Agricultural Economics Research Review 2018, 31 (Conference Number), 79-88
DOI: 10.5958/0974-0279.2018.00024.1

Sustainability of groundwater resources at the subnational level in the context of sustainable development goals

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Abstract The study examines long run trends in groundwater level and identifies areas that have been facing depletion of groundwater resources. The results show ample opportunity to harness the under-developed groundwater resources in the eastern region, but some areas have started facing the problem of groundwater depletion. This should be taken as an early warning signal, requiring adoption of sustainable approaches/practices for the groundwater use. The southern and western parts of the country witness a rising trend in groundwater depth. Punjab, Haryana and parts of Rajasthan continue to be hot spots of groundwater depletion. Promoting integrated water resources management, maintaining well density and optimum inter-well distance, rationalizing electricity subsidy and using water-efficient technologies stand important to improve the sustainability of groundwater resource.

Keywords Groundwater depth, Groundwater sustainability index, Agriculture

JEL classification Q01, Q25, Q28

1 Introduction

India is committed to the United Nation's development agenda for 2016-2030 which comprises 17 sustainable development goals (SDGs) and 169 related targets. Groundwater has a crucial role in meeting the SDGs related to agriculture and water resources. Specifically, productivity-enhancing and stability-improving impacts of groundwater are directly linked with SDG targets 2.3 and 2.4 that focus on accelerating agriculture productivity, and ensuring sustainable and climate resilient food production system, respectively. Similarly, the target 6.4 aims at a substantial increase in the water-use efficiency. Groundwater irrigation has a positive association with agriculture productivity on account of its reliable supply during the critical plant growth stages as well as its catalytic effects on inputs such as fertilizers (Pingali et al. 1997; Bhattarai et al. 2002). Further, access to reliable groundwater resources significantly contributes to averting moisture stress situations and therefore improving the stability of the food production system.

Over the years, groundwater has emerged as the main source of irrigation in India, raising its share in net irrigated area from 30.36% in 1964-65 to 62.82% in 2014-15. Undoubtedly, groundwater has immensely contributed to India's food security, but its use has become unsustainable in several regions (Srivastava et al. 2017). The Central Groundwater Board (CGWB) (2017) has categorized 15.7% of the assessment units (i.e. blocks/mandals/talukas) as overexploited. Apart from disrupting ecological balance, the depleting groundwater resources put heavy financial burden on farmers and may result in socio-economic inequality in its distribution (Sarkar 2011). Therefore, sustainable management of groundwater resources is a pre-requisite for attaining sustainable food production system in India. Concomitantly, groundwater resources remain under-exploited in the eastern region (Ghosh et al. 2014; Srivastava et al. 2014), indicating

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*Corresponding author: shivendraiari@gmail.com substantial potential to accelerate agricultural growth by harnessing the potential.

These evidences points towards dual challenges of reversing over-exploitation of groundwater in some regions, and promoting its sustainable use in others. In this context, this paper identifies hot spots of groundwater depletion, and potential regions for harnessing the potential of groundwater resources for accelerating agricultural growth in a sustainable manner. The specific objectives are: (1) to analyse the spatial pattern in long-run changes in groundwater depth, and (2) to construct groundwater sustainability indices based on factors determining groundwater utilization.

2 Data and methodology

2.1 Data

The study uses secondary data on various aspects of groundwater resources collected from CGWB, 5th Minor Irrigation (MI) Census, Power Finance Corporation Limited (PFCL), and Directorate of Economics and Statistics (DES). The description of the variables based on the data collected from these sources is presented in table 1. The CGWB monitors groundwater level through a network of observation wells located across the country. The change in groundwater level (pre-monsoon) was analysed for the period 2004 to 2014 for 18 states, viz., Punjab, Haryana, Rajasthan, West-Bengal, Uttar Pradesh, Bihar, Chhattisgarh, Tamil Nadu, Jharkhand, Kerala, Madhya Pradesh, Odisha, Karnataka, Telangana, Andhra Pradesh, Maharashtra, Assam and Gujarat. The hilly-states and north-eastern states (except Assam) were excluded from the analysis due to unfavourable geological conditions for groundwater exploitation. Of the total 15797 observation wells, 8987 wells with at least nine years groundwater level data between 2004 and 2014 were selected for trend analysis.

2.2 Methods

2.2.1 Mann-Kendall (MK) test

Mann-Kendall (MK) test, a non-parametric method developed by Mann (1945) and Kendall (1975) is used to test the significance of trend in groundwater level. MK test assesses the monotonic change (increase or decrease) in a given time-series and can suitably be used for the series with missing observations and skewed values. In this method, Kendall's S statistics is computed by comparing later measured values with earlier measured values for n(n-1)/2 possible pairs of data for n observations.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}(y_j - y_i)$$

Where

$$\operatorname{sign}(y_j - y_i) = \begin{cases} = +1 \text{ if } (y_j - y_i) > 0 \\ = 0 \text{ if } (y_j - y_i) = 0 \\ = -1 \text{ if } (y_j - y_i) < 0 \end{cases}$$

Large positive values of S indicate an increasing trend and large negative values indicate a decreasing trend. For a time series of more than equal to 10 years ($n \geq 10$), the MK test statistics is near normally distributed and normal approximation (Z statistics) is used to test the statistical significance. If the n is 9 or less, the absolute value of S is compared directly to the theoretical distribution of S derived by Mann and Kendall (Gilbert 1987).

2.2.2 Sen's slope estimator

Along with MK test, Sen's slope has been estimated to measure the magnitude of trend (change per unit time) in groundwater level. To derive an estimate of the slope, â, the slopes of all data pairs are calculated as:

$$\beta_i = \left(\frac{y_j - y_k}{t_j - t_k} \right)$$

Where, i=1,2,…, N, J>k, y_j and y_k are measurements at time t_j and t_k, respectively. If there are n values of y_j in the time series, we get as many as N= n(n-1)/2 slope estimates β_i. The Sen's slope estimator is the median of N values of β_i. The N values of β_i are ranked from the smallest to the largest and the Sen's slope is given by

$$\beta = \begin{cases} \beta_{\frac{N+1}{2}} & \text{if N is odd} \\ \frac{1}{2}\left(\beta_{\frac{N}{2}} + \beta_{\frac{N+2}{2}} \right) & \text{if N is even} \end{cases}$$

The distribution of observation wells across different levels of change in groundwater depth has been

Table 1. Indicators of groundwater sustainability

S.N.	Indicator	Description	Functional relationship	Data source
1	Groundwater dependency	Share of groundwater in net irrigated area (%)	Negative	GOI (2017a)
2	Well density	Number of functional wells per 1000 hectare net sown area (Number)	Negative	GOI (2017b)
3	Electricity subsidy	Estimated power subsidy for groundwater extraction per hectare net sown area (Rs/ha)	Negative	PFCL (2017)
4	Improved water conveyance system	Proportion of wells with improved water delivery system such as underground pipes, surface pipes, drip and sprinkler irrigation system in irrigated potential utilized (%)	Positive	GOI (2017b)
5	Groundwater development dummy	1 if the share of groundwater draft in total availability is ≤ 90% 0 if it is ≥ 90%	1: sustainable 0 : unsustainable	CGWB (2017)

examined through a cumulative distribution curve (CDC) of Sen's slope for each state. The trend analysis was done using the application MAKESENS developed by Salmi et al. (2002)

2.2.3 Groundwater sustainability index

Groundwater sustainability index (GSI) was constructed to rank the states in terms of sustainable use of groundwater resources in agriculture. GSI was constructed as a composite index of five indicators reflecting different aspects of groundwater use in agriculture. The description of these and their functional relationships with groundwater sustainability are presented in table 1.

As the measurement units of independent indicators of GSI are different, these indicators were normalized and transformed into a dimension-less number. An indicator exhibiting a positive relationship with groundwater sustainability (i.e. higher values are better) is transformed as:

$$S_i = \frac{X_i - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

The normalized values of negative indicators (i.e. lower values are better) were calculated as:

$$S_i = \frac{\text{maximum value} - X_i}{\text{maximum value} - \text{minimum value}}$$

After transformation, the indicators were scaled between 0 and 1, with the best performing state assuming a value of 1. Using the transformed indicators, the composite GSI was calculated as:

$$GSI = \frac{\sum W_i \times S_i}{\sum W_i}$$

Where, W_i is the weight attached to independent indicator S_i. Weights were equally divided among the indicators for estimating GSI.

3 Results and discussion

3.1 Changes in groundwater depth

The trends in pre-monsoon groundwater depth during 2004-2014 examined by applying MK test are shown in table 2. Interestingly, 74% of the selected 8987 wells did not exhibit significant trend in the groundwater depth. Only 14% and 12% of the wells showed a declining and rising trend, respectively. This indicates a fairly stable situation in groundwater use at the macro-level.

The trends in groundwater depth, however, vary considerably across states. The proportion of the wells with a significant trend (rising/declining) in groundwater depth ranges from 15% in Kerala to 58% in Punjab (table 2). Among those showing significant trends, the ones with declining groundwater depth and the ones with rising trend leading to water logging conditions are undesirable from sustainability point of view. In Punjab, Haryana, Rajasthan, Uttar Pradesh, Assam, West Bengal, Chhattisgarh, Bihar, Jharkhand,

Table 2. Distribution of observation wells according to trend in groundwater depth during 2004 to 2014 (Man-Kendall test results)

State	No significant trend (%)	Significantly rising trend (%)	Significantly declining trend (%)	Total wells (numbers)
Punjab	42	14	44	159
Haryana	49	15	36	259
Rajasthan	55	19	26	710
Assam	58	6	36	203
West Bengal	69	5	26	520
Chhattisgarh	70	10	20	323
Gujarat	73	17	10	718
Karnataka	75	16	9	738
Uttar Pradesh	75	7	18	678
Orissa	76	11	13	669
Bihar	78	5	17	184
Telangana	79	14	7	317
Andhra Pradesh	79	16	5	401
Maharashtra	81	14	5	807
Jharkhand	81	8	11	119
Madhya Pradesh	82	10	8	1018
Tamil Nadu	84	5	11	587
Kerala	85	8	7	577
All	74	12	14	8987

Source: Authors' calculations

and Tamil Nadu, the number of wells with declining groundwater depth far exceed the wells with rising trend. On the other hand, in Andhra Pradesh, Maharashtra, Telangana, Karnataka, Gujarat, Madhya Pradesh and Kerala, a rise in groundwater depth was recorded for most wells with significant trends. Bhanja et al. (2017) have also reported depleting groundwater resources in northern and eastern parts, and rising groundwater table in parts of western and southern India during 2002 to 2014. Geographical locations witnessing rising, depleting and no change in groundwater depth are depicted in figure 1a.

The CDC of Sen's slope shows distribution of wells (with significant trends) across different levels of rate of change in the groundwater depth. Accordingly, there is considerable variation in the rate of change in groundwater depth across states (figure 2a to 2r). The annual rate of change was higher in the states witnessing declining groundwater depth (Punjab, Haryana and Rajasthan). Notwithstanding, most of the areas in these states have groundwater at deeper level (figure 1b) and large number of wells have shown a significant declining trend. Therefore, most of the areas of Punjab and Haryana and parts of Rajasthan have continued as hot spots of depleting groundwater.

On the other hand, the rate of change in groundwater depth is relatively small in eastern states, and most areas there have shallow water table. Further, groundwater withdrawal in these states (at aggregate level) is much less than the annual replenishment (CGWB 2017). Thus, the overall groundwater situation in eastern states is safe, except some parts of West Bengal. Nevertheless, declining trend in groundwater depth in a few areas, even at a slower rate, shall be taken as an early warning signal warranting emphasis on sustainable management of groundwater resources.

Interestingly, most of the observation wells in Gujarat, Maharashtra, Andhra Pradesh, Telangana, Karnataka, and Madhya Pradesh have recorded either insignificant or rising trend. The replenishing trends in aquifers of southern and western states of India can be attributed

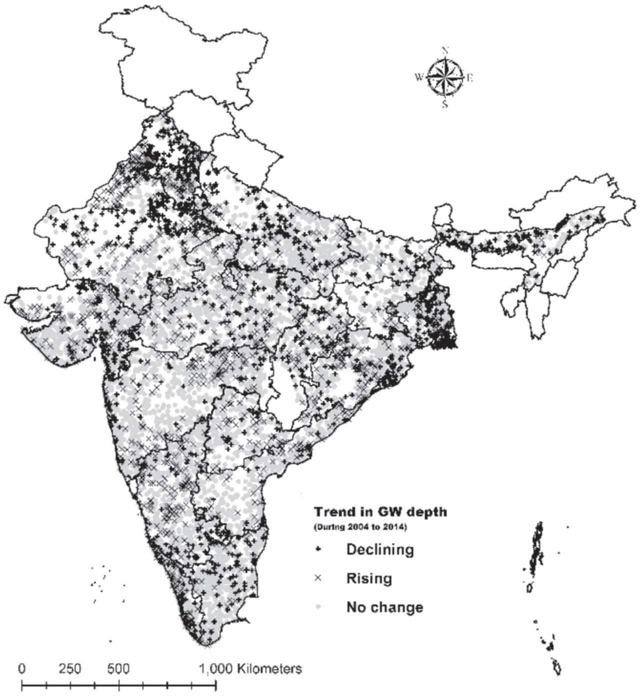


Figure 1a. Trend in groundwater depth (pre-monsoon) during 2004 to 2014

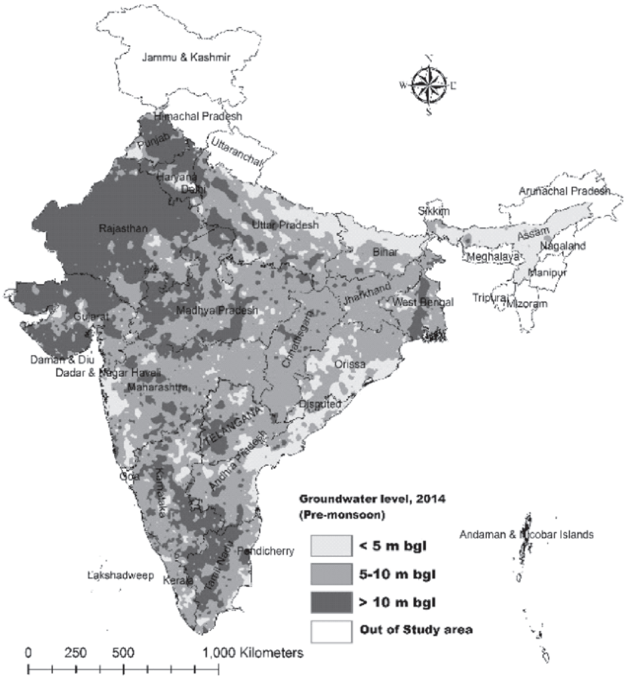
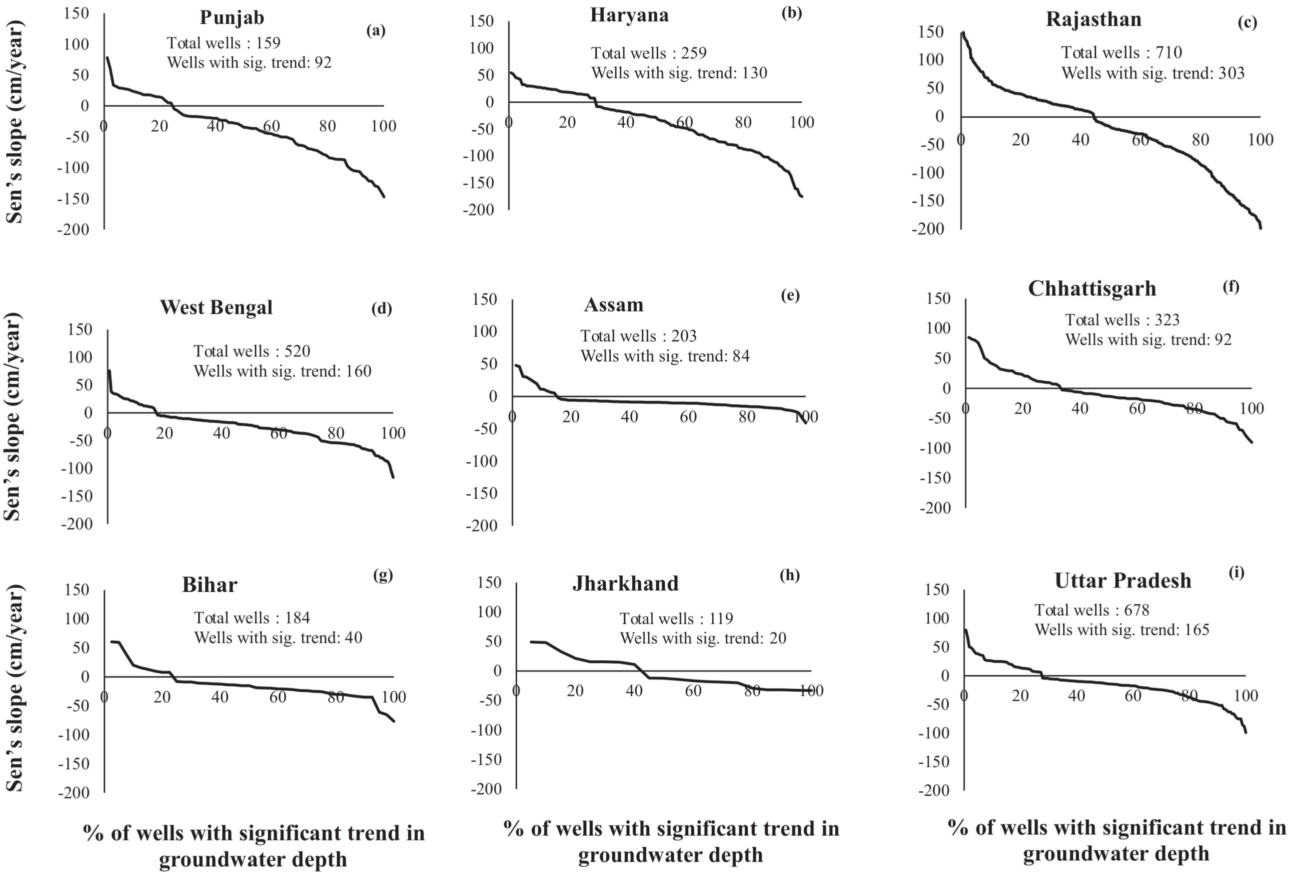


Figure 1b. Spatial variation in groundwater depth (pre-monsoon) in 2014

Source: Maps prepared based on authors' calculations in ArcMap 10.2.2 software



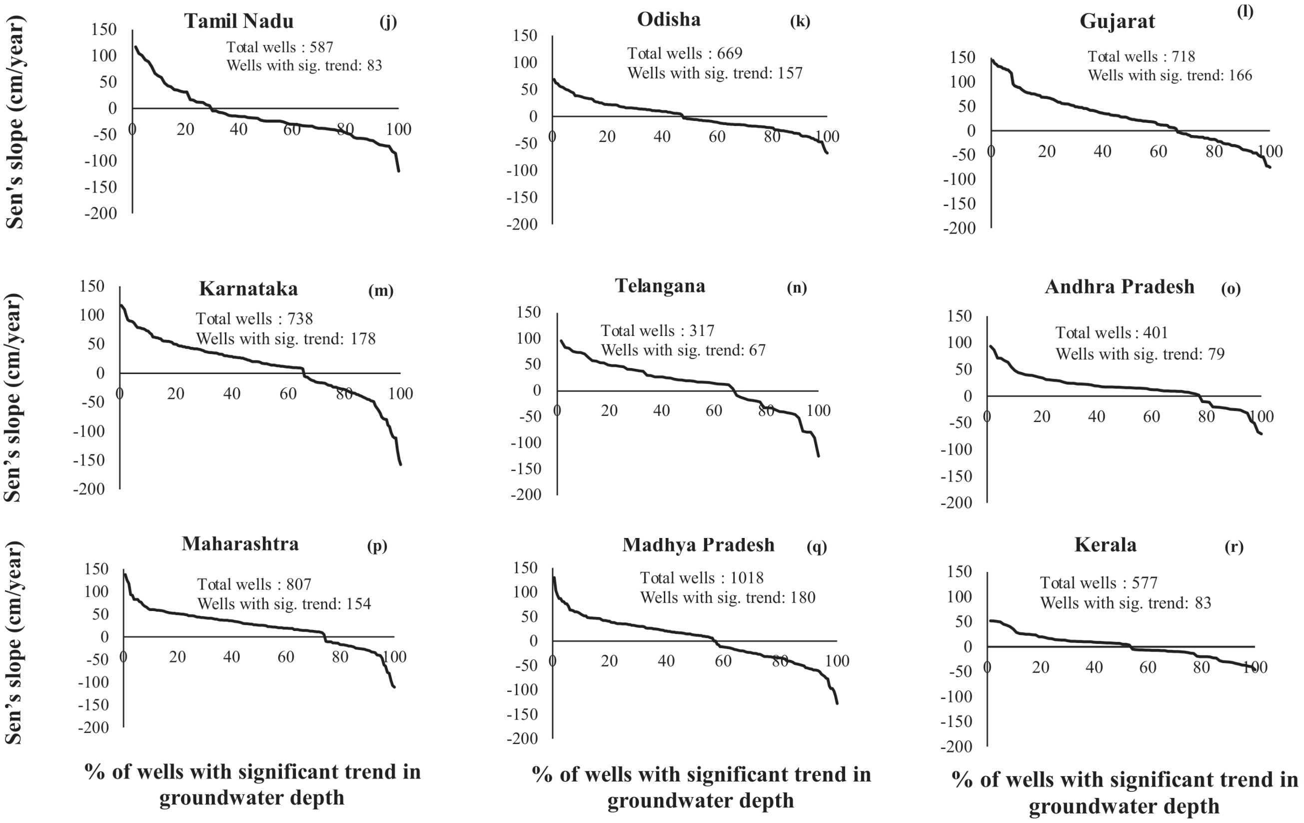


Figure 2. State-wise cumulative distribution curves of Sen's slope

to implementation of ingenious groundwater management strategies by both public and private sectors (Bhanja et al. 2017). The on-going efforts in these states can to be accelerated, especially in areas where groundwater is at deeper level.

It is to be noted that the groundwater level 10 meter below ground level (m bgl) is considered relatively safe where groundwater can be extracted using surface (centrifugal) pumps with less energy and cost. However, groundwater extraction beyond this requires costlier and energy-intensive technologies like submersible pumps (Sekhri 2013). In such situations, many farmers who cannot afford to invest in deep tube wells and heavy pumps, may loose access to groundwater resources thereby adversely affecting crop production.

3.2 Indicators of groundwater sustainability

Among all the sectors, agriculture is the biggest consumer of groundwater; 90.2 % of the total annual groundwater extraction (CGWB 2017). The injudicious use of groundwater resources is a major cause of their depletion (Dhawan 1995; Gandhi and Namboodiri 2009; Srivastava et al. 2015; Srivastava et al. 2017). At the same time, agriculture which heavily depends on groundwater for irrigation, bears negative consequences of groundwater depletion. In this paper, the states have been assessed and ranked on the basis of five indicators of groundwater sustainability (see, table 1). These indicators are: (1) share of groundwater in irrigated area (%), (2) well density (number of wells/ 1000 ha NSA), (3) electricity subsidy (Rs/ha NSA), (4) area under improved water conveyance system (%), and (5) groundwater development (dummy). These indicators represent dependence of agriculture on groundwater, withdrawal of groundwater over its availability, and efficiency in its use. The mean values of indicators of groundwater sustainability index (GSI) for each of the selected states are presented in table 3.

The dependence of agriculture on groundwater is increasing rapidly. This is reflected from a consistent increase in the share of groundwater sources in net irrigated area from 30.36% in 1964-65 to 62.82% in 2014-15. Although groundwater resources are

Table 3. Mean values of indicators of groundwater sustainability index in 2013-14

State	Share of groundwater in irrigated area (%)	Well density (no./1000 ha of NSA)	Electricity subsidy (Rs./ha NSA)	Area under improved water conveyance system (%)	Groundwater development (%)
Andhra Pradesh	37	131	10190	42	44
Assam	25	42	0	2	16
Bihar	63	122	331	90	45
Chhattisgarh	31	61	1696	58	37
Gujarat	78	123	4767	68	68
Haryana	59	100	18756	51	135
Jharkhand	49	91	482	3	23
Karnataka	49	120	7032	77	66
Kerala	39	40	552	50	47
Madhya Pradesh	66	126	6244	79	57
Maharashtra	67	151	6291	48	54
Odisha	20	76	253	37	30
Punjab	73	270	16148	3	149
Rajasthan	73	77	4911	82	140
Tamil Nadu	61	389	20359	21	77
Telangana	75	273	17016	46	58
Uttar Pradesh	80	226	3772	32	74
West Bengal	56	80	911	11	45

Source: Authors' calculations based on data sources given in table 1

comparatively more reliable and efficient than surface water (Sharma 2009), excessive dependence on these disrupts the surface and sub-surface water flow and creates imbalance in hydrological cycle. The share of groundwater in net irrigated area that varied from 20% in Odisha to 75% in Telangana in 2013-14, was taken as an indicator to assess status of integrated water resources use in agriculture. Over-dependence on groundwater sources for irrigation has a negative relationship with sustainability.

Well density was used as an indicator to assess withdrawal of groundwater resources. The rising demand of groundwater for irrigation is met by increasing number of groundwater extraction devices (GEDs). Successive minor irrigation (MI) censuses have revealed significant increase in well density, from 42 in 1982-83 to 145 in 2013-14 in India (table 3). Across states, it varied from 40 in Kerala to 389 in Tamil Nadu in 2013-14. Lower distance between two wells interferes in groundwater extraction because the zone of influence of one well overlaps the zone of influence of other well. Consequently, total groundwater output is less than the sum of the discharging capacity of individual wells, leading to decline in efficiency of each well. The higher well density has been assumed as an indicator of unsustainable groundwater extraction.

Regulation of energy supply and its pricing is often suggested as an effective indirect approach for sustainable groundwater management (Malik 2008). According to the latest MI census, 72% of the GEDs are operated using electricity. In order to provide affordable access to groundwater, many state governments supply electricity for irrigation free or at subsidized rates. Although free/subsidized power provides economic benefits to farmers and is effective in accelerating agricultural growth, particularly in regions with under-developed groundwater resources (Srivastava et al. 2014), it is most often found to be negatively associated with groundwater sustainability (Srivastava et al. 2017). We have estimated electricity subsidy per hectare of net sown area by multiplying per hectare electricity consumption in agriculture with the difference between revenue and cost of supply per unit of electricity. The estimated electricity subsidy varied from nil in Assam to Rs. 20359/- in Tamil Nadu in 2013-14 (table 3). Sustainability of groundwater resources was assumed to be negatively affected by the electricity subsidy.

Sustainable use of groundwater resources requires that its extraction should not cross replenishment limit. This is represented through the level of groundwater development which is the share of groundwater withdrawal in its availability. Among the states, groundwater development varies from just 16% in Assam to 149% in Punjab (table 3). As per the CGWB criteria, groundwater draft should not be more than 90% of its availability (CGWB 2017). Accordingly the states with less than 90% groundwater development were assigned a value of 1, otherwise 0. This indicates status of sustainability in the draft of groundwater resources. This indicator measures both demand and supply aspects of groundwater resources.

Efficiency in the use of extracted groundwater is another important dimension of its sustainability. An irrigation system with higher efficiency reduces wasteful use of groundwater resources. In the present study, proportion of wells with improved water conveyance system such as underground pipes, surface pipes, drip and sprinkler irrigation has been used as a proxy for the efficiency in groundwater use for irrigation. The state with higher proportion of wells with improved water conveyance system is more sustainable in groundwater use for irrigation. The mean value of this indicator varied from 2% in Assam to 90% in Bihar (table 3). Surprisingly, in Punjab, only 3% of the wells had improved water conveyance system in 2013-14.

3.3 Ranking of states based on groundwater sustainability index

Groundwater sustainability index (GSI) is a combined measure of equally weighted scaled values of the five indicators as discussed. A state with higher value of GSI is more sustainable in groundwater use for irrigation as compared to others. The estimated value of GSI varied from 0.137 for Punjab to 0.862 for Chhattisgarh (table 4). Accordingly, Chhattisgarh is found the most sustainable state in groundwater utilization, and Punjab the least. Odisha, Kerala, Bihar, and Assam also have a higher ranking in sustainability. On the other hand, Punjab, Tamil Nadu, Haryana, Telangana, and Uttar Pradesh have low level of sustainability in groundwater use. It is, however, important to mention that many states, which have emerged as unsustainable at aggregate level, may have sub-regions utilizing groundwater in a sustainable manner and *vice-versa*.

Table 4. State-wise groundwater sustainability index in 2013-14

State	Valued of groundwater sustainability index	Ranking
Chhattisgarh	0.862	1
Odisha	0.857	2
Kerala	0.842	3
Bihar	0.808	4
Assam	0.783	5
Karnataka	0.759	6
Madhya Pradesh	0.712	7
Andhra Pradesh	0.683	8
Jharkhand	0.672	9
West Bengal	0.670	10
Gujarat	0.663	11
Maharashtra	0.625	12
Rajasthan	0.537	13
Uttar Pradesh	0.526	14
Telangana	0.419	15
Haryana	0.365	16
Tamil Nadu	0.307	17
Punjab	0.137	18

Source: Authors' calculations

A perusal of table 3 shows that average value of the indicators, exhibiting negative functional relationship with groundwater sustainability, for the least sustainable states (Punjab, Tamil Nadu, Haryana, Telangana, and Uttar Pradesh) was significantly higher as compared to the most sustainable states (Chhattisgarh, Odisha, Kerala, Bihar, and Assam). On the other hand, least sustainable states had significantly lower average value of the positive indicator (area under improved water conveyance system) as compared to most sustainable states. Based on these, it can be inferred that groundwater sustainability can be improved to a large extent by promoting integrated use of surface and groundwater, controlling installation of wells within their area of interference, rationalising electricity subsidy, restricting groundwater draft within the sustainability limits, and improving water-use-efficiency in irrigation.

The integrated water resources management would reduce the demand for groundwater and augment its supply. Groundwater supply can also be augmented by using permanently non-functional wells as artificial recharge structures. Consequently, the groundwater table would rise with positive effects on well-discharge and food production system. Optimum inter-well distance shall be maintained through strong legislative measures and strict monitoring at field-level. Free/ subsidized electricity supply does not provide economic incentives to farmers to use groundwater efficiently and must be rationalized, particularly in the states with unsustainable groundwater use. Nevertheless, assured electricity supply at subsidized rates can also be used as a measure to improve economic access to groundwater in the eastern region where groundwater is under-developed and water table is shallow. Water-use efficiency can be improved significantly by promoting water saving technologies such as drip and sprinkler irrigation system.

4 Conclusions

Observation wells of CGWB recorded varying trend in groundwater depth across the states during the past decade. Punjab, Haryana and parts of Rajasthan have continued as hot spots of injudicious use of groundwater resources. On the other hand, eastern states have potential to improve utilization of under-developed groundwater resources and raise agricultural productivity and stability. However, some areas of eastern states have started facing depletion of groundwater resources though at a slower rate. Such evidences shall be taken as early warning signals followed by sustainable measures for using groundwater for irrigation. Most of the wells in the states like Gujarat, Maharashtra, Andhra Pradesh, Telangana, Karnataka, and Madhya Pradesh, have recorded either insignificant or rising trend in groundwater depth which imply a check in the groundwater depletion in these areas.

Groundwater depletion is an outcome of its injudicious and inefficient use, particularly in the agriculture sector. Based on the groundwater sustainability index, Chhattisgarh, Odisha, Kerala, Bihar, and Assam were found to be the most sustainable states in groundwater use for irrigation. On the other hand, Punjab, Tamil Nadu, Haryana, Telangana, and Uttar Pradesh emerged as the least sustainable states. Promoting integrated water resources management, maintaining well density and optimum inter-well distance, rational electricity subsidy and use of water efficient technologies are important measures to improve groundwater sustainability in India.

Acknowledgement

The authors express their sincere thanks to Prof. Ramesh Chand, Member, NITI Aayog for his valuable contribution in interpreting the results and improving the manuscript. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the organization they belong to.

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