Groundwater dynamics in North Bihar plains

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The plains of north Bihar, drained by numerous rivers originating in the Himalayas also experience a reasonably high rainfall of ~1200 mm per year. Still, more than 80% of the irrigation demand in this region is met by groundwater resources. Also, the increasing population and industrialization are likely to lead to overexploitation of groundwater as in several other states of northwest India over the last 4–5 decades. This article aims to assess the groundwater dynamics in the plains of north Bihar using 30 years (1983–2013) of groundwater level data to understand the spatial and temporal, pre- and post-monsoon characteristics using Geographical Information System (GIS) and ordinary kriging (interpolation technique) method. Groundwater storage change was estimated using the water table fluctuation method. Our analysis shows 2–3 m decline in groundwater level in several districts such as Begusarai, Bhagalpur, Samastipur, Katihar and Purnea in both pre- and post-monsoon periods in the last decade (2004–2013). Similar trends were observed in groundwater storage for Samastipur and Purnea districts; the maximum reductions in groundwater storage for the pre-monsoon period are computed as 636 MCM and 631 MCM respectively, and the values for the post-monsoon period are 289 MCM and 216 MCM respectively. Such large scale depletion in groundwater storage in such a short time span is alarming. If this trend continues unabated, it may lead to serious scarcity of water resources in this region, negatively impacting agricultural productivity and food security.

Keywords: Groundwater level, groundwater storage, GIS, ordinary kriging, water table fluctuation method.

GROUNDWATER is a valuable resource to support agricultural, industrial and domestic activities in many parts of the world. Overexploitation of groundwater can lead to scarcity in freshwater resources and adversely impact the ecosystem and social development[1]. Moreover, countries like India, Pakistan, Northeastern China, the Middle East and North Africa already suffer from water scarcity and this has now become a global issue[2,3]. India, the largest agricultural user of groundwater in the world, has seen a revolutionary shift from large-scale surface water management to widespread groundwater abstraction in the last 47 years, particularly in the northwestern states of Punjab, Haryana and Rajasthan. As a result, northwestern India is now a hotspot of groundwater depletion with the largest area of groundwater loss in any comparable-sized region on earth[4,5]. The alluvial plains of north Bihar have potential aquifers with ample source of water for recharge, but are witnessing accelerated groundwater draft over the last couple of decades. Despite being the land of rivers, more than 80% of irrigation demands in north Bihar is met mainly by groundwater resources due to easy availability and unreliable and insufficient surface water irrigation network. This unsustainable use of groundwater becomes even more challenging due to (a) increasing demand from a burgeoning population[6] and industrialization which leads to a risk of insufficient supply, and (b) poorly understood effects of climate-driven changes in water cycle such as increase in temperature and change in rainfall pattern that could affect the groundwater recharge rates[7].

Moreover, the global scenario of groundwater overdraft indicates that over-exploitation of groundwater from the shallow aquifers has deteriorated its quality. The declining trends of groundwater level, both long-term and short-term, tend to have a negative impact on groundwater quality as well[8]. Studies in several districts of north plains, viz. Patna, Bhojpur, Vaishali and Bhagalpur have indicated substantial arsenic content in groundwater[9] attributed mainly to overexploitation of groundwater. There is thus an urgent need to carry out a comprehensive analysis of groundwater dynamics and groundwater storage changes in the alluvial plains of north Bihar. Moreover, a comprehension of groundwater storage change, especially its long-term variability, would help maintain a healthy ecosystem, whereas the lack of realistic estimates of groundwater storage can slow down the rate of development and implementation of effective water management plans.

A major requirement for estimating changes in groundwater storage is complete and accurate groundwater level measurement with a good spatial and temporal coverage[10]. Many regions in the country including the plains of north Bihar do not have a very dense network of groundwater level measurement sites. This significantly hampers the understanding of spatio-temporal variability of changes in groundwater level and storage. Application of interpolation methods in a GIS framework can resolve some of these limitations and provide a reasonable assessment of spatial variation of groundwater variability

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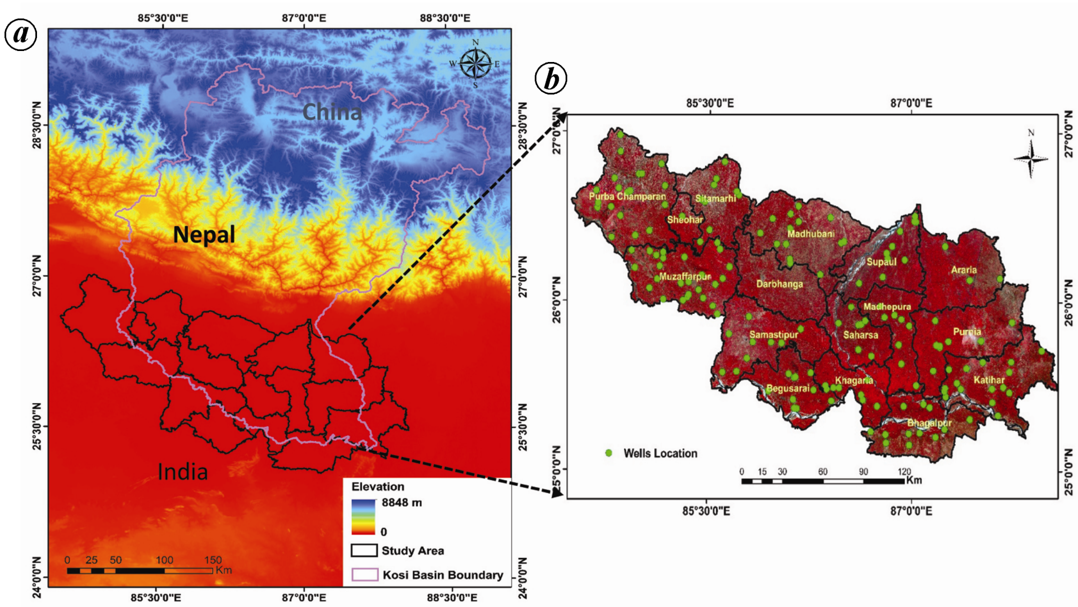

Figure 1. ***a***, Study area located in north Bihar plains. ***b***, Landsat FCC showing the alluvial plains of north Bihar; green dots represent the locations of groundwater wells for which historical (1984–2013) data has been analysed. The number of wells for which data was available varied from year to year.

in a region[11,12]. However, the selection of an optimal interpolation method is crucial for accurate results. Geostatistical methods, particularly kriging, have been widely used for mapping the spatial distribution of groundwater[13–15]. A comparison of eight interpolation techniques[16] has revealed that among all other methods ordinary kriging is the best for analysing the spatial distribution of groundwater. For this study, four different interpolation techniques were compared and the best suited technique for this dataset was selected (discussed later).

Techniques for estimating groundwater storage changes have traditionally been based on water level fluctuation data[17]. GRACE satellite data have been used for computing large-scale terrestrial storage change (TWS) on the basis of earth's global gravity field[18]; however, its spatial downscaling limitations may restrict its use for small basins[19]. The spatial resolution of GRACE data[20] is relatively low (~200,00 sq. km), limited by its altitude of ~450 km. In contrast, water table fluctuation method is considered one of the most promising and attractive methods due to its accuracy, ease of use and low cost of application[21]. This method was first applied for estimating groundwater recharge and has lately been used for groundwater storage change estimation as well[22]. The present study has used water table fluctuation method for computing groundwater storage change in the alluvial plains of north Bihar with an aim to identify the hotspots of groundwater depletion.

The study was carried out for 16 districts of north Bihar (Figure 1) lying between 26°52′28.92″ and 25°20′05.44″ lat. and 85°03′35.05″ and 86°44′16.24″ long. and covering 39,294 sq. km of geographical area. The Kosi (or Koshi) river is the major drainage in the study area and several other rivers such as the Baghmati, Kamla-Balan and other minor rivers join the Kosi River at various points. In the upstream part of the Kosi basin, seven major tributaries originating from the high-altitude areas of China and Nepal contribute to the river (known as Sapt Koshi). The Kosi itself meets the Ganga river at a point close to Kursela. The entire downstream area consists of monotonously flat alluvial plains with elevation ranging from 5 m to 75 m amsl. The mean annual rainfall in the Kosi basin is 1456 mm and most of the rainfall (80–90%) occurs during the monsoon season (mid-June to mid-October)[23]. In the upstream part of Kosi subcatchments in Nepal, 72–81% of the annual precipitation falls during June–September[24]. The soil of the alluvial plain area is very fertile and the most common types include terai soil, sandy soil and loamy soils. Agriculture is the main occupation of people in this area and the major crop grown in this area is paddy.

Methods

Pre-processing of groundwater data

Groundwater data for north Bihar plains was collected from Central Ground Water Board (CGWB) as well as State Ground Water Board (SGWB) covering the period 1983–2013. The CGWB has 341 monitoring wells in Bihar, of which 329 are dug wells and 12 are piezometer[25]. This study used 195 observation wells located in north

Table 1. District name, area (km^2), number of observation wells used, GWL depth range (m), mean annual precipitation (mm/year) and physiographic unit

District	Area (sq. km)	No. of wells	GWL depth range (m)	Rainfall (mm/year)	Physiographic unit
Araria	2792.840	4	1.1–5.37	1582	Alluvium plain
Begusarai	1923.961	12	1.58–9.37	1104	Thick unconsolidated alluvium
Bhagalpur	2538.265	12	0.95–12.25	1148	Flat Indo-Gangetic alluvium tract
Darbhanga	2288.039	4	0.76–6.68	1142	Alluvium
Katihar	3040.092	17	1.3–8.8	2194	Alluvium plain
Khagaria	1484.155	8	1.5–9.28	1170	Gangetic alluvium
Madhepura	1836.837	9	1.3–6.8	1231	Younger alluvium with newer flood plain
Madhubani	3428.438	17	0.8–7.61	1289	Alluvium
Muzaffarpur	3169.951	26	1.2–6.57	1284	Alluvium
Purba Champaran	3961.710	21	0.8–6.97	1242	Alluvium plain
Purnia	3238.809	8	1.41–5.84	1411	Gangetic alluvium
Saharsa	1687.619	7	1.3–4.61	1360	Younger alluvium with newer flood plain
Samastipur	2893.142	9	1.74–10.53	1142	Gangetic alluvium
Sheohar	574.557	1	1–6.53	1357	Gangetic alluvium
Sitamarhi	2039.483	10	1.53–5.06	1267	Gangetic alluvium
Supaul	2396.539	10	1.11–5.15	1404	Younger alluvium with newer flood plain

Table 2. Statistical summaries for distribution of sampling points of GWL in 1999 and 2013

	No. of wells	Mean	Std. Dev.	Skewness	Kurtosis	Maximum	Minimum	Medium
Pre-monsoon 1999	145	4.28	1.31	0.506	3.20	8.91	2	4.17
Post-monsoon 1999	133	2.29	0.77	0.654	3.42	4.52	0.89	2.29
Pre-monsoon 2013	195	5.14	1.90	0.574	3.35	12.25	0.44	4.77
Post-monsoon 2013	194	2.94	1.49	0.708	3.56	10.45	0.82	2.76

Bihar. The CGWB data include the measurements four times in a year (January, May, August and November) and cover the entire period, whereas the SGWB data is based on monthly or weekly measurements and is available for four years (2010–2013) only. Description on the number of wells used, ground water level (GWL) fluctuation and physiographic units is given in Table 1. Both datasets needed significant pre-processing and cleaning in terms of fixing their location and period of measurements. The dataset for pre- (May) and post-monsoon (November) periods from both sources were merged for analysing the spatio-temporal trends. All temporal datasets were checked for accuracy, frequency and trend and abrupt changes were corrected by comparing with the India Meteorological Department (IMD) rainfall data and flood events for the same period.

Land use and land cover data

Land use and land cover (LULC) images for Bihar were obtained from the National Remote Sensing Centre (NRSC), Hyderabad. The mapping was done by NRSC on 1 : 250,000 scale using multi-temporal AWiFS (56 m) dataset. This organization provides the annual LULC data with an average accuracy of 90.07% with a range of 86–95% for different states[26]. For this study, two years of data (2005–06 and 2010–11) were used to document the changes in LULC.

Groundwater level data analysis

After cleaning the dataset, pre- and post-monsoon data from 1999 to 2013 were selected as they contain the maximum observation wells compared to other years. Statistical analysis of this data shows that the skewness is close to zero and kurtosis is close to three (Table 2), suggesting that data is normally distributed and directly applicable for kriging interpolation technique[16]. Four different interpolation methods namely, ordinary kriging (OK), simple kriging (SK), universal kriging (UK) and inverse distance weightage (IDW) were compared to choose the best suited technique for this dataset. Coefficient of determination (r^2) and root mean square error (RMSE) were computed for each method. Table 3 shows that r^2 for OK and UK is similar and higher than the other interpolation techniques in all years. Similarly, the RMSE is minimum for OK and UK compared to other techniques. Moreover, OK and UK predictions are almost the same because the dataset has very less to negligible trend. This was also analysed using trend analysis tool in ArcGIS. Therefore, ordinary kriging was used for this study.

Data was then exported into ArcGIS platform for mapping the spatial distribution of GWL fluctuation for the period 1984–2013. The number of wells used for preparing the spatial maps varied for different years as new wells were added and old wells were abandoned. After preparing the GWL maps for each year, we generated the maps depicting GWL fluctuation at 10 years

Table 3. The statistic of the errors in the process of groundwater interpolation for 1999 and 2013 for both season

		Inverse distance weightage (IDW)	Ordinary Kriging (OK)	Simple Kriging (SK)	Universal Kriging (UK)
Pre-monsoon 1999	R^2	0.537	0.702	0.628	0.702
	RMSE	0.775	0.594	0.639	0.594
Post-monsoon 1999	R^2	0.517	0.668	0.224	0.668
	RMSE	0.478	0.431	0.615	0.431
Pre-monsoon 2013	R^2	0.667	0.667	0.637	0.667
	RMSE	0.846	0.690	0.779	0.690
Post-Monsoon 2013	R^2	0.535	0.664	0.635	0.664
	RMSE	0.929	0.814	0.861	0.814

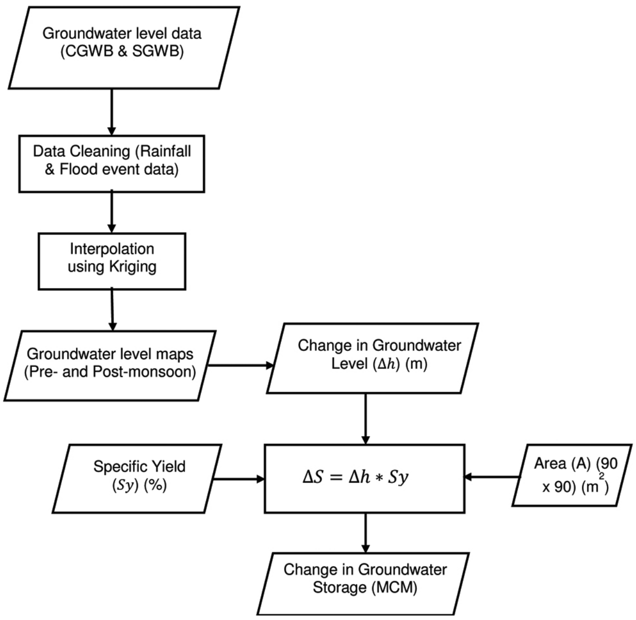

Figure 2. Methodology and steps followed for analysis of groundwater data.

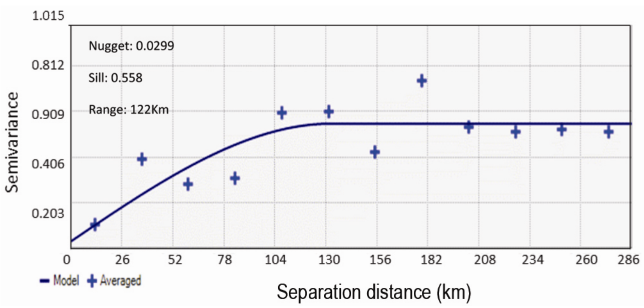

Figure 3. Semivariogram (points) and fitted model (line).

interval using a raster calculator tool in ArcGIS to understand the spatio-temporal trends of GWL variation.

For a better understanding of the spatial inhomogeneity of GWL fluctuation in this region, a cluster analysis was performed separately for pre- and post-monsoon periods. For this purpose, the spatial maps of each district for both pre- and post-monsoon periods were resampled into 20 × 20 km grids such that each grid contained at least two well points. Each grid was then assigned an average value of GWL for each year. We then plotted the temporal variability of each grid to generate district wise plots of GWL fluctuation. Based on the patterns for each district, we then clubbed the data into definite 'clusters' comprising data for several districts. This allowed us to analyse the temporal and seasonal variations in GWL and understand the causal factors better.

Groundwater storage change

Groundwater storage (GWS) change was estimated for the study area by water table fluctuation method[27] using the equation

$$\Delta S = \text{Sy} * \mathrm{d}h/\mathrm{d}t * A,$$

where ΔS is the change in GWS, Sy the specific yield, h the water level, t the time and A is the area of the grid.

This method is usually applied to shallow unconfined aquifers which display rapid responses to rainfall events and has been used in a number of studies[28–30] because of its simplicity and ease. However, there are some limitations[31] of this method, viz. (a) this method is best applicable in shallow water, (b) this method cannot be used for steady rate of recharge, (c) calculation of specific yield should be accurate, and (d) cause of water fluctuation should be known. The study area in north Bihar plains consists of shallow unconfined aquifers and changing water level with time due to rainfall and flood events and hence the water fluctuation method is suitable for use.

GWS was calculated from 1984 to 2013 for pre- and post-monsoon periods. To calculate the GWS, three parameters were used, viz. change in GWL (km), area (sq. km) and specific yield (%) as shown in Figure 2. The groundwater change was calculated by subtracting the GWL maps in Raster calculator tool in ArcGIS. The pixel area was considered as an area of the surface. The specific yield (the volume of water released from

Table 4. Results of cluster analysis of GWL data

Pre-monsoon clusters (districts)	Summary of trend	Post-monsoon clusters (districts)	Summary of trend
1A: Samastipur, Khagaria and Begusarai	Significant drop during 1993 and then an increasing pattern until 2002; significant lowering during 2009–2011, some locations showing a drop in GW level by 3–4 m.	1B: Samastipur, Khagaria, Begusarai	Significant decrease in GW level between 1985 and 1992 and then an increase until 1999; fluctuating trend after 1999 with major declines noted in 2001, 2005 and 2010
2A: Sitamarhi and Madhubani	Some sort of cyclic behaviour with some stabilization of GW level during 1996–2003 after the same cyclic behaviour continues.	2B: Sitamarhi, Madhubani, Supaul, Araria, Saharsa Muzaffarpur, Darbhanga, Bhagalpur	Significant decrease in GW level between 1985 and 1992 and then an increase until 1999; fairly stable afterwards with two major declines noted in 2005 and 2009–2010.
3A: Supaul and Araria	Fairly stable for most of the period except for a sharp (~4 m) rise in 1993; unstable since 2009		
4A: Saharsa and Muzaffarpur, Darbhanga, Purba Champaran	Extremely fluctuating groundwater level for the entire period; no visible trend.		
5A: Purnea and Madhepura	Slight increase in GW level between 1985 and 1991, sharp decrease in 1994 and then fairly stable until 2005; a declining trend after 2005 continues until 2013.	3B: Purnia, Katihar	Significant drop in GW level during 1992 but recovered in 1995 and then stable with minor variations; a major decline noted in 2010.
		4B: Madhepura, Purba Champaran	A declining trend between 1985 and 1992 and then fairly stable until 2013.
6A: Katihar and Bhagalpur	Slight increase in GW level between 1985 and 1991 but very fluctuating GW level after this for the rest of the period.		

groundwater storage per unit surface area of aquifer per unit decline in the water table) can be computed by many methods; one among them being the pumping test. For this study, the specific yield was taken from the published data[32–34] that have provided the specific yield map for the whole of India as well as for the Indo-Gangetic plains. Based on the published data, the specific yield for this region varies from 12% to 18%, and therefore, we have used a mean value of 15% for our computation.

Results and discussion

Cross-validation

The fitted semivariogram (spherical) and the associated parameters for OK are shown in Figure 3. The spatial dependence or autocorrelation was decided by the nugget to sill ratio criteria[35] – high if less than 0.25, medium for 0.25–0.75 and low if higher than 0.75. For our dataset, the spatial autocorrelation was high as the nugget-to-sill ratio was 0.0535 and spatial correlation was up to distance of 122 km.

Spatio-temporal patterns of GWL change

Figure 4 shows the change in GWL for the periods (a) 1984–1993, (b) 1994–2003 and (c) 2004–2013 for both pre- and post-monsoon periods. The positive values represent an increase in GWL and vice versa. For the period 1984–1993, the pre-monsoon GWL dropped in most areas except for Supaul, Araria and Madhubani districts (Figure 4 *a*). The districts of Saharsa, Samastipur and Khagaria show maximum decrease in water level. In the same period, the post-monsoon GWL also decreased by ~2 to 3 m in most areas (Figure 4 *b*). Such sharp fall in post-monsoon GWL in a short span of 9 years is alarming. However, the areas close to the Kosi River (Supaul, Araria and Madhepura) showed a positive trend during this period.

Similarly, the pre-monsoon groundwater change maps for the period 1994–2003 (Figure 4 *c*) illustrate a positive trend in most of the districts except for parts of Purba Champaran, Sheohar, Sitamarhi, Purnia, Katihar and Bhagalpur districts which show a negative trend. In contrast, the post-monsoon maps document a rise in the GWL during this period, except in parts of Bhagalpur district (Figure 4 *d*).

Spatio-temporal maps for the next ten years, i.e. 2004–2013 show a tremendous change in GWL. All districts of north Bihar experienced a lowering of pre-monsoon GWL by ~2 to 3 m in this period (Figure 4 *e*). In the same period, the post-monsoon GWL did not change appreciably in most northern districts, but the districts such as Bhagalpur, Samastipur, Begusarai, Katihar and Araria in

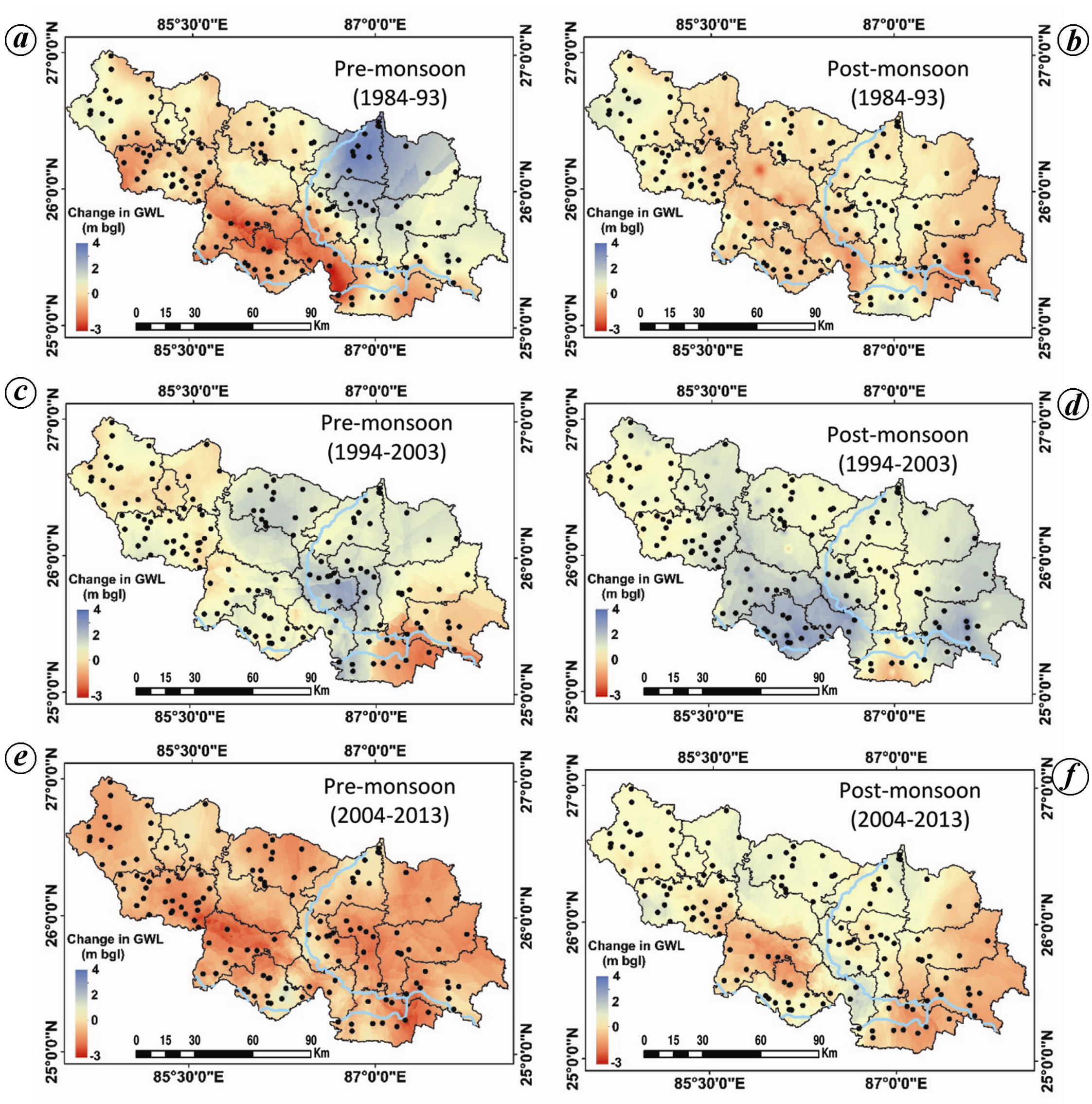

Figure 4. Change in groundwater level for pre- and post-monsoon periods for (***a***, ***b***) 1984–1993, (***c***, ***d***) 1994–2003 and (***e***, ***f***) 2004–2013.

the eastern and southern parts exhibited a significant drop in GWL (Figure 4*f*). Notably, Araria, Purnia, Supaul and Bhagalpur districts show a negative trend for the entire period of 30 years.

Cluster analysis of GWL change

Based on the patterns of temporal variability in different grids of a particular district, ten clusters were identified for both pre- and post-monsoon data. Table 4 summarizes the characteristic trend of each cluster and districts falling therein. The pre-monsoon data allowed us to identify 6 different clusters as shown in Figure 5. Cluster 1 comprises Samastipur, Khagaria and Begusarai districts. Despite the fact that all these are located close to the Ganga river, they show a continuous decline after 2003. Cluster 2 includes Sitamarhi and Madhubani districts in the northern part and the cyclic behaviour might be related to recharge induced by the rainfall of the previous years, also suggesting that abstractions have been fairly stable. Cluster 3 for Supaul and Araria districts shows a fairly stable trend except for a spike in 1993. Cluster 4 covers Saharsa, Muzaffarpur, Darbhanga, and Purba Champaran districts and the extremely fluctuating trend of this cluster possibly results from competing water demands from these heavily populated areas. Clusters 5 and 6 are quite similar in terms of increasing trend until 1991 but after that cluster 5 shows a fairly stable trend whereas cluster 6 shows a variable GWL.

The post-monsoon data shows a much tighter clustering and four distinct clusters are identified (Figure 6). It is important to note that the districts covered in each

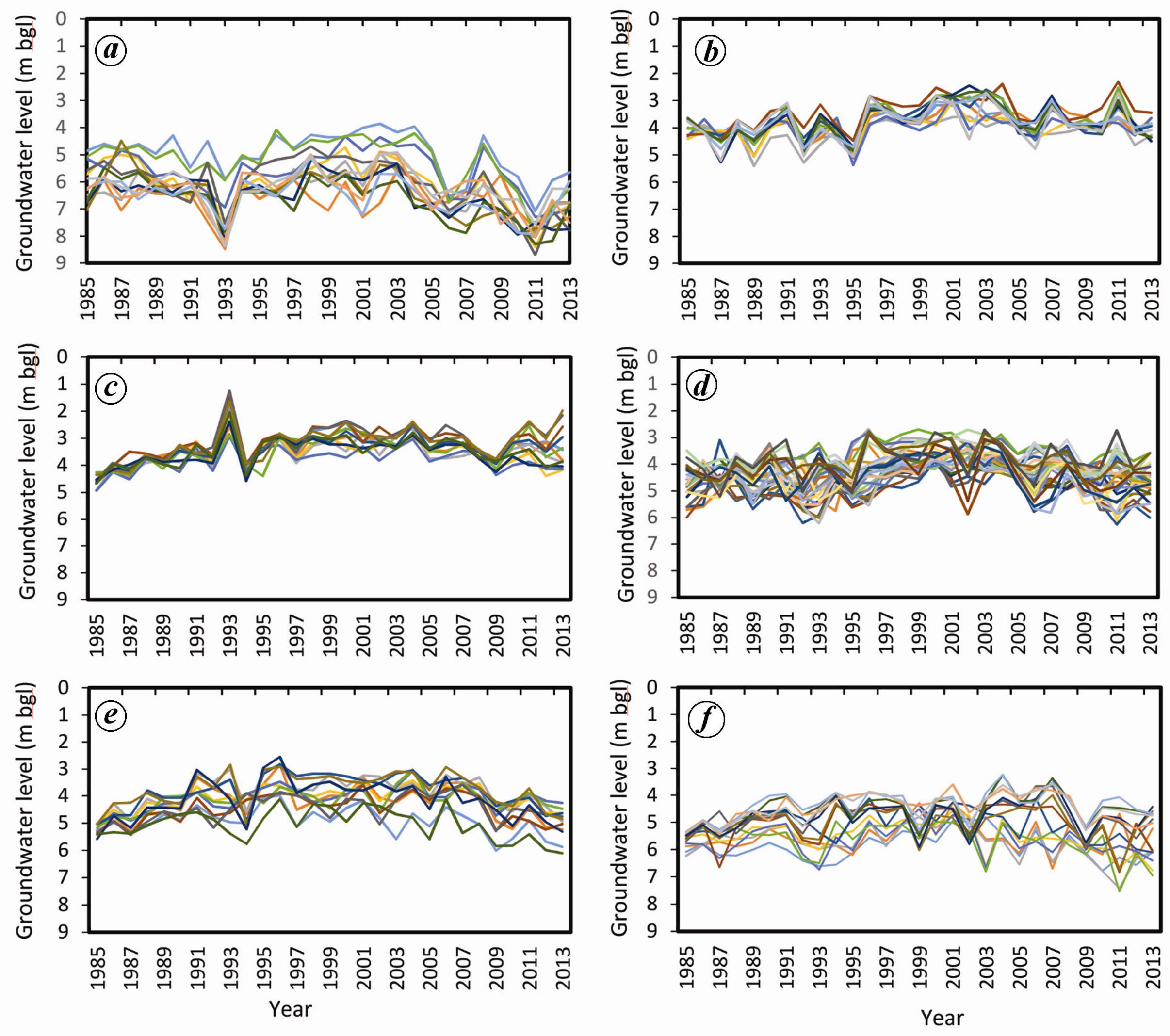

Figure 5. Synthetic cluster analysis for pre-monsoon GWL data. ***a***, Cluster 1A (Samastipur, Khagaria, Begusarai); ***b***, Cluster 2A (Sitamarhi and Madhubani); ***c***, Cluster 3A (Supaul and Araria); ***d***, Cluster 4A (Saharsa, Muzaffarpur, Darbhanga, P. Champaran); ***e***, Cluster 5A (Purnea and Madhepura) and ***f***, Cluster 6A (Katihar and Bhagalpur).

cluster for the post-monsoon data are slightly different in some cases compared to pre-monsoon clusters. A common point in all four clusters is a decreasing trend between 1985 and 1993 albeit with variable amounts. After 1993, a fairly stable trend is observed in all clusters with some exceptions. For example, clusters 1 and 2 show a major drop during 2005 and 2010 whereas cluster 3 shows a major drop in 2010.

GWS analysis

GWS change was mapped at an interval of 10 years for pre- and post-monsoon periods. The average statistics were also calculated for all spatial maps in ArcGIS for pre- and post-monsoon using zonal statistics tool and the results are listed in Table 5. The positive values suggest an increase in GWS and vice versa. In general, these maps follow a similar trend as the GWL maps but they allow us to estimate the volume change in each district.

Figure 7 shows the GWS change maps for the study area for both pre- and post-monsoon periods. Figure 7 *a* shows a significant decrease in groundwater storage in districts such as Samastipur, Begusarai and Khagaria with a total change of –577 MCM, –395 MCM and –385 MCM respectively (Table 2). A rise in GWS is documented in Supaul (+919 MCM) and Araria (+836 MCM). Likewise, the post-monsoon map (Figure 7 *b*) reflects a rise in GWS in Madhepura (+104 MCM) and Purba Champaran (+285 MCM) and a reduction in Katihar (–391 MCM) and Dharbhanga (–158 MCM) districts.

Furthermore, large variation is observed in the pre-monsoon data for the period 1994–2003 (Figure 7 *c*). Surprisingly, parts of the districts such as Bhagalpur and Katihar that are located close to the Ganga river showed a

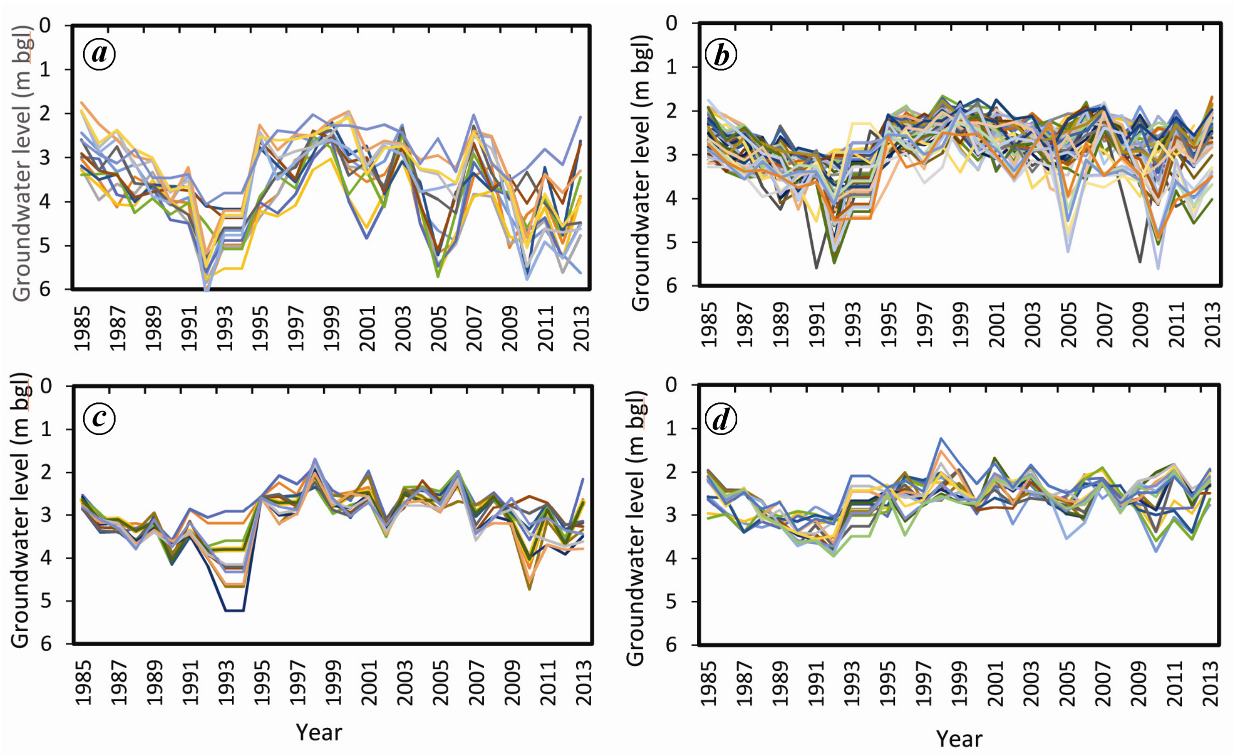

Figure 6. Synthetic cluster analysis for post-monsoon GWL data. ***a***, Cluster 1B (Samatipur, Khagaria, Begusarai); ***b***, Cluster 2B (Sitamarhi, Madhubani, Supaul, Araria, Saharsa, Muzaffarpur, Darbhanga, Bhagalpur); ***c***, Cluster 3B (Purnia, Katihar) and ***d***, Cluster 4B (Madhepura, P. Champaran).

Table 5. District wise analysis of groundwater storage change

District	Area (sq. km)	GWS (84-93) (MCM)		GWS (94-03) (MCM)		GWS (04-13) (MCM)	
		Post	Pre	Post	Pre	Post	Pre
Araria	2792.840	–8	836	462	451	64	–481
Begusarai	1923.961	–113	–395	696	194	–32	–144
Bhagalpur	2538.265	23	–210	204	–98	–278	–414
Darbhanga	2288.039	–158	37	434	389	154	–284
Katihar	3040.092	–391	248	818	–218	–390	–422
Khagaria	1484.155	–146	–385	466	242	156	–129
Madhepura	1836.837	104	422	152	394	77	–372
Madhubani	3428.438	–7	78	412	689	354	–479
Muzaffarpur	3169.951	3	–274	412	223	131	–517
Purba Champaran	3961.710	285	88	353	120	236	–477
Purnia	3238.809	–71	498	597	175	–216	–631
Saharsa	1687.619	–37	–27	361	480	145	–148
Samastipur	2893.142	–125	–577	750	255	–289	–636
Sheohar	574.557	–4	21	76	–5	44	–17
Sitamarhi	2039.483	–50	–21	353	37	214	–37
Supaul	2396.539	47	919	296	330	201	–103

significant drop in storage (–218 MCM and –98 MCM, respectively). Other districts showed a positive trend with Madhubani showing the maximum change in groundwater storage (+689 MCM). Further, Figure 7*d* demonstrates an increase in groundwater storage in the entire area during post-monsoon period, and the maximum storage change was observed in Katihar district (+818 MCM).

A drastic drop in groundwater storage is observed during the period 2004–2013 (Figure 7*e*). Groundwater storage reduced in all districts during pre-monsoon and maximum depletion was observed in Samastipur (–636 MCM) and Purnea (–631 MCM). More importantly, groundwater storage during post-monsoon also dropped in this period (Figure 7*f*). Our analysis shows that pre-monsoon groundwater storage has been decreasing

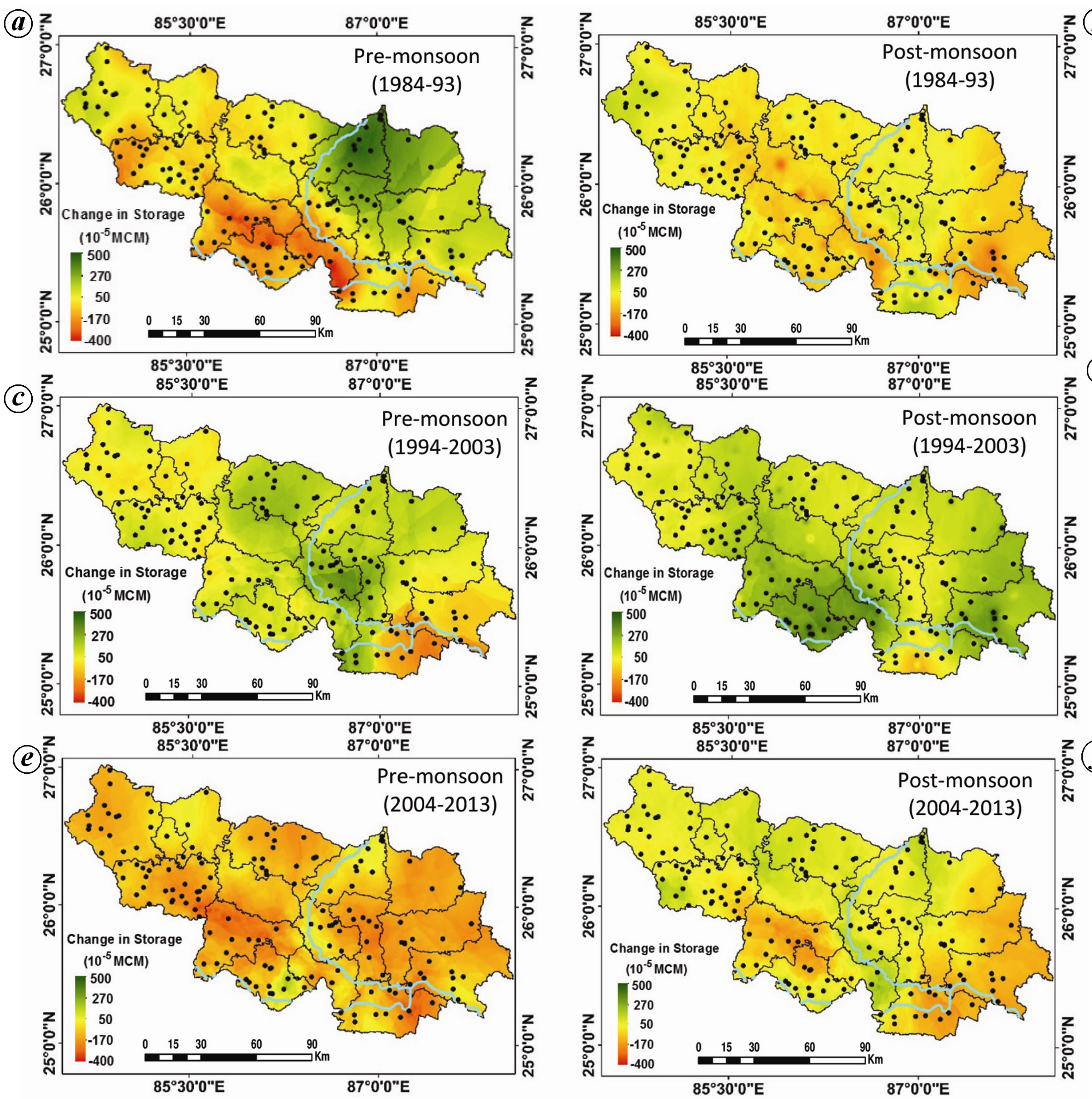

Figure 7. Change in groundwater storage for pre- and post-monsoon periods for (***a***, ***b***) 1984–1993, (***c***, ***d***) 1994–2003, (***e***, ***f***) 2004–2013.

continuously in the last 30 years in two districts namely, Begusarai and Katihar.

The results were also compared with the groundwater draft in million cubic metre (as on 31 March 2009) for different districts based on the data obtained from CGWB[36]. The districts which show very high groundwater drafts include Katihar (470.19 MCM), Samastipur (448.48 MCM) and Begusarai (351.5 MCM). This corroborates our findings that these districts are the worst affected districts in terms of groundwater depletion even though two of them (Samastipur and Begusarai) are located very close to the Ganga river. It is likely that reduction of surface water flow in the Ganga river in these stretches has led to reduction in groundwater recharge and therefore these aquifers have not been able to recoup in recent years.

Further, it is well established that LULC changes driven by population growth and demand for land for agriculture play a vital role in the depletion of GWL[37]. Keeping this in view, we have examined the LULC changes in the study area using six years (2006–2011) of data from NRSC, Hyderabad. The original LULC data was regrouped into five major classes namely, agriculture, built area, water bodies, scrubland and wasteland. Our analysis documents that agriculture land increased by 928 sq. km during this period and the area covered by

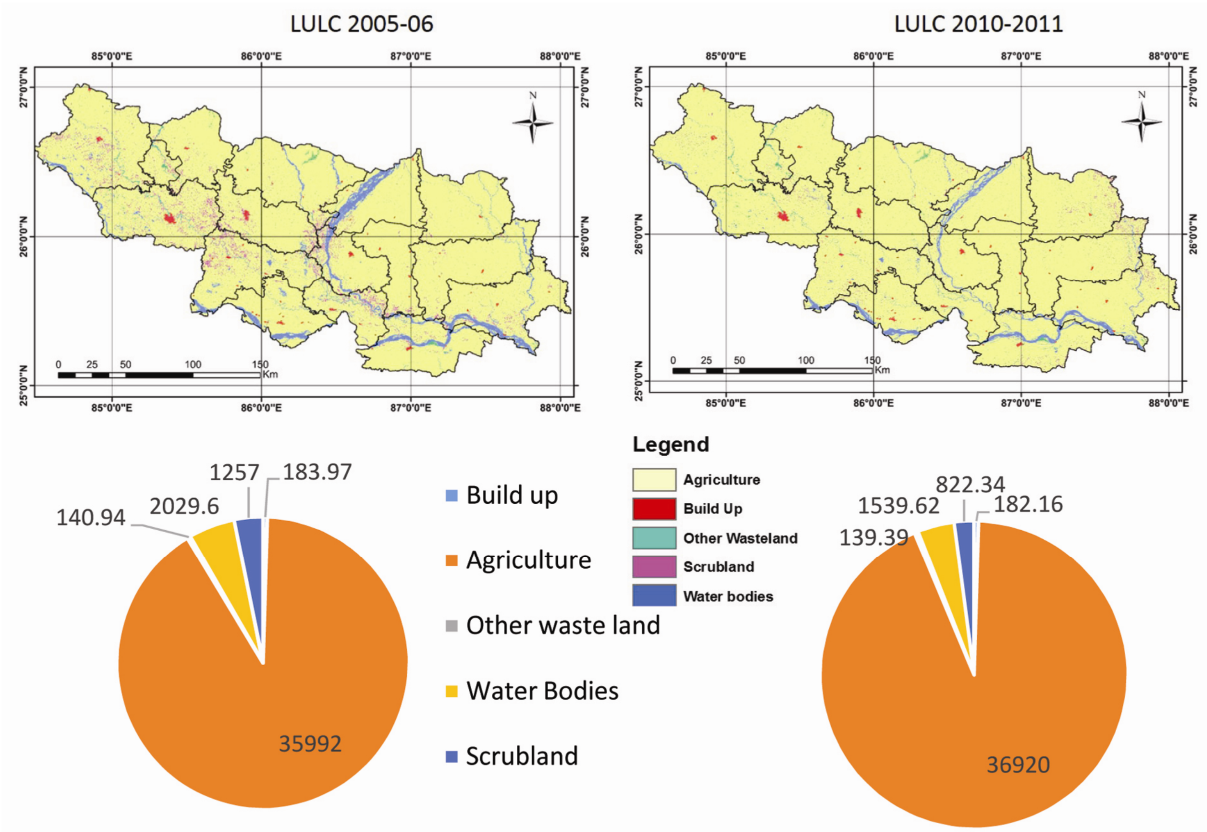

Figure 8. LULC maps of 2005–06 and 2010–11 and the related statistics.

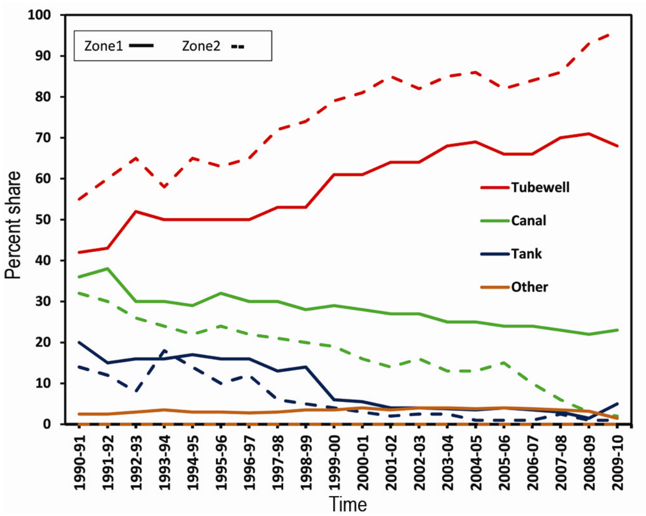

Figure 9. Share of different sources of irrigation in zones 1(a) and 2(b) in Bihar[38].

various water bodies diminished from 2029 to 1539 sq. km between 2006 and 2011 (Figure 8). Furthermore, scrub land also decreased by 435 sq. km during this period. We argue that increased agricultural land at the expense of scrub land and water bodies has led to increased water demand and therefore a rapid decline in GWL in this region. At the same time, natural recharge through water bodies has also decreased.

Increase in total water use in response to irrigation development has been analysed further. The state of Bihar has been divided into four major agro-climatic zones[38] and the study area falls in zone 1 (Sheohar, Sitamarhi, Madhubani, Darbhanga, Muzaffarpur, Samastipur and Begusarai) and zone 2 (Supaul, Khagaria, Saharsa, Madhepura, Purnea and Katihar). The available data suggest a significant growth of tube well irrigation during 1990–2010 in both zones 1 and 2 of north Bihar (Figure 9). In zone 1, the share of tube well irrigation increased from 48% in 1990 to 75.5% in 2009–10. In zone 2, the change is even more drastic, 54.7% in 1990 to 95.5% in 2009–2010, suggesting almost total dependence on groundwater for irrigation. The irrigation using canal and tanks has reduced to negligible levels in recent years primarily because the surface water infrastructure development has not kept pace with the increasing demands of water and also due to lack of any regulation for groundwater use.

According to the annual Bihar state profile[39], the per capita income of people in north Bihar is lowest in the region despite higher yield per hectare. This is because of excessive pressure of population and inequitable distribution of land. There is a concentration of sugar mills in the region. Some giant industrial complexes (like

Barauni Refineries and Fertilizers Factory, etc.) have also come up in the region. Moreover, population has also increased by 25% between 2001 and 2011. Therefore, to fulfill the demand of high population and the growing industry, the groundwater draft has also been increasing significantly.

While the northwest India has been recognized as a major global hotspot of groundwater depletion, the alluvial plains of eastern India such as north Bihar is often considered as the region is blessed with sufficient and under-exploited groundwater resources. Our study provides a quick snapshot of the groundwater depletion in this region and the data for the last ~10 years is particularly striking in terms of extensive use of groundwater and declining trends of groundwater storage in at least six districts of north Bihar namely, Begusarai, Bhagalpur, Purnea, Katihar, Samastipur and Khagaria. The cluster analysis reflects a variable trend until 2003, but all clusters show a declining trend after 2003. Although there are isolated peaks in the post-2003 data, none of these reaches the post-2003 level. This study assumes a significant importance as the north Bihar plains are being projected as a potential region for a second green evolution in the country. We emphasize that any such effort must take into account sustainable groundwater management plans to avoid any serious crisis.

Conclusions

We have analysed the spatial and temporal patterns of groundwater depletion both in terms of GWL as well as storage in north Bihar plains – an area which is generally considered as under-exploited in terms of organized groundwater development. Our analysis shows that significant depletion of groundwater resources has occurred in the last decade or so and the current groundwater usage is disorganized and unsustainable. Increasing population and LULC changes (mostly to agricultural land) seem to be the primary driver for drastic increase in water demand, most of which is met by groundwater, apparently due to the ease of availability. This is likely to get worse in the coming years due to increased urbanization leading to further changes in LULC and possible damage to recharge areas. It is urgent to develop sustainable groundwater management plans for this region before it turns into another hotspot of groundwater depletion. Some of the important measures may include accurate aquifer mapping in this extremely inhomogeneous alluvial tract, integration of all available data on GWL, agriculture and land use practices and formulation of groundwater usage regulations.

1. Gleeson, T., VanderSteen, J., Sophocleous, A. A., Taniguchi, M., Alley, W. M., Allen, D. M. and Zhou, Y., Commentary: groundwater sustainability strategies. *Nat. Geosci.*, 2010, **3**, 378–379.
2. Vörösmarty, C. J. *et al.*, Global threats to human water security and river biodiversity. *Nature*, 2010, **467**, 555–561.
3. Wada, Y., van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R. and Bierkens, M. F. P., Global monthly water stress: II. Water demand and severity of water. *Water Resour. Res.*, 2011, **47**, W07518; doi:10.1029/2010WR009792.
4. Rodell, M., Velicogna, I. and Famiglietti, J. S., Satellite-based estimates of groundwater depletion in India. *Nature*, 2009, **460**, 999–1002.
5. Tiwari, V. M., Wahr, J. and Swenson, S., Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophys. Res. Lett.*, 2009, **36**, L18401.
6. Census of India, Population, size and decadal change. In primary census data highlights – India. Government of India, Ministry of Home Affairs, Office of the Registrar General and Census Commissioner, New Delhi, 2011.
7. Bovolo, C. I., Parkin, G. and Sophocleous, M., Groundwater resources, climate and vulnerability. *Environ. Res. Lett.*, 2009, **4**, 035001.
8. Pophare, A. M., Lamsoge, B. R., Katpatal, Y. B. and Nawale, V. P., Impact of over-exploitation on groundwater quality: a case study from WR-2 Watershed, India. *J Earth Syst. Sci.*, 2014, **123**(7), 1541–1566.
9. Ghosh, A., Singh, S. K., Bose, N. and Chowdhary, S., Arsenic contaminated aquifers: a study of the Ganga levee zone in Bihar, India. In Symposium on Arsenic: the geography of a global problem, Royal Geographical Society, London, 29 August 2007.
10. Shah, T., Molden, D., Sakthivadivel, R. and Seckler, D., The global groundwater situation: overview of opportunities, and challenges. International Water Management Institute, Colombo, Sri Lanka, 2000.
11. Burrough, P. H., Methods of spatial interpolation. In *Principles of Geographic Information Systems for Land Resources Assessment*, Clarendon Press, Oxford, 1986, pp. 147–166.
12. Flowerdew, R. and Green, M., Areal interpolation and types of data. In *Spatial Analysis and GIS* (eds Fotheringham, S. and Rogers, P.), Taylor & Francis, London, 1994, pp. 121–146.
13. Ahmadi, S. H. and Sedghamiz, A., Geostatistical analysis of spatial and temporal variations of groundwater level. *J. Environ. Monit. Assess*., 2007, **129**, 277–294.
14. Sun, Y., Kang, S. Z., Li, F. S. and Zhang, L., Comparison of interpolation methods for depth to groundwater and its temporal and spatial variations in the Minqin oasis of northwest China. *Environ. Model. Softw*., 2009, **24**, 1163–1170.
15. Triki, I., Trabelsi, N., Hentati, I. and Zairi, M., Groundwater levels time series sensitivity to pluviometry and air temperature: a geostatistical approach to Sfax region, Tunisia. *Environ. Monit. Assess.*, 2014, **186**(3), 1593–1608.
16. Yao, L., Huo, Z., Feng, S., Mao, X., Kang, S., Chen, J. and Steenhuis, T. S., Evaluation of spatial interpolation methods for groundwater level in an arid inland oasis, northwest China. *Environ. Earth Sci.*, 2014, **71**(4), 1911–1924.
17. Varni, M., Comas, R., Weinzettel, P. and Dietrich, S., Application of the water table fluctuation method to characterize groundwater recharge in the Pampa plain, Argentina. *Hydrolog. Sci. J.*, 2013, **58(7)**, 1445–1455.
18. Yi, H. and Wen, L., Satellite gravity measurement monitoring terrestrial water storage change and drought in the continental United States. Scientific Reports, 6, 2016.
19. Kuss, A. *et al.*, Comparison of changes in groundwater storage using GRACE data and a hydrological model in California's Central Valley. In ASPRS Ann. Conf., Sacramento, CA, 2012.
20. Longuevergne, L., Scanlon, B. R. and Wilson, C. R., *GRACE Hydrological Estimates for Small Basins: Evaluating Processing Approaches on the High Plains Aquifer, USA*. *Water Resour. Res*., 2010, **46**, doi: 10.1029/2009wr008564.

21. Beekman, H. E. and Xu, Y., Review of ground water recharge estimation in arid and semiarid Southern Africa, Council for Scientific and Industrial Research (South Africa), University of the Western Cape, Report, 2003.
22. Ruud, N., Harter, T. and Naugle, A., Estimation of groundwater pumping as closure to the water balance of a semi-arid, irrigated agricultural basin. *J. Hydrol*., 2004, **297**(1–4), 51–73.
23. Flood Management Information System (FMIS). Water Resources Department Government of Bihar, Flood Report, 2011.
24. Nepal, S., Evaluating Upstream-Downstream Linkages of Hydrological Dynamics in the Himalayan Region (Ph D thesis). Friedrich Schiller University of Jena, Jena, 2012.
25. Central Ground Water Board (CGWB), GOI, Ministry of Water Resources. Ground Water Year Book – India 2013–14, 2014.
26. NRSC, National Land use and land cover mapping using multi-temporal AWIFS data. RS and GIS Application area, Government of India, Hyderabad, 2006.
27. Healy, R. W. and Cook, P. G., Using groundwater levels to estimate recharge. *Hydrogeol. J*., 2002, **10**(1), 91–109.
28. Wahid, S. M., Babel, M. S., Gupta, A. D. and Clemente, R. S., Spatial assessment of groundwater use potential for irrigation in Teesta Barrage Project in Bangladesh. *Hydrogeol. J.*, 2007, **15**(2), 365–382.
29. Varni, M., Comas, R., Weinzettel, P. and Dietrich, S., Application of the water table fluctuation method to characterize groundwater recharge in the Pampa plain, Argentina. *Hydrolog. Sci. J.*, 2013, **58**(7), 1445–1455.
30. Brears, E., Post, R. and Authority, N. V. C., NVCA Water Table Fluctuation Study, 2014.
31. Maréchal, J. C., Dewandel, B., Ahmed, S., Galeazzi, L. and Zaidi, F. K., Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *J. Hydrol.*, 2006, **329**(1), 281–293.
32. Central Groundwater Board (CGWB). Kosi Megafan–potential groundwater reservoir, Conjunctive use study in Eastern Kosi canal command, Bihar, a model based approach. Ministry of Water Resources, Government of India, New Delhi, 2012.
33. MacDonald, A. M. *et al.*, Groundwater depletion and quality in the Indo-Gangetic Basin from in situ observations. *Nat. Geosci.*, 2016, **9**.
34. Bhanja, S. N., Rodell, M., Li, B., Saha, D. and Mukherjee, A., Spatio-temporal variability of groundwater storage in India. *J. Hydrol.*, 2017, **544**, 428–437.
35. Cambardella, C., Moorman, T., Novak, J., Parkin, T., Karlen, D., Turco, R. and Konopka, A., Field-scale variability of soil properties in central Iowa soils. *Soil Sci. Soc. Am. J*., 1994, **58**, 1501–1510.
36. CGWB, Groundwater information booklet. Ministry of Water Resources, Government of India, Patna, 2013.
37. Mishra, N., Khare, D., Gupta, K. K. and Shukla, R., Impact of land use change on groundwater – a review. *Adv. Water Resour. Protect*., 2014, **2**(28), 28–41.
38. Kishore, P., An Economic study of groundwater use in irrigated agriculture in Bihar (M Sc dissertation), IARI, Division of Agricultural Economics Indian Agricultural Research Institute New Delhi, 2013.
39. Ministry of Micro, Small and Medium Enterprises., Bihar State Profile 2015–16, Government of India, 2015.

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