidies provided to groundwater irrigation sector at current prices (when energy reforms have been started) have increased from Rs.1906 million in 1990–91 to Rs. 54,360 million in 2013–14. Despite the introduction of minimum tariff rates under the common minimum plan for power sector reforms, there has been an increase in subsidies. Besides, increasing energy subsidy bills have mainly been owing to political intervention in pricing of energy and usually it has been in the form of waiver of energy dues as part of political populism. However, this has encouraged the farmers' nonpayment approach, who expects another round of waiver in near future. Energy subsidies thus have become the reason as well as the consequence of groundwater depletion. Therefore, energy subsidy has substantial impacts on sustainability of groundwater resources of the state.

Energy consumption for groundwater withdrawals is an indication of density of tube-wells and its use in a region. Table 1 clearly shows that the proportion of both groundwater and energy use is very high in the state and differs completely from other Indian states. The principal source of energy for pumping groundwater in the state is generated and purchased electricity. The share of energy purchased by the state has increased from about 34 percent of its generated units in 1990 to around 71 percent of its generated units in 2008 (Fig. 6). According to a recent estimate, electric tube-wells accounts for about 72 percent of the total tube-well population in Haryana (Sharma et al. 2015). Electric tube-wells as a percentage of total tube-wells for groundwater irrigation are depicted in Fig. 7. In addition, electric tube-wells have consumed approximately 45 percent of consumption of total energy in 1990, while it has declined to 28 percent during the year 2013 (Fig. 8a). The increased usage of energy in the domestic and industrial sectors can be due to the decline in energy use by tube-wells. Conversely, Fig. 8b–d shows an increasing trend in number of electric tube-well connections, total consumption of energy in irrigation sector and energy consumption per electric tube-well. A significant increase in these attributes over the last 24 years clearly exhibits the increasing curiosity of farmers in electric tube-wells. This triggering interest toward electric tube-wells among farmers can be anomalously attributed to farmer-centric energy policy of the state government. Nonetheless, these increasing trends have placed a phenomenal pressure on groundwater resources as well as on the energy supply agencies like state electricity board of the state.

Energy and groundwater irrigation nexus

Operating factor of tube-wells

There is a close link between energy and groundwater economy of the state, as energy pricing and supply policies significantly affect the operational factor of tube-wells i.e., per tube-well mean annual operational hours. The State Government has abandoned farm energy supply based on metering in the year 1978 and has switched to flat-rate energy tariff related to horsepower rating of tube-wells. With the introduction of the flat tariff, energy subsidy emerged as

Table 4 Energy subsidies to electric tube-well users in groundwater irrigation sector of Haryana during 1990–2013

Years	Energy subsidy in irrigation sector (million Rs.)	Energy subsidy paisa/unit	Energy subsidy (per acre in Rs.)		Energy subsidy in Haryana as a percent of India
			India	Haryana	
1990–91	1906	70	83.3	130.5	5.0
1991–92	2599	83	106.4	182.8	5.3
1992–93	3436	95	129.5	238.3	5.6
1993–94	4550	113	162.1	315.8	6.1
1994–95	5216	126	198.0	354.5	5.8
1995–96	5867	143	245.2	396.0	5.2
1996–97	6566	160	293.8	438.6	4.8
1997–98	7711	193	349.8	513.6	4.7
1998–99	8848	222	414.4	586.7	4.5
1999–2000	11,053	264	480.3	729.2	5.6
2000–01	13,890	309	520.8	912.0	5.6
2001–02	16,194	349	534.8	1049.0	6.4
2002–03	16,545	345	574.8	1074.9	6.3
2003–04	16,958	335	630.6	1084.5	5.9
2004–05	17,967	330	717.8	1141.4	5.4
2005–06	19,898	341	707.1	1237.7	6.4
2006–07	25,059	383	697.2	1586.7	7.5
2007–08	30,220	425	695.7	1894.5	9.0
2008–09	36,270	503	816.3	2259.1	9.2
2009–10	48,530	542	958.4	3093.7	10.8
2010–11	40,970	515	907.5	2549.9	9.2
2011–12	46,600	754	944.7	2907.4	10.2
2012–13	51,860	631	1205.2	3293.0	9.0
2013–14	54,360	599	1394.5	3451.7	8.1

Source: Various Issues of Annual Reports on the Working of State Electricity Boards and Electricity Departments, Planning Commission, Government of India, New Delhi

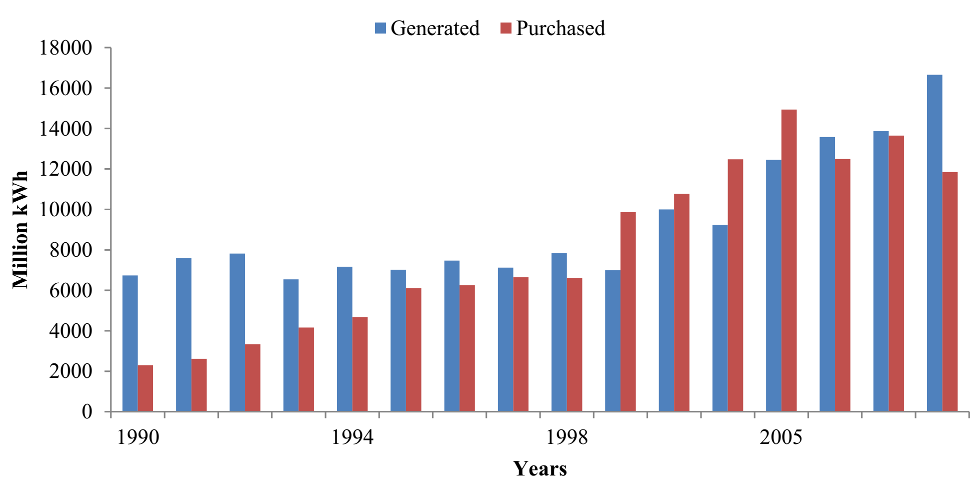

Fig. 6 Details of energy generation and purchase in Haryana during 1990–2008

by far the strongest tool for populist policies, marking a seminal moment in the evolution of the state's groundwater economy. Given the situation, it has been hypothesized that the operating factor of electric tube-wells would be significantly high on account of effective and substantial energy subsidy. Figure 9a shows the electric tube-wells total average hours and hours per hectare of pumping. Electric tube-wells have significantly higher operating hours of pumping. These results are well in correspondence with other Indian states, which enjoy an energy subsidy and a flat tariff rate

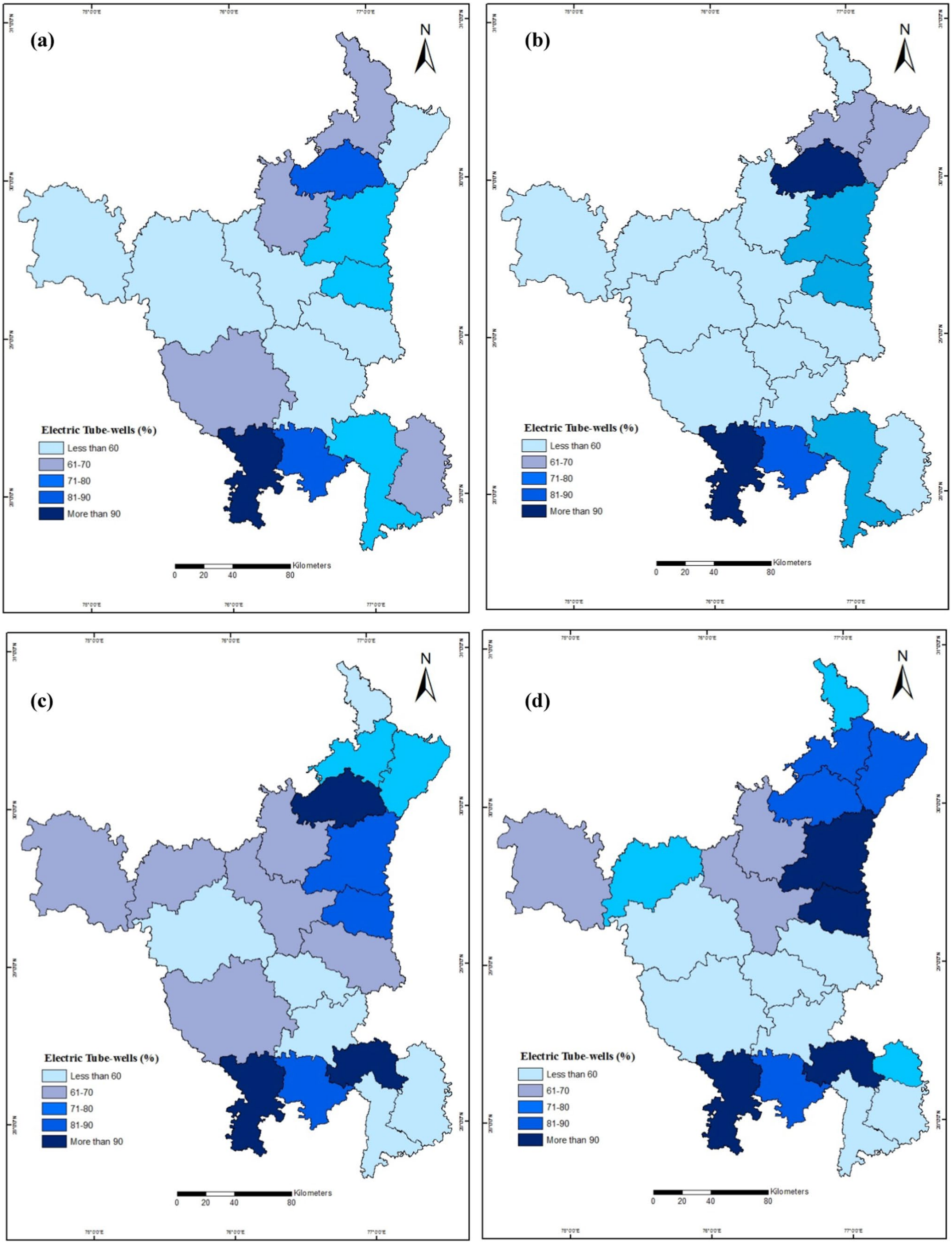

Fig. 7 Electric tube-wells as percent of total tube-wells used for groundwater irrigation in Haryana during **a** 1990, **b** 1998, **c** 2006 and **d** 2012

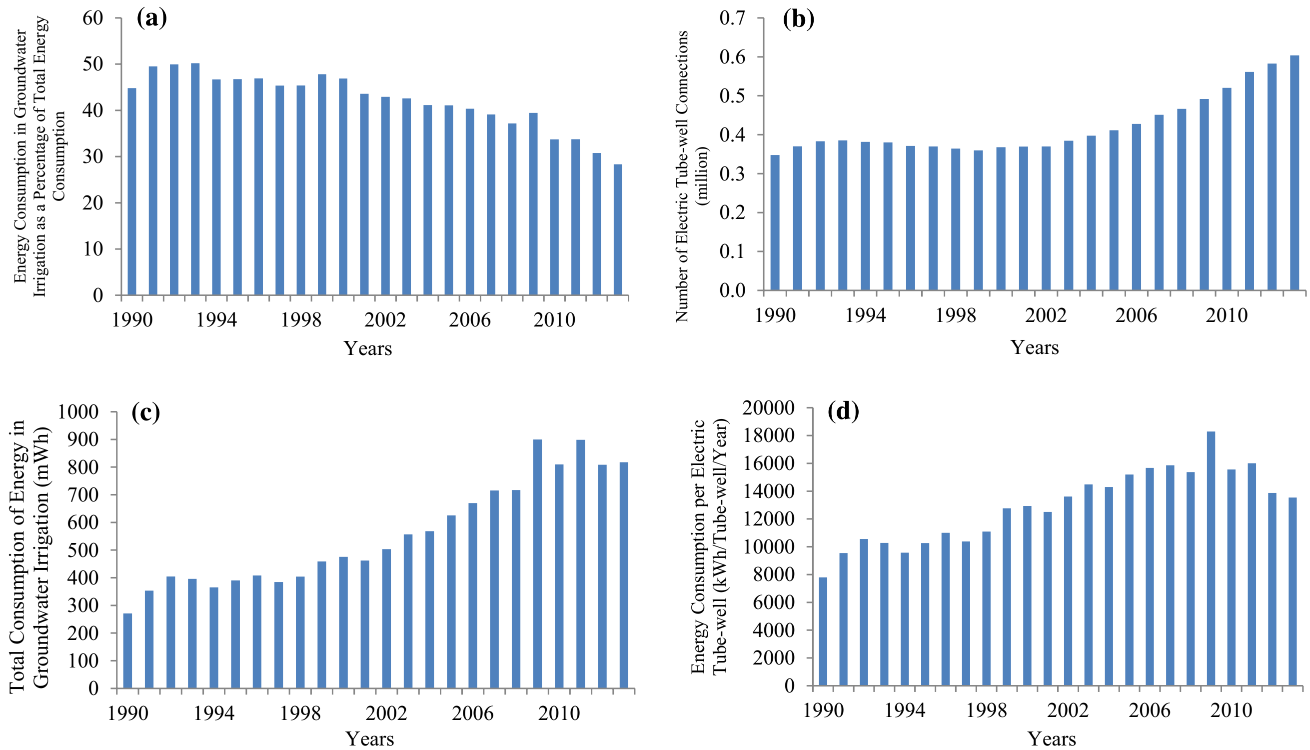

Fig. 8 Growth in **a** energy consumption in groundwater irrigation as a percent to total energy consumption, **b** number of tube-well connections **c** total consumption of energy in groundwater irrigation and **d** consumption of energy per tube-well per year in Haryana during 1990–2013

for groundwater irrigation (Modi 2005; Shah et al. 2006). Interestingly, it has been also revealed that electric tube-well owners are paying a flat tariff to operate their tube-wells for 40–250 percent more hours per year than owners of diesel tube-wells in different parts of country. Figure 9b–f shows the total average hours of irrigation used and hours per hectare to irrigate major crops. These results are broadly in conformity that more operating hours of pumping as well as hours per hectare for rice cultivation are required. Furthermore, if there is a significant difference in the energy rating of the tube-wells, operating hours of electric tube-wells pumping cannot be a true representative of energy usage and groundwater extraction per electric tube-well. Figure 10a shows average energy consumption in kilowatt hours and energy consumption per hectare of cultivated land. As a result, electric tube-well owners in Haryana have been observed to make more intensive use of energy for groundwater withdrawal in irrigating their crops, as the marginal cost of running electric tube-wells is substantially lower due to flat tariff rates. Also, Figure 10b–f demonstrates the similar attributes in relation to major crops grown and it has been observed that rice and sugarcane are the key consumers of energy both in terms of average energy consumption as well as per hectare of cultivated land. Again, it can be attributed to significant effective subsidy on energy use.

Apart from this, energy subsidies are usually validated on the basis that they reach up to poor or small farmers. Tables 5 and 6, however, show that both hours of pumping as well as consumption of energy among the large farmers is higher than the twofold of small farmers. This analysis clearly validates that large farmers have acquired more benefit from the subsidized energy than small farmers. Similar results have been noticed in a study of Karnataka state of India, which has shown that energy subsidies allocated to small farmers are often trapped by wealthy farmers (Howes and Murgai 2003). It has been observed during the field survey that energy supply in the state is unreliable and farmers having larger size of landholdings invest in higher horsepower rating tube-wells to extract more groundwater to irrigate their lands. Surprisingly, about 15 percent of large farmers in Haryana have 4 tube-wells with higher horsepower ratings, consuming more energy and groundwater (Table 7).

Use factor of tube-wells

The use factor of tube-wells is among the most important parameters to estimate the total groundwater extraction. It depends on several factors comprising tube-well type, cropping season, climatic zone, groundwater markets, tariff and energy policy (Qureshi et al. 2003). Table 8 shows a significant difference in average use factor depending on

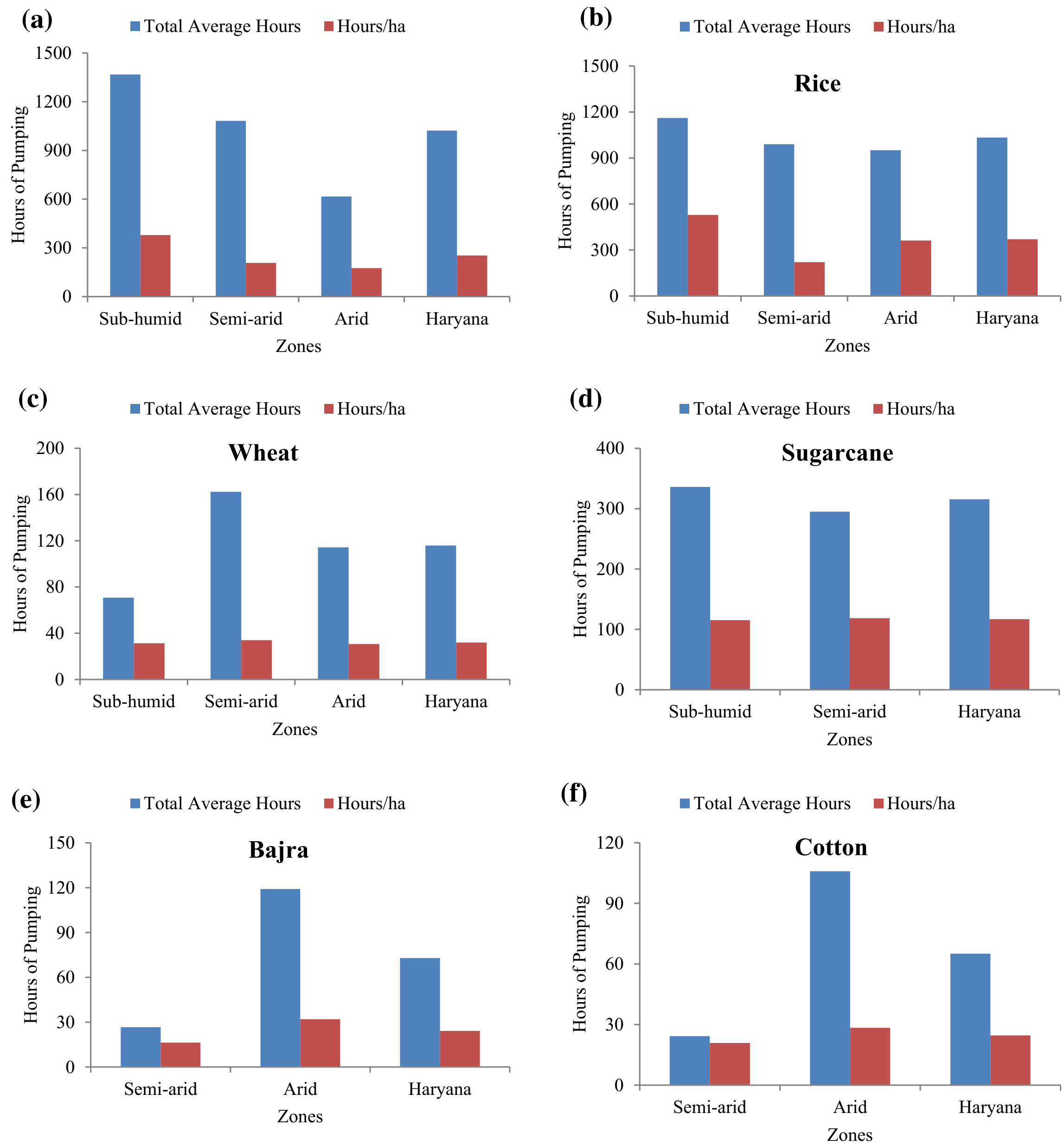

Fig. 9 Impact of flat rate tariff energy pricing regime **a** on hours of pumping and pumping hours per ha and **b**–**f** hours of pumping and pumping hours per ha with respect to major crops grown in Haryana

landholding size of farmers, cropping season and climate. The usage factor of large farmers is more than double that of small and medium farmers, confirming the fact that large farmers consume more energy and profit from subsidies. Higher use factor of large farmers can be ascribed to higher average number of days per year for which they operate their tube-wells in a year. The higher number of tube-well operating days in case of large farmers are owing to the fact that each tube-well is serving about 6.3 hectare of irrigated land, which is more or less twofold of the land irrigated by small farmers and the average area irrigated by each tube-well (Tables 7 and 8).

The use factor also significantly differs during diverse growing seasons. During the *kharif* season, the average use factor is around 7.5 times higher than during the *rabi* season (Table 8). During *rabi* season, evapotranspiration is modest due to cool climatic conditions and mostly less water consuming crops are grown (mustard and wheat). Among the climatic zones, sub-humid zone has the highest use factor followed be semi-arid and arid zone (Table 8).

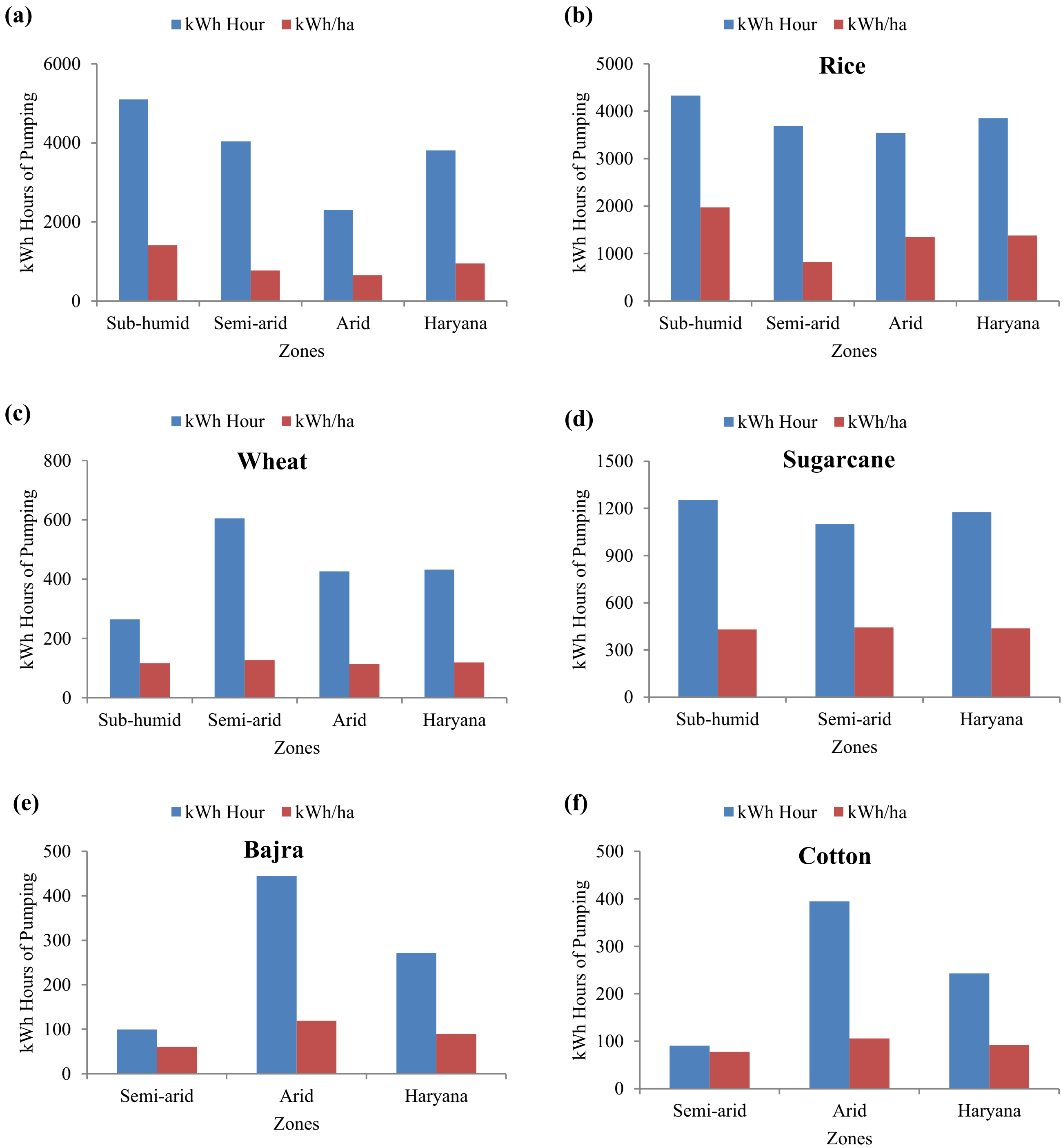

Fig. 10 Impact of flat rate tariff energy pricing regime **a** on consumption of energy and energy use per ha and **b**–**f** consumption of energy and energy use per ha with respect to major crops grown in Haryana

The wide ranges of use factor among the climatic zones are attributed to diversified cropping patterns. Among the zones where wheat, cotton, mustard and bajra cropping pattern is dominant, the use factor is comparatively low as these crops consume less water. However, in the zones where rice and sugarcane crops are dominant, both water requirement and subsequently use factor is high. The survey data have conspicuously revealed that the amount of groundwater applied to rice and sugarcane crops is about 6 and 2.5 times more than wheat and cotton, respectively. The amount of groundwater applied to rice crop have been found even higher than the sugarcane crop although growing period for rice is less than half of the sugarcane.

The usage factor is also influenced by the average area irrigated by each tube-well. According to the results of the survey, each tube-well irrigates an average of 3.4 hectares. In arid and semi-arid zones, where rainfall is low to moderate, the average area irrigated by each tube-well is higher than that in the sub-humid zone (Table 7). Additionally, changes in the tariff policy for tube-wells have a direct impact on use factor of tube-wells. During the metered tariff period, the average annual use factor in Pakistan Punjab has been observed to the tune of 8.8 percent, whereas in the present study it has been found 11.7 percent during the flat tariff regime of energy supply, which is relatively on the higher side. Accordingly, metered tariff policy may be more advantageous in regulating excessive pumping of groundwater in Haryana.

Groundwater application and cropping patterns

The use factor of tube-wells leads to development of groundwater resources and thus supports in selecting the cropping patterns of an area. Therefore, analyses of cropping pattern of tube-well owners and non-tube-well owners (buyers) have been presented in Table 9. The major crops grown in the study area are wheat, rice, sugarcane, cotton, mustard, bajra and fodder. During the *kharif* season, both tube-well and non-tube-well owners allocate the larger portion of their landholding to rice crop. Tube-well owners cultivate rice crop over approximately 58 percent of the gross cropped area, while non-tube-well owners only over about 28 percent. In addition, tube-well owners also grow sugarcane, cotton and fodder crops, whereas the non-tube-well owners assign higher percentage of their cropped area to cotton, bajra and fodder crops. Wheat, fodder, and mustard are the main crops grown during the winter season (*rabi*). The percentage area allocated for fodder and mustard crops is low both for owners and buyers, while area allocated to wheat is very high in both the cases. Surprisingly, there is no discernible difference in cropping patterns between tube-well owners and groundwater buyers during the *rabi* season. Similar results have been observed under different climatic regimes of the state except mustard crop in arid region. Overall, tube-well owners allocate larger area to wheat, rice and sugarcane crops, whereas groundwater buyers allocate it to bajra, cotton, fodder and mustard crops, which consume less water.

Groundwater application, productivity and net returns

Adoption of water efficient crops and appropriate cropping patterns can play a major role in reducing the groundwater use for irrigation and increasing the water productivity and sustaining groundwater aquifers. Table 10 shows the estimates of irrigation water application, physical water productivity (kg/m^3) and water productivity in economic terms (Rs. /m^3) for major crops grown by tube-well owners and non-tube-well owners (buyers). Higher physical productivity of irrigation water use for a specific crop denotes more effective irrigation water use via on-farm water management, while higher water productivity in economic terms denotes better irrigated output viability if land is plentiful (Kumar et al. 2011). While comparing the water application and water productivity of crops raised by two categories of farmers the analysis shows that tube-well owners and non-tube-well owners grow almost similar crops during *kharif* and *rabi* season. However, for all of the major crops grown, the overall amount of irrigation water applied for crop production is higher for owners than for buyers because owners have a much greater access to water. Further, for most of the crops physical productivity of water is higher for buyers as compared to tube-well owners. In contrast, economic productivity of water except the mustard crop is higher for tube-well owners. Similar results for different climatic zones have been observed. These results from this study do not correspond with the earlier findings in Uttar Pradesh, Bihar and Gujarat, where buyers have achieved higher economic productivity (Shah et al. 2003; Kumar et al. 2011). This can be corroborated to the fact that water buyers incur higher cost (Rs. /hr) for irrigation water in volumetric terms, which ultimately lowers net return from crop production than their counterpart farmers in Uttar Pradesh, Bihar and Gujarat. Besides, owners as compared to buyers achieve higher economic productivity on account of prevailing flat tariff rates of energy in Haryana (Table 1; Fig. 5). This study, therefore, contradicts the earlier findings that economic productivity of owners under flat rate provision is comparatively less than the farmers who have metered connections in India (Shah et al. 2003; Kumar et al. 2011). Additionally, the results of this study reveal that tube-well owners in Haryana are able to maintain high soil moisture, which reduces the need for fertilizer input and thus minimizing the input cost and enhancing the economic productivity. These results indicate that Haryana has reaped the optimum benefits of Package Technology; however, growing of rice crop has completely depleted the water resources.

In addition, as regards the water application, physical and economic productivity, the comparative figures for the study area with that of other areas are presented in Fig. 11. When compared to Uttar Pradesh, Bihar, and Gujarat, both tube-well owners and non-tube-well owners achieve higher economic efficiency in all crops except rice, but at the expense of more water application in most crops. Therefore, it is suggested that farmers in Haryana should try to economize on the application of water since it is water deficient region in physical terms in India. Reduction in

Table 5 Impact of flat rate tariff energy pricing regime on hours of pumping and pumping hours per ha in Haryana

Size of land holding	Average		Rice		Wheat		Sugarcane		Bajra		Cotton	
	Hours of pumping	Hours/ha	Hours of pumping	Hours/ha	Hours of pumping	Hours/ha	Hours of pumping	Hours/ha	Hours of pumping	Hours/ha	Hours of pumping	Hours/ha
Sub-humid zone												
Small	862	788	927	1172	26	31	47	94	–	–	–	–
Medium	1128	434	984	575	53	28	145	128	–	–	–	–
Large	2164	297	1562	389	138	33	539	155	–	–	–	–
Average	**1385**	**506**	**1158**	**712**	**72**	**31**	**243**	**126**	–	–	–	–
Semi-arid zone												
Small	511	321	662	470	51	34	–	–	15	17	10	11
Medium	803	255	738	288	90	33	129	160	15	16	48	30
Large	1726	177	1264	172	303	34	309	118	54	16	29	24
Average	**1013**	**251**	**888**	**310**	**148**	**34**	**219**	**139**	**28**	**16**	**29**	**22**
Arid zone												
Small	434	324	825	908	47	47	–	–	17	33	23	40
Medium	486	155	824	385	79	39	–	–	33	32	43	31
Large	799	107	769	172	139	23	–	–	29	30	61	23
Average	**573**	**195**	**806**	**488**	**89**	**36**	**–**	**–**	**26**	**32**	**43**	**32**
Haryana												
Small	602	477	805	850	42	37	47	94	16	25	17	25
Medium	806	282	849	416	74	33	137	144	24	24	46	31
Large	1563	440	1199	244	193	30	424	136	41	23	45	24
Average	**990**	**400**	**951**	**503**	**103**	**34**	**203**	**125**	**27**	**24**	**36**	**27**

The boldface values are showing the average values

Table 6 Impact of flat rate tariff energy pricing regime on consumption of energy and energy use per ha in Haryana

Size of land holding	Average		Rice		Wheat		Sugarcane		Bajra		Cotton	
	kWh hour	kWh /ha	kWh hour	kWh /ha	kWh hour	kWh /ha	kWh hour	kWh /ha	kWh hour	kWh /ha	kWh hour	kWh /ha
Sub-humid zone												
Small	3216	2938	3459	4372	98	116	174	352	–	–	–	–
Medium	4208	1620	3672	2144	198	105	541	477	–	–	–	–
Large	8070	1109	5826	1451	514	123	2010	577	–	–	–	–
Average	**5165**	**1889**	**4319**	**2656**	**270**	**115**	**908**	**469**	**–**	**–**	**–**	**–**
Semi-arid zone												
Small	1904	1196	2469	1754	191	128	–	–	57	64	36	40
Medium	2996	951	2753	1076	336	122	482	597	54	60	181	112
Large	6439	661	4716	643	1131	128	1152	439	201	60	108	90
Average	**3780**	**936**	**3313**	**1158**	**552**	**126**	**817**	**518**	**104**	**61**	**108**	**80**
Arid zone												
Small	1620	1208	3077	3385	177	174	–	–	64	124	87	149
Medium	1812	580	3074	1435	294	146	–	–	122	121	161	117
Large	2979	398	2870	641	520	87	–	–	109	110	229	86
Average	**2137**	**729**	**3007**	**1820**	**330**	**135**	**–**	**–**	**98**	**118**	**159**	**118**
Haryana												
Small	2247	1780	3002	3170	155	139	174	352	60	94	62	95
Medium	3005	1050	3166	1552	276	124	512	537	88	90	171	115
Large	5829	1640	4471	912	722	113	1581	508	155	85	169	88
Average	**3694**	**1490**	**3546**	**1878**	**384**	**125**	**756**	**466**	**101**	**90**	**134**	**99**

The boldface values are showing the average values

Table 7 Number of tube-wells, horsepower of tube-wells and area irrigated each tube-well in Haryana

Size of landholding	Number of tube-wells	Horsepower of tube-wells	Area irrigated by each tube-well (ha)	Number of farmers without electric tube-wells	Number of farmers owning one electric tube-well	Number of farmers owning two electric tube-wells	Number of farmers owning three electric tube-wells	Number of farmers owning four electric tube-wells	Number of farmers owning more than four electric tube-wells	Total number of farmers
Sub-humid zone										
Small	44	7.5	1.3	19 (36.5)	24 (46.2)	7 (13.5)	2 (3.8)	0 (0.0)	0 (0.0)	52 (100.0)
Medium	48	13.1	2.0	4(10.0)	24 (60.0)	8 (20.0)	3 (7.5)	1 (2.5)	0 (0.0)	40 (100.0)
Large	83	17.4	3.0	0 (0.0)	10 (30.3)	8 (24.2)	5 (15.2)	10 (30.3)	0 (0.0)	33 (100.0)
Total/Average	**175**	**12.6**	**2.3**	**25 (18.4)**	**58 (46.4)**	**23 (18.4)**	**10 (8.0)**	**11 (8.8)**	**0 (0.0)**	**125 (100.0)**
Semi-arid zone										
Small	21	7.2	1.9	21 (52.5)	18 (45.0)	1 (2.5)	0 (0.0)	0 (0.0)	0 (0.0)	40 (100.0)
Medium	23	14.9	3.0	3 (13.0)	20 (87.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	23 (100.0)
Large	60	17.1	5.5	2 (5.4)	25 (67.6)	5 (13.5)	2 (5.4)	1 (2.7)	2 (5.4)	37 (100.0)
Total/Average	**104**	**13.1**	**4.2**	**26 (26.0)**	**63 (63.0)**	**6 (6.0)**	**2 (2.0)**	**1 (1.0)**	**2 (2.0)**	**100 (100.0)**
Arid zone										
Small	35	8.4	1.9	29 (48.3)	31 (51.7)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	60 (100.0)
Medium	28	8.0	3.9	15 (35.7)	26 (61.9)	1 (2.4)	0 (0.0)	0 (0.0)	0 (0.0)	42 (100.0)
Large	26	11.4	8.5	2 (6.1)	26 (78.8)	2 (6.1)	2 (6.1)	0 (0.0)	1 (3.0)	33 (100.0)
Total/Average	**89**	**9.3**	**4.4**	**46 (34.1)**	**83 (61.5)**	**3 (2.2)**	**2 (1.5)**	**0 (0.0)**	**1 (0.7)**	**135 (100.0)**
Haryana										
Small	100	7.7	1.6	69 (45.4)	73 (48.0)	8 (5.3)	2 (1.3)	0 (0.0)	0 (0.0)	152 (100.0)
Medium	99	12	2.8	22 (21.0)	70 (66.7)	9 (8.6)	3 (2.9)	1 (1.0)	0 (0.0)	105 (100.0)
Large	169	15.3	4.7	4 (3.9)	61 (59.2)	15 (14.6)	9 (8.7)	11 (10.7)	3 (2.9)	103 (100.0)
Total/Average	**368**	**11.7**	**3.4**	**95 (26.4)**	**204 (56.7)**	**32 (8.9)**	**14 (3.9)**	**12 (3.3)**	**3 (0.8)**	**360 (100.0)**

Figures within the parentheses are percentage of total

The boldface values are showing the average values

Table 8 Variations in utilization factor as influenced by landholding size of farmers, cropping season and climatic zones under flat rate tariff energy pricing regime in Haryana

Size of landholding	Cropping intensity (%)	Average days per year			Operating hours per day			Utilization factor (%)		
		Kharif	*Rabi*	Annual	*Kharif*	*Rabi*	Annual	*Kharif*	*Rabi*	Annual
Sub-humid zone										
Small	191	88	16	104	6.6	6.4	6.5	18.5	1.0	9.7
Medium	182	107	16	123	6.5	5.5	6.0	24.4	1.7	13.0
Large	161	112	11	123	6.8	6.5	6.7	45.6	0.7	23.2
Average	**178**	**102**	**14**	**117**	**6.7**	**6.0**	**6.0**	**29.5**	**1.1**	**15.8**
Semi-arid zone										
Small	200	67	15	81	7.4	6.3	6.9	11.2	1.4	6.3
Medium	199	88	23	111	7.8	5.7	6.8	15.7	2.6	9.2
Large	190	102	23	125	7.7	5.9	6.8	31.5	7.9	19.7
Average	**196**	**86**	**20**	**106**	**7.6**	**6.0**	**6.8**	**19.5**	**4.0**	**11.7**
Arid zone										
Small	198	53	22	62	6.2	5.3	5.8	8.5	1.5	5.0
Medium	192	51	18	68	6.3	4.9	5.6	8.2	2.9	5.5
Large	195	79	18	89	5.9	4.0	5.0	19.8	4.3	11.9
Average	**195**	**61**	**19**	**73**	**6.1**	**4.7**	**5.4**	**12.2**	**2.9**	**7.5**
Haryana										
Small	196	69	18	82	6.7	6.0	6.4	12.7	1.3	7.0
Medium	191	82	19	101	6.9	5.4	6.1	16.1	2.4	9.2
Large	182	98	17	112	6.8	5.5	6.1	32.3	4.3	18.7
Average	**190**	**83**	**18**	**101**	**6.8**	**5.6**	**6.2**	**20.4**	**2.7**	**11.7**

The boldface values are showing the average values

irrigation water consumption can be achieved by selecting less water consuming and highly valued crops. The comparative figures for number of watering, net water consumption, yield and returns from crop production under major crops are presented in Table 11. In Haryana, the tube-well owners water their crops for a greater number of times, therefore consume more water and obtain higher yield and income per hectare than non-tube-well owners except the mustard crop. These findings, however, are dependent on specific socioeconomic characteristics of farmer, availability and quality of infrastructure and services, including energy, and other variables that could influence income levels. Sugarcane and rice are the most remunerative crops followed by mustard, cotton and wheat among both owners and non-owners. A higher net return for different crops is attributed to cheap energy (10 paisa/kWh) in Haryana. If actual cost of energy production (646 paisa/unit) applies in agriculture sector then farmers will have higher energy bills, thereby resulting into an increase in input cost of farmers and consequently net returns will decline. Likewise, buyers will not be able to grow even less water consuming crops if actual cost of energy applies in agriculture. Certainly, power supply policies will affect the net return of farmers.

Funding for electric tube-wells installation

Decline in groundwater levels have compelled farmers to shift from centrifugal to submersible tube-wells, which call for large number of investments on behalf of farmers. Therefore, in the absence of desired money for tube-well installations farmers have to rely on funding from other sources. Rural credit markets in Haryana are characterized by co-existence of formal, semi-formal and informal lenders. Nationalized commercial and State co-operative banks dominate the formal lending institutions, whereas informal lenders include commission agents and money lenders. The survey results show that about 42 percent farmers acquire funds for their own tube-well installation from commission agents and money lenders, followed by own savings and commercial and co-operative banks (Table 12). The survey data also show that farmers do not choose to lend from government institutions on account of dishonesty, red-tapesim and exploitation. Therefore, informal institutions such as commission agents and money lenders are preferred over the formal, which the farmers believe is relatively hassle free for them. Conversely, these informal institutions charge very high interest rate on endowments, resulting increased indebtedness leading to suicides among farmers, which is out of scope of this study.

Table 9 Cropping patterns of tube-well owners and non-tube-well owners under flat rate tariff energy pricing regime in Haryana

Kharif crops	Tube-well owners		Non tube-well owners (buyers)		*Rabi* crops	Tube-well owners		Non tube-well owners (buyers)	
	Area (ha)	Gross cropped area (%)	Area (ha)	Gross cropped area (%)		Area (ha)	Gross cropped area (%)	Area (ha)	Gross cropped area (%)
Sub-humid Zone									
Rice	2.3	58.6	1.2	49.2	Wheat	2.3	92.4	1.3	78.6
Fodder	0.6	8.3	0.7	36.9	Fodder	0.4	7.1	0.4	20.8
Sugarcane	2.3	31.9	1.1	10.1	Others	0.6	0.5	0.4	0.6
Others	0.8	1.1	0.5	3.9		–	–	–	–
Semi-arid Zone									
Rice	4.5	71.7	1.3	31.1	Wheat	4.8	92.8	1.5	92.8
Sugarcane	2.4	8.6	0.4	1.0	Fodder	0.4	6.3	0.3	7.2
Bajra	1.8	4.5	1	27.8	Others	3.2	0.8	0.0	0.0
Cotton	1.4	1.1	1.2	8.6		–	–	–	–
Fodder	0.8	13.3	0.6	28.7		–	–	–	–
Others	3.2	0.8	1.2	2.9		–	–	–	–
Arid Zone									
Rice	2.6	37.0	1.7	18.7	Wheat	2.6	76.8	1.5	63.6
Bajra	0.7	8.9	0.8	16.6	Fodder	0.2	4.0	0.2	4.0
Cotton	1.5	36.3	1.1	37.1	Mustard	1.56	18.3	1.6	32.4
Fodder	0.3	6.1	0.4	5.7	Others	0.8	0.9	0.0	0.0
Others	0.9	11.8	1.4	21.9		–	–	–	–
Haryana									
Rice	3.1	58.2	1.4	28.4	Wheat	3.2	88.0	1.4	60.7
Sugarcane	2.4	14.6	0.8	2.7	Fodder	0.3	5.8	0.3	7.7
Bajra	1.3	4.1	0.9	14.2	Mustard	1.6	5.4	1.6	15.2
Cotton	1.5	9.7	1.2	23.3	Others	1.5	0.8	0.1	16.4
Fodder	0.6	9.7	0.6	17.2		–	–	–	–
Others	1.6	3.7	1.0	14.3		–	–	–	–

Farmers' perception regarding energy supply and groundwater development

The energy and groundwater irrigation nexus cannot be understood without the farmers' perspectives and responses. Table 13 demonstrates farmers' perception regarding energy and groundwater irrigation nexus in Haryana state. The analyses show that most of the farmers are not satisfied with voltage and energy supply hours for irrigation, whereas a mixed response regarding energy cuts and damage of tube-wells due to poor voltage have been observed. Farmers are used to get almost 24 h of three phase power supply per day during 1980s, but at present they are getting 6–8 h per day even during the peak cropping season. The quality and timing of energy supply have become unreliable over time, compelling farmers to invest in higher horsepower of motors. Often, energy is supplied with low voltage and during nights with frequent tripping, which damages the operating efficiency and motors installed. Even knowing that poor voltage is detrimental to motors, farmers are forced to run their pumps, because the limited and restricted hours of power supply.

Additionally, joint ownership of tube-wells is an important mechanism for all categories of farmers in Haryana. An irregular supply of energy leads to disagreements and conflicts among the shareholders regarding their turns of using the tube-wells. Since, energy supply is irregular and for only a few hours, a shareholder may lose his turn, promoting many farmers to establish their own tube-well in future. Also, poor-quality energy supply leads to transformer burnouts, causing a heavy toll on net returns of the farmers due to lower crop yields caused by the lack of irrigation water, while transformers are repaired. Transformer burnouts tend to peak during July and August months of *kharif* season, when the irrigation requirement is greatest. Figure 12 shows the transformer burnout rates in Haryana during the year 2001 to 2015. It has been observed during the field survey that all tube-wells work simultaneously whenever

Table 10 Groundwater application in major crops and their productivity (physical and economic terms) under flat rate tariff energy pricing regime in Haryana

Crops	Tube-well owners			Non tube-well owners (Buyers)		
	Depth of irrigation water applied (cm)	Water productivity (kg/m^3)	Net water productivity (Rs. /m^3)	Depth of irrigation water applied (cm)	Water productivity (kg/m^3)	Net water productivity (Rs. /m^3)
Sub-humid zone						
Rice	70.4	0.7	5.4	69.6	0.7	1.4
Wheat	7.4	6.4	35.2	6.0	7.0	23.6
Sugarcane	34.8	30.2	54.5	34.2	27.7	54.0
Semi-arid zone						
Rice	163.6	0.3	4.1	153.3	0.3	3.6
Wheat	9.7	4.8	36.4	9.1	4.7	25.1
Sugarcane	40.1	25.7	35.2	36.0	27.7	27.3
Cotton	7.0	2.5	51.2	6.2	2.6	43.6
Bajra	4.0	2.9	4.1	2.3	4.9	3.8
Arid zone						
Rice	168.0	0.3	5.3	153.8	0.3	5.1
Wheat	10.4	4.8	44.3	9.9	4.6	30.6
Cotton	9.6	1.9	27.5	9.3	2.0	27.0
Bajra	2.0	8.7	65.2	2.0	9.2	38.9
Mustard	3.9	4.5	110.5	3.6	5.3	132.9
Haryana						
Rice	134.0	0.4	4.9	125.6	0.4	3.4
Wheat	9.2	5.3	38.6	8.3	5.4	26.4
Sugarcane	37.5	27.9	44.9	35.1	27.7	40.7
Cotton	8.3	2.2	39.4	7.8	2.3	35.3
Bajra	3.0	5.8	34.7	2.2	7.1	21.2
Mustard	3.9	4.5	110.5	3.6	5.3	132.9

electricity comes on stream, putting a tremendous load on transformers. The high burnout rate of transformers can be partly attributed to over-loading problems caused both by too many tube-wells being connected to a transformer and the use of higher horsepower than the horsepower registered. With regard to flat tariff rates of energy supply and subsidy given to farmers for running their tube-wells, over 90 percent of the farmers have been found satisfied, however, a cut will curtail their procurement with respect to fertilizers, seeds, insecticides and pesticides. Interestingly, all farmers have supported a fixed energy policy for irrigation sector. Remarkably, 84 percent of the surveyed farmers are willing to pay more for better quality of energy supply, but if higher tariffs are loaded on without quality improvements, then burden on farmers will indeed by very high.

Table 14 shows the evaluations of the issue pertaining to the energy and groundwater irrigation nexus that have been rated as "most significant," "second most critical," and "third most critical." An unreliable power supply and falling groundwater levels have been perceived to be the most critical problems by the interviewed farmers, hence, the most critical problem areas. The high rate of tube-wells failure and decreased tube-wells yield are the next criticality levels. However, high energy cost is also critical but for a minuscule proportion of surveyed farmers. Furthermore, a large number of farmers across all climate zones have described inadequate electricity supply as the most pressing issue. Conversely, falling groundwater levels and reduced tube-well yields are relatively less important issues in sub-humid and semi-arid zone, respectively. Finally, while reduced tube-well yield is a critical concern, it does not appear in the farmers' responses, despite the fact that declining groundwater levels have been identified as the most critical.

Findings, conclusions and policy implications

The energy use pattern, which is directly related with the development of groundwater, has emerged as a major concern in highly irrigated ecosystem of north western India. Therefore, the key findings emerging from the present study

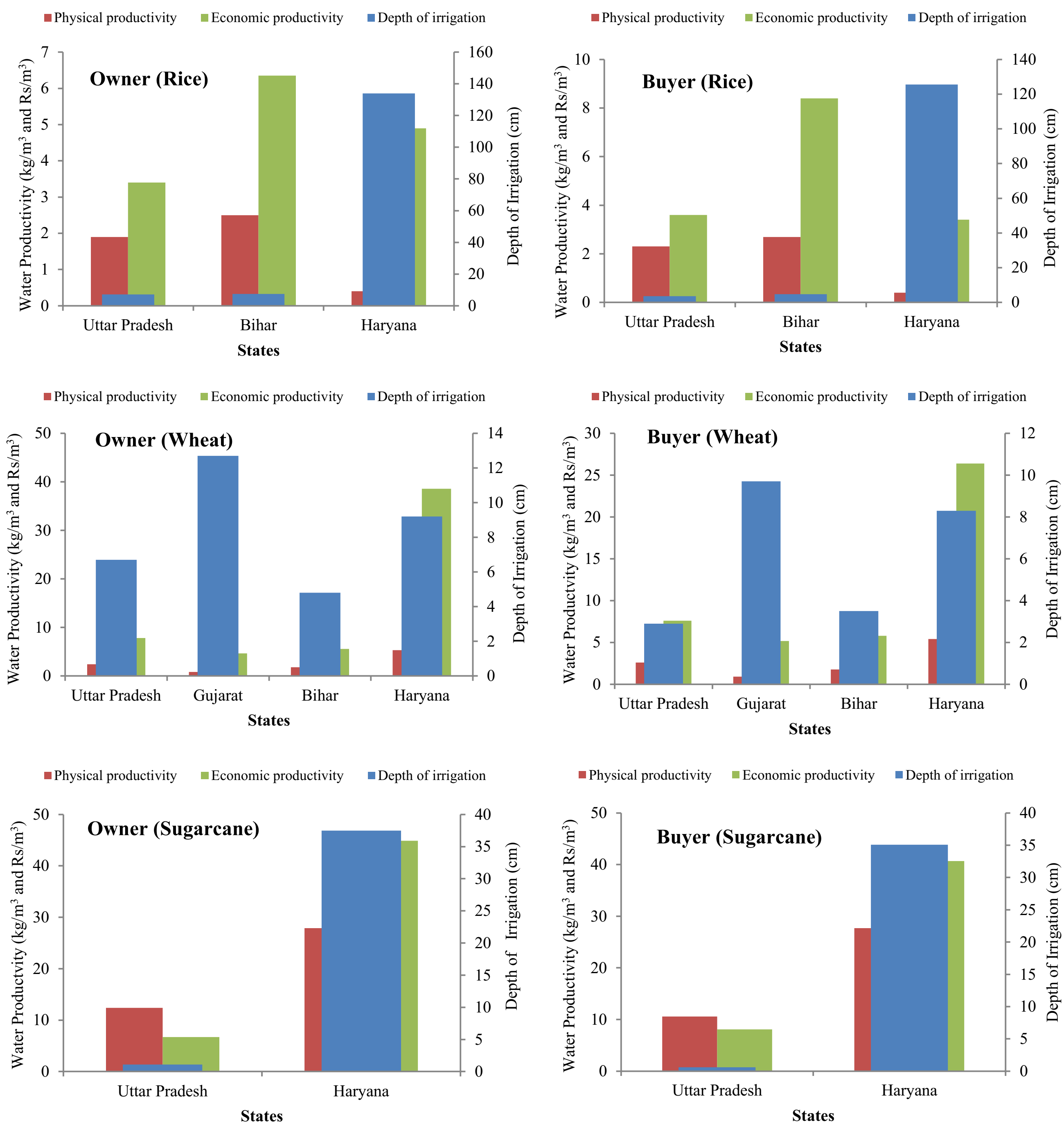

Fig. 11 Comparison of depth of irrigation and water productivity (physical and economic) under major crops for tube-well owners and non-tube-well owners (buyer) in Uttar Pradesh, Bihar, Gujarat and Haryana

can be summarized as follows. First, an increase in number, density and pumping of groundwater has been observed on account of higher efficiency of tube-wells, subsidized energy supplies and introduction of a flat tariff-based horsepower rating. However, the share of energy consumption in groundwater irrigation sector has declined from 45 percent in 1990 to 28 percent in 2013. The continuing energy subsidies at unmanageable levels have threatened the state's fiscal health and also the groundwater resources. Second, the study shows that tube-wells operating hours and its per hectare running hours in addition to energy consumption and its per hectare usage in rice crop is far superior to other crops grown. Third, about 15 percent of large farmers have four tube-wells with high horsepower ratings, which use more energy and

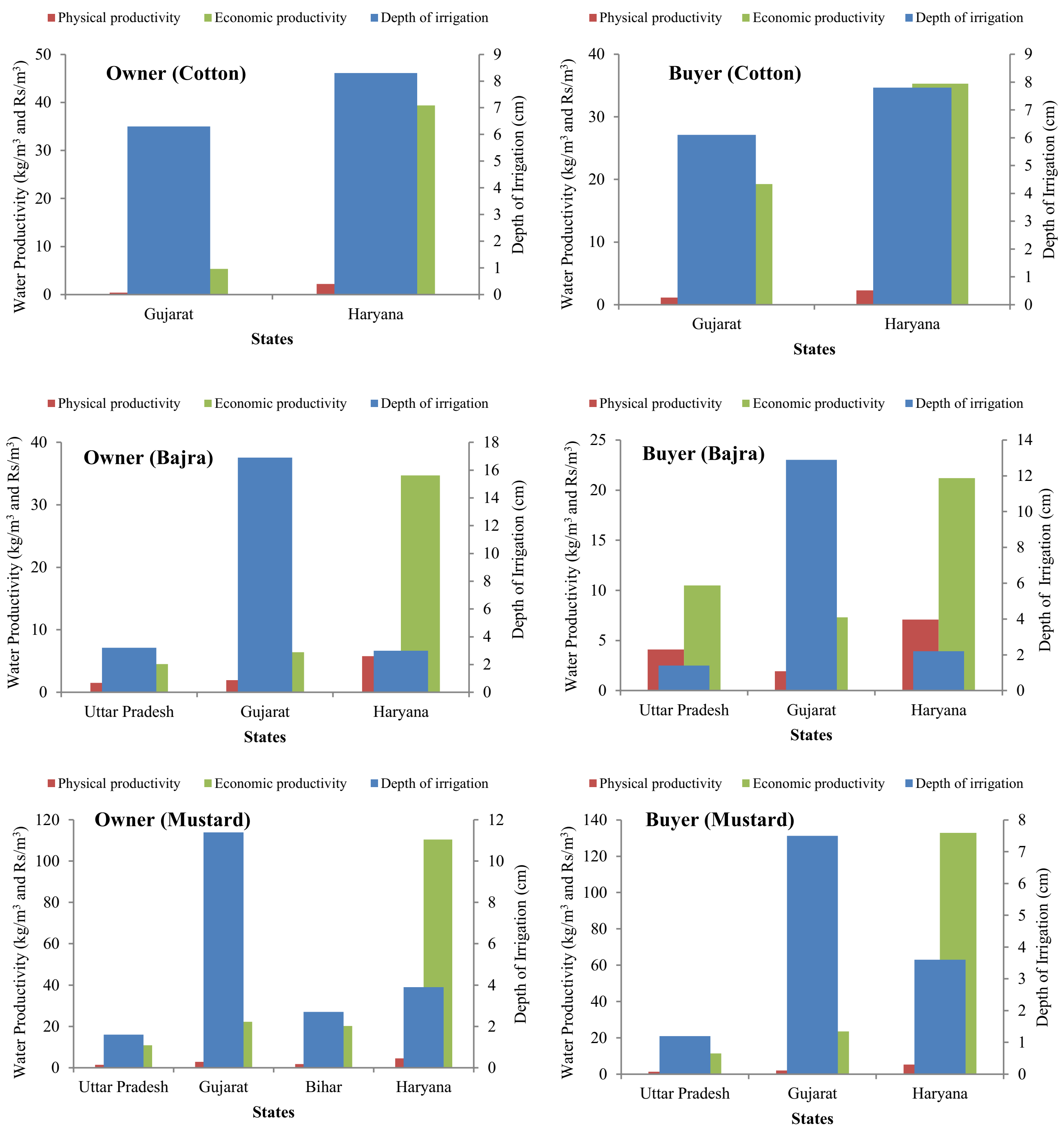

Fig. 11 (continued)

groundwater. As a result, large farmers profit more from subsidized energy, while small farmers remain excluded from energy subsidies. Fourth, subsidized energy made a great impact on the use factor of tube-wells. The use factor of large farmers is more than double that of small and medium farmers, confirming the fact that they consume more resources and benefit from subsidies. Fifth, the traditional low value crops have been replaced by high delta and high value crops like rice, cotton and sugarcane. Farmers' secure fairly high economic productivity as compared to their counterparts in Uttar Pradesh, Bihar and Gujarat. In addition, tube-well owning farmers obtain higher net returns than buyers on account of subsidized energy. Sixth, despite the availability of excellent banking facilities, Haryana's groundwater economy is largely supported by commission agents and money lenders, followed by personal savings. Finally, farmers are

Table 11 Number of watering, net water consumption, yield and return for major crops under flat tariff energy pricing regime in Haryana

Crops	Tube-well owners				Non tube-well owners (Buyers)			
	Number of watering	Volume of water applied (m^3/ha)	Yield (kg/ha)	Net return (Rs. /ha)	Number of watering	Volume of water applied (m^3/ha)	Yield (kg/ha)	Net return (Rs. /ha)
Sub-humid zone								
Rice	20	7040.7	4851.6	35,749.8	19	6963.5	4875.0	9190.4
Wheat	4	742.9	4260.9	22,705.3	6	758.3	3945.1	13,954.9
Sugarcane	16	3484.7	100,000.0	177,708.8	15	3416.7	91,666.7	180,977.8
Semi-arid zone								
Rice	25	16,356.1	4403.2	65,393.7	24	15,332.0	3950.0	54,887.5
Wheat	4	969.2	4304.8	32,316.8	5	907.7	4211.5	22,909.9
Sugarcane	16	4014.3	95,000.0	136,392.9	12	3600	100,000.0	98,250
Cotton	3	700	1633.3	41,166.7	3	616.7	1500.0	24,416.7
Bajra	2	400	1145.0	1645.8	1	229.2	1108.3	2385.4
Arid zone								
Rice	23	16,804.5	4736.5	87,619.9	21	15,384.6	4661.8	81,509.0
Wheat	5	1040.0	4450.0	40,962.2	4	990.5	4297.5	27,623.0
Cotton	4	962.1	1729.8	26,361.4	4	931.5	1810.2	25,426.6
Bajra	2	200.0	1747.1	13,036.5	1	197.6	1775.8	7414.9
Mustard	2	394.7	1733.3	42,543.3	2	358.8	1842.6	47,478.7
Haryana								
Rice	23	13,400.4	4663.8	62,921.1	21	12,560.0	4495.6	48,529.0
Wheat	4	917.4	4338.6	31,994.8	5	885.5	4151.4	21,495.9
Sugarcane	16	3749.5	97,500.0	157,050.85	14	3508.35	95,833.35	139,613.9
Cotton	4	831.1	1681.6	33,764.1	4	774.1	1655.1	24,921.7
Bajra	2	300	1446.1	7341.2	1	213.4	1442.1	4900.2
Mustard	2	394.7	1733.3	42,543.3	2	358.8	1842.6	47,478.7

Table 12 Different sources of funds used by farmers for tub-wells installation in Haryana (percent of farmers)

Source of funding	Small	Medium	Large	Average
Sub-Humid Zone				
Own savings	11.7	28.6	22.2	20.8
Commercial and co-operative banks	42.8	25.1	30.1	32.6
Commission agents and money lenders	32.8	46.3	47.7	42.2
Relatives, friends and others	12.7	0.0	0.0	4.2
Semi-arid zone				
Own savings	30.3	35.7	54.2	40.1
Commercial and co-operative banks	0.0	0.0	0.0	0.0
Commission agents and money lenders	69.7	64.3	45.8	59.9
Relatives, friends and others	0.0	0.0	0.0	0.0
Arid Zone				
Own savings	18.7	29.4	23.3	23.8
Commercial and co-operative banks	20.1	16.3	32.2	22.9
Commission agents and money lenders	34.7	43.8	24.5	34.3
Relatives, friends and others	26.4	10.5	20.0	18.9
Haryana				
Own savings	17.7	30.6	29.5	25.9
Commercial and co-operative banks	26.2	15.3	24.7	22.1
Commission agents and money lenders	39.5	49.5	36.8	41.9
Relatives, friends and others	16.6	4.5	9.1	10.1

Table 13 Farmers perception regarding energy policy in irrigation sector of Haryana (percentage of farmers agreed)

Particulars	Small	Medium	Large	Average
Sub-humid Zone				
Are you satisfied with energy supply policy related to irrigation?	20.0	13.9	17.1	17.0
Does energy supply for running tube-wells come according to your schedule?	19.4	17.1	18.9	18.5
Are you satisfied with numbers of hours of energy supply for irrigation?	20.0	2.8	8.6	10.5
Do you face shortage of energy for irrigation?	93.8	97.1	94.3	95.1
Do you experience frequent cuts in energy supply?	38.2	41.9	37.0	38.7
Do you experience low voltage for running tube-wells?	26.3	22.1	30.4	26.3
Do you experience damage to your tub-well due to low voltage?	77.4	75.0	76.5	76.3
Do you think metered rates for running tube-wells are satisfactory?	17.1	19.4	14.3	16.9
Do you think flat rates for running tube-wells are satisfactory?	94.3	94.4	91.4	93.4
Do you think subsidy on energy for running tube-wells is satisfactory?	100.0	100.0	100.0	100.0
Do you want a fixed energy policy?	100.0	100.0	100.0	100.0
Are you willing to pay for better energy supply?	78.1	88.9	82.9	83.3
Semi-arid Zone				
Are you satisfied with energy supply policy related to irrigation?	26.1	10.0	8.3	14.3
Does energy supply for running tube-wells come according to your schedule?	6.7	10.5	2.9	6.7
Are you satisfied with numbers of hours of energy supply for irrigation?	21.7	10.0	16.7	13.1
Do you face shortage of energy for irrigation?	86.7	100.0	100.0	95.6
Do you experience frequent cuts in energy supply?	51.7	50.0	46.5	49.4
Do you experience low voltage for running tube-wells?	0.0	2.6	2.8	1.8
Do you experience damage to your tub-well due to low voltage?	0.0	5.3	2.9	2.7
Do you think metered rates for running tube-wells are satisfactory?	56.5	35.0	52.8	48.1
Do you think flat rates for running tube-wells are satisfactory?	82.6	89.5	91.9	88.0
Do you think subsidy on energy for running tube-wells is satisfactory?	95.7	100.0	100.0	98.6
Do you want a fixed energy policy?	100.0	100.0	100.0	100.0
Are you willing to pay for better energy supply?	73.3	100.0	97.1	90.1
Arid Zone				
Are you satisfied with energy supply policy related to irrigation?	11.8	20.7	6.5	10.9
Does energy supply for running tube-wells come according to your schedule?	0.0	0.0	6.3	2.1
Are you satisfied with numbers of hours of energy supply for irrigation?	20.6	37.9	16.1	24.9
Do you face shortage of energy for irrigation?	81.3	82.1	87.5	83.6
Do you experience frequent cuts in energy supply?	45.9	50.0	45.2	47.0
Do you experience low voltage for running tube-wells?	9.8	4.3	6.5	6.9
Do you experience damage to your tub-well due to low voltage?	25.8	14.8	12.9	18.9
Do you think metered rates for running tube-wells are satisfactory?	36.4	46.7	58.1	47.0
Do you think flat rates for running tube-wells are satisfactory?	91.2	100.0	87.1	92.8
Do you think subsidy on energy for running tube-wells is satisfactory?	100.0	96.6	100.0	98.9
Do you want a fixed energy policy?	100.0	100.0	96.8	98.9
Are you willing to pay for better energy supply?	80.6	60.7	96.6	79.3
Haryana				
Are you satisfied with energy supply policy related to irrigation?	18.7	15.1	10.8	14.9
Does energy supply for running tube-wells come according to your schedule?	9.1	9.9	9.6	9.5
Are you satisfied with numbers of hours of energy supply for irrigation?	20.7	16.5	13.7	16.9
Do you face shortage of energy for irrigation?	87.3	92.7	94.1	91.4
Do you experience frequent cuts in energy supply?	43.4	45.9	42.2	43.8
Do you experience low voltage for running tube-wells?	15.7	12.9	15.1	15.6
Do you experience damage to your tub-well due to low voltage?	41.6	37.2	31.0	36.6
Do you think metered rates for running tube-wells are satisfactory?	34.1	32.6	41.2	35.9
Do you think flat rates for running tube-wells are satisfactory?	90.2	95.2	90.3	91.9
Do you think subsidy on energy for running tube-wells is satisfactory?	98.9	98.8	100.0	99.2
Do you want a fixed energy policy?	100.0	100.0	99.0	99.6
Are you willing to pay for better energy supply?	78.2	81.9	91.8	83.9

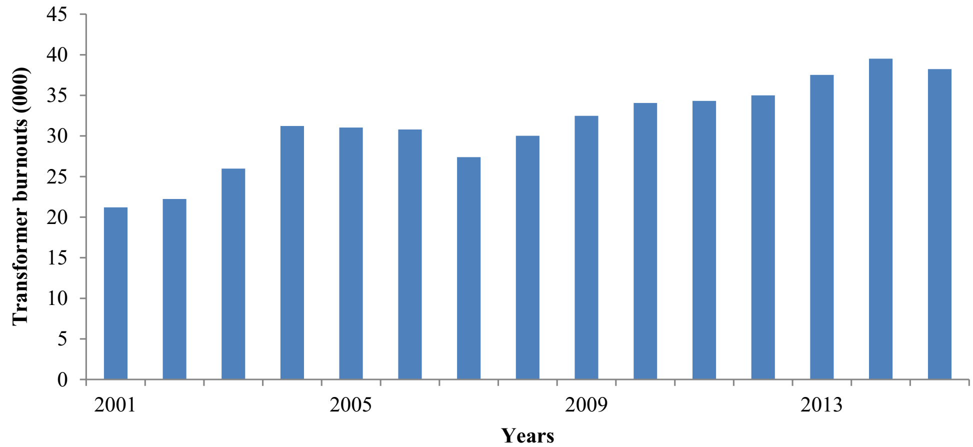

Fig. 12 Transformer burnouts in Haryana during 2001–2015

Table 14 The most critical problems faced by farmers in energy-groundwater irrigation sector of Haryana

Percentage of farmers	High energy costs	Unreliable electricity supply	Falling groundwater levels	High rate of tube-well failure	Reduced tube-well yield
Sub-humid Zone					
Percentage of farmers who rated this as the most critical problem	7.2	76.0	49.6	36.8	32.0
Percentage of farmers who rated this as the second most critical problem	4.0	23.2	24.0	28.0	15.2
Percentage of farmers who rated this as the third most critical problem	88.8	0.8	26.4	35.2	52.8
Semi-arid Zone					
Percentage of farmers who rated this as the most critical problem	11.0	74.0	92.0	55.0	26.0
Percentage of farmers who rated this as the second most critical problem	10.0	17.0	8.0	23.0	35.0
Percentage of farmers who rated this as the third most critical problem	79.0	9.0	0.0	22.0	39.0
Arid Zone					
Percentage of farmers who rated this as the most critical problem	8.1	75.6	74.1	51.9	37.8
Percentage of farmers who rated this as the second most critical problem	15.6	23.7	25.9	28.1	34.8
Percentage of farmers who rated this as the third most critical problem	76.3	0.7	0.0	20.0	27.4
Haryana					
Percentage of farmers who rated this as the most critical problem	8.6	75.3	70.6	47.5	32.5
Percentage of farmers who rated this as the second most critical problem	10.0	21.7	20.3	26.7	28.1
Percentage of farmers who rated this as the third most critical problem	81.4	3.1	9.2	25.8	39.4

becoming increasingly concerned about inadequate energy supplies and declining groundwater levels.

To summarize, there is nothing that can be done in the state to boost the groundwater economy without having an effect on the energy economy. Therefore, it is suggested that farmers should make a judicious use of energy while irrigating their fields as saving of energy will save groundwater and vice versa. A robust energy policy, especially for tube-wells, must be implemented as a powerful tool for controlling groundwater overdraft. Inability to handle this nexus would be a huge opportunity for both energy and groundwater resource management to be more sustainable.

To solve the energy-groundwater irrigation nexus, the following options must be introduced. First, the most sensible alternative is an acceptable tariff (flat or metered) that is closer to the cost of production, as well as limits on new connections. However, doing this will remain a political sensitive issue in the state. Therefore, the scheme like *Jyotigram* implemented in Gujarat offers a practical solution to restore health to the finances of energy utilities. Second, proper groundwater withdrawal rationing combined with energy unit pricing can play a complex role in energy and groundwater resource management. As a result, it will be a powerful tool for achieving productivity, long-term sustainability, and equity. The third alternative is to set an electricity tariff based on how much groundwater is used. The Haryana Electricity Regulatory Commission currently sets energy tariffs for various customers in the state, which are based on the state's pooled average cost of supply. Instead of using a pooled average cost of electricity, tariffs should be based on the classification of groundwater as over-exploited, critical, or protected. This will not only put the two sectors closer together, but it will also provide some transparency for the use of groundwater. As compared to areas classified as safe, it is proposed that areas classified as over-exploited should have higher energy tariffs, either flat or metered. Farmers will be unable to grow water-intensive crops in over-exploited and critical areas due to high energy tariff rates. Higher tariff rates for over-exploited and critical areas would serve as an environmental cess, which farmers in these areas will be required to pay in order to use groundwater.

Furthermore, energy availability is good and reliable, when the irrigation needs of the farmers are low, and of inferior quality and short in supply when the irrigation needs are higher during rice transplantation. When the irrigation needs are higher and power supply is unreliable, farmers are frustrated and opt for options such as excessive pumping of groundwater resulting into energy pilferage. Such groundwater pumping behavior on behalf of the farmers not only leads to stress the distribution infrastructure and transformer burnouts, but also increase the monetary losses. Therefore, the matching energy supply according to irrigation needs of the farmers will result into a beneficial situation both for farmers and policy makers in controlling the volume of groundwater and energy subsidy. Therefore, intelligent power supply is suggested for Haryana, which will match the energy supply pattern with crop water requirements.

Another policy choice is to ensure that all energy supplied to the irrigation sector is of prescribed quality, standard voltage, and frequency, as this will reduce motor damage and transformer burnout. One of the criticisms of the subsidized energy supply is that the subsidies in irrigation sector are regressive because higher the energy consumed by a farmer, the higher the subsidy benefits offered. Therefore, it is suggested that large farmers need to be excluded from the ambit of subsidized energy supply in a phased manner. Apart from this, to take off the burden of electricity subsidy for irrigation sector, the state government should start advocating the use of solar powered tube-wells. If installation of solar powered tube-wells becomes effective, then the state's economy will get respite from the debits of electricity subsidy in the upcoming years. Rice cultivation in arid and semi-arid areas should also be checked for sustainable groundwater management. A good measure in this regard can be encouragement to maize cultivation through higher minimum support price (MSP) to reduce groundwater mining or provision of drought resistant rice varieties for future sustainability of agriculture in the state. Finally, prepaid meters deter energy theft and can be powered with tokens or magnetic cards, as well as digitally recharged. Such methods are extensively used to meter the energy consumption of tube-wells in the North China Plains and general energy consumers in South Africa.

To conclude, Haryana is a state in north western India. Other states sharing identical environmental conditions in north western India, are likely to be symptomatic of the energy and groundwater characteristics of the Haryana. It is, therefore, hoped that the implementation of above suggested policies in energy and groundwater sectors will not only be beneficial for Haryana but would find applications to other states of north western India.

Author contributions OS designed and conceived the research idea, took lead in the supervision and prepared the initial draft. AK did field survey, analyzed data, did literature review and prepared figures and tables. PB provided suggestions and edited the final version of the manuscript. The listed authors have made a significant contribution to warrant their being part of authorship and have approved the work.

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Declarations

Conflict of interest The author declares no conflict of interest.

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