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Groundwater Regulation Bills in Haryana – A Call for Groundwater Conservation and Management for Sustainable Irrigation Supply Services – Opportunities and Challenges

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ABSTRACT

Over-reliance on groundwater resources for irrigation has helped achieving food/nutritional targets, at the expense of growing increased vulnerability of water resources in the northwest Indian states. In this reconnaissance study, we take Sonipat district, Haryana as a microcosm, to evaluate potential impacts of *Haryana State Groundwater Management and Regulation Bill, 2008* and *Haryana Preservation of Sub-Soil Water Act 2009*, to understand future requirements of groundwater resources conservation/management. Well-level groundwater level (GWL) information was obtained from the Central Groundwater Board's archive, between 1996 and 2018, disaggregated by tehshils and growing seasons. Results indicated statistically significant ($p<0.05$) 'shallowing' of median GWLs in the Post-Bill periods (2009-2013 and 2014-2018) in the Sonipat and Ganaur tehshils, for all growing seasons, which might gratify the authorities about 'success' of the two Regulatory Bills to conserve groundwater. However, (i) presence of 'outliers' in Sonipat and Ganaur tehshils (deeper GWLs); (ii) dropping monitoring efficiency over years; and (iii) growing water resources vulnerability by predictive geostatistical modeling, question the above. For future conservation efforts, we urge the authorities to integrate three spheres: (1) Process-based Groundwater Research and Development; (2) Creating an Enabling Environment at Grassroots; and (3) Policy Appraisal and Institutional Changes.

Key words : *Haryana State Groundwater Management and Regulation Bill 2008; Haryana Preservation of Sub-Soil Water Act 2009; irrigation; groundwater level; Inverse Distance Weighted (IDW) interpolation; monitoring efficiency; community mobilization, multi-stakeholder arrangement; micro-irrigation; institutional reform*

Introduction

Groundwater forms the mainstay of current Indian irrigation system (Mukherjee *et al.*, 2014; Shah, 2010; Hira, 2009), a means of agricultural expansion, livelihood creation, income generation, and thus, a policy instrument for poverty alleviation and holistic rural development (Sekhri, 2014, 2011; Sarkar, 2011). Over the years, however, unregulated groundwater drafting, has led to significant declines

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in water levels (Chaudhuri and Kaur, 2017; Nelson *et al.,* 2013), that threatens sustainable agrarian development opportunities on many levels (Humphreys *et al.,* 2010). The northwestern states of India (Rajasthan, Punjab, Haryana) form the prime hot seat of agricultural excellence in the nation, and by the same token, hotspot of groundwater depletion (Chaudhuri *et al.,* 2021; Srivastava *et al.,* 2017; Rodell *et al.,* 2009). Besides limiting future irrigation opportunities, groundwater depletion has raised many adverse eco-environmental (Chaudhuri and Lakshmanan, 2017) and health outcomes, including rural Water-Sanitation-Hygiene (WaSH) (Chaudhuri and Roy, 2017a), potable water crises (Chaudhuri and Roy, 2017b, 2016a), even farmers' suicides (Chinnasamy *et al.,* 2019).

In an attempt to conserve vanishing groundwater resources, the state government of Haryana devised the Ground water Management and Regulation Authority in 2008, with diverse advisory and regulatory functions. A notable outcome of this authority is formulation of the *Haryana State Groundwater Management and Regulation Bill* in 2008 (HSGMRB-08) (IELRC, 2008). Subsequently, the government brought out another policy measure on similar lines namely, Haryana Preservation of Sub-Soil Water Act 2009 (HPSSWA-09). In the present narrative we take up Sonipat District in Haryana to assess potential impacts of the two Regulatory Bills on long-term spatio-temporal trends of groundwater levels. In Sonipat, Haryana the demand for groundwater for irrigation has soared through the past few decades (CGWB, 2013). With the advent of improved groundwater extraction mechanisms (submersible pumps, replacing age-old centrifugal pumps), groundwater has become more accessible to farmers, and by the same token, even more vulnerable (IIPS, 2015).

Both the Regulatory Bills had various regulatory and statutory powers such as systematic registration of existing wells and well users, regulating well which are in periphery of drinking water sources, granting permission to amend/vary the terms of permit etc to name a few. In essence the Bills profess to: (I) collect information and investigate measurements concerning the land which is located on underground and surface; (II) provide directives on submitting borehole record and analyses of soil samples; (III) install measuring device to monitor groundwater level (GWL); and (IV) seize mechanical equipment which were utilized for illegal sinking. ("Haryana State Groundwater Management and Regulation Bill", 2008).

In the present context, we assume a water conservationist's approach to elucidate to the regulatory authorities (groundwater, irrigation, and environmental systems' managers) the combined impacts of the HSGMRB-08 and HPSSWA-09, by reflecting on set of development questions:

1. Is there any statistically significant evidence of impacts of the two Regulatory Bills across Sonipat district? (implications for future conservation policy making)
2. Which regions yet demand stringent implementation of the Bills?
3. Is the monitoring coverage adequate to make informed policy decisions about the Bills? (Do We *Really Know* What We Claim to Know?)
4. Are there any 'outliers' in the region? Is there any spatio-temporal pattern to the 'outliers' (e.g. Are the outliers spatially clustered? Have the 'outliers' become more common over time, say, in the Post-Bill period?)

The above are approached within a spatio-temporal framework as follows:

- Spatial Dimension: Groundwater level (GWL) information for four tehshils (Sonipat, Ganaur, Gohana and Kharkhauda)
- Temporal Dimension:
  → GWL for four periods: 1995-2002; 2003-2008; 2009-2013; and 2014-2018. The first two periods are deemed as 'Pre-Bill Period' while the latter two, 'Post-Bill Period'
  → GWL for four growing seasons: Pre-monsoon, Post-Monsoon, Post-Monsoon Rabi, Post-Monsoon Kharif

Besides irrigation and water resources managers, HSGMRB-08 and HPSSWA-09 is of interest to the environmental health sector as well. A recent study insinuates trade-offs between the Bills and air quality in the NCR (Sing *et al*., 2019). The Haryana Preservation of Sub-Soil Water Act 2009 require farmers to transplant rice later in the year. The Bills, especially the HPSSWA-09, recommended shifting sowing and transplanting times of rice-paddy from May (when farmers are solely dependent on groundwater for irrigation) to June, in order to bring cultivation closer to the monsoon season. However, such recommendations push back the harvest season, thereby 'compelling' uncontrolled and open incineration of crop residues (rice-paddy stubbles) in November for timely seedbed preparation for winter wheat. However, November is a month when meteorological conditions in the NCR favors air pollution (elevated levels of PM_{10} and $PM_{2.5}$ in ambient atmosphere), and open incineration of crop residues only but aggravated environmental health concerns further.

Here we take Sonipat as a microcosm of growing groundwater vulnerability in Haryana as a whole. Although the study may appear context specific, the normative and conceptual reasons for shifting the discourse remain applicable to groundwater-dependent agrarian economies anywhere in the world, and could be replicated for similar purposes with nominal modification of the methods outlined herein.

Methodology

Sonipat district lies between 28° 47′ 48′′ N to 29° 17′ 31′′ N latitude and 76° 28′ 36′′ E to 77° 13′ 40′′ E longitude. It comprises of 4 tehsils or 7 blocks within itself for revenue and administration purposes. It has a low annual precipitation, high humidity which gets exacerbated in the summer seasons. With a total geographical area of about 2,122 Sq. Km, less than 1% of the land is forest area (ISFR Haryana 2019). The irrigation intensity is around 187%, far above the national average for India (~134%), which indicates the dire state of groundwater dependency (Singh *et al.,* 2019). About a third of the households in Sonipat district are dependent on groundwater sources (hand pumps and tube/bore wells) as the main source of drinking water (Directorate of Census Operations 2014). Additional challenges around groundwater resources include salinity and water logging in eastern part (Sonipat District Administration, 2021).

Information about groundwater level observations (GWLs), for four growing seasons (Pre-monsoon, Post-Monsoon, Post-Monsoon Rabi, Post-Monsoon Kharif), disaggregated by four year-period (1995-2002; 2003-2008; 2009-2013; and 2014-2018), were obtained from the open-sourced repository of the Central Ground Water Board (CGWB) for four tehshils namely, Sonipat, Ganaur, Gohana and Kharkhauda.

For the temporal aspect, we employed the Mann-Whitney U Test is used to detect statistically significant differences ($p<0.05$) in median concentrations of groundwater levels (GWLs) between (i) years periods and (ii) seasons. The Mann-Whitney U Test takes the general notion as follows:

$$U = \sum_{i=1}^{n} \sum_{j=m}^{m} S(X_i, Y_j)$$

where S (X, Y) = 1 if Y < X
= ½ if Y = X
= 0 if Y > X
U = Mann-Whitney U Statistic
X and Y = GWLs from two year-periods)
n and m = Sample sizes of X and Y, respectively

The Mann-Whitney U test is a non-parametric counterpart for two-sample location test (used to test the hypothesis if two sample means are equal when the samples have unequal variances and/or unequal sample sizes. Prime assumptions of the test include: (i) samples are random, (ii) independent, and (ii) continuous (McKnight and Julius, 2010). Being a nonparametric test, MannWhitney has fewer constraints and assumptions (e.g. normality of data distribution) unlike the parametric counterparts (e.g. Student's t-test) (Chaudhuri *et al.,* 2012).

In the next stage, we performed a surface interpolation technique, to estimate GWLs at locations without a well (unmonitored locations), namely Inverse Distance Weighted (IDW). In a generalized way, the IDW takes on the following form:

$$GWL(X_0) = \sum_{i=1}^{n} W_i Z_i$$

where $GWL(X_0)$ = Estimated value of GWL at the point of interest X_0

W_i = Weight assigned to the sampled point X_i with respect to X_0

Zi = Observed GWL at the sampled point X_i

The weight parameter 'W' in the above is computed by following equation:

$$W_i = \frac{d_i^{-p}}{\sum_{k=1}^{n} d_k^{-p}}$$

where d_i = Euclidean distance between X_i and X_0

p = Positive power parameter chosen between 0 and 2

k = Observed GWL at the sampled point X_i

Presence of 'Outliers' in the GWL observations were determined at individual well-level for each growing season, year-period, and tehshil, by using following equations,

Deeper Outlier (OUT_{dp}) = $Q_3 + (1.5 * IQR)$
Shallower Outlier (OUT_{sl}) = $Q_3 + (1.5 * IQR)$
where OUT_{dp} = Outlying GWL observation at deeper level
OUT_{sl} = Outlying GWL observation at shallower level
Q_3 and Q_1 = 3rd and 1st Quartile in the GWLs, respectively
IQR = Inter Quartile Range ($Q_3 - Q_1$)

In the present context, the OUT_{dp} and OUT_{sl} were deemed equivalent to groundwater depletion, and restoration (improvement), respectively.

Monitoring Efficiency (ME), taken as the frequency of GWLs monitored for each well across four year-periods, were expressed as (i) area-wise percentages of wells monitored in each tehshil, and (ii) at individual well-level. For the later, we introduced an objective classificatory scheme as follows:

1. Poor ME = 0.25 (monitored once in four year-periods)
2. Moderate ME = 0.50 (monitored twice in four year-periods)
3. Satisfactory ME = 0.75 (monitored thrice in four year-periods)
4. Good ME = 1.00 (monitored each time in each year-periods)

Results and Discussion

Bird's Eye View: Sonipat District Summary

Groundwater levels (GWLs) revealed an overall declining pattern, throughout the study period (1995-2018), in the study region, as evident from the median values (Table 1). For each growing season (monsoon, Post-monsoon Rabi, Post-monsoon Kharif and Pre-monsoon), the deepest GWLs were consistently observed in recent times (2014-2018 year-period), which questions the influence of the two Regulatory Bills (HSGMRB-08 and HPSSWA-09) to stall water-level drops. The Mann-Whitney U test results indicated statistically significant differences ($p<0.05$) between 1996-2002 (Pre-Bill) and 2014-2018 (Post-Bill). For each year-period (1996-2002, 2003-2008, 2009-2013, 2014-2018), deepest median GWLs were observed for the pre-monsoon season (Table 1). What might worry the regulatory authorities is, besides overall dropping GWL trend:

- Highest variability (IQR in Table 1) observed in recent times (2014-2018)
- Consistently increasing variability (IQR) over time

The above calls for more intensive monitoring and process-level assessment of groundwater dynamics (human-water interaction) in future to anticipate GWL status. Such assessments will be particularly of value to the farmers in the wake of climatic anomalies that are projected to affect groundwater availability and accessibility, thereby limiting irrigation potentials. The latter might affect agrarian livelihood and income generation opportunities,

Table 1. Temporal pattern of depth to groundwater level (expressed as meters below ground level) in different seasons and year periods, considering all the four tehshils together *(Data source: CGWB)*

		Pre-Bill Period		Post-Bill Period	
		1996-2002	2003-2008	2009-2013	2014-2018
Monsoon	Median	$3.84^{a\,m}$	$4.34^{a\,m}$	$4.71^{a\,m}$	$6.65^{b\,m}$
	IQR	3.13	5.11	5.83	8.22
	Maximum	17.90	24.13	24.95	26.80
Post-Monsoon Rabi	Median	$3.04^{a\,m}$	$3.80^{a\,m}$	$3.54^{a\,m}$	$5.83^{b\,m}$
	IQR	2.06	3.42	5.59	10.08
	Maximum	12.37	23.14	22.77	27.91
Post-Monsoon Kharif	Median	$3.51^{a\,m}$	$3.21^{a\,m}$	$4.08^{a\,m}$	$5.99^{b\,m}$
	IQR	1.86	3.16	9.92	9.80
	Maximum	12.24	23.60	27.06	32.06
Pre-Monsoon	Median	$4.30^{a\,m}$	$4.66^{a\,m}$	$4.26^{a\,m}$	$5.55^{b\,m}$
	IQR	2.82	3.70	4.40	9.21
	Maximum	14.00	23.52	22.87	30.14

NOTE: For each median value, significance ($p<0.05$) of Mann-Whitney U test is indicated by (i) first letter superscript ('*a*' or '*b*') across the year-periods within a same season (horizontal comparison of medians), and (ii) second ('*m*') within each year-period, across seasons (vertical comparison of medians); 'n' represents number of water-level observations; 'IQR' represents variability in water-level observations; 'Maximum' represents the deepest water level observation recorded food/nutritional security, collectively, which might undermine sustainable rural development initiatives in Sonipat district.

Spatial Heterogeneity: ***Which Regions Are More at Risk?***

Tehshil-wise, there was considerable heterogeneity in GWLs over time (Figure 1 a-d**)**. During the pre-Bill period (1996-2002), deepest median GWLs were observed in Ganaur, for Post-monsoon Rabi and Kharif and Pre-monsoon seasons. It was followed by Sonipat in 1996-2002, Kharkhauda and Gohana. Both in Ganaur (Figure 1a) and Sonipat **(Fig. 1d)** tehshils, the median GWLs registered an exponential 'shallowing' over time, indicating positive impact of the two Regulatory Bills (HSGMRB-08 and HPSSWA-09) on groundwater resources. The Mann-Whitney U test results for Ganaur and Sonipat, revealed significant differences between 1996-2002 median GWLs and all other year-periods, respectively. However, there was no statistically significant differences ($p<0.05$) in mean GLWs since 2003-3008, which questions the sustained effectiveness of the Regulatory Bills. Moreover, there was no statistically significant differences in median GWLs in Gohana (Fig. 1b) and Kharkhauda **(Fig. 1c)**, which re-emphasizes the doubt about on-ground implementation of the two Regulatory Bills (HSGMRB-08 and HPSSWA-09). However, the absolute figures (median GWLs) in Kharkhauda revealed a slightly deepening trend in recent times **(FIGURE 1c)**. There were no statistically significant seasonal differences ($p<0.05$) in median GWLs for any tehshil within individual year-periods. However, in Gohana and Sonipat tehshils, deepest median GWLs in the Post-Bill periods were observed for the Pre-monsoon season.

The IDW interpolated surface (approximation of GWL at locations without wells), however, portrayed an overall 'shallow' depth throughout the

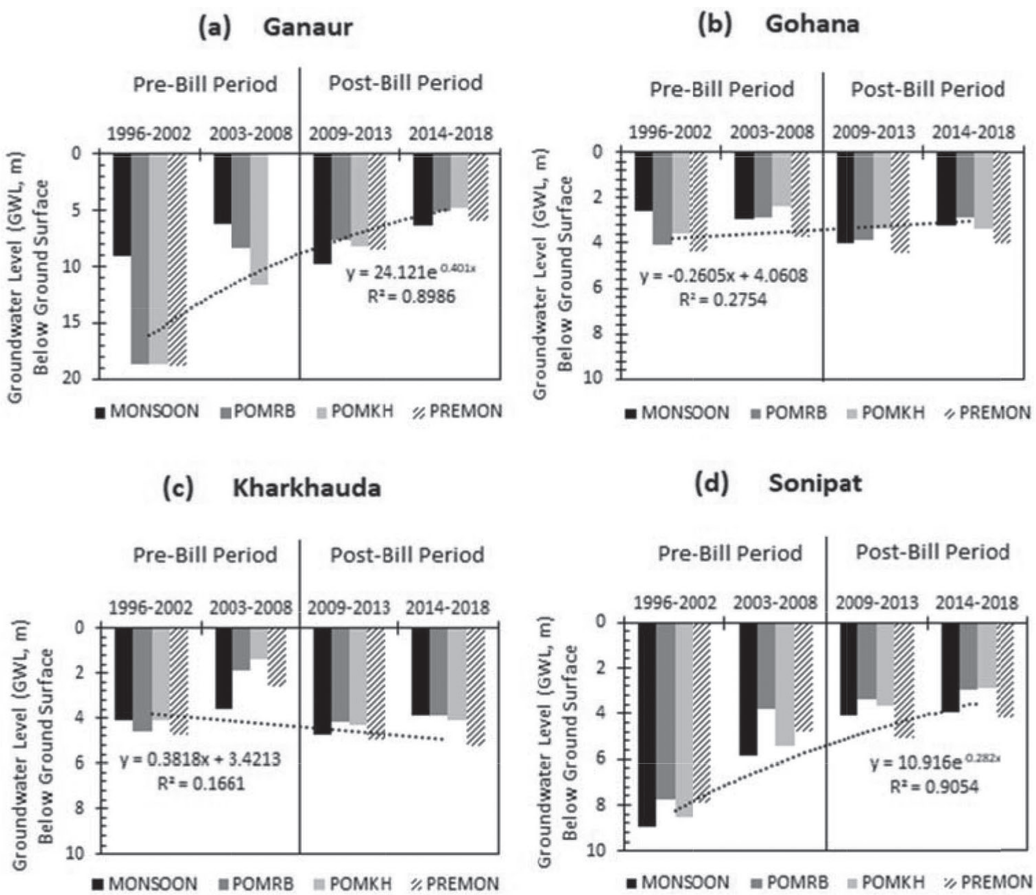

Fig. 1. Tehshil-wise median groundwater levels (GWLs) disaggregated by growing season and year-period: NOTE: POMRB = Post-monsoon Rabi; POMKH = Post-monsoon Kharif; PREMON = Pre-monsoon *(Data source: CGWB)*

region, during the Pre-Bill Periods (1996-2002 and 2003-2008) with water levels registering at <1 m below the ground surface for most part (Fig. 2 and 3). Few exceptions were, however, observed in the southeastern parts of the study region (Sonipat tehshil) where GWLs were observed were at depths below 30 m from ground surface. Deeper GWLs, became more apparent in the Post-Bill Periods (2009-2013 and 2014-2018) and have extended throughout the western part of the study region (Sonipat and Ganaur tehshils) for all growing seasons. In the present context we use IDW as potential GWL modeling tool to draw attention of the regulatory authorities to regions that might need future policy attention (intensive water level monitoring, identifying potential cites for artificial recharge, imposing restrictions on groundwater drafting etc.).

In recent times, IDW has been a potent predictive

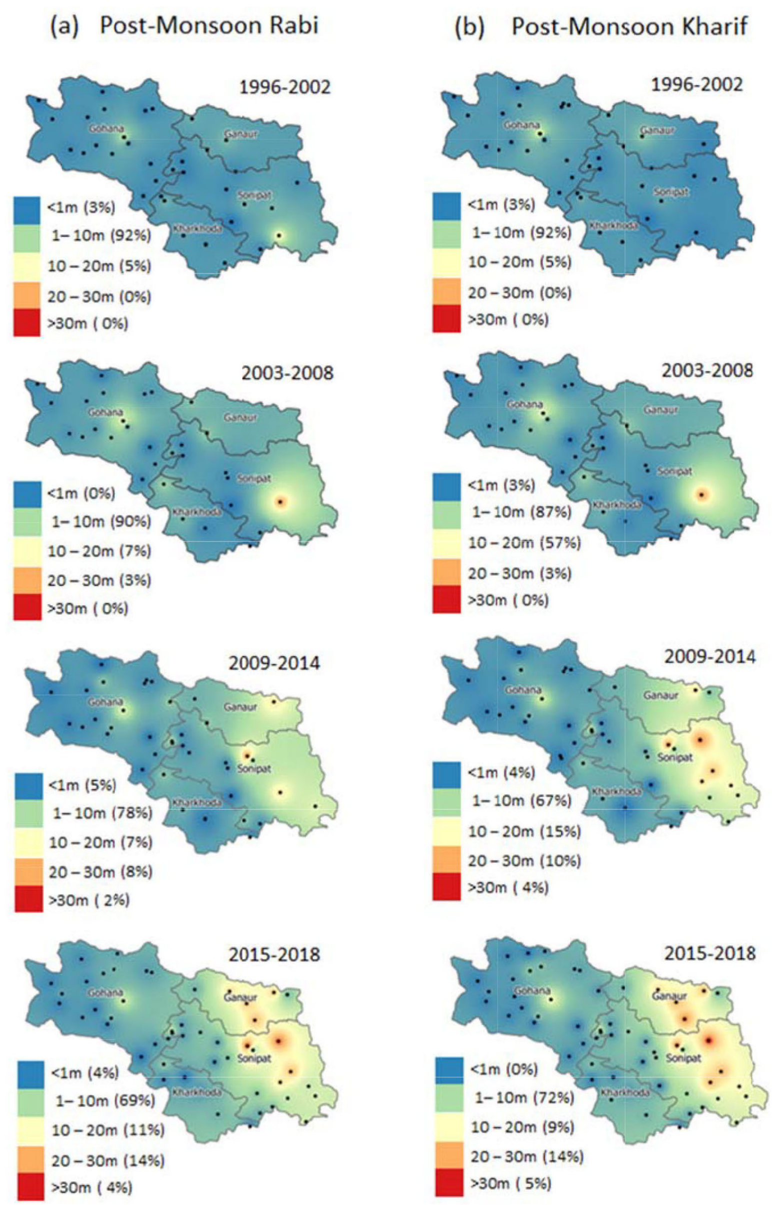

Fig. 2. Inverse Distance Interpolation (IDW) surfaces representing depths to groundwater level (below ground surface) for Post-Monsoon (a) Rabi and (b) Kharif seasons across different time periods. Values in the parentheses represent percentages of wells, out of all wells monitored during that time period for Soinpat district as a whole, falling in each water level depth category. Black dots represent monitoring wells. *(Data Source: CGWB)*

geostatistical modeling tool, used by researchers and decision-makers alike around the world, to ideate spatio-temporal variability (changes) in groundwater table (Nistor *et al.*, 2020; Goyal and Chaudhary, 2010), as well as assessing regional groundwater quality (Goyal *et al.*, 2010). IDW interpolation is based on a prime assumption that the sampled values closest to the prediction location have more in-

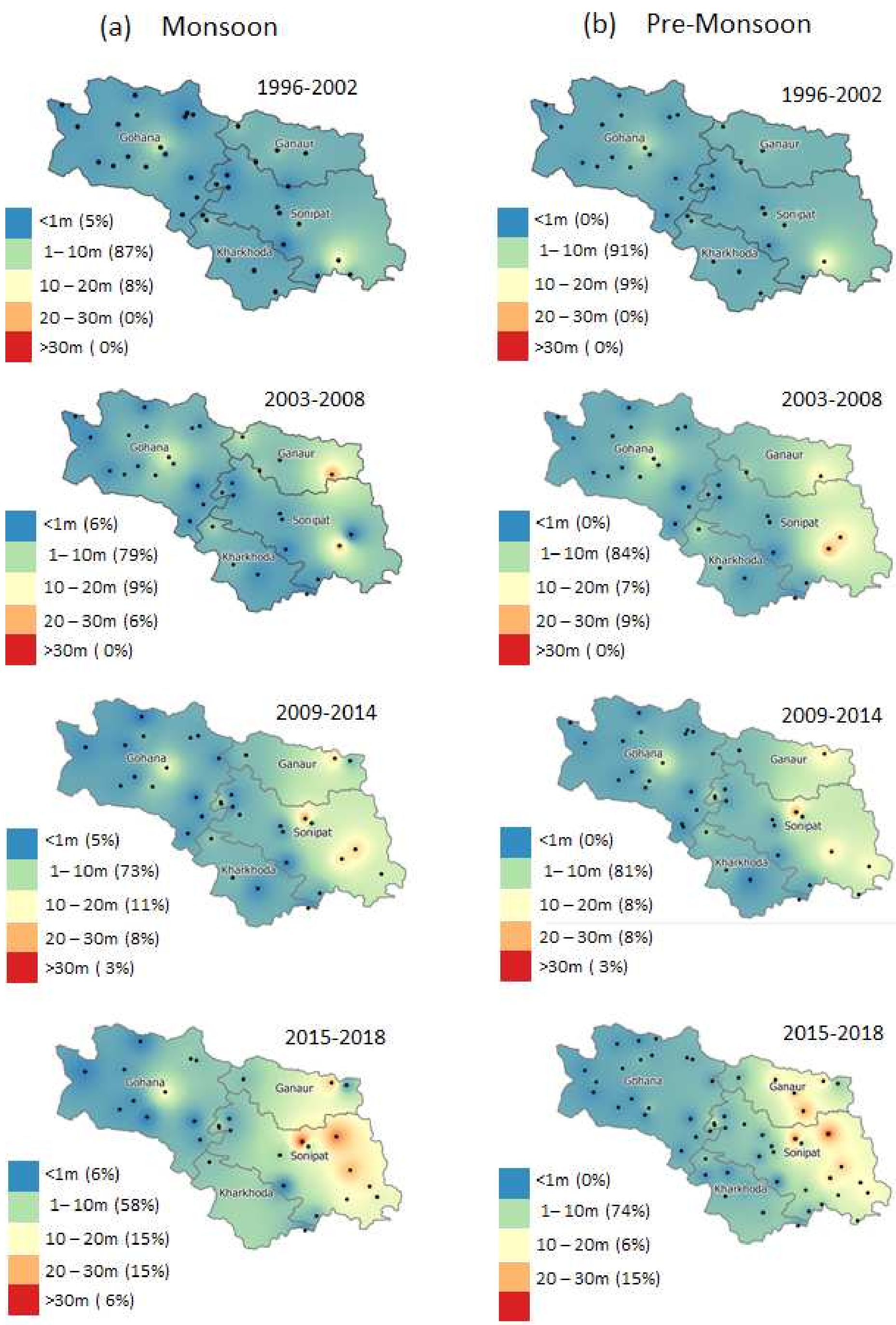

Fig. 3. Inverse Distance Interpolation (IDW) surfaces representing depths to groundwater level (below ground surface) for (a) Monsson and (b) Pre-Monsoon seasons across different time periods. Values in the parentheses represent percentages of wells, out of all wells monitored during that time period for Soinpat district as a whole, falling in each water level depth category. Black dots represent monitoring wells. *(Data Source: CGWB)*

fluence on the predicted value, than those farther away. This causes that predictions are obtained from the nearest sampling points. IDW has unique advantages over other geostatistical modeling techniques such as kriging (Bronowicka-Mienlniczuk *et al.,* 2019; Gong *et al.,* 2014). However, there is need to perform cross-validation on IDW-predictions of GWL, for which, there is need to pay special heed to monitoring (spatial configuration of wells to be selected for IDW).

Outlier Analysis: *Exception Proves the Rule?*

Outliers often provide valuable keys to shifts in groundwater dynamics (aberrant trends), essential to formulate context-relevant conservation measures. We identified 11 such wells, mostly clustered in the Sonipat tehshil (Table 2). Interestingly, all the outlier were identified as 'Deeper Outlier (OUT_{dp})' which indicates progressive deepening of groundwater levels, and thus questions the extent ground-level implementation of HSGMRB-08 and HPSSWA-09. For the regulatory authorities, however, the woe lies in the heterogeneity in Monitoring Efficiency (ME) of the outliers. Most outlying observations featured in the 'Poor' ME category, implying lack in monitoring frequency. As added aggravation, several wells classified as outliers in the Pre-Bill year-periods (1996-2002 and/0r 2003-2008) were not monitored 'adequately' in the Post-Bill period. For example, Garhi-ujlekhan (Gohana tehshil); Kheora-1, Kheaora-2, Jhakauli-Pz and Murthal-Pz (all in Sonipat tehshil) were measured once in the Post-Bill period. Interestingly, Jhakauli-Pz and Murthal-Pz were, as the names suggested, 'piezometric' wells, specifically meant for GWL measurements. Larsauli (Ganaur) and Bayanpur-1 (Sonipat) were never monitored in the Post-Bill period.

Of particular interest to the regulatory authorities should be 'Gohana-1' and Rai (Bahalgarh) wells, classified as outliers in all previous Pre- and Post-Bill year-periods but the most recent one (2014-2018). Was this outcome of natural causes? Or was it instrumental/human error? Whichever might be the case, the outlier wells, as a whole, demand special policy attention to understand likely influences of local human dynamics, irrigation preferences, land management history, crop types, vegetation, topography, soil characteristics etc. Of immediate need it to moderate groundwater extraction at or near the outlier wells and increase the frequency of monitoring.

Groundwater Data Quality: Do We Really *Know* What We Know?

Understanding of spatio-temporal changes in GWLs, and groundwater regulations developed/implemented thereof, are keyed to the level of monitoring of groundwater wells. In the present context, we present this analysis as a plea to the groundwater conservationists to self-assess the current monitoring strategy so as to avoid over-/under-estimating the impacts of the two Regulatory Bills (HSGMRB-08 and HPSSWA-09). We offer the authorities two perspectives at groundwater data quality:

- *Regional*: Identifying tehshils that lack adequate

Table 2. Identifying outlier wells in the study region, based on GWL observations during year-periods, along with Monitoring Efficiency (ME) scores *(Data Source: CGWB)*

Well Code	Site	Tehshil	Coordinate (Lat /Long)	Pre-Bill Period 1996-2002	Pre-Bill Period 2003-2008	Pre-Bill Period 2009-2013	Pre-Bill Period 2014-2018	ME
W16736	Garhi-ujlekhan	Gohana	29.13/76.71	11.58	17.1	NM	NM	Moderate
W16737	Gohana-1	Gohana	29.13/76.71	13.23	16.14	17.025	NOut	Satisfactory
W20904	Larsauli	Ganaur	29.10/77.07	NM	24.13	NM	NM	Poor
W29933	Datauli0Pz	Ganaur	29.15/77.08	NM	NM	24.05	26.80	Moderate
W16740	Bayanpur-1	Sonipat	28.9/77.09	11.9	NM	NM	NM	Poor
W16746	Rai (Bahalgarh)	Sonipat	28.94/77.09	NM	23.99	23.45	NOut	Moderate
W22410	Kami-Pz	Sonipat	29.029/77.01	NM	NM	32.65	40.18	Moderate
W29912	Murthal-Pz	Sonipat	29.04/77.09	NM	NM	NM	34.00	Poor
W29918	Kheora-1	Sonipat	28.96/77.12	NM	NM	NM	29.26	Poor
W29923	Jhakauli-Pz	Sonipat	28.93/77.16	NM	NM	NM	24.48	Poor
W31944	Kheaora-2	Sonipat	28.96/77.12	NM	NM	24.95	NM	Satisfactory

NOTE: NOut: Was not an outlier; NM: GWL Not Monitored.

water-level monitoring over time. This part of the assessment was aimed at helping the authorities establish a zonal protocol to improve monitoring (infrastructure, finance, manpower, training and community mobilization etc.)

- *Point Location*: Identifying wells that lack desired level temporal coverage. In this part we offer the regulatory authorities an objective classification scheme - Monitoring Efficiency (ME), that assigns numeric scores to each well in the study region, based on frequency of GWL monitoring during the study period (discussed in details earlier in the METHODOLOGY Section).

Groundwater Monitoring: *Regional Assessment*

In the study region, total number of groundwater wells monitored during the study period (1996-2018) has dropped over time, from over 230 wells during the 1996-2002 (Pre-Bill Period) to about 200 in 2014-2018 (Post-Bill Period), which makes the regulatory body's task difficult to develop evidence-based groundwater conservation measures **(**Figure **4a)**. Tehshil-wise assessment revealed lack of spatial uniformity GWL monitoring (Figure 4b). For example, for each year-period, over 40% of all wells monitored in the study region was accounted Sonipat tehshil alone, followed by Gohana, Kharkhauda and Ganaur. In Sonipat tehshil itself, however, monitoring has dropped from over 50% wells in the Pre-Bill Period to about 41% in the in recent times. Similar drop was noted for Ganaur tehshil as well, 12% wells in 1996-2002 to about 9% in 2014-2018 (Fig. 4b). Given the emergence of deeper GWLs (>30 m below ground surface), and especially occurrences of the outliers, in Sonipat and Ganaur tehshils, lack of systematic and informed monitoring might undermine future groundwater conservation efforts, which in turn, might limit sustainable irrigation opportunities. In Gohana, percentages of wells monitored in the Post-Bill Periods have dropped (39% in 209-2013 to 33% in 2014-2018). In Kharkhauda, monitoring has consistently improved over time; however, only but accounting for about 15% wells in the 2014-2018 period.

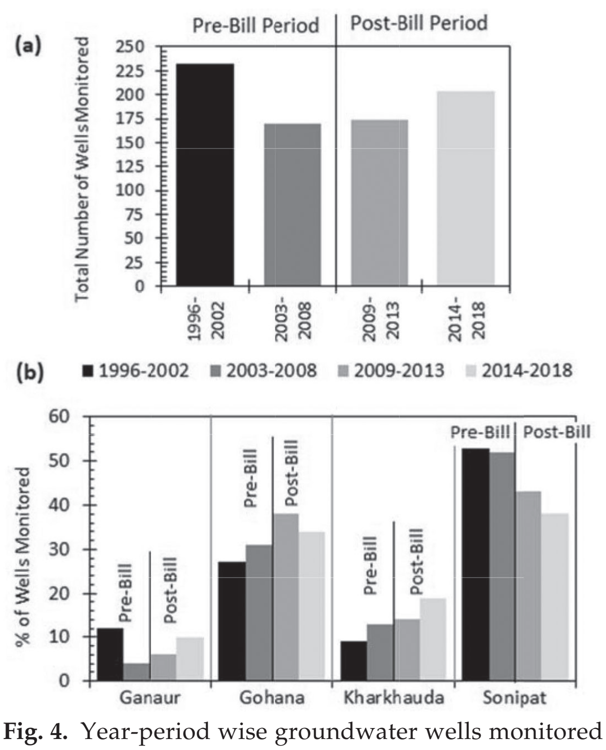

Fig. 4. Year-period wise groundwater wells monitored (a) Sonipat district total (combining all tehshils and growing seasons), and (b) disaggregated by tehshil and year-periods *(Data Source: CGWB)*

Moreover, we identified considerable seasonal differences in GWL monitoring coverages (Fig. 5). For example, out of total number of wells monitored in the study region as a whole (district total), Sonipat tehshil accounted for over half in all the growing season in 1996-2002, rising up to over 60-70% during the 2003-2008 and 2009-2013 periods. However, monitoring coverage in Sonipat tehshil dropped back to about 50% in the 2014-2018 period, which indicated lack of 'consistency' in area coverage over time. Overall, the Pre-monsoon season registered the deepest median GWLs in the study region **(**Figure 1 a-d). However, tehshil-wise percentages of wells monitored during the Pre-monsoon appeared highly variable in the Post-Bill period **(**Figure 5).

Groundwater Monitoring: Point Location

Overall spatial distribution of groundwater monitoring efficiency (ME) at well-level across the study area (Sonipat District as a whole) revealed high heterogeneity and lack of systematic approach for monitoring (by space and time). By the same token, certain shortcomings came to light that the regulatory authorities need to pay heed to in future:

- In each tehshil, over 40% of the wells were classified as having 'Poor' ME (monitored only once during the entire study period, 1996-2018), which exposes the flaws in the existing monitoring approach (Fig. 6a). Over 60% of wells at Kharkhauda classified as 'Poor'. Such lags in monitoring could owe to lack of infrastructure, outlook, understanding of groundwater dynamics, finance, manpower, community mobilization (participation of farmers at grassroots to help the authorities monitor GWLs) etc that the authorities need to look into and develop context-relevant means to address in days to come.

- About 20-40% wells came under the 'Good' ME category (monitored at least once in all four year-periods) (Fig. 6a). The lowest tally was observed in Sonipat tehshil, while complete absence of 'Good' category in Ganaur. Given that these two tehshils account for most deeper GWL observations in the study region, lack on clear idea of GWL changes may impede future conservation/management efforts.

For aiding future groundwater conservation efforts, we identified the outlier observations across the study region (Fig. 6b). The Sonipat Tehsil, one that presently registers the highest tally of outliers in the study region, with none qualifying in the 'Good' category for ME (ME = 1.00; monitored in all four years-periods) appeared particularly vulnerable and deserves urgent regulatory intervention (Table 2). Nearly half of outliers in Sonipat tehshil were classified as 'Poor' (ME = 0.25; monitored once in four year-periods). Integrating information from ME analysis with outlier scrutiny can help authorities identify the 'problem' wells and formulate context-relevant groundwater conservation measures.

Concluding Remarks: Reviving A Groundwater-dependent Rural Economy

In this narrative we investigated the spatio-temporal changes in GWLs in Sonipat, taken as a microcosm of current groundwater conditions in northwestern India, and highlighted the appalling lack of monitoring efficiency (temporally consistent across space). The latter demands more informed monitoring drives, based on observational evidences, to develop context-relevant conservation measures. We, par-

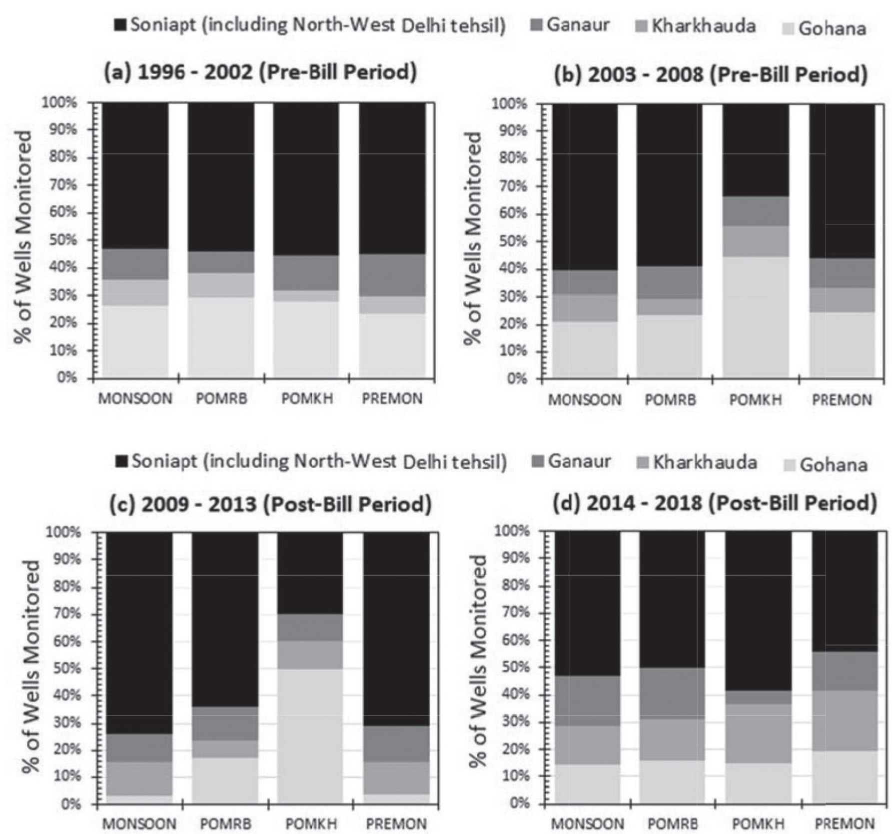

Fig. 5. Tehshil- and growing season-wise percentages of groundwater wells monitored across different year-periods. (NOTE: For each growing season, tehshil-wise well percentages were computed by diving the number of wells monitored for the tehshil, by the total number of wells monitored in that growing)

ticularly, draw attention of the authorities to the 'outliers', to identify process-level drivers of any aberrant hydrogeological shifts over time (human-groundwater-climate nexus).

While conducting the analysis, a prime challenge (and future opportunity) we realized was, lack of specific information to evaluate the success and/or failure of the Bills. For example, (i) number of well registrations in Post-Bill periods (as compared to Pre-Bill Periods); (ii) locations of wells in the periphery of drinking water sources (any new wells during Post-Bill Periods?); (iii) number of new permits issued for well installation; (iv) data for borehole records (depth, aquifer type, geology, structure etc.); (v) monitoring and seizure of illegal equipment; (vi) assessment of land and soil property in Post-Bill Periods etc. Besides, the Bills lack concrete directives for the farmers to adopt groundwater conservation practices (instruction manuals). Moreover, for increased adoption, there should be concerted effort at regional/local administrative level to convince the farmers/well owners about the long-term benefits of the Bills (against any potential short-term losses). For that, offering incentivizing the farmers might be useful (e.g. tax rebates, fast-track loan/subsidy disbursal, recognition at village/Panchayat level s 'Model Farmer' etc.).

Under the circumstances, we urge the regulatory

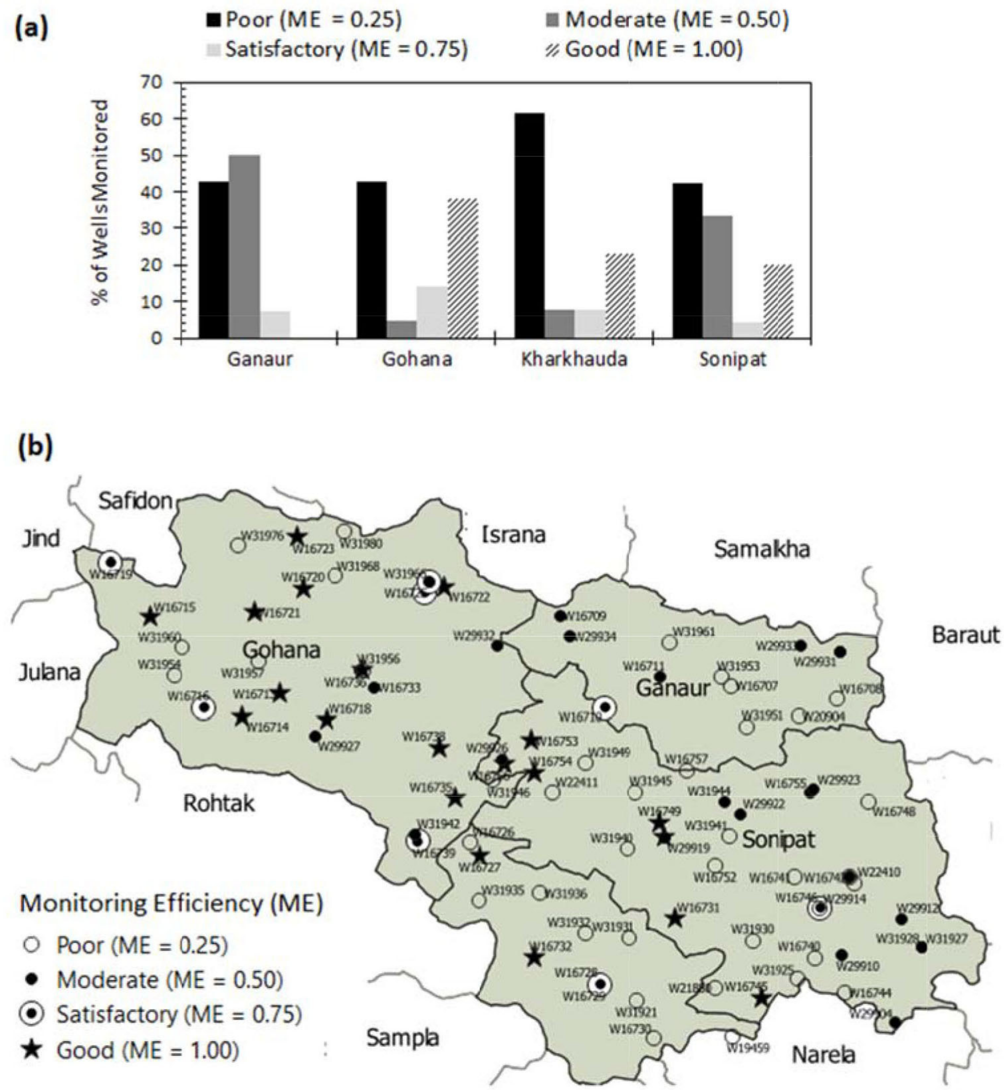

Fig. 6. Considering all year-periods and growing season together, (a) tehshil-wise monitoring coverage, and (b) Monitoring Efficiency (ME) computed for each well unit *(Data Source: CGWB and Author's calculation)*

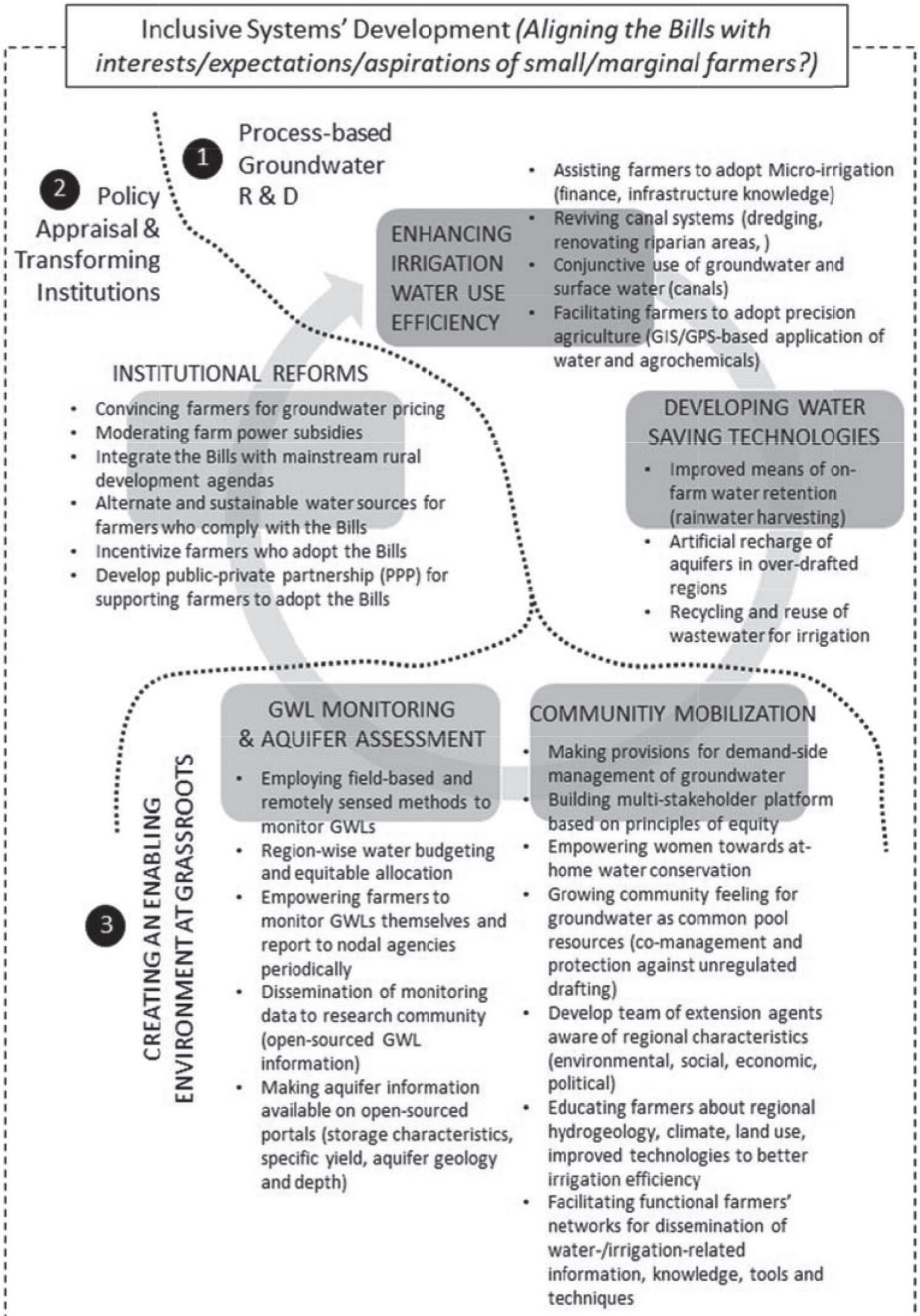

Fig. 7. A systems' thinking approach to encourage the farmers adopt the two Regulatory Bills with special attention to less-endowed population, by integrating three main spheres of development. The three spheres should be ideated in a cyclic feedback loop, one reinforcing the implementation of the other.

authorities to adopt a system' thinking approach (inclusive development with a pro-poor lens) by integrating three main spheres of groundwater resources (Fig. 7):

I. Process-based Groundwater Research & Development (R & D)
II. Creating an Enabling Environment at Grassroots
III. Policy Appraisal and Transforming Institutions

The idea is to create an inclusive systems' framework, with special attention to the expectation/aspirations of less-endowed population (e.g. small/marginal farmers), which, besides regulating groundwater extraction, should also provide means to conserve/mange groundwater sustainably for years to come.

Process-based Groundwater Conservation R & D

This should include two mutually reinforcing components:

- Enhancing irrigation water use efficiency
- Developing novel water saving techniques

The first primarily includes helping the farmers (especially the small/marginal clan with limited economic capacity, technical expertise and knowledge of irrigation systems' design) adopt improved irrigation techniques such as micro-irrigation (drips and sprinklers) over conventional flood irrigation that leads to great deal of water wastage (Suresh and Samuels, 2020). However, micro-irrigation adoption in Haryana is yet low due to a confluence of factors including (i) high installation, operation and maintenance cost, (ii) lack of financial support (subsidy/loan), (iii) lack of technical know-how among farmers, (iv) high risk of infrastructural damage (pipe wear and tear, pipe clogging etc.), (v) apprehension and lack of willingness to adopt 'new' technology (Grant Thornton, 2016). Under the circumstances, the authorities need to promote the 'success stories' of micro-irrigation, using social/print/electronic media, which includes cost savings on water, energy, fertilizer, labor, increased crop diversification opportunities, higher income etc. to name a few (Singh *et al.,* 2015; Kumar and Palanisami, 2010; Narayanmoorthy, 2010).

The regulatory authorities should, with active consultation with the local farmers, devise tech-

Fig. 8. Key considerations in bolstering community mobilization and capacity building initiatives at the grassroots for adoption of the Regulatory Bills and advance towards sustainable groundwater conservation practices.

niques for on-farm water retention: runoff prevention and utilization. It involves building of rain/storm water retention structures to conserve water during wet season to be used during dry spells (summer). This should be of particular importance for groundwater deficient regions. At the same time, some effort needs to be divested to understand feasibility of artificial recharge - focused injection of surplus water (e.g. harvested rain/storm water) into geologic strata to feed the aquifers. However, this calls for clear understanding of local hydrogeologic processes, land management history, topography, soil characteristics, vegetation etc.

Some effort needs to divested to test potential of recycled wastewater for irrigation. Wastewater is already loaded with a variety of nutrients, which, besides offsetting the mounting pressure on groundwater resources, this might also address nutrient input requirements. In a recent study in Gujarat, Palrecha *et al.* (2012) identified three determining factors in wastewater reuse in the irrigation sector: (i) reliability of water supply, (ii) level of urbanization, and (iii) profitability of using nutrient loaded water in irrigation. The latter might reduce the agricultural input costs for the farmers (cutting back of fertilizer expenses?). However, there will be need to comply with the environmental and health benchmarks recommended by the Central and/or the State Pollution Control Boards (Suresh and Samuel, 2020). Noncompliance with the benchmarks might lead to bioaccumulation of toxins in crops and later in human body, leading to undesirable health outcomes.

Last but not the least, there is need rejuvenate the surface water-based irrigation schemes (canals) to help farmers understand the benefits of conjunctive water use – integrated use of groundwater and surface water for irrigation. This requires a shift in the policy level conceptualization of water management towards integrated monitoring (Srinivasan and Lele, 2017). Hydrological cycle and the spatial discontinuation of groundwater level explains the close relationship between surface water (river Yamuna), rainfall and groundwater. In this case, having rainfall level, soil moisture and type, aquifer type data with the groundwater well datasets could provide a more holistic viewpoint for budgeting the scale of extraction. To answer this question there is need of strategic field survey among the famers.

Community Mobilization: Demand-side Groundwater Conservation

- → How aware are the farmers about HSGMRB-08 and HPSSWA-09?
- → Were the Bills developed by active consultation with the farmers (stakeholder involvement)?
- → Have they enough means (financial, infrastructural, knowledge, training) to take up the recommendations forwarded by the Bills?
- → Do the farmers view the Bills as potential roadblocks to irrigation and future production expansion?

A main flaw with the HSGMRB-08 and HPSSWA-09, as we understand, is the Top-Down approach – policies made at the upper levels of administrative hierarchy without constatation with the farmers (farmers aspirations, expectations, and capacities). Along that line, we urge the authorities to conduct ground-level surveys to understand the socio-cognitive barriers to take up the recommendations forwarded by the two Bills:

- What are farmers' perceptions about groundwater resources in the area?
  - o What is the frequency of 'well dry-out' events in Pre- and Post-Bill Periods?
  - o How are the farmers coping up with irrigation shortages (specially, the small/marginal farmers with limited economic means)?
  - o Do the farmers view groundwater depletion as a threat to current and future production details, income, livelihood, rural development?
- How aware are the farmers about groundwater depletion (and irrigation crises) of adjacent areas (or other parts of the country)?
- Is groundwater-related information easily available to the farmers?
- What are the hurdles for farmers to access groundwater-related information?

To facilitate the above, and growing a deeper sense of community feeling and responsibility for the local farmers towards groundwater conservation (optimal drafting and minimum wastage) we propose three social instruments to the regulatory authorities: developing (i) developing multi-stakeholder platform, (ii) functional farmers networks; and (iii) a dedicated team of extension agents (Fig. 8) (Chaudhuri *et al.*, 2020).

Groundwater Monitoring and Strategic Assessment

A prime upshot of the present study was lack of monitoring coverage, both at regional and well level, which impedes appropriate ideation of the extent on-ground implementation of HSGMRB-08 and HPSSWA-09. Moreover, till date, there is very little or no Bill specific information available to evaluate the success/failure.

GWL monitoring in the study regions, as in most of India, is still solely carried out by the water officials, with little involvement of the local farmers/ well owners. Farmers need to be empowered (convinced, trained and equipped) to record GWLs at their own wells, and regularly report it to the local regulatory bodies. The CGWB database should have means to incorporate such farmer-reported data.

Table 3. Potential policy appraisals to bolster the Regulatory Bills and promote groundwater conservation efforts *(Source: Chaudhuri et al.,* 2020)

Policy Appraisal	Means of Implementation	Potential Barriers
Enforcing Robust Groundwater Pricing System	• Focused group discussions in multi-stakeholder platform to dispel misconception about groundwater pricing (long-term benefits vs. short-term gains) • Consultation with farmers to determine viable pricing rates • Introducing volumetric pricing (actual water used) instead of area-based pricing (flat rate) • Community engagement for accurate and automated billing • Aligning the Bills with groundwater pricing • Incentives for 'progressive' farmers (cash or kinds)	• *My Land My Water* – age old belief about groundwater • Irrigation is farmers birth right • Ulterior political motives *"pricing groundwater is against fundamental right and anti-farmer"* • Lack of transparency in billing (bribery, fabrication of paper bills) • Possibly tampering with, stealing of automated meters • Diminishing returns from existing irrigation projects • Lack of knowledge about groundwater dynamics • Lack of team of dedicated extension agents for mentoring and support • Unexpected climate anomalies
Moderating Farm Power Subsidy	• Briefing farmers on economic losses of power companies, and its negative feedback on quality of farm power supply services • Transferring subsidy directly to farmers' accounts • Developing ICT-based smart metering system • Determine internal norms to operate pumps and other electrical equipment only for stipulated period daily Access to solar powered pumps	• Lack of right political will Power piracy – diverting farm power illegally for other uses • Yet limited capacity of solar-powered pumps High installation and maintenance costs of the above • Threat to food security • Lack of appropriate development of rainfed areas • Possibly damage, stealing of automated meters for billing
Groundwater Governance	• Basin/watershed scale hydrologic budgeting • Inter-basin water transfer • Water accounting and allocation • Wastewater recycling and reuse • Basin/watershed-scale afforestation (catchment management) • Periodic land potential evaluation	• Lack of detailed hydrologic and land surface modelling • Shortfalls in micro-irrigation • Conflicting opinions at policy level and lack of right political will • Disconnect between policy and research • Lack of cross-sectoral connection (mutually exclusive policy making) • Lack of relevant information for research community • Unexpected climate anomalies

However, we also urge the authorities to combine field-level GWL measurement (farmer-led initiatives), with satellite-based monitoring of groundwater conditions. In this regard, the GRACE satellite imagery (The Gravity Recovery and Climate Experiment, a joint mission of NASA and the German Aerospace Center, launched in 2002), if combined with regional land surface and hydrologic modeling, could be effective to keep tab on groundwater changes (Rodell *et al.*, 2009). The GRACE is a twin satellite system that provides detailed information about earth gravity field anomalies, especially changes in distribution of water resources across the planet over time. GRACE provides a more than 10 year-long data record for scientific analysis. This makes a huge difference for scientists and water managers who want to understand trends in how our resources are being consumed over the long term.

Policy Appraisal and Institutional Transformations

Growing reliance on groundwater resources for irrigation has raised grave eco-environmental concerns in India (Chaudhuri and Roy, 2016b; Mukherjee et al., 2014; Shah, 2010), as much as in other parts of the world (Chaudhuri and Ale, 2014 a-d). By the same token, such socio-cognitive thinking works counter to the fundamental aim of the Regulatory Bills. Presently, India is the forerunners among the global groundwater users (Sekhri, 2014; Tyagi *et al.* 2012), with about 85% of groundwater fed to the irrigation sector alone (Mukherjee et al. 2014). Main institutional and policy reforms necessary to bolster the Bills include (i) development of a robust groundwater pricing system (Chaudhuri and Roy, 2019); (ii) basin/watershed-scale groundwater governance framework (Kumar, 2018; Narayanmoorthy, 2018; Kulkarni *et al.*, 2015; Mukherji *et al.*, 2012, 2009), and (iii) moderating subsidized farm power (Chaudhuri *et al.*, 2021; Shah and Chowdhury, 2017; Shah and Verma, 2008) **(Tables 3)**. The latter allows the farmers run their pumps 24 x 7, without paying heed to sustainability limits of the aquifers, thus depleting groundwater resources at will (Gulati and Pahuja, 2015).

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