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Agricultural intensification and groundwater depletion in Haryana: A post-Green Revolution analysis

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ABSTRACT

Agriculture in Haryana rests on groundwater, and the state's stage of groundwater extraction has risen from 92.57 per cent in 1992 to 134.56 per cent. A single state figure, however, hides large differences between districts. This paper examines the long-term behaviour of annual average groundwater depth (metres below ground level, mbgl) in five districts selected to represent all four stress categories of the Central Ground Water Board (CGWB): Sirsa and Mahendergarh (over-exploited), Palwal (critical), Hisar (semi-critical) and Jhajjar (safe). CGWB data for 1990–2023, with 34 annual observations per district, are analysed using the Mann–Kendall test, Sen's slope estimator and the Pettitt change-point test. The water table has deepened significantly in the three most stressed districts, at 0.74 m per year in Mahendergarh and at about 0.14 m per year in both Sirsa and Palwal ($p < 0.001$). Jhajjar shows a significant shallowing of the water table (-0.081 m per year, $p < 0.001$), while Hisar shows a weak and only marginally significant one (-0.034 m per year, $p = 0.060$). Abrupt shifts in mean groundwater level are detected between 2006 and 2012 in four districts and in 1995 in Hisar. Depletion is therefore not confined to officially over-exploited districts, since the critical district of Palwal is deepening at the same rate as Sirsa. District-specific demand management, recharge and monitoring measures are suggested.

Keywords: Groundwater depletion, Mann–Kendall test, Sen's slope, Pettitt test, Stage of groundwater extraction, Haryana

1. Introduction

1.1 Background

Groundwater is the largest source of irrigation water in the world, and in many aquifers, withdrawals now exceed natural replenishment (Famiglietti, 2014) [1]. India is the largest user of groundwater, and its north-western plains have become one of the most closely studied cases of aquifer decline. Satellite gravity measurements first showed substantial groundwater loss across Haryana, Punjab and Rajasthan (Rodell *et al.*, 2009; Tiwari *et al.*, 2009) [2, 3], and observations from wells in the Indo-Gangetic Basin have since confirmed that depletion is concentrated in this part of the basin (Macdonald *et al.*, 2016) [4]. Both pumping and changes in monsoon precipitation shape groundwater storage in India. Governance is made harder by the sheer number of small, privately operated wells, a condition Shah (2009) [5] describes as an anarchy of decentralised users, and by the limits of supply-side responses (Shankar *et al.*, 2011) [6].

Haryana illustrates these pressures clearly. The Green Revolution raised the output of staple cereals, and its environmental costs became visible within a few decades (Singh, 2000) [7]. The state was the first in India to reach complete village electrification, in 1970, only four years after its formation. Tubewells multiplied from 25,311 at the time of formation to about 4.97 lakh in 1990-91 and to more than eight lakhs in 2022-23. Gross cropped area expanded and the cropping pattern tilted towards rice and wheat. According to CGWB (1995) [8], the stage of groundwater extraction in Haryana was 92.57 per cent in 1992, which was high but below the over-exploitation threshold. It has since reached 134.56 per cent, and 16 of the state's 22 districts are now classified as over-exploited.

1.2 Drivers of groundwater depletion: A brief review

The literature agrees that the depth of the water table in a region reflects several forces acting together: the number of extraction structures, recharge, rainfall, irrigated area, cropping pattern, cropping intensity and irrigation intensity (Bhardwaj *et al.*, 2024; Bhattarai *et al.*, 2021; Khara *et al.*, 2024; Rahman *et al.*, 2022) [9, 10, 11, 12]. Studies of Haryana point to the replacement of Persian wheels by tubewells as a turning point, and more than 90 per cent of groundwater in the state is now drawn through tubewells (Kasana *et al.*, 2017; Rosencranz *et al.*, 2022) [13, 14]. Irrigated area matters because it sets the agricultural demand for water (Dangar *et al.*, 2021) [15], and that demand is among the principal drivers of extraction (Das *et al.*, 2026) [16]. On the supply side, the volume available for extraction depends on geography, past extraction and recharge, and on rainfall (Meng *et al.*, 2024; Moeck *et al.*, 2020) [17, 18]. The stage of groundwater extraction

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combines these demand and supply influences in one ratio of draft to availability (Kumar *et al.*, 2022; Velis *et al.*, 2017) [19, 20], which is why it is the basis of the CGWB classification of assessment units.

Non-parametric tests are the usual instruments for detecting change in hydrological series. The Mann–Kendall test (Mann, 1945; Kendall, 1975) [22, 21] and Sen's slope estimator (Theil, 1950; Sen, 1968) [24, 23] make no assumption of normality and are not unduly affected by outliers, while the Pettitt test (Pettitt, 1979) [25] locates a single abrupt change in the central tendency of a series. Applied together, they allow a trend to be established, measured and dated. Their main weakness is that serial correlation in a series can overstate significance, which has led to corrected versions of the test (Hamed *et al.*, 1998; Yue *et al.*, 2002) [26, 27].

1.3 Research gap and objectives

Much of the evidence on groundwater decline in north-west India comes from satellite products that cover large regions, or from state-level aggregates. Both can conceal the fact that districts of the same state follow very different trajectories. District-level comparisons across the full range of CGWB stress categories, covering three decades and using formal tests of trend, magnitude and structural break, appear to have received less attention. This is the gap the present paper addresses. The specific objectives are:

1. to describe the long-run growth in tubewells, irrigated area and water-intensive cropping, which together shape groundwater extraction in Haryana;
2. to test the direction, statistical significance and magnitude of groundwater level trends in five districts representing all four CGWB categories; and
3. to identify the year in which each district's groundwater series shifted abruptly, and to draw suggestions for groundwater management from the results.

The remainder of the paper is organised as follows. Section 2 describes the study area, data and methods. Section 3 presents the results, Section 4 discusses them, and Section 5 concludes with suggestions.

2. Study area, data and methods

2.1 Selection of districts

Districts were selected using the CGWB classification of assessment units into four groundwater stress categories. The classification rests on the stage of groundwater extraction, defined as the ratio of annual groundwater draft to net annual groundwater availability, expressed as

a percentage (Table 1). Using this classification as the sampling frame ensures that the districts examined span the full range of exploitation conditions in the state instead of a single level of stress.

Selection proceeded in stages. In the first stage, the 22 districts of Haryana were assigned to the four categories (16 over-exploited, one critical, two semi-critical and three safe). In the second stage, districts were drawn at random within each category using IBM SPSS Statistics, at approximately 20 per cent for the over-exploited category and 40 per cent for the others, which gave Sirsa and Mahendergarh (over-exploited), Palwal (critical), Hisar (semi-critical) and Jhajjar (safe). In the third stage, blocks were drawn at random within each district at approximately 40 per cent: Rania, Dabwali and Ellenabad in Sirsa; Mahendergarh, Ateli Nangal, Narnaul and Nangal Chaudhary in Mahendergarh; Hassanpur in Palwal; Barwala in Hisar; and Badli, Beri, Matanhail and Machhrauli in Jhajjar. Villages were then chosen purposively, in consultation with the District Agriculture Officer, according to the irrigation technique practised. The block and village stages serve the primary survey of the wider study; the trend analysis reported here uses district-level data.

2.2 Data and variables

The analysis uses annual average groundwater level data from the CGWB Ground Water Year Books, which report piezometric levels at the well, block and district levels. District-level series were used for the five selected districts. Groundwater level is measured as depth to the water table in metres below ground level (mbgl), so a rising value signals a deeper water table and greater depletion, and a falling value signals shallowing. Annual averages were preferred to separate pre-monsoon and post-monsoon readings, since the interest lies in the long-term trajectory over three decades and not in seasonal swings. The series run from 1990 to 2023, giving 34 annual observations per district. The period begins roughly two decades after the introduction of the Green Revolution, when gross cropped and irrigated area had expanded considerably and cereal yields had roughly doubled, and it ends with the most recent year for which data are available for all selected districts.

Contextual variables were taken from the Statistical Abstract of Haryana, published by the Department of Economic and Statistical Analysis, Government of Haryana, and from the Agriculture Census. These include net sown area, gross cropped area, cropping intensity, net and gross irrigated area, source-wise irrigation and the number of tubewells. Cropping pattern is the share of each crop in gross cropped area and is used to trace the shift towards water-intensive crops such as paddy. These variables are used to interpret the groundwater trends and are not entered into the statistical tests.

Table 1. CGWB categories and selection of study districts

Category	Stage of extraction	Districts in Haryana	Approx. sampling rate	District selected
Safe	$\leq 70\%$	3	40%	Jhajjar
Semi-critical	$> 70\%$ and $\leq 90\%$	2	40%	Hisar
Critical	$> 90\%$ and $\leq 100\%$	1	40%	Palwal
Over-exploited	$> 100\%$	16	20%	Sirsa, Mahendergarh

Source: CGWB, Dynamic Ground Water Resources of India.

2.3 Trend and change-point analysis

Three complementary non-parametric techniques were applied to the annual series of each district. Using several tests, rather than one, gives a fuller picture of how groundwater levels changed over three decades and of the different features of that change. All tests were run in R through the Posit Cloud environment.

Mann–Kendall test

The Mann–Kendall test is a rank-based test for the presence of a monotonic trend. It does not require normally distributed data and is relatively insensitive to extreme observations. For a series $x_1, x_2, \dots, x_n$, the test statistic S compares each observation with all later ones:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

where $\text{sgn}(\theta)$ equals +1, 0 or –1 according to whether θ is positive, zero or negative. A positive S indicates a predominance of increasing pairs and a negative S a predominance of decreasing pairs. The variance of S , allowing for ties, is

$$\text{Var}(S) = [n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5)] / 18 \quad (2)$$

where q is the number of tied groups and t_p the number of observations in the p -th group. The standardised statistic is

$$Z = (S - 1) / \sqrt{\text{Var}(S)}, \text{ if } S > 0; Z = 0, \text{ if } S = 0; Z = (S + 1) / \sqrt{\text{Var}(S)}, \text{ if } S < 0 \quad (3)$$

The null hypothesis (H_0) is that the series has no monotonic trend; the alternative (H_1) is that a significant monotonic trend exists. Kendall's τ is reported alongside Z as a measure of the strength of the association between level and time. Because levels are measured as depth, a significant positive Z signals deepening of the water table and hence depletion, and a significant negative Z signals shallowing.

Sen's slope estimator

Sen's slope is the median of the slopes between all pairs of observations, which makes it resistant to outliers. The slope between observations i and j is

$$Q_{ij} = (x_j - x_i) / (j - i), j > i \quad (4)$$

An approximate two-sided p -value is given by

$$p \approx 2 \exp \left[-6K^2 / (n^3 + n^2) \right] \quad (8)$$

Throughout, significance is reported at the 1 per cent (***), 5 per cent (**) and 10 per cent (*) levels. The straight lines in Figures 1 and 2 are ordinary least squares fits and serve only as a visual guide; inference rests on the tests described above.

3. Results

3.1 Expansion of extraction capacity and water-intensive cropping

Before the groundwater series are examined, it is useful to see what has happened to the factors that drive extraction. Table 2 shows the change between 1966-67, the first year after the state's formation, and 2023-24. Gross cropped area grew by almost half, but gross irrigated area more than tripled, so that cultivation became far more dependent on irrigation. The area under rice rose about nine-fold and that under wheat by more than three-fold, whereas the area under bajra fell by about two-fifths and that under jowar almost vanished.

Table 2. Change in cropped area, irrigated area and crop acreage in Haryana ('000 hectares)

Indicator	1966-67	2023-24	Change (%)
Gross cropped area	4,599	6,737	+46.5
Gross irrigated area	1,736	6,295	+262.6
Rice	192	1,778	+826.0
Wheat	743	2,509	+237.7
Bajra	893	527	-41.0
Jowar	270	19	-93.0

Source: Statistical Abstract of Haryana (2023-24, 2024-25) [28].

Extraction capacity moved in the same direction. Tubewells increased from 25,311 at formation to over one lakh by 1970-71, about 4.97 lakh in 1990-91 and more than eight lakh in 2022-23. The share of net sown area under irrigation was 37.8 per cent in 1966-67, roughly doubled by 1990-91, and reached 93.3 per cent in 2021-22. Taken together, more tubewells, near-universal irrigation and a larger area un-

der water-intensive cereals have raised the demand on aquifers, and the state's stage of extraction rose from 92.57 per cent in 1992 to 134.56 per cent. The state-level picture is one of sustained and growing pressure. The district series show how unevenly that pressure has translated into changes in the water table.

There are $N = n(n-1)/2$ such slopes. When arranged in ascending order, the Sen's slope is their median:

$Q_{\text{Sen}} = Q_{(N+1)/2}$, if N is odd; (5) $Q_{\text{Sen}} = \frac{1}{2} [Q_{N/2} + Q_{(N+2)/2}]$, if N is even

A positive slope indicates a rising depth to groundwater, that is, depletion, and a negative slope indicates shallowing. The slope is expressed in metres per year and is reported with its 95 per cent confidence interval.

Pettitt test

The Pettitt test detects a single abrupt change in the central tendency of a series. It builds on the Mann-Whitney statistic between the two parts of the series on either side of each candidate point t :

$$U_{t,n} = \sum_{i=1}^t \sum_{j=t+1}^n \text{sgn}(x_i - x_j) \quad (6)$$

The test statistic is the largest absolute value of $U_{t,n}$, and the year at which it occurs is the probable change point:

$$K = \max_{1 \leq t < n} |U_{t,n}|, t^* = \arg \max_{1 \leq t < n} |U_{t,n}| \quad (7)$$

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3.2 Graphical patterns in district groundwater levels

3.2.1 Over-exploited and critical districts: Sirsa, Mahendergarh and Palwal

Figure 1. plots the annual groundwater depth of the two over-exploited districts and the critical district, with fitted linear trends. Despite differences in aquifer conditions and CGWB category, the three series share a common shape. From the early 1990s to the late 2000s, levels were relatively stable or fluctuated within a band, with short dips and recoveries that appear to reflect rainfall variability, cropping intensity and recharge and not sustained depletion. A structural transition is visible around 2011–2012 in each district, after which depth rises along a deeper and more persistent path, with abrupt increases followed by only partial correction, which is characteristic of aquifers under heavy tubewell extraction.

In Sirsa, the water table stood near 11.5 mbgl in the early 1990s and eased to about 10.5 mbgl by 1996. Between 1997 and 2008 it oscillated within a narrow band of roughly 9.8 to 11.8 mbgl. After 2008, depth rose more steeply and year-to-year variability grew, with a sharp rise to nearly 15 mbgl around 2012 and peaks above 16 mbgl around 2018–2019, the deepest in the series. Each peak was followed by a partial recovery to a level still deeper than before, which indicates that the aquifer does not fully recover between dry spells. From 2021 to 2023 levels stayed above 13 mbgl. The fitted trend rises from below 10 mbgl in 1990 to above 14 mbgl in 2023.

Mahendergarh began the period at a much greater depth, around 22.5 mbgl, and shallowed to about 16.5 mbgl in 1998. Levels then rose in a fluctuating manner to 23–26 mbgl by 2008, receded to 18–20 mbgl during 2008–2011, and then rose abruptly from about 18 to nearly 27 mbgl within a single year from 2012, crossing 32 mbgl by 2014. A plateau of 37–39 mbgl held until 2018, followed by a spike to about 43.5 mbgl in 2019, a fall back to about 38 mbgl, and a renewed climb to roughly 45 and then close to 47 mbgl in 2022 and 2023, the deepest in the series. The fitted trend rises from about 14 to about 39 mbgl, a far steeper rise than in Sirsa.

Palwal had a shallow water table of about 6.5 mbgl in the early 1990s. It fluctuated between roughly 4.5 and 7 mbgl until 2011, with a low of about 4.5 mbgl in 1999. From 2011 the series climbed from about

6.3 to over 8 mbgl by 2013 and about 9.3 mbgl by 2016, touched about 10 mbgl in 2019 and 2021, and peaked near 11 mbgl in 2022 before easing to about 10.7 mbgl in 2023. The fitted trend rises from about 5.1 to 9.4 mbgl. In contrast to the two over-exploited districts, the observed series tracks the fitted line closely in the later years, suggesting a steadier and more predictable pace of deepening.

The three districts thus differ in magnitude but not in direction. Mahendergarh is the most acute case, Sirsa shows moderate but persistent deepening accompanied by growing variability, and Palwal has the shallowest absolute depths but follows the same upward path. The deepening is therefore not confined to the over-exploited districts.

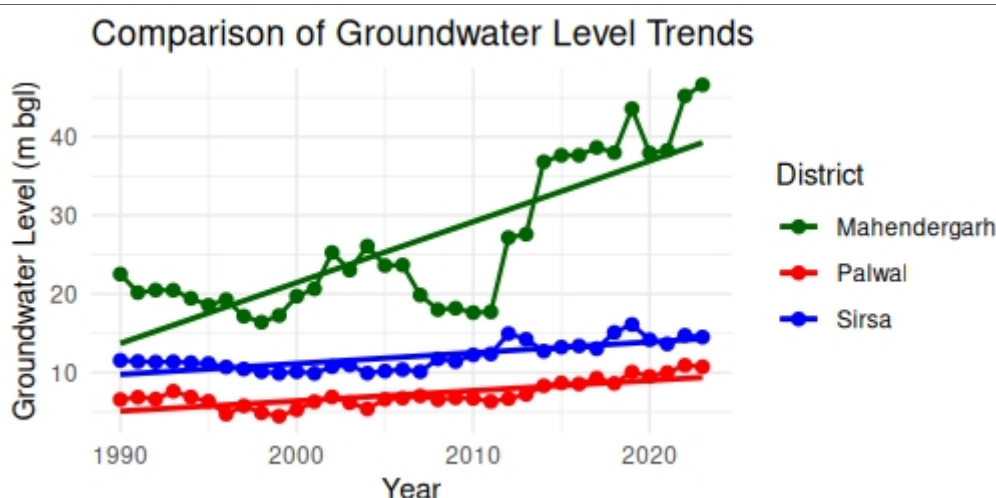


Figure 1. Trends in groundwater level (mbgl) in Sirsa, Mahendergarh and Palwal districts, 1990–2023, Source: CGWB.

3.2.2 Semi-critical and safe districts: Hisar and Jhajjar

Figure 2 shows a different picture for Hisar and Jhajjar. In both, the fitted trend slopes downward, so that depth to water decreased over the period, and in both the steepest change took place in the mid-1990s, when the water table shallowed sharply within a short span. Later conditions fluctuated, shaped more by rainfall and recharge than by sustained depletion.

In Hisar, depth was at its highest point of about 10.4 mbgl in 1990, fell to about 8.7 mbgl by 1994–95 and reached a series low of around 6.8 mbgl in 1999. Between 2000 and 2010 it rose again, to a local peak near 9 mbgl, and from 2011 to 2023 it moved between about 7.2 and 8.7 mbgl without a clear direction before declining to about 7.6 mbgl in 2021 and 6.8 mbgl in 2023, the lowest since 1999. The fitted trend falls from about 8.95 to 7.4 mbgl. This gentle decline owes much to the sharp early recovery of the 1990s, and the series has been fluctuating, and at times reversing, since about 2010.

Jhajjar started at about 6.1 mbgl and was stable until 1994, then fell to about 4.7 mbgl in 1995 and 4.3 mbgl in 1996. It varied between about 4.4 and 5.3 mbgl from 1997 to 2004, and then shallowed steadily to a low of about 2.9 mbgl in 2011. After 2012 it fluctuated, rising to about 4.5 mbgl in 2015–2016, falling to about 2.8 mbgl in 2019, the lowest of the series, and ending at about 3.6 mbgl in 2023. The fitted trend falls from about 5.65 to 3.1 mbgl and is the steepest downward trend among the five districts. Unlike in Hisar, the improvement is spread across much of the period and is not driven by a single early episode.

3.3 Statistical assessment of trends and change points

Tables 3 and 4 report the formal tests. Each district's series has 34 observations. Districts are listed in order of CGWB category, from over-exploited to safe.

Table 3. Mann–Kendall trend test and Sen's slope estimates for groundwater level, 1990–2023

District (CGWB category)	Kendall's τ	Z	p-value	Sen's slope (m/yr)	95% CI	Trend classification
Sirsa (over-exploited)	0.465	3.854	< 0.001***	0.143	0.080 to 0.187	Significant increasing (deepening)
Mahendergarh (over-exploited)	0.535	4.433	< 0.001***	0.740	0.450 to 0.960	Significant increasing (deepening)
Palwal (critical)	0.551	4.566	< 0.001***	0.144	0.085 to 0.201	Significant increasing (deepening)
Hisar (semi-critical)	−0.228	−1.883	0.060*	−0.034	−0.082 to 0.001	Marginally significant decreasing (shallowing)
Jhajjar (safe)	−0.604	−5.011	< 0.001***	−0.081	−0.112 to −0.058	Significant decreasing (shallowing)

Source: CGWB data; authors' calculations. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Note: Positive values indicate deepening of the water table.

The Mann–Kendall results confirm the visual pattern. In Sirsa, Mahendergarh and Palwal, Z exceeds 3.8 and the associated p-values are below 0.001, so the null hypothesis of no trend is rejected at the 1 per cent level. Kendall's τ is moderate to strong in all three (0.465, 0.535 and 0.551). Sen's slope puts the rate of deepening at 0.143 m per year in Sirsa, 0.74 m per year in Mahendergarh and 0.144 m per

year in Palwal. The 95 per cent confidence intervals lie wholly above zero in each case. Mahendergarh's rate is about five times that of Sirsa and Palwal, which implies, as a rough scale, a cumulative deepening of about 24 m over the 33 years between the first and last observation, against about 4.7 m in each of the other two (slope multiplied by 33 years).

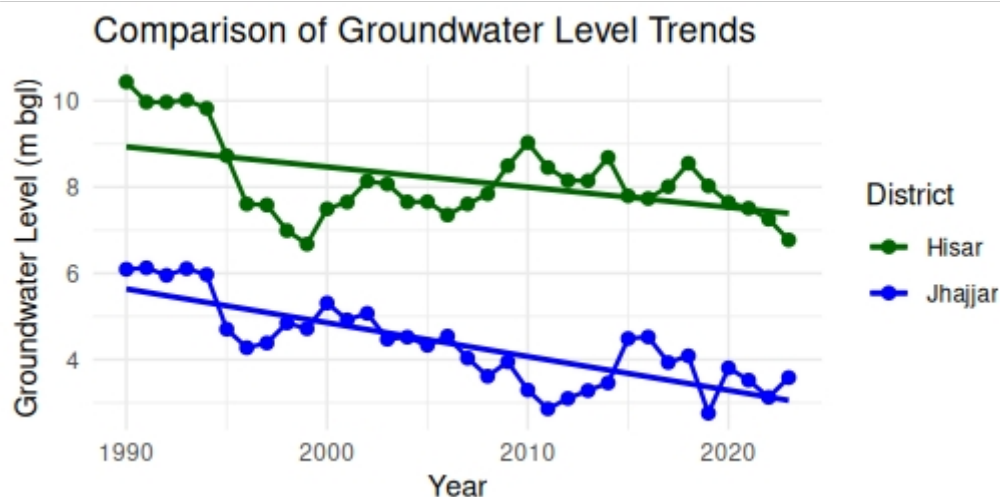


Figure 2. Trends in groundwater level (mbgl) in Hisar and Jhajjar districts, 1990–2023, Source: CGWB.

Palwal deserves particular note. Although it carries the milder “critical” label, its Z and τ are slightly higher than Sirsa’s and its rate of deepening is practically identical (0.144 against 0.143 m per year). By the evidence of trend alone, the critical district is deteriorating as steadily as an over-exploited one.

Hisar and Jhajjar move in the opposite direction. Jhajjar records a strong and highly significant fall in depth ($Z = -5.011$; $\tau = -0.604$), at

0.081 m per year, and its confidence interval lies entirely below zero. Its τ is, in absolute terms, the largest of the five. Hisar’s result is much weaker. The Z value of -1.883 and p -value of 0.060 reach significance only at the 10 per cent level, the slope of -0.034 m per year is less than half that of Jhajjar, and its confidence interval (-0.082 to 0.001) includes values at and just above zero. The improvement in Hisar is therefore suggestive and not firmly established.

Table 4. Pettitt change-point test for groundwater level, 1990–2023

District (CGWB category)	Statistic U^*	Change-point year (position in series)	p -value	Nature of the break
Sirsa (over-exploited)	286	2007 (18th)	1.079×10^{-5} ***	Shift to a steeper, more variable phase of deepening
Mahendergarh (over-exploited)	264	2011 (22nd)	6.492×10^{-5} ***	Sharp escalation of deepening after 2011–12
Palwal (critical)	251	2012 (23rd)	1.752×10^{-4} ***	Transition to a steeper, sustained rise in depth
Hisar (semi-critical)	166	1995 (6th)	0.0336 **	End of early recovery, followed by fluctuation
Jhajjar (safe)	271	2006 (17th)	3.725×10^{-5} ***	Sustained shallowing from the mid-2000s

Source: CGWB data; authors’ calculations. ** $p < 0.05$, *** $p < 0.01$.

Note: U^* is the maximum absolute value of the Pettitt statistic.

The Pettitt test finds a statistically significant change point in every district (Table 4). In the three depleting districts the break falls between 2007 and 2012: 2007 in Sirsa, 2011 in Mahendergarh and 2012 in Palwal. These dates agree with the visual evidence of a steeper, more variable regime after 2008 in Sirsa and after 2011 in Mahendergarh and Palwal. In Sirsa, the result is best read as an abrupt break and not a slow transition. In Jhajjar the break is dated to 2006, consistent with the sustained downward drift from the mid-2000s. In Hisar the break falls early, in 1995, and is significant at the 5 per cent level only. It marks the tail of the sharp early recovery after the deep starting position of 1990, so that its meaning differs from the breaks in the depleting districts: it separates a phase of rapid recovery from a phase of moderate fluctuation and not a phase of stability from one of accelerating depletion.

4. Discussion

4.1 A stress gradient that follows the CGWB classification, with one exception

The five districts line up along a gradient that broadly mirrors the CGWB categories. Deepening is strongest and most significant in the over-exploited districts, present at a comparable rate in the critical district, weak and marginal in the semi-critical district, and reversed

in the safe district. This agreement with the official classification is reassuring, because the classification is based on a different quantity (extraction relative to availability) than the water level used here. The consistency suggests that the stage of extraction captures real differences in the condition of the aquifers.

The exception is the closeness of Palwal and Sirsa. If categories were a precise guide to the speed of decline, the critical district would be expected to deepen more slowly than the over-exploited ones. It does not, and its τ and Z are somewhat higher. This is a warning that the category labels describe the state of an aquifer at a point in time, while the trend describes its direction. A district can sit in the milder category and yet be on the same downward path, and there is a case for treating it as a district in which preventive action is still cheap. The shallower absolute depths of Palwal (the fitted line reaches only about 9.4 mbgl by 2023) mean that it has more room than Sirsa and far more than Mahendergarh, but the rate of use of that room is similar to Sirsa’s.

4.2 Mahendergarh as the outlier

Mahendergarh stands apart. Its rate of 0.74 m per year, its starting depth of more than 20 m and its observed levels approaching 47 mbgl place it in a different class from the other districts. The finding is consistent with the expectation that the state’s most acute depletion is

concentrated in a few districts, which is where interventions are likely to yield the greatest returns. Two cautions apply. First, the rise from about 18 to nearly 27 mbgl within a single year is large for an aquifer response, and an increase of this size can also arise from changes in the set of observation wells included in the district average, from well deepening, or from measurement conditions. Checking the well-level records behind the district mean would show how much of the jump is physical. Second, the same sharpness is what gives the 2011 change point its high significance, so the two findings should not be treated as independent evidence.

4.3 Timing of the shifts

Four of the five change points fall within 2006–2012, and the three depleting districts cluster in 2007–2012. The period is one in which tubewells continued to multiply, the shift towards rice and wheat was well established, and irrigated area was already extensive. Rainfall variability is another candidate, because years of weak monsoon recharge combined with undiminished pumping will deepen the water table sharply, as the abrupt rises followed by partial correction in the figures suggest. The present data do not allow these explanations to be separated, and the cause of the break is a hypothesis to be tested and not a finding of the paper. One further point of method is relevant. When a series trends steadily, the Pettitt test tends to place its break near the middle of the record, and the dates for Sirsa (2007) and Jhajjar (2006) lie almost exactly at the midpoint of 1990–2023. The dates should therefore be read as approximate markers of a regime change and not as exact years.

4.4 Is the improvement in Hisar and Jhajjar secure?

The improvements in Hisar and Jhajjar should be read with care. Both owe much to a sharp shallowing in the mid-1990s, and in both the later record shows reversals: troughs in Jhajjar in 2011 and 2019, a rise to about 4.5 mbgl in 2015–2016, and renewed shallowing in Hisar at the very end of the series. These swings suggest that the water table in both districts remains sensitive to annual rainfall and recharge. A shallower water table is not necessarily a sign of ample water for all purposes. Very shallow levels can bring waterlogging and salinity problems in some irrigated tracts, and the study does not assess groundwater quality. The “safe” status should therefore be understood as a margin to be protected, not as a licence to expand extraction.

4.5 Limitations

Several limitations qualify the results. The series are district averages of annual readings, so spatial variation within districts and seasonal behaviour are not captured, and the number and location of wells in the average may have changed over time. The Mann–Kendall test as applied here assumes serially independent observations, and the analysis does not adjust for autocorrelation, which could overstate significance (Hamed *et al.*, 1998; Yue *et al.*, 2002) [26, 27]; the large Z values in the depleting districts make it unlikely that the conclusions would change, but the weaker Hisar result is more exposed to this concern. The Pettitt test finds only one change point, whereas some series may contain more. Finally, rainfall, tubewell density and cropping pattern are used to interpret the findings but are not included as explanatory variables, so the paper describes the pattern of depletion without estimating its causes.

5. Conclusions and suggestions

5.1 Conclusions

This paper has examined three decades of groundwater level data for five Haryana districts chosen to represent the four CGWB stress categories. Groundwater depth has increased significantly in Sirsa (0.143 m per year), Mahendergarh (0.74 m per year) and Palwal (0.144 m per year), each with $p < 0.001$, and abrupt shifts in the mean level occurred between 2007 and 2012. In the safe district of Jhajjar the water table has become significantly shallower (-0.081 m per year), and in

the semi-critical district of Hisar the shallowing is small and only marginally significant (-0.034 m per year, $p = 0.060$), largely reflecting a recovery in the 1990s. The results therefore support the claim that groundwater depletion in Haryana is spatially uneven, strongly concentrated in a few districts, and not limited to those formally classified as over-exploited. The depleting districts hold the greatest need for intervention, while the districts that are improving need protection of what has been gained.

5.2 Suggestions

The following suggestions are drawn from the findings and from the wider literature on groundwater management in north-west India. They are offered as directions for policy and not as outputs of the statistical analysis, and the details of current schemes should be verified before they are cited in a policy context.

- 1. Differentiate management by district.** The 0.74 m per year decline in Mahendergarh and the 0.14 m per year decline in Sirsa and Palwal call for different levels of intensity. Mahendergarh warrants priority attention with stronger demand management and recharge measures. Palwal should be treated as a case for early action, since its decline matches that of an over-exploited district even though its depths are still modest.
- 2. Reduce the area under water-intensive crops in stressed districts.** The rise in rice area from 192 thousand to 1,778 thousand hectares is the most conspicuous change in the cropping pattern. Incentives for shifting from paddy, such as Haryana’s “*Mera Pani Meri Virasat*” scheme and support for direct-seeded rice, should be concentrated where depletion is fastest, and paired with assured procurement and remunerative prices for alternatives such as maize, pulses, oilseeds and bajra. The decline in bajra area suggests that a return to such crops in dry districts is agronomically plausible, but it will not happen without a reliable market.
- 3. Promote efficient irrigation, with a cap on total extraction.** Drip and sprinkler systems can lower the water applied per hectare, but savings at the field level do not always become savings at the aquifer level, because farmers may expand irrigated area or switch to thirstier crops (Grafton *et al.*, 2018) [29]. Subsidies for micro-irrigation should therefore be linked to crop choice and to limits on district-level draft, so that efficiency gains are not absorbed by additional consumption.
- 4. Reform the energy–water link.** Where electricity for tubewells is supplied at a flat rate or free of marginal charge, the farmer has little reason to economise on pumping. Metering of agricultural connections, rationing of supply hours, feeder separation and pilot schemes that pay farmers for electricity saved deserve consideration. Subsidised solar pumps should be accompanied by caps on extraction, since a zero-marginal-cost source can otherwise encourage more pumping.
- 5. Invest in recharge where aquifer conditions allow.** Rainwater harvesting, rejuvenation of village ponds, check structures and managed aquifer recharge using surplus canal or treated water can reduce the deficit between draft and availability. Sites should be selected using aquifer mapping, and efforts should focus on Mahendergarh, Sirsa and Palwal. Conjunctive use of canal water and groundwater, where canal supply exists, can ease pressure on tubewells.
- 6. Strengthen regulation, registration and monitoring.** Registration of tubewells, volumetric measurement of draft, and the effective use of the state’s groundwater authority and community-based programmes such as the Atal Bhujal Yojana would give regulators the information they now lack. A denser network of piezometers with telemetric recording would allow block-level trends to be tracked and the sudden jumps noted in Mahendergarh to be verified.

7. **Protect the gains in Hisar and Jhajjar.** Improving districts should not be treated as free of constraint. Continued monitoring of both levels and quality, caution in expanding paddy, and preservation of recharge areas are advisable, since the later series show that the improvement can reverse in dry years.

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