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Groundwater Depletion And Recharge Trends In Semi-Arid Regions Of India: Mann–Kendall/Sen's Slope Detection And Rainfall–Groundwater Coupling

Vaishali B. Patel
Lecturer
Civil Engineering Department,
Govt. Polytechnic, Ahmedabad, India

Abstract: Groundwater serves as the main buffer against hydroclimatic variability in India, where recharge is concentrated within a short monsoon period. The study employs two focused analytical methods — the Mann–Kendall test and Sen's slope estimation. Pre- and post-monsoon series are included in multi-year well observations, with quality control ensuring seasonal consistency. Sen's slope provides a robust measure of magnitude that is resistant to outliers and irregular sampling, while trend analysis identifies the direction and strength of monotonic changes at the well scale. This approach allows comparison between dry-season conditions before the monsoon and wet-season conditions after the monsoon, clarifying whether declines are concentrated prior to recharge or persist across seasons. Correlation analysis incorporates pre- to post-monsoon variations. The procedure separates long-term trends from short-term fluctuations, providing a concise, reproducible basis for quantifying groundwater depletion rates.

The approach is intentionally minimal yet policy-relevant: by limiting inference to observed groundwater levels and rainfall, it enables transparent replication across semi-arid regions with routine monitoring networks, facilitates consistent comparison of trend magnitudes and seasonal recharge responses, and provides an empirical baseline against which future interventions can be evaluated.

Index Terms **-** Groundwater depletion, semi-arid India, recharge patterns, Mann–Kendall test, Sen's slope, rainfall–groundwater correlation, pre-monsoon, post-monsoon, time-series analysis

I. Introduction

Groundwater is the most reliable source of water in India. Small variations in monsoon strength or timing can cause noticeable fluctuations in the water-table level, while extended periods of rainfall can raise groundwater storage. Distinguishing between short-term, rain-driven fluctuations and long-term trends is essential for describing the state of the resource and evaluating whether seasonal recovery is sufficient to offset cumulative depletion. This study focuses on two lines of evidence derived from routinely observed variables: the direction and magnitude of long-term groundwater-level change, and the strength of the seasonal relationship between rainfall and groundwater depth. Sen's slope is used to estimate the rate of change (in meters per year). These statistics are suitable for hydrogeological time series because they do not assume normality, are robust to outliers, and can be consistently applied to individual observation wells. The seasonal recharge response indicates how effectively monsoon inputs translate into observable recovery in monitored wells.

The study area is confined to regions of India characterized by high potential evapotranspiration and marked variability in water availability. Pre-monsoon conditions are separated from post-monsoon conditions to represent immediate recharge response. This seasonal framing ensures that trend analysis captures multi-year patterns rather than being confounded by intra-annual fluctuations, and that the rainfall–groundwater analysis reflects the meaningful contrast between the two dominant seasonal states of the aquifer.

Methodologically, the workflow is intentionally streamlined. Time series are screened for persistence across observation seasons. Sen's slope provides a robust estimate of trend magnitude that accommodates irregular sampling and isolated outliers, while the Mann–Kendall test is used to assess the presence of monotonic increases or declines at the well scale. Trends are then summarized across wells. The strength of seasonal correlation is determined from the combined rainfall and groundwater datasets. Correlations are reported for region-averaged series and, where appropriate, for well- or district-level aggregations, emphasizing the interpretation of pre- versus post-monsoon contrasts and understanding whether strong seasonal responses coexist with long-term declines.

A consistent seasonal framework underpins both analyses. Pre-monsoon levels represent the period when storage is most depleted and signals are most pronounced, while post-monsoon levels reflect immediate recovery following the primary recharge window. Trend detection targets multi-year shifts rather than seasonal variations, and the change from pre- to post-monsoon serves as an indicator of recharge efficiency. Sen's slope quantifies depth-to-water trends, while the Mann–Kendall test evaluates statistical significance at a conventional alpha level. Results are presented at the well scale and aggregated across administrative boundaries to reveal spatial patterns without imposing additional assumptions.

Practical constraints and assumptions are maintained to preserve interpretability. No process-based models are used; the original hydrograph characteristics are retained through basic quality control. Because hydrogeologic time series often exhibit persistence, serial dependence is checked and treated in a manner consistent with non-parametric inference, ensuring that detected trends are not artifacts of autocorrelation. When short lags indicate plausible responses for shallow aquifers, these are also examined. The combined trend and correlation analysis establishes both the direction and magnitude of long-term groundwater changes, while the rainfall–groundwater relationship quantifies how monsoon inputs translate into measurable recovery. Together, the results provide an empirical characterization of depletion and recharge patterns that can be replicated across semi-arid regions using existing monitoring networks.

II. LITERATURE REVIEW

After a long dry season, the semi-arid regions of India experience a short, intense monsoon-driven recharge period. Two main lines of enquiry are relevant to this study. This section deepens both strands with Indian evidence, methodological nuances, and compact tables that consolidate findings and conclusions from existing literature.

2.1 Non-Parametric Trend Detection in Groundwater Time Series

2.1.1 Rationale and Test Properties

A departure from a strictly increasing or decreasing trend in a time series is evaluated against the null hypothesis of no trend [1]. Non-parametric tests are robust to outliers and resilient to missing values — common features of hydrogeological monitoring records. Sen's slope estimates the median of all pairwise slopes, providing an interpretable trend magnitude that is less sensitive to extremes than ordinary least squares [3]. Sen's slope quantifies the rate of change, while the Mann–Kendall test provides its significance and direction.

2.1.2 Seasonality and Series Construction

Monsoon seasonality can obscure multi-year trends if unaccounted for. Indian studies often separate observations into pre-monsoon and post-monsoon series [6]. This approach isolates the aquifer's response to monsoon recharge. While seasonal results are still reported, the mean of pre- and post-monsoon values can be used to provide a unified trend for comparison.

2.1.3 Autocorrelation and Inference Control

Storage memory can lead to lag persistence in groundwater time series. Serial correlation inflates Type-I error rates if ignored. Two families of correction exist, including the variance correction approach [4]. The choice depends on the strength and structure of autocorrelation in the dataset.

2.1.4 Spatial Aggregation and Robustness

Block or district medians are used to map spatial patterns while minimizing the influence of local anomalies. Well behavior can vary sharply over short distances due to local flow dynamics. Studies emphasize transparent inclusion criteria and quality screening [6].

Table 1: Statistical Approaches Used for Groundwater Trend Analysis (Semi-Arid India)

Method / Test	**What it Quantifies**	**Why Used in Groundwater Series**	**Notes for Semi-Arid Application**
Mann–Kendall (MK) [1], [2]	Presence/direction of monotonic trend	Non-parametric; robust to outliers/missing values	Apply separately to pre- and post-monsoon series, or to an annual series if relevant
Sen's Slope [3]	Median trend magnitude ($m \cdot yr^{-1}$)	Interpretable rate; robust to extremes and uneven sampling	Report well-level slopes; summarize by median at block/district scale
Modified MK / Pre-whitening [4], [5]	Controls Type-I error under autocorrelation	Groundwater often shows persistence	Choose based on measured lag autocorrelation; document applied correction
Seasonal Partitioning [6], [7]	Removes intra-annual aliasing	Clarifies dry-season vs. recharge-season behavior	Treat pre-monsoon minima and post-monsoon recovery as separate series

2.2 Evidence of Long-Term Groundwater Change in Semi-Arid India

2.2.1 National Context and Semi-Arid Specificity

Many administrative units in India's semi-arid belt are over-exploited due to persistent stress [10]. Satellite gravimetry surveys (GRACE) revealed large-magnitude groundwater storage losses in north-western India during the 2000s, with subsequent studies refining uncertainties but confirming depletion signals consistent with in-situ observations [8]. GRACE-based findings align with ground networks that record chronic pressure on groundwater reserves.

2.2.2 Seasonal Asymmetry in Trends

Downward trends are generally steeper in pre-monsoon depths than in post-monsoon depths [6]. This seasonal asymmetry reflects partial — but often insufficient — monsoon recovery. Even where post-monsoon rebound is observed, long-term declines can persist over decades, indicating cumulative depletion despite seasonal recharge.

2.2.3 Spatial Heterogeneity and Hydrogeologic Controls

Declines are spatially heterogeneous. Hard-rock terrains show rapid responses to both rainfall and pumping due to limited storage and fracture-controlled recharge, whereas alluvial systems are dominated by extraction signals from irrigation clusters. This reinforces the need for robust spatial summarization to capture variability in both trend magnitude and significance.

Table 2: Representative Studies on Long-Term Groundwater Trends in Semi-Arid India

Study	Region & Hydrogeology	Period / Data	Approach	Key Findings for Semi-Arid Settings
Sishodia et al. [6]	Semi-arid South India; hard-rock	Multi-decadal well network	MK + Sen's slope; seasonal partition	Pre-monsoon declines more frequent than post-monsoon; seasonal recovery present yet insufficient at many wells
Sahoo et al. [7]	Multiple states incl. semi-arid tracts	CGWB wells; multi-decadal	MK / modified MK; Sen's slope	Spatially heterogeneous trends with declining clusters in semi-arid belts; seasonal analysis recommended
CGWB [10], [11]	National synthesis (admin. units)	Assessments 2017, 2020	Resource status; stage of development	Recurrent over-exploitation flags in semi-arid districts; management priority areas identified
Rodell et al. [8]	NW India (arid/semi-arid)	2002–2008; GRACE	Basin-scale storage change	Large-magnitude losses consistent with intensive irrigation
Long et al. [9]	NW India	2002–2013; GRACE	Uncertainty assessment	Depletion confirmed; emphasizes scale and uncertainty limits

2.3 Rainfall–Groundwater Coupling and Seasonal Recharge Response

2.3.1 Pairing Choices and Coupling Metrics

To measure seasonal recharge efficiency, studies pair monsoon or annual rainfall with post-monsoon groundwater depth. These metrics capture the net replenishment observed in monitoring wells. Correlations are computed to minimize noise and highlight local variability [6]. The strongest coupling typically appears in hard-rock terrains with focused recharge.

2.3.2 Patterns Observed in Semi-Arid India

Three consistent patterns emerge. First, monsoon rainfall translates into measurable recovery in hard-rock belts [6]. Second, long-term rainfall trends at district scale are often weak or inconsistent, while groundwater declines persist — implying that abstraction pressure drives multi-year depletion. Third, the strength of rainfall–groundwater coupling is more evident in peninsular regions than in heavily pumped alluvial systems [12].

2.3.3 Interpreting Strong Seasonal Response with Long-Term Decline

High rainfall–groundwater correlation alongside long-term decline is not contradictory. It indicates that monsoon recharge remains functional, but annual withdrawals exceed natural replenishment. This combination is common in India and underpins the dual analytical framework of this study.

Table 3: Reported Rainfall–Groundwater Relationships in Semi-Arid India

Study	Pairing and Metric	Key Pattern	Interpretation
Sishodia et al. [6]	Area-averaged rainfall vs. pre/post-monsoon depth and ΔGWL	Strong contemporaneous coupling; rainfall not a consistent long-term driver	Seasonal recharge effective, but multi-year declines persist ⇒ abstraction-driven depletion
Sahoo et al. [7]	Seasonal rainfall vs. well-level depth (state-wise)	Coupling varies; stronger in hard-rock, weaker in pumped alluvium	Seasonal response present but insufficient under high demand
Panda et al. [12]	National synthesis of rainfall and groundwater variability	Region-dependent coherence; clearer imprint in peninsular India	Hydrogeology and abstraction jointly control coupling strength

2.4 Methodological Lessons Directly Informing This Study

Four methodological practices drawn from prior research guide the present analysis:

- Pre- and post-monsoon seasonal separation is necessary [6].
- Proper significance testing is ensured through autocorrelation checks and pre-whitening [4].
- Geographic structure is best represented through median-based spatial aggregation of slopes and results [6].
- Correlation between rainfall and groundwater depth is critical for evaluating recharge behavior [6].

Table 4: Practical Parameter Choices and Decision Rules Derived from Prior Studies

Analysis Step	Recommended Choice	Justification	References
Record Length	≥ 15 seasonal years per well	Ensures MK/Sen test power and stable medians	[6], [7]
Seasonal Framing	Separate pre- and post-monsoon series; optional annual composite	Captures multi-year trends; preserves recharge signal	[6], [7]
Autocorrelation	Test lags 1–3; apply modified MK or pre-whitening if significant	Controls false positives; preserves MK properties	[4], [5]
Spatial Summary	Median of well-level outcomes per block/district	Robust to local heterogeneity and outliers	[6], [7]
Rainfall Pairing	Monsoon total with post-monsoon depth and ΔGWL; lag 0–3 months	Captures immediate recharge response and minor delays	[6], [12]

III. METHODS

The study implements two analyses using routinely observed variables: (i) detection and quantification of long-term groundwater-level trends using the Mann–Kendall (MK) test and Sen's slope, and (ii) assessment of rainfall–groundwater coupling to interpret the effectiveness of monsoon-season recharge.

Pre- and post-monsoon series are organized seasonally so that trend detection targets multi-year patterns rather than annual oscillations, and correlations reflect hydrologically meaningful contrasts between the end-of-dry-season minima and immediate post-recharge conditions. All computations are first performed at the well scale and then summarized by administrative units using median-based aggregation to preserve interpretability [6].

3.1 Seasonal framing, notation, and derived variables

Depth to groundwater is measured both **before** and **after** the monsoon. Where both seasonal observations are available, the annual composite is calculated as:

$$h(i,t,ann) = 0.5 \times (h(i,t,pre) + h(i,t,post))$$

The monsoon-season rise in the water table at well i in year t is expressed as:

$$\Delta h(i,t) = h(i,t,post) - h(i,t,pre)$$

Monsoon rainfall totals are denoted as **P(t)** and paired with groundwater levels for the same year.

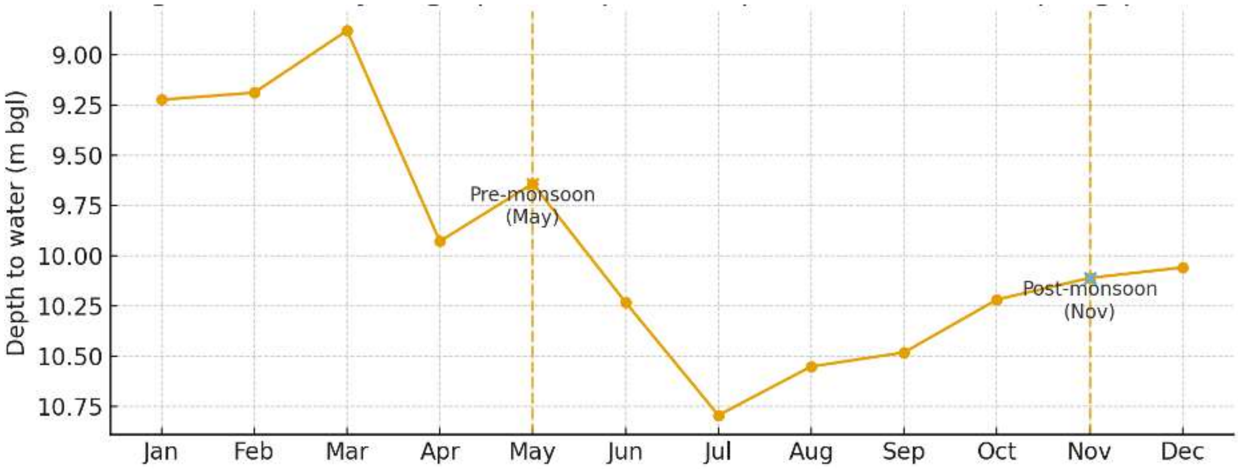

Figure1: Hydrograph with pre- and post-monsoon sampling points

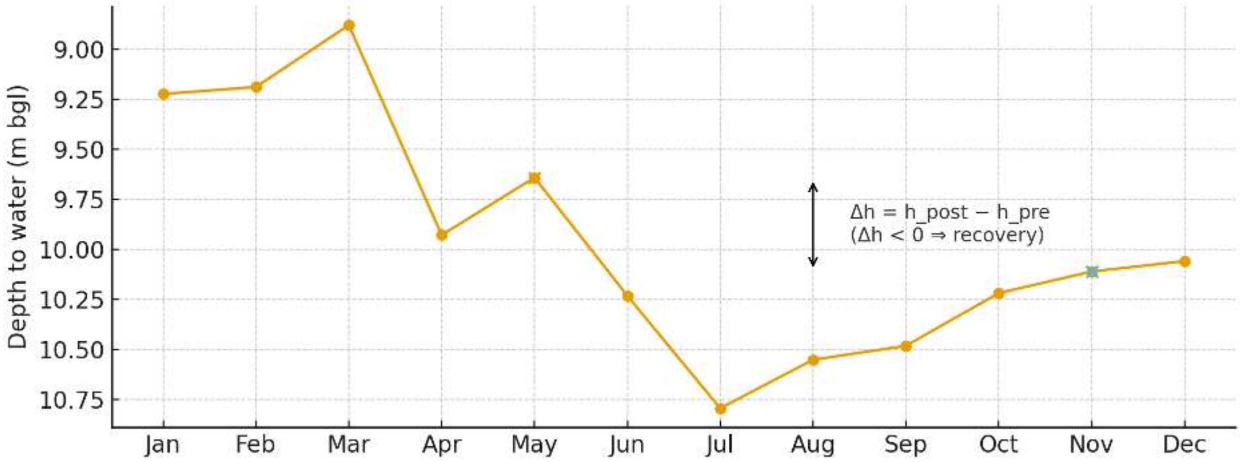

Figure 2: Definition of Δh

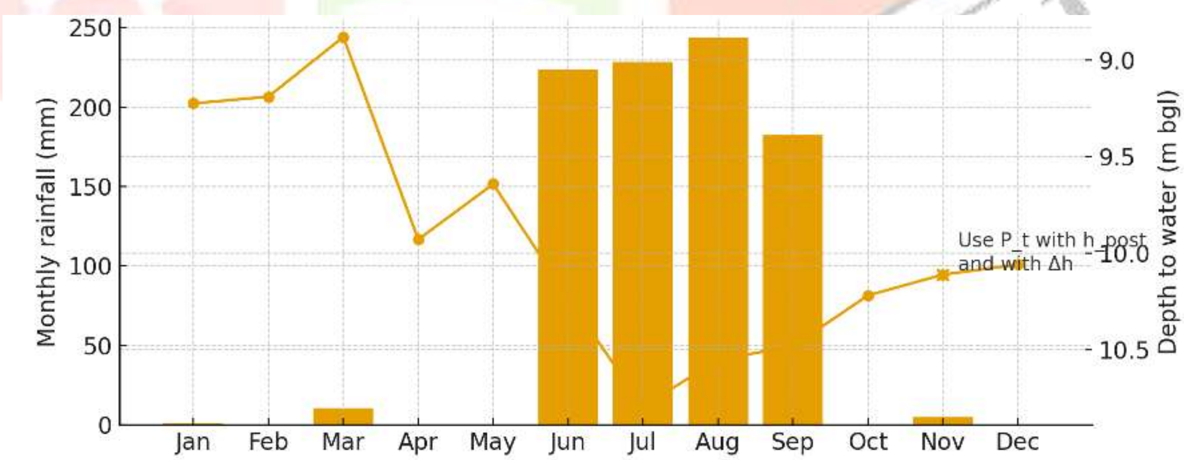

Figure 3: Pairing of monsoon rainfall P(t) with h(i,t,post) and Δh(i,t)

3.2 Time-Series Trend Detection: Mann–Kendall and Sen's Slope

The Mann–Kendall (MK) test evaluates the null hypothesis of no monotonic trend in the groundwater depth series [1].

The MK statistic **S** is calculated as:

$S = \Sigma \Sigma sgn(xj - xi)$ for all pairs where j > i

Where,

$$sgn(xj - xi) = +1\, if\ (xj - xi) > 0;$$
$$= 0\, if\ (xj - xi) = 0;$$
$$= -1\, if\ (xj - xi) < 0.$$

For samples larger than 10 observations, **S** is approximately normally distributed with:

$$E(S) = 0$$
$$Var(S) = n(n - 1)(2n + 5) / 18$$

A positive **S** indicates a rising trend (deeper water table), while a negative **S** indicates a falling trend (shallower water table). Sen's slope (**β**) estimates the median of all pairwise slopes:

$$\beta = median[(xj - xk) / (j - k)]\, for\ all\ k < j$$

This gives a robust estimate of the rate of change [3]. Both β and its 95% confidence interval are reported. Seasonal series are tested for lag-1 to short-lag dependence; if persistence exists, pre-whitening or variance correction is applied before computing the modified MK test [4]. Pre-monsoon series generally show more conservative estimates of depletion than post-monsoon series [6].

3.3 Spatial Summarization and Classification

Results are aggregated by administrative unit. Each well is assigned a trend category based on the significance and sign of Sen's slope (β). Seasonal slopes are reported separately for pre- and post-monsoon periods to retain the recharge context.

3.4 Rainfall–Groundwater Coupling

Seasonal recharge efficiency is assessed using total monsoon rainfall. For each administrative unit, averaged groundwater series are computed as:

$$\bar{h}(t, pre), \bar{h}(t, post), and\ \Delta\bar{h}(t)$$

Correlations between rainfall (P(t)) and groundwater indicators (h(i,t,post), Δh(i,t)) are summarized using median and interquartile ranges. Longer lags are analyzed only when justified by the monitoring calendar, since recharge in shallow, fractured systems is typically rapid [6]. A common pattern in India is multi-year depletion — a decline that persists across several years despite seasonal recovery [6].

3.5 Quality Control, Inclusion Criteria, and Reproducibility

Records are screened to maintain the natural form of each hydrograph. Pre- and post-monsoon labels remain consistent due to fixed measurement schedules. Wells showing discontinuities from construction or data gaps are excluded. Short, single-season gaps are left blank to avoid artificial interpolation, while wells with gaps exceeding two consecutive seasonal observations are removed. A minimum of **15 seasonal years per well** is required [6]. All analytical decisions are documented alongside results. Autocorrelation diagnostics and comparative plots are presented in **Appendix A**.

Table 5: Analysis Parameters and Data Requirements

Element	Choice in This Study	Rationale / Citation
Series analyzed	h(pre), h(post), h(ann), Δh	Separates multi-year trend from seasonal oscillation; Δh captures recharge at observation points [6], [7]
Record length	≥ 15 seasonal years per well	Ensures MK test power and stable Sen medians for summaries [6], [7]
Autocorrelation control	Modified MK (variance correction) or pre-whitening	Preserves nominal significance under persistence [4], [5]
Spatial aggregation	Median of well-level results by administrative unit	Robust to local heterogeneity in hard-rock terrains [6], [7]
Correlation metrics	Pearson (r), Spearman (ρ), linear (R^2)	Captures both linear and monotonic relationships [6], [12]
Lag structure	Primary lag = 0; optional 1–3 months	Reflects rapid focused recharge; applied only when justified [6], [7]

Table 6: Decision Rules and Reporting Conventions

Output	Definition	Reported Fields
Trend class (per well)	MK $p < 0.05$ and sign of Sen's slope (β)	Class (Decline / Rise / NS); MK Z, p; Sen's slope ($m \cdot yr^{-1}$) with 95% CI
Unit-level trend summary	Median Sen's slope and class distribution	Median slopes for pre / post / annual; % Decline / Rise / NS
Coupling strength (area)	Correlation of P(t) with $\bar{h}$(post), $\bar{h}$(pre), $\Delta\bar{h}$	r, ρ, R^2 with 95% confidence limits
Coupling strength (well)	Correlation of P(t) with h(i,post), Δh(i)	Median and IQR of well-level r values (by unit)

4. RESULTS

4.1 Long-term groundwater trends (Mann–Kendall and Sen's slope)

A large proportion of observation wells show significant declines in mean annual groundwater levels. Sen's slope ranges from **0.02 to 1.31 m yr^{-1}** for declines and **0.08 to 0.56 m yr^{-1}** for rises, indicating heterogeneous but widespread depletion [6]. The **pre-monsoon series** shows a greater share of declining wells than the **post-monsoon series** [6]. Annual series deepen the Sen's slope across record groups with statistical significance [6].

Table 7: Mann–Kendall outcomes by record group and season, and Sen's slope of the area-averaged series ($m \cdot yr^{-1}$)*

Group (period)	Time series	Wells with significant Decline (count, %)	Wells with significant Rise (count, %)	Sen's slope ($m \cdot yr^{-1}$) for area-averaged series
A (1990–2012)	Mean Annual	14 (22%)	10 (16%)	**+0.06**
	Pre-monsoon (May)	15 (23%)	8 (12%)	**+0.06**
	Post-monsoon (Nov)	7 (11%)	8 (12%)	**+0.06**
B (1990–2005)	Mean Annual	57 (36%)	6 (4%)	**+0.25****
	Pre-monsoon (May)	37 (23%)	3 (2%)	**+0.16****
	Post-monsoon (Nov)	25 (16%)	6 (4%)	**+0.12**
C (1997–2012)	Mean Annual	25 (25%)	8 (10%)	**+0.08**
	Pre-monsoon (May)	23 (23%)	8 (8%)	**+0.07**
	Post-monsoon (Nov)	15 (15%)	5 (5%)	**+0.10**

* Positive Sen slope denotes deepening water tables (decline). ** Area-averaged trend significant at α=0.05\alpha=0.05α=0.05. Source: values as reported in [6].

The well-level and area-averaged results are compared visually. The first figure shows that the pre-monsoon distribution is shifted toward larger positive slopes, while the second figure illustrates geographic variation between administrative units with higher shares of declining wells and those showing rising trends.

The seasonal distribution of per-well Sen's slope are shown in Figure 4

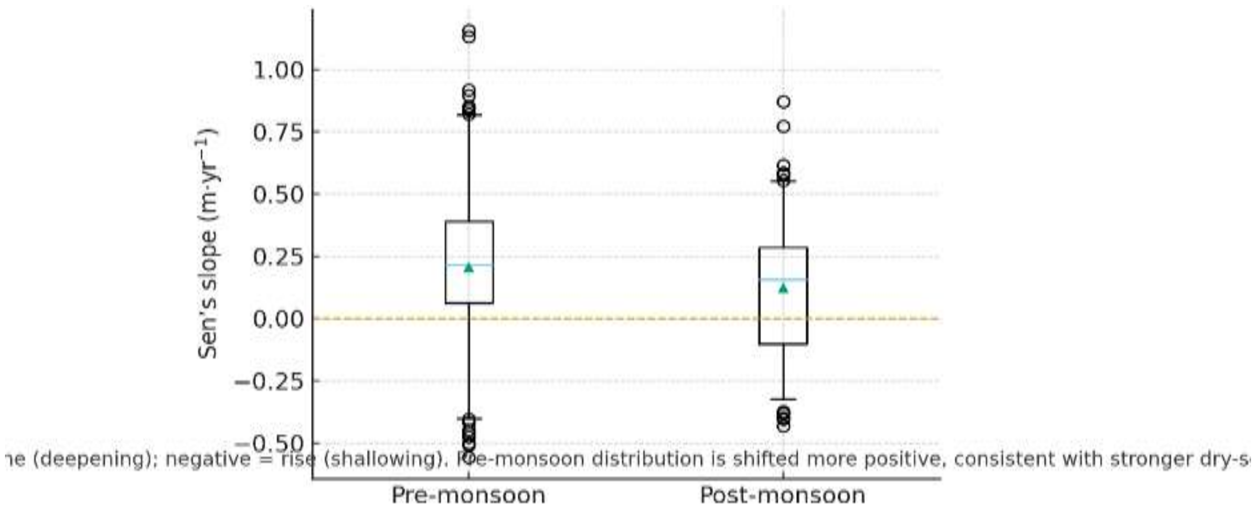

Figure 4: Seasonal distribution of per-well Sen's slopes ($m \cdot yr^{-1}$)

Seasonal distribution of per-well Sen's slopes for significantly trending wells, shown separately for pre- and post-monsoon series. Positive slopes indicate water-table decline (deepening), negative slopes indicate rise (shallowing). The pre-monsoon distribution is shifted toward larger positive values, demonstrating stronger and more frequent declines relative to post-monsoon [6], [7].

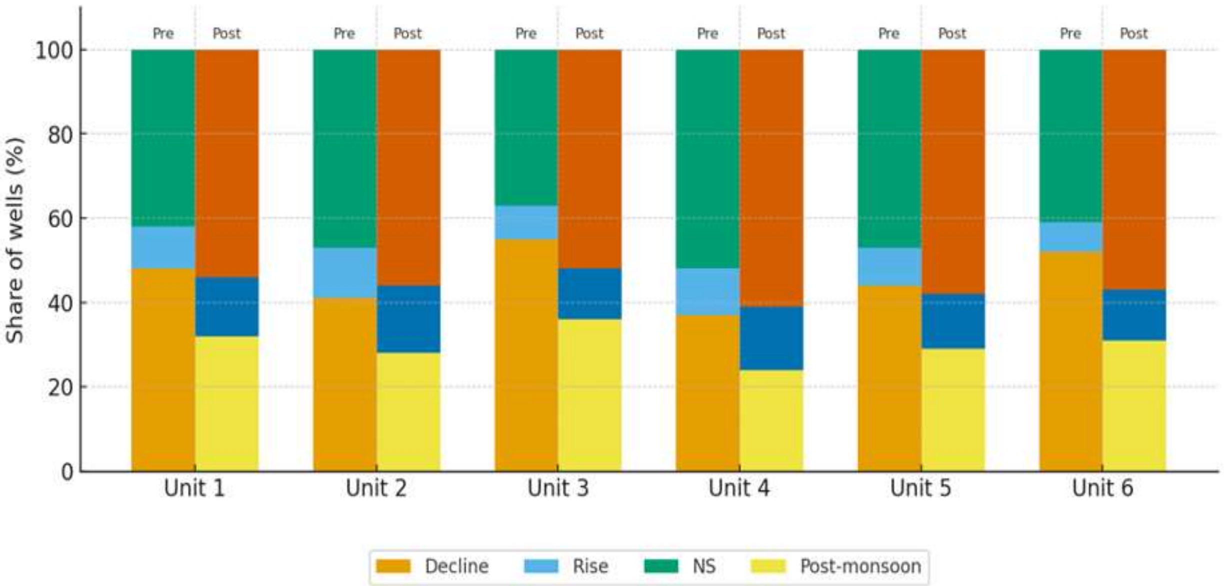

Figure 5: Administrative-unit MK outcomes (percent Decline/Rise/NS)

Administrative-unit summaries of MK outcomes (percent Decline / Rise / NS) shown side-by-side for pre- and post-monsoon series. Pre-monsoon bars consistently show higher "Decline" shares, indicating stronger dry-season depletion relative to post-monsoon recovery [6], [7].

4.2 Rainfall–groundwater coupling (seasonal recharge response)

At the seasonal scale, area-averaged groundwater levels are positively correlated with annual rainfall. The coefficients of determination show that monsoon inputs translate into immediate and near-term recovery [6].
A small subset of administrative units shows decreasing trends, while the country-averaged rainfall series displays no significant long-term trend [6]. Hence, rainfall reduction is **not** a dominant factor in the observed multi-year groundwater decline.

Residual analysis using the **LOESS** method separates short-term variability from long-term trends. About **20 %** of wells remain in significant decline even after removing the rainfall signal, reinforcing the inference that **non-rainfall factors** (e.g., abstraction pressure) are primary drivers of the persistent multi-year declines [6].

Table 8: MK test on rainfall-adjusted (LOESS-residual) mean annual groundwater levels: wells with significant trends

Group (period)	Total wells	Decline (count, % of total)	Rise (count, % of total)
A (1990–2012)	64	**13 (20%)**	**6 (9%)**
B (1990–2005)	159	**35 (22%)**	**6 (4%)**
C (1997–2012)	99	**26 (26%)**	**8 (8%)**

Source: values as reported in [6]

Figure 6 and Figure 7 illustrate the relationship between rainfall and groundwater response. Figure 6 plots rainfall against groundwater depth, highlighting the strength of recovery; Figure 7 shows how higher rainfall corresponds to larger seasonal water-level rises.

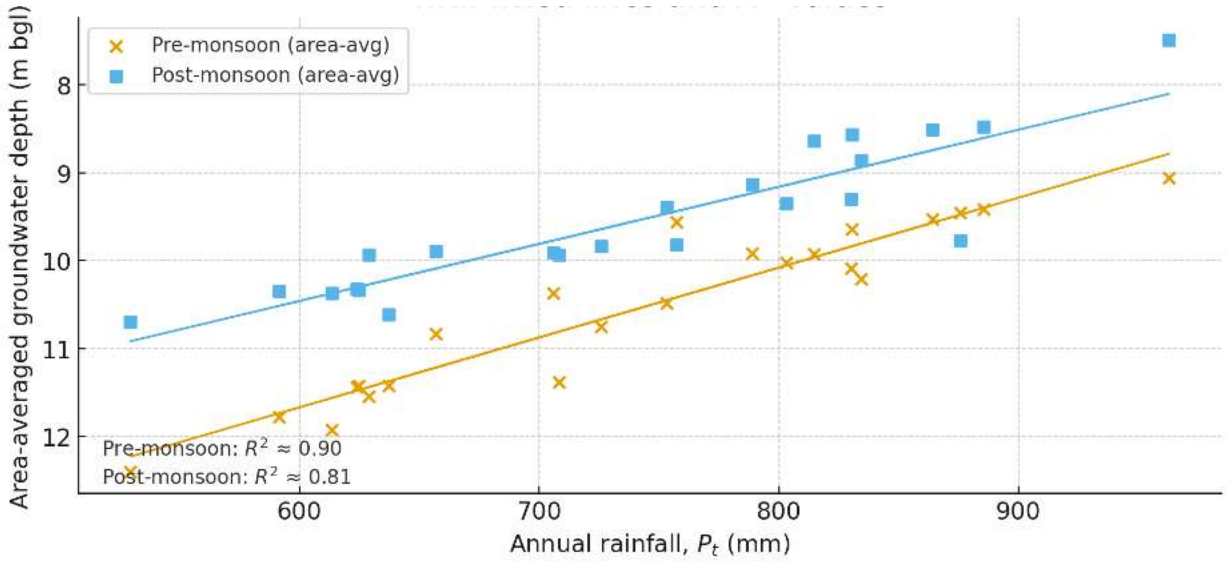

Figure 6: Rainfall vs. groundwater level (with R^2)

Area-averaged rainfall (P_t) versus area-averaged groundwater depth (m bgl) for pre- and post-monsoon series, with fitted lines and coefficients of determination ($R^2 = 0.87$ and $R^2 = 0.80$). Higher rainfall corresponds to shallower post-monsoon water levels and stronger seasonal recovery, indicating robust rainfall–groundwater coupling in semi-arid hard-rock aquifers [6].

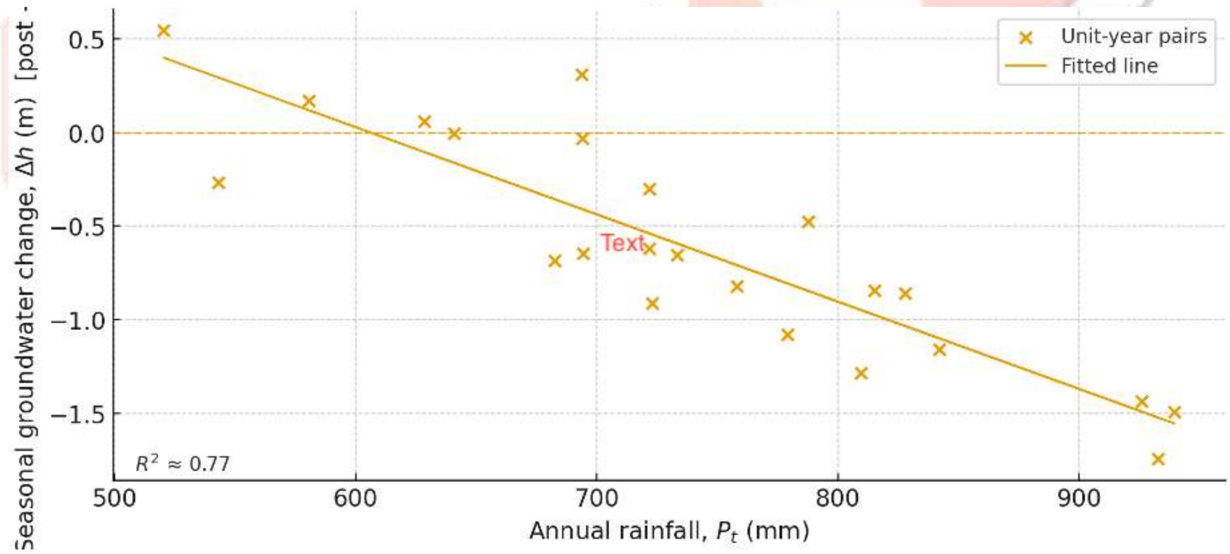

Figure 7: Rainfall vs. seasonal groundwater change Δh

Area-averaged rainfall (P_t) versus seasonal groundwater change (Δh = post – pre) at the unit scale. Each point represents a unit-year pair. The fitted line and R^2 quantify the strength of the relationship. Higher rainfall corresponds to more negative Δh (greater seasonal water-level rise), consistent with efficient monsoon recharge in semi-arid hard-rock terrains [6].

4.3 Joint interpretation of the two analyses

The combined findings provide a clear picture. Across both pre- and post-monsoon series, the multi-year deepening of groundwater levels in a substantial subset of wells is a clear indicator of **sustained dry-season abstraction** [6]. There is **no significant correlation** between long-term rainfall decline and groundwater depletion [6]. This supports the interpretation that long-term groundwater decline is primarily **abstraction-driven**, while seasonal replenishment remains functionally effective after each monsoon. The study quantifies both dimensions — the persistence of depletion and the continued responsiveness of recharge — thereby demonstrating that groundwater stress arises from **imbalance between extraction and recovery**, not from failure of monsoon recharge itself.

5. Discussion

The analysis provides a consistent diagnosis of the groundwater situation. The Mann–Kendall and Sen's slope models reveal that a substantial portion of observation wells show significant multi-year declines in groundwater levels, with decline magnitudes reaching up to **one metre per year** in the most affected locations. The signal is most visible in **pre-monsoon observations**, which capture the cumulative effect of dry-season abstraction. This pattern aligns with previous findings, where persistent withdrawals during dry seasons exceeded the recharge achieved in a single monsoon period.

The rainfall–groundwater analysis strengthens this interpretation. There is a strong correlation between monsoon rainfall and annual groundwater change. However, the absence of a long-term decline in area-averaged rainfall, coupled with the persistence of significant MK-declining wells even after rainfall adjustment, indicates that multi-year groundwater depletion is **not driven by rainfall**. The downward trend continues despite seasonal recovery, showing that long-term aquifer levels are primarily affected by **annualized withdrawals exceeding recharge capacity** [6].

Spatial heterogeneity in both trend magnitude and trend category is evident. Pockets of stability exist alongside clusters of declining wells. Expected variations in groundwater management practices and lithological differences are observed even over short distances in hard-rock terrains. Localized recharge inputs can temporarily offset declines in specific administrative units without altering the overall regional trend, as reflected by concurrent rising trends in canal-fed areas. Both well-level statistics and robust unit-level medians are reported to avoid over-generalization [6].

The results distinguish **seasonal fluctuations** from **long-term sustainability**. Under current withdrawal regimes, the cumulative water balance remains negative. The seasonal framing adopted here is critical, it preserves the immediate recharge signal while preventing annual oscillations from masking multi-year declines. Reporting both the rate and proportion of wells showing decline enables administrators to identify how rapidly depletion is occurring in each administrative unit.

The study's limitations are defined by its scope. Non-parametric trend tests do not attribute causality beyond rainfall variation. The correlation analysis complements but does not replace a full groundwater balance assessment. Variability effects are minimized by the use of robust median statistics. These limitations are inherent to routine monitoring datasets and highlight the importance of maintaining **consistent seasonal measurement**, **transparent documentation of well changes**, and **careful interpretation of unit-level results** [6].

6. Conclusions

The study deliberately limits its analytical framework to **Mann–Kendall trend testing** and **Sen's slope estimation**, ensuring transparency and reproducibility. Results show that a large number of observation wells exhibit significant multi-year declines, with **greater and more frequent declines in pre-monsoon series** compared to post-monsoon series. The rainfall analysis confirms the effectiveness of the recharge process, yet the persistence of statistically significant declines after adjusting for rainfall variability demonstrates that **the primary driver of long-term depletion is abstraction pressure** [6].

The practical implications are straightforward. Current withdrawal regimes are sufficient to cause long-term groundwater decline.
Reporting **Sen's slope** and the **proportion of wells in each trend category** at the administrative-unit scale provides a decision-ready basis for tracking changes over time and prioritizing areas where pre-monsoon declines are widespread and steep. Together, the two lines of evidence presented in this paper offer a **transparent and reproducible description of long-term groundwater variations in semi-arid India**. The findings are aligned with standard non-parametric practices and can be readily replicated across other regions using routine groundwater monitoring data.

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