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Exploring the Determinants of Groundwater Exploitation Among Indian Districts

G. Karthiga Devi, A. Narayanamoorthy, K. S. Sujitha and R. Suresh *

ABSTRACT

The annual groundwater draft of India is the largest in the world as of 2020. The agricultural sector alone consumes about 89 per cent of groundwater draft. Besides providing assured irrigation, groundwater has significantly helped increase the cropping intensity, productivity and production of crops. But, due to the continuous exploitation of groundwater, not only has the water level been depleted but the cost of water has increased. An attempt is made in this study to find out the determinants of groundwater exploitation by taking data from 235 Indian districts drawn from different states covering two-time periods namely 1990-93 and 2017-20. The study indicated that the number of districts exploiting groundwater more than 50 per cent to its annual recharge has increased from 21 per cent in 1990-93 to 69 per cent in 2017-20. The regression analysis shows that the average size of holding is the most important factor in positively influencing groundwater exploitation, whereas the percentage of surface irrigated area to net irrigated area negatively and significantly influences the groundwater exploitation. The analysis also suggests that the impact of these two variables in determining groundwater exploitation have increased significantly over time.

Keywords: Cropped area; groundwater; irrigated area, over-exploitation; Indian irrigation

JEL: Q15, Q18, Q24, Q25

I

INTRODUCTION

Groundwater is the major source of water in India, which contributes over 65 per cent to irrigation, 85 per cent to rural water supply and 50 per cent to urban water supply as of 2020 (Shah, 2009; Narayanamoorthy, 2010a; Shankar *et al*., 2011; Sinha and Densmore, 2016; CGWB, 2021). The net area groundwater irrigation has increased from 7.30 million hectares (mha) in 1960-61 to about 48 mha in 2018-19 (Government of India, 2022), while its share in the total irrigated area has increased from 29 per cent to 68 per cent during the same period.[1] About 89 per cent of groundwater is used for irrigation purposes alone in India. Besides providing assured irrigation facilities for the farmers, it helps increase cropping intensity, productivity and production of crops significantly as compared to other irrigation sources namely canals and tanks (Shankar *et al*., 2011; Narayanamoorthy, 2022). But, the continuous exploitation of groundwater of late has created many problems (Reddy, 2005; Bhalla, 2007; Sarkar, 2011; Narayanamoorthy, 2015; Srivastava *et al*., 2017; Bhattarai *et al*., 2021). A study conducted by NASA in 2009 underlined that groundwater level has been declining about one meter every three years in states like Rajasthan, Punjab and Haryana. Shockingly, between 2002 and 2008, about 109 cubic km of groundwater reportedly vanished from these regions due to reckless exploitation (cited in CSE, 2019). Recent data published by CGWB (2021) shows that the number of blocks classified as other than safe has increased from 28.74 per cent (1645) in 2004 to 36.44 per cent (2538) in 2020. Importantly, a World Bank (2010) study cautioned that about 60 per cent of its aquifers will reach a critical stage by 2032.

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* Ph.D., Scholar , ** Senior Professor and Head, ***Research Associate and **** Assistant Professor ,Department of Economics and Rural Development, Alagappa University, Karaikudi - 630 003, Tamil Nadu.

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Groundwater exploitation in different states has changed completely since the 1990s mainly because of the intensification of agriculture and rapid changes in overall economic activities (see, Table 1). The speedy development of borehole technology in the 1990s has further accentuated the exploitation of groundwater. The exploitation of groundwater has also increased significantly because of faulty minimum support price policies, which did not consider the water consumption of the crops for fixing prices (Narayanamoorthy, 2021 and 2022). Due to this, farmers are forced to cultivate more water-loving crops like paddy, sugarcane, banana and vegetables. Though groundwater exploitation (defined as groundwater withdrawal to its annual recharge) has been increasing since the introduction of green revolution technology, the cheaper electricity pricing policies followed by the successive state governments reportedly encouraged the over-exploitation of groundwater (Kumar, 2005; Palanisami *et al*., 2008; Kondepati, 2011; Gill and Nehra, 2018; Dangar *et al*., 2021; Kumar *et al*., 2022). Studies show that the heavily subsidised flat-rate and free electricity given to agricultural purposes often encourages the farmers to exploit groundwater recklessly, as the marginal cost of lifting water from the wells under a flat-rate tariff is close to zero (Narayanamoorthy, 1994 and 1997; Kumar *et al.*, 2011).

TABLE 1: ANNUAL GROUNDWATER DRAFT BY MAJOR STATE, 1993 AND 2020

States	Annual groundwater draft (BCM)		Stage of groundwater development (per cent)		Per cent increase in groundwater draft over 1993
	1993	2020	1993	2020	
(1)	(2)	(3)	(4)	(5)	(6)
1. Andhra Pradesh	4.35	15.64	25.58	33.26	259.54
2. Bihar	4.47	13.02	18.56	51.14	191.28
3. Gujarat	5.81	13.30	41.74	53.39	128.92
4. Haryana	3.72	11.61	92.57	134.56	212.10
5. Karnataka	3.87	10.63	32.09	64.85	174.68
6. Madhya Pradesh	6.42	18.97	16.67	56.82	195.48
7. Maharashtra	6.60	16.63	29.37	54.99	151.97
8. Odisha	1.17	6.86	8.34	43.65	486.32
9. Punjab	7.99	33.85	93.79	164.42	323.65
10. Rajasthan	5.07	16.63	54.76	150.22	228.01
11. Tamil Nadu	9.88	14.67	61.50	82.93	48.48
12. Uttar Pradesh	19.97	46.03	37.05	68.83	130.50
13. West Bengal	4.20	11.84	24.34	44.60	181.90
All India	85.66	244.92	30.04	61.60	185.92

Sources: CGWB (1995 and 2021), Dynamic Groundwater Resources Assessment of India.

The free supply of electricity appears to harm more than providing benefits particularly to farmers having shallow tube-wells, besides increasing the subsidy burden to the states (Monari, 2002; Ramaswami, 2019). As bore-wells with long depths exploit more groundwater, the water in shallow wells gets depleted and they ultimately become defunct. The depleting water level also shortens the life period of the wells, making a huge impact on the resource-poor farmers, who cannot install deep bore-wells with larger size HP pumpsets. The Fifth Minor Irrigation Census (MoWR, 2017) shows a total of 4.14 lakh open wells in India defunct between 2006-07 and 2013-14. Falling groundwater tables also result in the escalation of irrigation costs for farmers and thereby a rise in the cost of cultivation of crops. The NITI Aayog (2018) in its *Report on Composite Water Management Index* has warned that if the situation persists, there will be a 6 per cent loss in the country's

Gross Domestic Product (GDP) by 2050. And up to a quarter of India's harvest has been estimated to be at risk due to groundwater depletion (Shah, 2001).

Given the increased importance of groundwater irrigation, several studies have been carried out covering various aspects of groundwater irrigation over time in India (Shah, 1993; Dhawan, 1995; Saleth, 1991; 1997; Moench, 1992, 1994; Vaidyanathan, 1996; Saleth and Thangaraj, 1993; Ramasamy *et al*., 1999; Shah *et al*., 2003; Kumar, 2000; 2007; Narayanamoorthy, 2010a; 2022). The severity of the exploitation of groundwater has also been explained by studies (Shankar et al., 2011; Kaur and Vatta, 2015; Sinha and Densmore, 2016; Jain *et al*., 2021). The report of the expert group on "Groundwater Management and Ownership" surmises that "Since groundwater is an open access resource, the tragedy of commons often occurs where everyone tries to extract as much water as she can and degrades the resource" (Planning Commission, 2007, p.v). After analysing the issue of exploitation of groundwater in an in-depth manner, Shankar *et al.,* (2011, p.45) underline that "Recent data on the status of groundwater resources in India reveal alarming trends. The rate of withdrawal of groundwater has reached "unsafe" levels in 31 per cent of the districts, covering 33 per cent of the land area and 35 per cent of the population. The situation has dramatically worsened within a short span of nine years between the assessment done in 1995 and 2004". This situation may have worsened further now. Though many studies are available focusing on various issues of groundwater, detailed studies on the determinants of groundwater and that too covering data from a large number of districts are seldom available. Groundwater exploitation is determined by many factors which are expected to change over time because of rapid changes that are taking place in the agricultural sector, which also consumes close to 90 per cent of groundwater withdrawal. Keeping in view all these developments, using data from 235 districts covering two-time periods namely 1990-93 and 2017-20, an attempt is made in this study with following two major objectives: (1) to find out the level of change in the groundwater exploitation among the districts between the two-time periods and (2) to study whether the determinants of groundwater exploitation are changing between the two time periods.

II

DATA AND METHOD

This study is carried out entirely by using secondary data from 235 Indian districts covering two-time periods namely 1990-93 and 2017-20. These 235 districts accounted for about 48 per cent of India's gross cropped area of 197 million hectares in 2018-19. A total of eight variables are used for the analysis, which are compiled from various sources. The data on the irrigated area including Groundwater Irrigated Area (GWA), area under different crops, Net Sown Area (NSA) and Gross Cropped Area (GCA) and Cropping Intensity (CI) were compiled from the publication of *District Wise Land Use Statistics* (published by the Ministry of Agriculture and Farmers Welfare, Government of India, New Delhi). The data on Average Size of Holding (ASH) and number of pumpsets (PS) were compiled from the *All India Report on Input Survey* (published by the Ministry of Agriculture and

Farmers Welfare, Government of India, New Delhi). The Value of Agricultural Output (VAO) at 1990-93 prices and Fertiliser Use per hectare (FERT) were compiled from Bhalla and Singh (2001 and 2012) and *Fertiliser Statistics* (FAI, 2021). The data on VAO for the period 2017-20 was estimated by taking into account its average increase between 1990-93 and 2003-06, as the latest data was not available from Bhalla and Singh (2012).

A major part of the study is carried out using multiple regression (OLS method) analysis. To study the changes in the level of groundwater exploitation across the 235 districts, a descriptive analysis is conducted by classifying the districts into various groups in terms of the level of groundwater exploitation. The regression model (1) presented below is employed to study the determinants of groundwater exploitation:

$$GWE = a + b_1ASH + b_2CI + b_3FERT + b_4PSI/GCA + b_5SIA/NIA + b_6VAO + b_7WIC/GCA + \mu \quad \ldots (1)$$

Where,

ASH	= Average size of holding in hectares
CI	= Cropping intensity in percent
FERT	= Fertiliser consumption in kg/hectare
GWE	= Groundwater exploitation to its annual recharge in percent
PSI/GCA	= Pumpset intensity per 1000 hectare of gross cropped area
SIA/NIA	= Share of the surface irrigated area to net irrigated area in percent
VAO	= Value of agricultural output per hectare at 1990-93 prices
WIC/GCA	= Share of water-intensive crops' area to gross cropped area in percent
a	= constant to be estimated
b	= regression coefficient to be estimated
μ	= error term

Of the eight variables used for the analysis, the percentage of Groundwater Exploitation (GWE) to its annual recharge is used as dependent variable to capture the exploitation level. The remaining seven variables are used as independent variables (ASH, CI, FERT, PSI/GCA, SIA/NIA, VAO and WIC/GCA,) in the regression model. There are valid reasons for using these seven independent variables in this study. The increased area under water-intensive crops is expected to accelerate the exploitation of groundwater and therefore, WIC/GCA is used as an independent variable. Besides wheat and sugarcane, crops like banana, coconut, turmeric, vegetables, etc., are also predominantly cultivated using groundwater. But, due to the non-availability of district-wise data on various water-intensive crops, we have considered crops such as wheat and sugarcane plus 10 per cent of these crops area as the total area of water-intensive crops in this study. The variable ASH is used in the analysis because the size of holding and exploitation of groundwater are highly correlated due to a variety of reasons. Cropping intensity (CI), which is the ratio of gross cropped area to net cropped area, is included in the analysis to capture its impact on the exploitation of groundwater. The increased adoption of modern inputs such as fertilisers, HYV seeds, mechanisation, etc, reflects the intensity of agriculture (Bhalla and Singh, 2001). But, due to data constraints, the fertiliser (FERT) variable is used to reflect the development of agriculture, as most yield augmenting factors tend to move in tandem with fertiliser use. The variable PSI/GCA is used in the study because wherever pumpset intensity is higher (number of pumpsets per 1000 ha of cropped area), the exploitation of groundwater is also expected to be higher. The VAO (value of agricultural output per hectare) is another variable used to reflect the development of agriculture, which is expected to play a big role in determining groundwater exploitation.

III

RESULTS AND DISCUSSION

Characteristics of the Districts:

Since the study uses a total of 235 districts from different states, it will be useful to understand the overall characteristics of the districts before getting into the analysis. For this, the averages and standard deviation (SD) are worked out for all eight variables for two-time periods, which are presented in Table 2. The averages of all the variables by and large reflect the national level picture. For instance, the average size of holding of the selected districts has declined from 2.08 ha in 1990-93 to 1.53 ha in 2017-20, which is in line with the national level picture. Similarly, the surface (includes canals plus tanks area) irrigated area to net irrigated area has declined from 32.08 per cent to 28.29 per cent, which is also in conformity with the national level picture (Narayanamoorthy, 2007 and 2022; Kimberly *et al*., 2016; Reddy *et al*., 2018).

TABLE 2: AGRO-ECONOMIC CHARACTERISTICS OF 235 DISTRICTS

Sl. No.	Variables	Unit	1990-93		2017-20		Per cent change in Mean over 1990-93
			Mean	Standard deviation	Mean	Standard deviation	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.	Area under Water-Intensive Crops to Gross Cropped Area (WIC/GCA)	Per cent	32.68	21.08	8.77	26.63	18.64
2.	Average Size of Holding (ASH)	ha	2.08	1.90	1.53	1.19	-26.44
3.	Cropping Intensity (CI)	Per cent	132.34	23.34	147.12	34.50	11.17
4.	Fertiliser Use per hectare (FERT)	Kg/ha	77.59	67.45	171.48	104.73	121.01
5..	Groundwater Exploitation (GWE)	Per cent	38.07	32.56	75.31	49.90	97.82
6.	Pumpset Intensity per 1000 ha of Gross Cropped Area (PSI/GCA)	Per cent	60.16	53.89	77.39	68.77	28.64
7.	Surface Irrigated Area to Net Irrigated Area (SIA/NIA)	Per cent	32.08	26.69	28.29	24.76	-11.81
8.	Value of Agricultural Output per hectare at 1990-93 Prices (VAO)	Rs (in '00)	70.33	34.93	91.27	54.96	29.77

Sources: Bhalla and Singh (2001 and 2012); CGWB (1995 and 2021); FAI (2021); GoI (various years); Government of India (2007 and 2021).

Except for ASH and SIA/NIA, the averages of all other variables have increased considerably between the two-time periods considered for the analysis. The most important yield-increasing input namely fertiliser has massively increased from 77.59 kg/ha to 171.48 kg/ha, while the cropping intensity has increased from about 132 per cent to 147 per cent between the two time periods. As a result of increased cropping intensity and fertiliser consumption, the value of agricultural output (at 1990-93 prices) has also increased from Rs. 7033/ha to 9127/ha. Predictably, the groundwater exploitation of the selected districts has increased almost double between the two periods (from about 38 per cent to 75 per cent) along with the pumpset intensity that increased from 60.16 to 77.39 per 1000 hectare of gross cropped area. With increased irrigation coverage, the share of area under water-intensive crops to gross cropped area has also increased from about 33 per cent to 39 per cent. Although there are no surprising results in the averages worked out for different parameters, the value of standard deviation suggests that the inequality in the use of such parameters has increased among the districts between the two time periods.

Dynamics of Groundwater Exploitation by Districts:

The annual draft of groundwater for various purposes has been increasing continuously over time in India. The data published by CGWB (2021) reveals that the number of blocks classified as other than safe has increased from 1645 (28.74 percent) in 2004 to 2538 (36.44 percent) in 2020 (see, Figure 1). Keeping this in view, as a precursor to the analysis of determinants of groundwater exploitation, an attempt is made to find out whether any drastic change has taken place among the selected 235 districts in the level of groundwater exploitation between the two time periods: 1990-93 and 2017-20. For the purpose of analysis, the districts are classified into seven categories starting from less than 20 percent to over 70 per cent based on the exploitation of groundwater, as specified in Table 3.

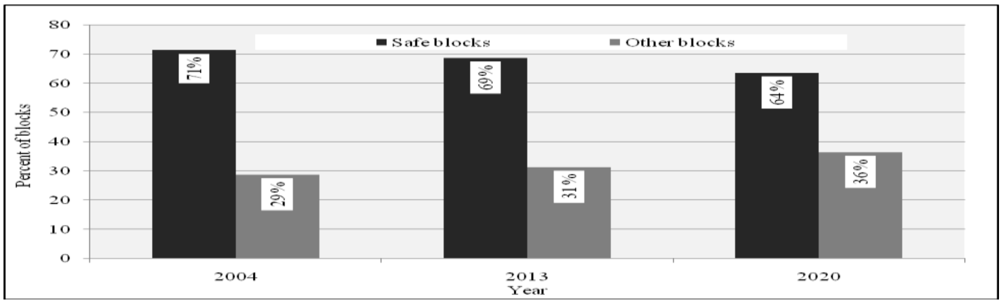

Figure 1: Trends in Safe and Over-Exploited Groundwater Blocks in India

TABLE 3: CLASSIFICATION OF DISTRICTS BY LEVEL OF GROUNDWATER EXPLOITATION

Level of groundwater exploitation (1)	1990-93 (2)	2017-20 (3)	Per cent change over 1990-93 (4)
< 20 per cent	68 (28.94)	11 (4.68)	-83.82
20 - 30 per cent	34 (14.47)	14 (5.96)	-58.82
30 - 40 per cent	46 (19.57)	23 (9.79)	-50.00
40 - 50 per cent	37 (15.74)	25 (10.64)	-32.43
50 - 60 per cent	16 (6.81)	31 (13.19)	93.75
60 - 70 per cent	12 (5.11)	44 (18.72)	266.67
> 70 per cent	22 (9.36)	87 (37.02)	295.45
Total number of districts	235 (100)	235 (100)	---

Sources: CGWB (1995 and 2021); GoI (various years).

Note: Figures in parentheses are percentage to total number of districts.

It is evident from the table that the situation of groundwater exploitation has dramatically worsened between 1990-93 and 2017-20. Two distinct patterns emerge from the district-wise level of groundwater exploitation between the two time periods. First, there is a sharp increase in the number of districts exploiting groundwater by more than 70 per cent which has increased from 22 to 87 (an increase of about 295 per cent). Second, a significant reduction (about 83 per cent) has also taken place in the number of districts with less than 20 per cent of groundwater exploitation between 1990-93 and 2017-20. In other words, the number of districts exploiting more than 50 per cent of groundwater has increased dramatically from 50 to 162 between the two time periods, an increase of 224 per cent. One may be interested to know where are these over-exploited districts located? An in-depth analysis shows that districts with a sharp increase in groundwater exploitation (over 50 percent) are mostly from states like Punjab, Haryana, Gujarat, Maharashtra, Karnataka and Tamil Nadu. While all these states are also practicing intensive agriculture for many years now (Narayanamoorthy, 2021), the state-wise data on the extraction of groundwater in 2020 also reinforces this fact (see, Figure 2). The rapid depletion of groundwater is likely to emerge as a threat to agriculture-led rural development in the future (Fishman *et al.*, 2021).

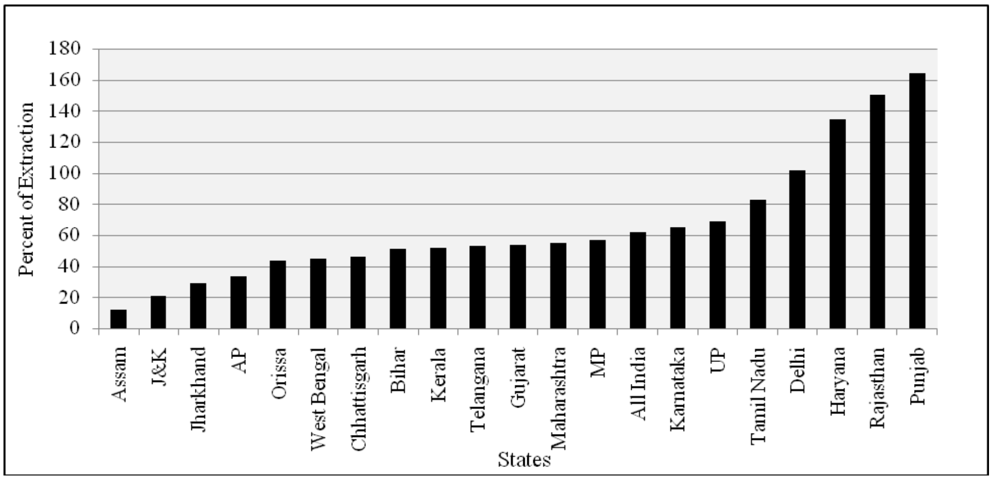

Figure 2: Percentage of Groundwater Extraction by Major States in 2020

Determinants of Groundwater Exploitation:

As reported earlier, the major focus of the study is to find out the determinants of groundwater use. For this, a multiple regression analysis is employed where the percentage of GWE is treated as a dependent variable. A total of seven independent variables (ASH, CI, FERT, PSI/GCA, SIA/NIA, VAO and WIC/GCA) are used in the regression analysis to capture their influence on groundwater exploitation. Table 4 presents the regression results estimated treating the per cent of GWE as a dependent variable for two time periods namely 1990-93 and 2017-20. At the all India level, the GWE was only about 30 per cent in 1990-93, but it increased significantly to 62 per cent in 2017-20. As the intensity of groundwater exploitation is very high in the later period as compared to the former period, it is expected that the sign and the magnitude of regression coefficients of different variables will be different between the two periods considered for the analysis. As expected, there are wide differences in the magnitude of regression coefficients including the value of R^2 and adjusted R^2 between the two periods. The value of R^2 estimated for the period 1990-93 was only 0.368, but it increased to 0.455 for 2017-20, which suggests that the independent variables included in the regression model explain the variation in groundwater exploitation strongly in the latter period as compared to its previous period 1990-93.

TABLE 4: REGRESSION RESULTS ON FACTORS DETERMINING GROUNDWATER EXPLOITATION

Variables	Dependent variable: Per cent of GWE	
	1990-93	2017-20
(1)	(2)	(3)
1. ASH	3.645 (3.764)[a]	16.743 (7.512)[a]
2. CI	0.304 (3.119)[a]	0.283 (3.690)[a]
3. FERT	0.062 (2.022)[b]	0.095 (3.758)[a]
4. PSI/GCA	0.114 (2.876)[a]	0.003 (0.089)[ns]
5. SIA/NIA	-0.455 (-6.374)[a]	-0.821 (-7.989)[a]
6. VAO	0.095 (1.283)[d]	-0.016 (-0.345)[ns]
7. WIC/GCA	0.035 (0.319)[ns]	0.197 (1.815)[c]
Constant	-14.631 (-1.234)[ns]	23.940 (1.853)[c]
R^2	0.368	0.455
Adjusted R^2	0.348	0.438
F-value	18.855[a]	27.031[a]
N	235	235

Sources: Computed using sources referred in Table 2.

Notes: a, b, c and d are significant at 1, 5, 10, 20 percent level respectively; ns-not significant; figures in parentheses are 't' values.

The sign and the magnitude of regression coefficients of most variables are on the expected line. The values of correlation matrix computed for the variables included in the study are also on the expected line (see, Table 5). Groundwater use is also closely related to the land holding size of farmer households because the large size holders will have more wells and also use higher horsepower pumpsets to lift water from the wells (see, MoWR, 2017). Therefore, the average size of holding (ASH) is used in the study to find out its impact on groundwater use. As expected, among all the variables included in the study, the coefficient of ASH appears to be the most important factor in positively determining groundwater exploitation in both time periods. The coefficient of ASH has increased from 3.645to 16.743, meaning that its impact is getting stronger over time in determining groundwater exploitation. This is plausible because the withdrawal level of groundwater by the large size farmer is reportedly higher in recent years in different regions in India (Shah, 2009; Saleth, 2011).

It is expected that CI will positively influence groundwater use because the increased groundwater availability allows the farmers to cultivate two or more crops on a piece of land per year. The coefficient of CI turned out to be positive in both periods, though its magnitude is very high in 1990-93, which is something unexpected. As expected, the percentage of water-intensive of crops to GCA has positively influenced groundwater exploitation. The magnitude of the regression coefficient of WIC/GCA has increased from 0.035 to 0.197 between the two periods, suggesting that the influence of water-intensive crops in the exploitation of groundwater has increased over time.[2] This is not a surprising result because the farmers in the groundwater regions are increasingly allocating more area for water-intensive crops like sugarcane, wheat, banana, turmeric, coconut, vegetables, etc., to increase the profitability.

TABLE 5: CORRELATION MATRIX OF THE VARIABLES USED IN THE STUDY: 1990-93 AND 2017-20

Variables	ASH	CI	FERT	GWE	PSI/GCA	SIA/NIA	VAO	WIC/GCA
For the period 1990-93								
1. ASH	1	0.238[a]	0.186[a]	0.372[a]	-0.243[a]	-0.046[ns]	-0.300[a]	-0.277[a]
2. CI		1	0.274[a]	0.324[a]	0.273[a]	-0.025[ns]	0.457[a]	0.618[a]
3. FERT			1	0.231[a]	0.295[a]	0.093[d]	0.547[a]	0.264[a]
4. GWE				1	0.382[a]	-0.405[a]	0.246[a]	0.172[a]
5. PSI/GCA					1	-0.258[a]	0.469[a]	0.184[a]
6. SIA/NIA						1	0.164[b]	0.124[b]
7. VAO							1	0.503[a]
8. WIC/GCA								1
For the period 2017-20								
1. ASH	1	0.083[ns]	0.138[b]	0.453[a]	0.035[ns]	-0.084[d]	-0.155[b]	-0.273[a]
2. CI		1	0.70[ns]	0.234[a]	-0.123[b]	-0.048[ns]	0.039[ns]	0.263[a]
3. FERT			1	0.113[c]	0.126[c]	0.024[ns]	0.238[a]	0.298[a]
4. GWE				1	0.062[ns]	-0.461[a]	-0.050[ns]	0.158[b]
5. PSI/GCA					1	-0.155[b]	0.194[a]	0.167[b]
6. SIA/NIA						1	0.055[ns]	0.136[b]
7. VAO							1	0.033[ns]
8. WIC/GCA								1

Sources: Computed using sources referred in Table 2.
Notes: a, b, c and d are significant at 1, 5, 10, 20 percent level respectively; ns-not significant.

It is expected that the pumpset intensity (number of pumpsets per 1000 hectare of GCA), which is termed as PSI/GCA in the study, will positively and significantly impact groundwater exploitation. But, its coefficient turned out to be positive and significant in 1990-93, but not significant in 2017-20. The fertiliser (FERT) variable, which is used to reflect the development of agriculture of the district, shows a significant and positive relationship with groundwater exploitation in both periods. The significant regression coefficient of fertiliser indicates that the exploitation of groundwater is higher wherever the application of fertiliser is also higher, which is not a surprising result. It is worth mentioning here that a large number of studies carried out in different regions in India have found a positive and significant relationship between the consumption of fertiliser per hectare and the availability of irrigation facilities. For instance, a study carried out by NCAER

(1991) shows that about 34 per cent of irrigated areas consumed about 69 per cent of India's total fertiliser consumption. A recent estimate available from the Fertiliser Association of India (FAI, 2021) for the period 2011-12 shows that the consumption of fertiliser was 187 kg/ha for irrigated areas as against the consumption of 82 kg/ha for the un-irrigated area. If an estimate is made separately for groundwater-irrigated areas, the share of fertiliser consumption might go up significantly.

The value of agricultural output (VAO) per hectare is used as a proxy variable to reflect the development of agriculture. It is expected that VAO will positively influence groundwater exploitation because high-value water-intensive crops are mostly cultivated in groundwater-irrigated areas. But, the coefficient of VAO turned out to be positive in 1990-93, but negative in 2017-20. This is an unexpected result. Probably, the growth variables such as CI and WIC/GCA, which are also closely related to VAO, may have dampened its impact on groundwater exploitation.

As expected, the percentage of surface irrigated area to net irrigated area (SIA/NIA) turned out to be the most important factor in negatively impacting groundwater exploitation. Interestingly, the magnitude of the regression coefficient of the variable has increased from -0.455 in 1990-93 to -0.821in 2017-20. The coefficient estimated from the data of 2017-20 suggests that a one per cent increase in SIA/NIA would decrease about 0.82 per cent of groundwater exploitation. The regression results also suggest that the influence of SIA/NIA in the exploitation of groundwater has increased considerably over time. This is plausible because wherever the availability of surface irrigation is higher, the farmers need not exploit groundwater for irrigating crops.

One of the objectives of the study is to find out whether the determinants of groundwater exploitation have changed between the two time periods. Given the rapid changes in the cropping pattern and cropping intensity across different states over time, it was presumed that the determinants of the groundwater exploitation may have changed considerably between two time periods. But, against our expectation, the regression analysis suggests that the factors determining groundwater exploitation have not changed dramatically in 2017-20 as compared to the period 1990-93. Out of seven independent variables, the coefficients of five variables turned out to be positive and significant in 1990-93, whereas only three variables turned out to be positive and significant in 2017-20. But, the magnitude of regression coefficients of two important variables namely ASH and SIA/NIA have increased substantially in determining the groundwater exploitation. This means that the strength of these variables in determining the groundwater exploitation have increased over time.

A caveat needs to be added here in connection with the regression results. Most of the variables considered for the regression analysis in this study are endogenous in nature. There are possibilities that the exogenous variables like changes in government policies (electricity tariff, bank credit, subsidy level for pumpsets, etc), variation in rainfall, etc., may have also triggered the over-exploitation of groundwater. For instance, the rainfall variability (deviation from normal rainfall) can induce the farmers to invest in water augmentation infrastructures to cope up with the droughts that can ultimately lead to over-exploitation of groundwater. Unfortunately, due to the non-availability of district-level data particularly the deviation of rainfall from its normal level, we could not include the exogenous variables in the regression analysis. However, due to the impact of climate change, the variation in rainfall is not uncommon and varying within a district or blocks. Hence, quantification of the rainfall variation is beyond the scope of this study.

IV

CONCLUDING REMARKS

Groundwater accounts for about 65 per cent of India's net irrigated area in 2017-20. It helps the farmers to harvest more profit from crop cultivation by increasing cropping intensity and productivity of crops. But, due to increased exploitation of groundwater, not only has the water level been depleted but also increased the cost of water along with environmental problems. An attempt is made in this study to find out the determinants of groundwater exploitation by taking data from 235 Indian districts drawn from different states covering two-time periods namely 1990-93 and 2017-20. This study shows that the percentage of districts exploiting more than 50 per cent of groundwater has increased substantially from 21 percent in 1990-93 to 69 per cent in 2017-20.

The regression analysis shows that among the seven independent variables, the average size of holding appears to be the most important factor in positively influencing groundwater exploitation; its influence has also increased substantially in 2017-20 over its previous period 1990-93. The percentage of surface irrigated area to the net irrigated area has negatively and significantly influenced groundwater exploitation in both periods. While the factors determining groundwater exploitation are more or less the same between the two time periods, the magnitude of regression coefficients of the average size of holding and the percentage of surface irrigated area to net irrigated area have increased considerably over its previous period 2017-20.

The negative regression coefficient of the percentage of surface irrigated area to net irrigated area suggests that the exploitation of groundwater can be reduced by increasing the availability of surface irrigated area. Though most of the surface irrigation potential of the country estimated at 75.85 mha has already been utilised, a huge gap exists between the potential created and potential utilised particularly in major and medium irrigation (MMI) surface sources (Planning Commission, 2013; Narayanamoorthy, 2010b; 2022). Concerted efforts are needed to reduce such gaps to expand the coverage of surface irrigated areas. Besides improving the utilisation level of MMI sources, efforts are also needed to revitalise the long-neglected small water bodies (tanks, lakes, etc) which were irrigating about 4.56 mha in 1960-61, but reduced to 1.63 mha in 2018-19. Unlike the mega irrigation projects, the loss of irrigated areas from the source of small water bodies can be brought back to utilisation with lesser investment.

Reckless exploitation of groundwater has already created irreparable damage in different regions of coastal areas. As per the data of CGWB (2021), the over-exploited/critical/semi-critical blocks have increased from 1645 in 2004 to 2538 in 2020 due to over-exploitation. It is proved that by increasing the productivity of crops, micro-irrigation method (drip and sprinkler) helps reduce the consumption of water substantially in different crops as compared to the conventional surface irrigation method (Narayanamoorthy, 2005; 2010; 2022). Though the area under micro-irrigation (MI) has increased from 0.23 mha in 1985-86 to 13.48 mha in 2020-21 because of strong government subsidy support, such area constitutes only less than 10 per cent of GIA in 2020-21. State specific *target*-oriented measures need to be introduced with incentives to bring all the water-intensive crops, especially in the over-exploited blocks under the micro-irrigation method to control the exploitation of groundwater. There is also a need to introduce a dedicated scheme to bring all the water-intensive crops, especially sugarcane and banana under micro-irrigation method. A target may also be fixed for each sugar industry to bring sugarcane cultivation under micro-irrigation in a phased manner, as it consumes a considerable amount of water in many states by occupying a very small share of area in GCA. In addition to this, as the involvement of private companies in crop cultivation has been increasing over time in India due to various reasons, the adoption of MI must be made mandatory wherever water-intensive crops are cultivated under a contract farming system using groundwater.

The paddy-wheat cropping system followed continuously in certain regions in India has not only increased the exploitation of groundwater but also created irreparable damages to the environment. Studies have shown that the paddy-wheat crop rotation in Punjab and other states has increased the exploitation of groundwater and reduced the water table to an alarming level (Sarkar and Das, 2014; Kaur *et al*., 2015; Bhogal and Vatta, 2021 and Paria *et al*., 2021). These studies have also pointed out how crop diversification can reduce the exploitation of groundwater. Increased incentives given to certain water-intensive crops in the form of minimum support price (MSP) with procurement support have also encouraged the farmers to cultivate such crops that also lead to the depletion of groundwater in many parts of the country (Narayanamoorthy, 2021). There are ample opportunities available to cultivate less water intensive crops such as pulses, oilseeds and others that can give more output with less water. By providing the right mix of incentives (MSP with better procurement facility), these less water-intensive crops can be promoted to reduce the level of groundwater exploitation. If strict measures along with more awareness programs are not introduced to control the over-exploitation of groundwater, there is every possibility that the increased depletion of groundwater will be burden on the growth of the agricultural and energy sectors due to groundwater-energy nexus.

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NOTES

1. There is always a debate on how the area irrigated by wells in surface systems could be accounted for as this gives an upward bias in areas irrigated by surface irrigation systems. As the irrigated area by conjunctive sources (groundwater plus surface source) is not published by government agencies on a regular basis, there are difficulties in computing the actual irrigated area by groundwater source (World Bank, 2006). Given the increased water scarcity in surface irrigated areas in recent years, it is likely that more groundwater may have been exploited to compensate for such water scarcity. Therefore, the actual area irrigated by groundwater source may be little higher than what is

reported by the government agencies. Though addressing this is beyond the scope of this paper, the authors are thankful to the anonymous referee for highlighting this issue.

2. It is worth mentioning here that for the regression analysis, we have earlier considered only the area under paddy, wheat and sugarcane to calculate the percentage of area under water-intensive crops to the gross cropped area due to the non-availability of district-level data on other water-intensive crops like banana, turmeric, coconut, vegetables, etc. But, unfortunately the regression coefficients of the water-intensive crops came out with negative sign in impacting the groundwater exploitation. Now, following the suggestions of the anonymous referee, we have considered the area under wheat and sugarcane plus 10 percent of these two crops area to account for the other water-intensive crops. After broadening the definition of water-intensive crops, its regression coefficients came out with a positive sign. The authors are thankful to the anonymous referee for provoking us to think more about the variable of water-intensive crops.

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