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Research Article

Attenuation of hydroclimatic influence on groundwater dynamics under anthropogenic stress: A decadal spatiotemporal analysis in Jaipur, India

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Abstract: Groundwater constitutes the primary freshwater resource in semi-arid regions, where low and erratic rainfall combined with high evapotranspiration limit effective recharge. Jaipur, a rapidly expanding metropolitan city in western India, is experiencing increasing groundwater stress due to the combined influence of climatic variability and anthropogenic pressures. While groundwater depletion in Rajasthan is well documented, the extent to which interannual climatic variability, particularly rainfall fluctuations, translates into measurable groundwater-level response in urban fractured hard-rock aquifer systems remains uncertain. This study evaluates groundwater-level dynamics (2013–2023) in relation to climatic variability and examines the apparent decoupling between climatic signals and groundwater response under combined hydrogeological and anthropogenic influences in Jaipur. Groundwater and gridded climatic datasets were analyzed using geospatial mapping, kriging-based spatial interpolation, and correlation-based statistical approaches. Pearson, Spearman, and Kendall correlation methods were employed to assess statistical relationships. Interannual groundwater variations were further analyzed to characterize temporal depletion patterns. In addition, event-based proxy analysis using extreme precipitation indices (R×1d and R×5d) was conducted to evaluate the influence of short-duration and cumulative rainfall events on groundwater response. Results indicate weak and spatially inconsistent relationships between climatic variables and groundwater levels, suggesting that groundwater response cannot be adequately explained by linear climatic relationships alone and is influenced by non-linear and lagged recharge processes. A strong inverse correlation between relative humidity and evapotranspiration ($r = -0.9272$, $p < 0.0001$) highlights the dominant role of atmospheric moisture conditions in regulating evapotranspiration fluxes, with implications for reduced effective recharge. These findings suggest that groundwater dynamics in the study area exhibit partial decoupling from climatic variability, likely driven by hydrogeological constraints and sustained anthropogenic pressures. This underscores the importance of adopting integrated groundwater management strategies that account for both climatic variability and anthropogenic pressures.

Keywords: Groundwater-climate interaction; Climatic signal attenuation; Semi-Arid urban; Fractured aquifer; Geospatial Analysis

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Introduction

Groundwater is a primary source of freshwater for domestic, agricultural, and industrial uses, particularly in regions with limited surface water availability. It provides drinking water to more than 2 billion people worldwide and accounts for almost one-third of all freshwater resources (Tiwari and Rao, 2025). Concern over groundwater dependency is growing driven by increasing climatic variability and unsustainable abstraction practices, particularly in vulnerable regions. India accounts for approximately 25 percent of global groundwater extraction, which is making it the largest consumer worldwide (Panda et al., 2022). This

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dependence is especially pronounced in arid and semi-arid regions, where the availability of surface water is characterized by high seasonality and uncertainty. In Jaipur, groundwater is the primary source for drinking, irrigation, and urban growth, as there is no perennial river (Frommen et al., 2021). Increasing climatic variability and rising water demand have intensified pressure on local aquifers, raising serious concerns for long-term water security.

Groundwater dynamics in semi-arid regions are strongly influenced by climatic parameters, including precipitation, evapotranspiration, and atmospheric conditions. These factors govern recharge and water loss processes (Pandey et al., 2023; Monir and Sarker, 2024). Changes in precipitation patterns, more frequent drought events, and high evapotranspiration rates collectively disrupt the hydrological cycle and reduce effective recharge, particularly in arid regions (Dey et al., 2020; Song et al., 2023; Mondal et al., 2024). The delayed and heterogeneous groundwater response to climatic variations, widely reported in arid and semi-arid environments, reflects the complex dependence of recharge processes on regional hydrogeology, groundwater flow regimes, and water balance conditions (Wang et al., 2021). Although temperature influences hydrological processes, its effects on groundwater in semi-arid regions are largely mediated through evapotranspiration; it is therefore not treated as an independent climatic variable in this study (Pandey et al., 2024; Swain et al., 2022; Li et al., 2024). Instead, its influence is indirectly represented through evapotranspiration, maintaining consistency between climatic forces and the groundwater response system. The study analyzes the dynamics at the groundwater level in Jaipur from 2013 to 2023 and their correlation with the precipitation, Relative Humidity (RH), and Evapotranspiration (ET) using spatio-temporal and statistical approaches.

Groundwater levels in Jaipur have been declining steadily over recent decades as a result of extensive groundwater extraction and shifting climatic conditions (Das et al., 2025; Saxena and Singh, 2025; Dadhich et al., 2021; Kumar et al., 2024). According to recent assessments by the Central Groundwater Board (CGWB), all the 16 administrative blocks of Jaipur district have been listed as over-exploited, with groundwater being extracted over the last few years more than the natural recharge (Saxena and Singh, 2025). The rate of decline exhibits spatiotemporal variability, with areas heavily dependent on urban water supply and irrigation showing more pronounced depletion (Ahamad et al., 2023; Siziba and Chifamba, 2023; Shiferaw et al., 2024). The gap between abstraction and natural recharge has been widened by urbanization, population growth, and increasing irrigation, domestic, and industrial water demand. While some studies have reported groundwater depletion and climate fluctuations across Rajasthan, most assessments focus either on broad regional-scale trends or on any of the causes of changes like rainfall variability or land-use change (Singh et al., 2021; Swain et al., 2022; Monir and Sarker, 2024). As a result, the applicability of existing findings to city- or district-scale groundwater management remains limited, particularly in rapidly urbanizing semi-arid regions where climatic variability and anthropogenic factors interact at localized scales (Saha et al., 2024; Ayadi et al., 2025).

Given these limitations, the spatiotemporal correspondence between groundwater level decline and multiple climatic factors at the urban scale remains poorly quantified, particularly in arid and semi-arid regions. Systematic evaluation of how precipitation, relative humidity, and evapotranspiration jointly relate to groundwater level fluctuations over a decadal period in rapidly urbanizing semi-arid cities such as Jaipur has received limited attention. This study aims to provide a city-scale assessment of groundwater level dynamics in Jaipur for the period 2013–2023 by analysing spatiotemporal trends in groundwater levels, quantifying statistical associations between groundwater levels and key climatic variables, and assessing whether these relationships are sufficient to explain observed groundwater trends.

This study conducts a diagnostic analysis of groundwater dynamics and their relationships with climatic factors at the city scale in a semi-arid environment. It extends beyond spatial mapping by integrating groundwater level and gridded climatic data within a geospatial framework to provide quantitative trend and correlation analyses (Raju et al., 2023; Khatami and Khazaei, 2025). Although the study does not explicitly model groundwater recharge processes or groundwater storage changes, it provides practical insights for urban water management by identifying spatial patterns of groundwater stress linked to climatic variability. The methodological framework can be extended to other semi-arid metropolitan areas facing similar groundwater sustainability issues. Specifically, this study investigates the extent to which climatic variability explains groundwater-level dynamics at the city scale and evaluates whether observed groundwater trends are consistent with climatic

forcing or indicative of decoupling due to hydrogeological constraints and anthropogenic pressures.

1 Materials and methods

This study is an analysis of groundwater level dynamics and climatic parameters during 11 years from 2013 to 2023. The groundwater level data were obtained from the India-WRIS (Water Resources Information System) portal, where the data on monitoring wells are maintained by the Central Groundwater Board (CGWB), and are presented in the long term. The initial dataset comprised groundwater level records from 74 monitoring stations obtained from India-WRIS. After spatial filtering to retain only stations located within the Jaipur district boundary and ensuring coordinate consistency, a total of 34 monitoring wells were used for subsequent geospatial analysis Fig. 2. The spatial distribution of these monitoring wells is non-uniform, with relatively higher station density in the northeastern and central parts of the district and sparse coverage in the western and southern regions Fig. 2. This spatial variability reflects monitoring infrastructure distribution and accessibility constraints.

Climatic parameter data, including precipitation, relative humidity, and evapotranspiration, were sourced from CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations) and ERA5 (European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis v5) accessed via Google Earth Engine (GEE). Topographic variations were considered in the analysis of groundwater dynamics using depth-to-water level measurements, which represent relative groundwater depths rather than absolute hydraulic head.

1.1 Study area

Jaipur is a semi-arid region in the northwest of India. The average rainfall in this area is 500–600 mm annually, and maximum rainfall occurs during the monsoon season, between July and September. The sparse and irregular rainfall limits surface water availability and constrains groundwater recharge rates (Singh et al., 2021). The study area has a complex topography, including mountains and plains, with the Aravalli Range passing through the city, which affects water storage and flow (Frommen et al., 2021). Jaipur is one of the fastest-developing cities in the state of Rajasthan, with a population of above 3 million. The region heavily depends on groundwater as a source of water consumption across all sectors. Rapid population growth and infrastructure expansion have further increased groundwater demand, particularly given the absence of perennial water resources (Amit et al., 2025; Saxena and Singh, 2025).

Agriculture is a significant land use in the Jaipur district and peri-urban and rural areas, relying heavily on groundwater due to the seasonality of monsoon rainfall. Major types of cropping systems are cereals, oilseeds, and horticultural crops, many of which require substantial irrigation, particularly in non-monsoon periods. The simultaneous expansion of urban areas and agricultural activities that rely on groundwater has intensified the stress on the groundwater resources across the district and added stress to the local aquifer systems (Singh et al., 2021). Land use statistics for the Jaipur district indicate that approximately 55%–60% of the total geographical area is agricultural land, 15%–20% is built-up or urban land, and the remainder comprises wasteland, scrubland, and patches of forest. This land use pattern reflects the dual pressure of intensive irrigation in the peri-urban and rural regions and growing domestic groundwater demand in urban areas. These patterns are essential context for interpreting the spatial distribution of groundwater depletion across the district (CGWB, 2023; Directorate of Economics and Statistics, Rajasthan, 2022). Geologically, the Jaipur area is characterized by Precambrian hard rock formations of the Aravalli Supergroup, which include quartzite, schist, phyllite, and gneiss rocks, with weathered and alluvial deposits in the plains. The geomorphology of the area is that of denudational hills, pedi-plains, and shallow valleys. Hydro-geologically, groundwater is found in weathered and fractured hard rock aquifers that are unconfined to semi-confined, with groundwater flow controlled by patterns of fracture, lineaments, and topographic gradients. Limited aquifer storage capacity and low natural recharge rates render groundwater highly vulnerable to sustained abstraction (Frommen et al., 2021).

To address groundwater depletion, various artificial recharge and rainwater harvesting structures have been implemented across the district, including check dams, percolation tanks, recharge shafts, and traditional water harvesting structures like johads. Government policies have also encouraged the use of rainwater harvesting systems on the roofs of urban centers (Saxena and Singh, 2025). The location of the study area is shown in Fig. 1.

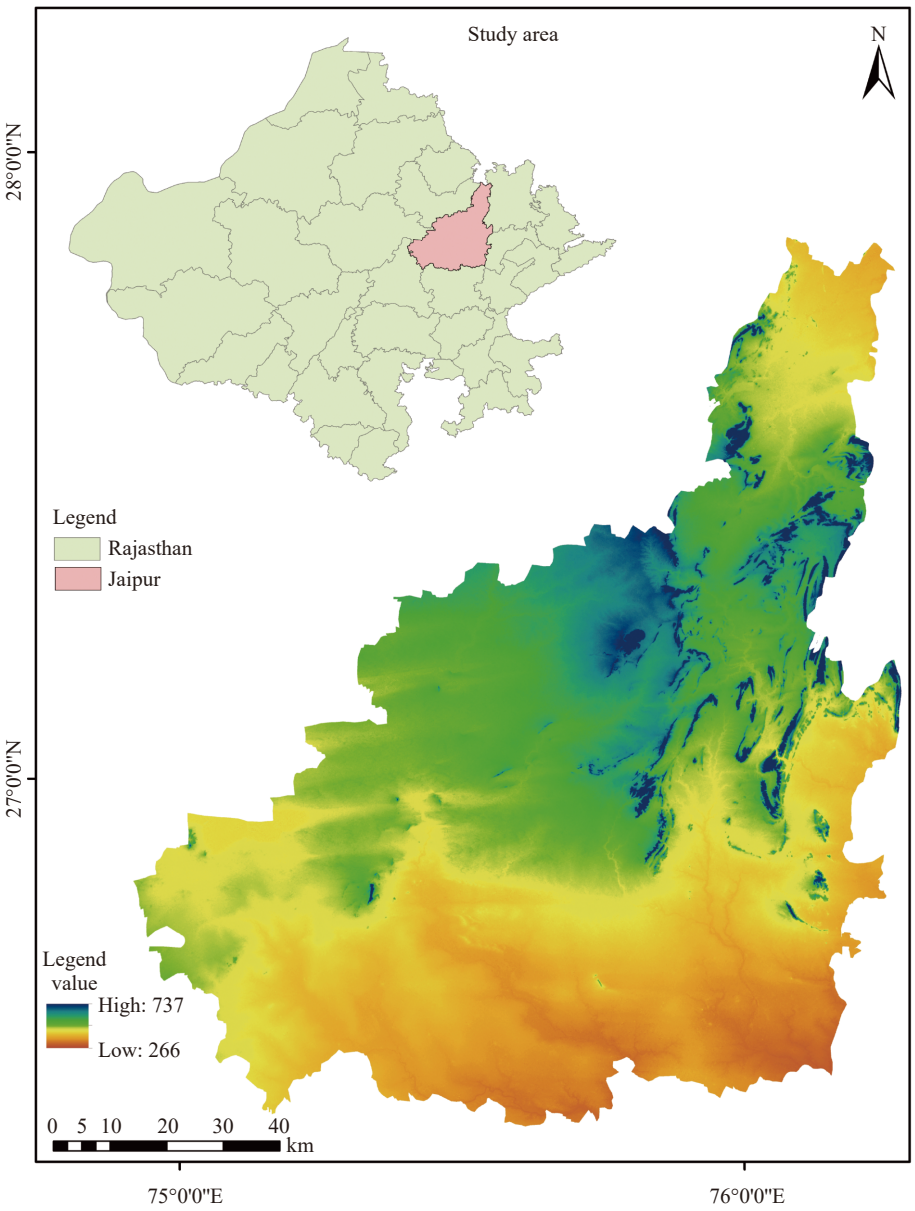


Fig. 1 Location of the study area

1.2 Methodology

The methodological framework, presented as a flowchart in Fig. 2, integrates geospatial and statistical approaches to explore linkages between groundwater dynamics and climatic variability. Groundwater and climatic datasets were acquired from credible secondary sources, processed to ensure temporal consistency, and analyzed using GIS-based spatial mapping techniques. Thematic maps were created to explore the spatial and temporal patterns of groundwater levels and climatic variables in Jaipur. Statistical methods, including Pearson correlation analysis, were applied to quantify linear relationships between groundwater levels and climatic factors at the city scale. Although the analysis covers a decade-long period, the period 2013–2023 represents the current groundwater dynamics, which are of special significance for short- to medium-term urban groundwater resource management under current climatic and human-induced stress conditions.

1.3 Data sources and process

1.3.1 Groundwater data

Groundwater level data obtained from the India-WRIS (Water Resources Information System) portal were integrated into a GIS platform to develop a spatial database comprising groundwater depth, geographic coordinates, and temporal attributes. The groundwater observations represent

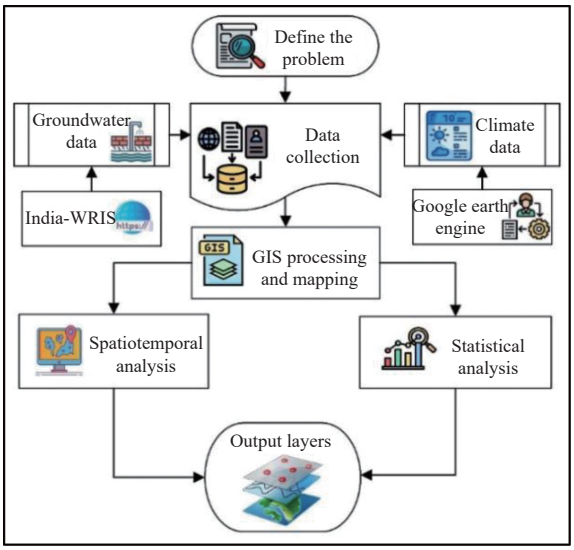


Fig. 2 Methodology flowchart

depth-to-water-table measurements (below ground level) rather than groundwater level elevations or hydraulic heads. Therefore, the interpolated outputs should not be interpreted as groundwater flow surfaces, but rather as regional-scale representations of groundwater-depth variability across the Jaipur district. The spatial distribution of monitoring wells is shown in Fig. 3, which clearly reveals higher density in the northeastern and central parts, and lower density in the western and southern parts of the district, a pattern attributable to existing monitoring network coverage and accessibility constraints. Groundwater observations from wells within the Jaipur district boundary were retained for analysis, yielding 34 monitoring wells (Fig. 3) that provide a regional-scale representation of groundwater variability across the district.

Prior to interpolation, the spatial distribution of monitoring wells was evaluated to minimize potential bias associated with localized clustering and non-uniform spatial coverage. The semi-variogram was modeled, and parameters were adjusted

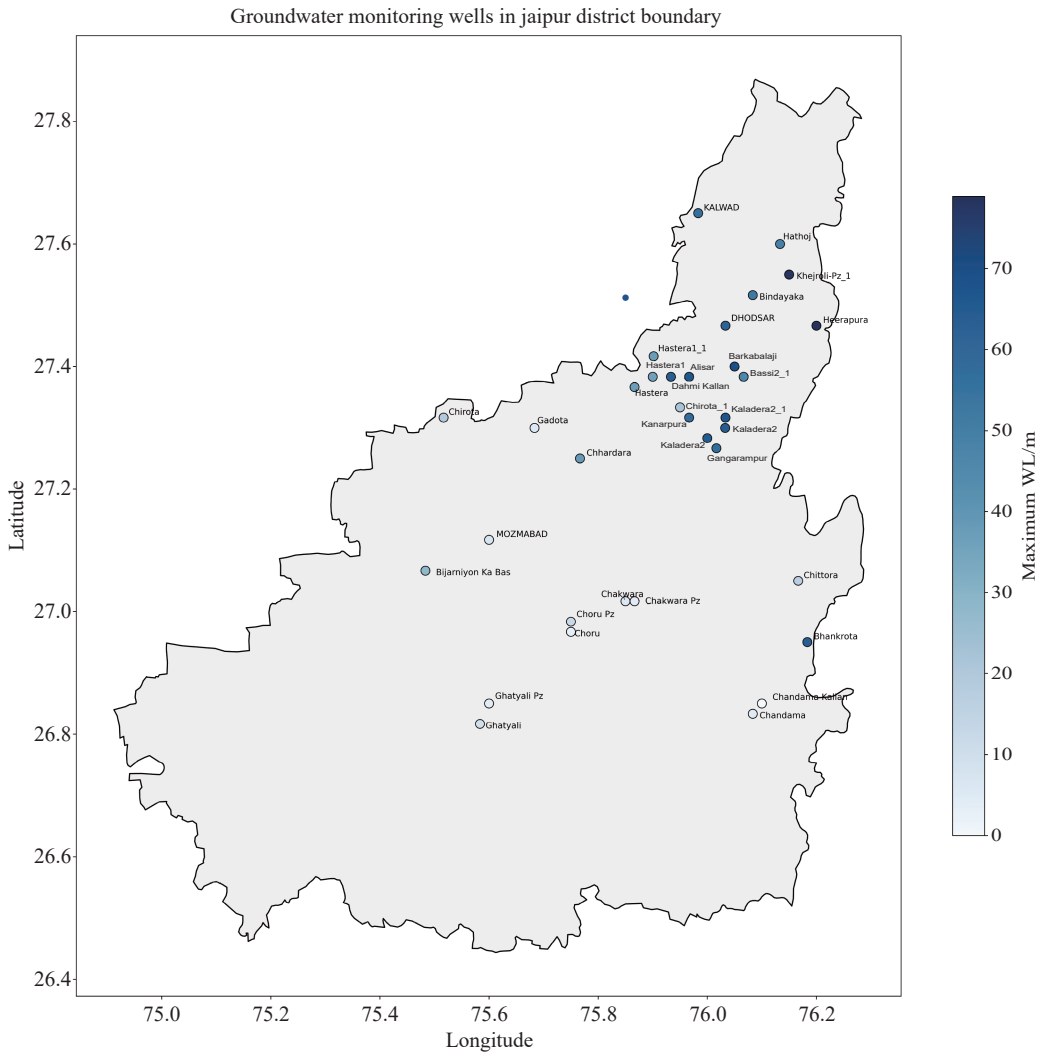


Fig. 3 Spatial distribution of groundwater monitoring wells in the study area

to provide minimal station distribution-related estimation bias during the kriging process. Kriging was favored over other deterministic interpolation methods for its utilization of spatial correlation and acknowledgment of spatial uncertainty. The annual interpolated surfaces represent relative spatial patterns of groundwater depth variability rather than potentiometric surfaces or hydraulic head distributions. Due to the uneven spatial distribution of monitoring wells, particularly in the southern part of the district, localized interpolation artifacts and isolated extrema may occur in the kriging outputs (Xiao et al., 2016). These anomalies are inherent to geostatistical interpolation under sparse monitoring conditions and were interpreted cautiously within the regional hydrogeological framework. Accordingly, the interpolated surfaces are intended to represent regional groundwater-depth variability rather than precise local groundwater conditions.

1.3.2 Climatic data

Precipitation, evapotranspiration, and relative humidity were accessed through Google Earth Engine (CHIRPS and ERA5 Datasets) and aggregated to annual time scales to ensure temporal consistency with groundwater measurements. CHIRPS precipitation was expressed as annual totals ($mm \cdot a^{-1}$), relative humidity as percent (%), and ERA5 evapotranspiration, originally provided as surface fluxes ($kg \cdot m^{-2} \cdot s^{-1}$), was converted to water-equivalent annual totals ($mm \cdot a^{-1}$) before statistical analysis, processed to annual temporal scales to ensure consistency with groundwater observations. The datasets used, their sources and their spatial resolutions are listed in Table 1.

All datasets were obtained from established national and international repositories and follow documented quality-control and validation protocols. Groundwater data from India-WRIS are managed and quality-checked by CGWB, while CHIRPS and ERA5 datasets have been widely validated in previous hydrological and climatological studies.

1.4 Statistical correlation analysis

Statistical analyses were conducted to evaluate climate–groundwater relationships at the city scale using spatially averaged raster datasets. ArcGIS Band Collection Statistics were used to calculate the annual mean values and correlation statistics across the Jaipur study area. Pearson correlation was used to determine the linear associations between climatic variables and groundwater level changes, while simple linear regression was employed to examine the relationship between Relative Humidity (RH) and Evapotranspiration (ET). The Coefficient of Variation (CV) was calculated to assess the variability of climatic variables.

1.4.1 Pearson correlation coefficient

The Pearson correlation coefficient (r) was used to assess linear relationships between annual values of groundwater level and climatic parameters. It is acknowledged that, in hard-rock aquifer systems, the groundwater response to precipitation is likely non-linear and lagged, owing to threshold-controlled recharge and subterranean storage limitations.

$$r = \frac{n\sum(X_i Y_i) - \sum X_i \sum Y_i}{\sqrt{\left[n\sum X_1^2 - \left(\sum X_i\right)^2\right]\left[n\sum Y_1^2 - \left(\sum Y_i\right)^2\right]}} \quad (1)$$

Where: X_i = Mean Relative Humidity (RH), Y_i = Mean Evapotranspiration (ET), n = number of paired observations. The statistical significance of correlation coefficients was evaluated using the corresponding t-statistic:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (2)$$

1.4.2 Linear regression analysis

A simple linear regression model was applied to assess the dependence of evapotranspiration on relative humidity:

$$ET = a + b \cdot RH \quad (3)$$

Where: a intercept, b is the regression slope, both estimated from the observed data.

1.4.3 Coefficient of Variation (CV)

The coefficient of variation (CV) was calculated to

Table 1 Details of climatic datasets used in this study

Data	Source	Resolution	Link/Citation
Precipitation	CHIRPS	0.05° (–5 km)	UCSB Climate Hazards Group (CHIRPS Daily), https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY
ET	ERA5	0.1° × 0.1° (– 9 km)	ECMWF ERA5-Land Daily Aggregated, https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_DAILY_AGGR
RH	ERA5	0.1° × 0.1° (– 9 km)	ECMWF ERA5-Land Daily Aggregated, https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_DAILY_AGGR

assess the relative temporal variability of climatic parameters:

$$CV = (\sigma/\mu) \times 100 \quad (4)$$

Where: σ is the standard deviation and μ is the mean of the dataset.

This statistical approach provides clear and interpretable diagnostics suitable for city-scale groundwater assessment, rather than predictive or non-linear modeling, which would require additional process-level and abstraction data beyond the scope of this study.

2 Results and discussion

2.1 Spatial and temporal distribution of groundwater

Spatial patterns of groundwater-depth variability in Jaipur were analyzed using interpolated surfaces of annual maximum and minimum depth-to-water-table observations for 2013–2023 (Figs. 4 and 5). The interpolated surfaces represent regional groundwater-depth variability rather than hydraulic head distributions or potentiometric surfaces. The results indicate a consistent expansion of groundwater depletion zones, particularly in the central and western parts of the district. These regions exhibit deeper groundwater levels, which can be attributed to high population density, rapid urbanization, and intensive agricultural water demand. Hydrogeological conditions further intensify groundwater stress in these regions as the fractured hard-rock aquifer system is characterized by low primary porosity, limited storage capacity, and restricted recharge potential, making it highly vulnerable to sustained groundwater abstraction. In contrast, the northern and northeastern regions show relatively moderate groundwater conditions, likely to reflect localized recharge and comparatively lower abstraction pressure. Jaipur is predominantly characterized by fractured hard-rock aquifers, which have low primary porosity, limited storage capacity, and highly heterogeneous fracture networks, thereby restricting recharge and increasing vulnerability to over-extraction. Groundwater recharge in these systems primarily occurs through localized infiltration during favorable rainfall conditions, while a significant portion of rainfall is lost as surface runoff and evapotranspiration. Groundwater discharge is dominated by anthropogenic abstraction, resulting in persistent groundwater decline under sustained extraction pressure. The relatively moderate groundwater conditions observed in peripheral regions may reflect localized recharge enhancement, lower abstraction intensity, and the presence of favorable hydrogeological settings in peri-urban zones. Field investigations in Jaipur reveal that historic reservoirs and local alluvial pockets improve aquifer conditions in peri-urban regions, and the rate of groundwater abstraction in urban regions is so high that it causes deeper depletion (Frommen et al., 2021). Overall, the analysis shows that there is a discrepancy between groundwater abstraction and recharge. Addressing the deteriorating groundwater situation and ensuring long-term water resource sustainability will require urgent action, including enhanced stakeholder awareness and adoption of integrated watershed-scale management approaches.

Localized maxima and minima in the interpolated groundwater-depth surfaces (Figs. 4 and 5) likely reflect interpolation uncertainty arising from the uneven distribution of monitoring wells, particularly in the sparsely monitored southern part of the district. Such isolated extrema are a recognized feature of geostatistical interpolation under limited sampling and were therefore interpreted cautiously within the broader regional hydrogeological context (Xiao et al., 2016). Accordingly, these maps should be interpreted as representations of regional groundwater-depth variability rather than precise local groundwater conditions.

For temporal analysis, a subset of 12 monitoring wells was selected based on data completeness and temporal consistency over the study period (2013–2023). Only those wells with available records were included in the interannual trend analysis. The selected wells are distributed across the study area and represent a range of groundwater conditions, encompassing both deep and shallow water table settings as well as urban and peri-urban environments. In the absence of high-frequency groundwater records, inter-annual variation was characterized using annual maximum and minimum groundwater level values as upper and lower bounds, respectively, forming an envelope that enables trend identification.

The hydrographs indicate that groundwater behavior is significantly spatially varied; several wells exhibit prolonged downward trends, especially in the urban and peri-urban areas, indicative of a sustained depletion process, while some wells reflect moderate fluctuations, suggesting some localized recharge or less depletion stress. Although considerable interannual variability exists for rainfall amount, groundwater response to this variability has been relatively slow; no sharp rises

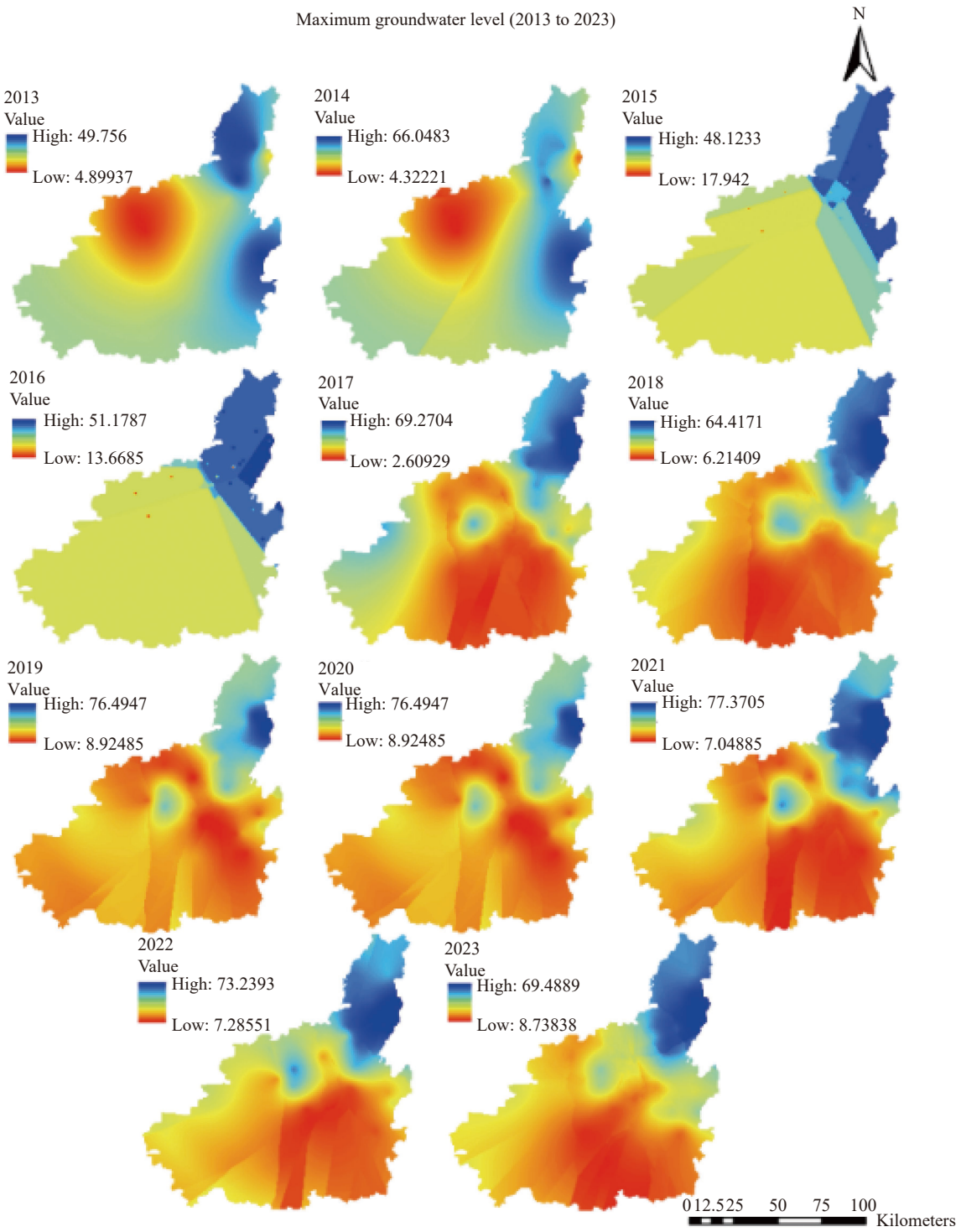


Fig. 4 Year-wise spatial distribution of annual maximum groundwater levels (2013–2023)

occurred even after a heavy rainfall season. In semi-arid hard rock regions, recharge is possible only if rainfall is sufficient to overwhelm infiltration losses and evapotranspiration, resulting in a characteristically non-linear and lagged groundwater response. Fractured hard rock aquifer systems respond slowly to external forcing because recharge is a site-specific event controlled by fissure connectivity and the groundwater storage capacity.

2.2 Climatic trends and variability

2.2.1 Precipitation

Fig. 7 shows the spatial distribution and interannual variability of annual rainfall across Jaipur during 2013–2023, with relatively higher rainfall in the northern and northeastern regions and lower rainfall in the southern and western parts. The

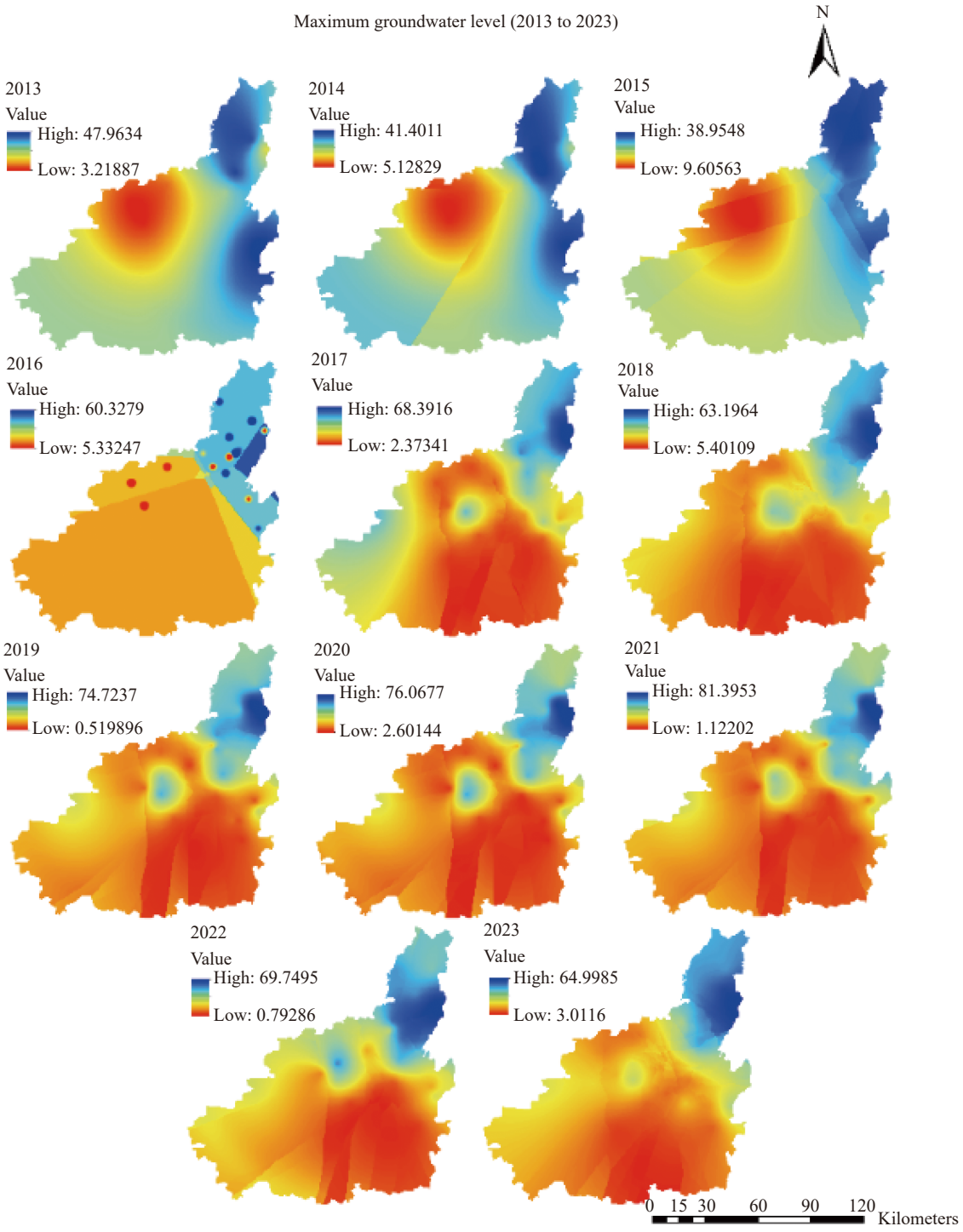


Fig. 5 Year-wise Spatial distribution of annual minimum groundwater levels (2013–2023)

highest annual rainfall values were recorded in 2013, 2016, and 2021, with peak values reaching approximately 974 mm, whereas years such as 2015 and 2017 exhibited significantly lower rainfall, indicating drought-like conditions. These variations are primarily influenced by monsoonal dynamics and regional topographic controls. In hard rock regions within the semi-arid climatic zone, recharge can only be expected if rainfall exceeds a certain value, which is required to sustain the process of infiltration beyond evapotranspiration and other losses, resulting in a nonlinear and delayed groundwater response further modulated by fracture connectivity and subsurface storage. Despite substantial interannual rainfall variability (Fig. 7), the absence of corresponding groundwater level recovery suggests that the fractured hard-rock aquifer system has a limited capac-

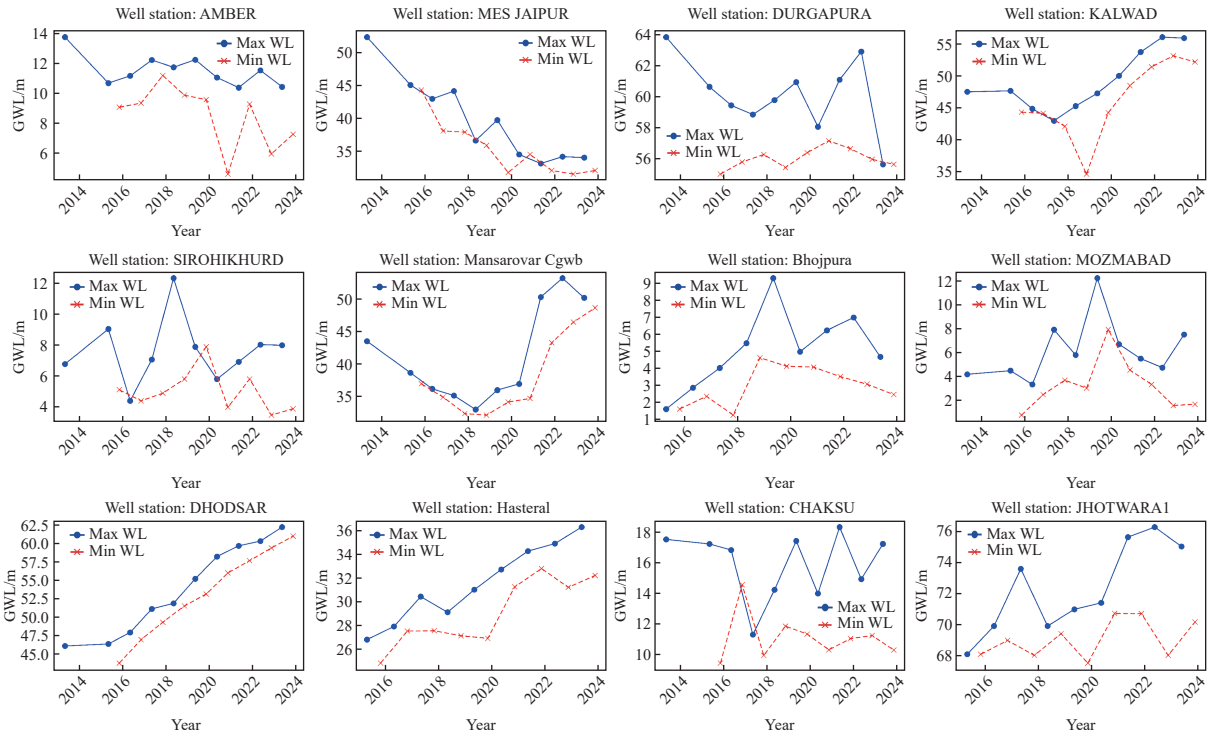


Fig. 6 Hydrographs (2013–2023) of maximum and minimum groundwater levels (GWL) for representative wells, illustrating temporal trends and spatial variability under hydroclimatic and anthropogenic influences

ity to convert rainfall into effective recharge, particularly under infrequent monsoonal events and high abstraction pressure (Yadav et al., 2022).

Event-based rainfall–groundwater response analysis

An event-based analysis of extreme precipitation indices derived from monthly rainfall was conducted to explore the influence of precipitation characteristics on groundwater response. R×1d (maximum 1-d rainfall) and R×5d (maximum 5-d accumulated rainfall) were correlated with mean annual minimum groundwater levels to test whether single-day intense events and/or sustained rainfall events affect groundwater recharge.

R×1d showed only a weak correlation with groundwater levels ($r=0.19$, $p > 0.05$) indicating that single intense rainfall events do not contribute significantly to effective groundwater recharge. R×5d showed a more pronounced but still non-significant correlation ($r=0.45$, $p > 0.05$), suggesting that recharge is more effective over a sustained period of rainfall. Such a response is consistent with established hydrological understanding that effective recharge depends not only on rainfall intensity but also on infiltration persistence and antecedent moisture conditions, which collectively influence subsurface water movement and storage (Cui et al., 2022).Year-to-year variability (Fig. 8) further shows that higher accumulation rainfall does not immediately translate into elevated groundwater levels, confirming that recharge processes in semi-arid regions are not instantaneous.

The correlation analysis (Fig. 9) indicates that recharge is not driven by precipitation intensity alone, but rather by accumulated precipitation exceeding hydrological thresholds. A minimum total precipitation must be reached before recharge is initiated, overcoming infiltration capacity and evaporation rates.

The weak correlations should not be interpreted as an absence of precipitation influence; rather, they reflect a time-lagging groundwater response potentially complex recharge mechanism. Recharge appears to occur over extended accumulation periods rather than in response to individual events. In the absence of high-frequency groundwater level measurements, extreme precipitation indices (R×1d, R×5d) were used as proxies, as they capture both intensity and persistency of rainfall events relevant to recharge. Recharge in fractured aquifer system can occur through multiple pathways, producing a time-delayed response that may not be apparent at the event timescale.

2.2.2 Evapotranspiration

Fig. 10 presents the annual Evapo-Transpiration (ET) maps, illustrating substantial spatial and temporal variability across Jaipur during 2013–2023. Areas of higher annual ET values (blue

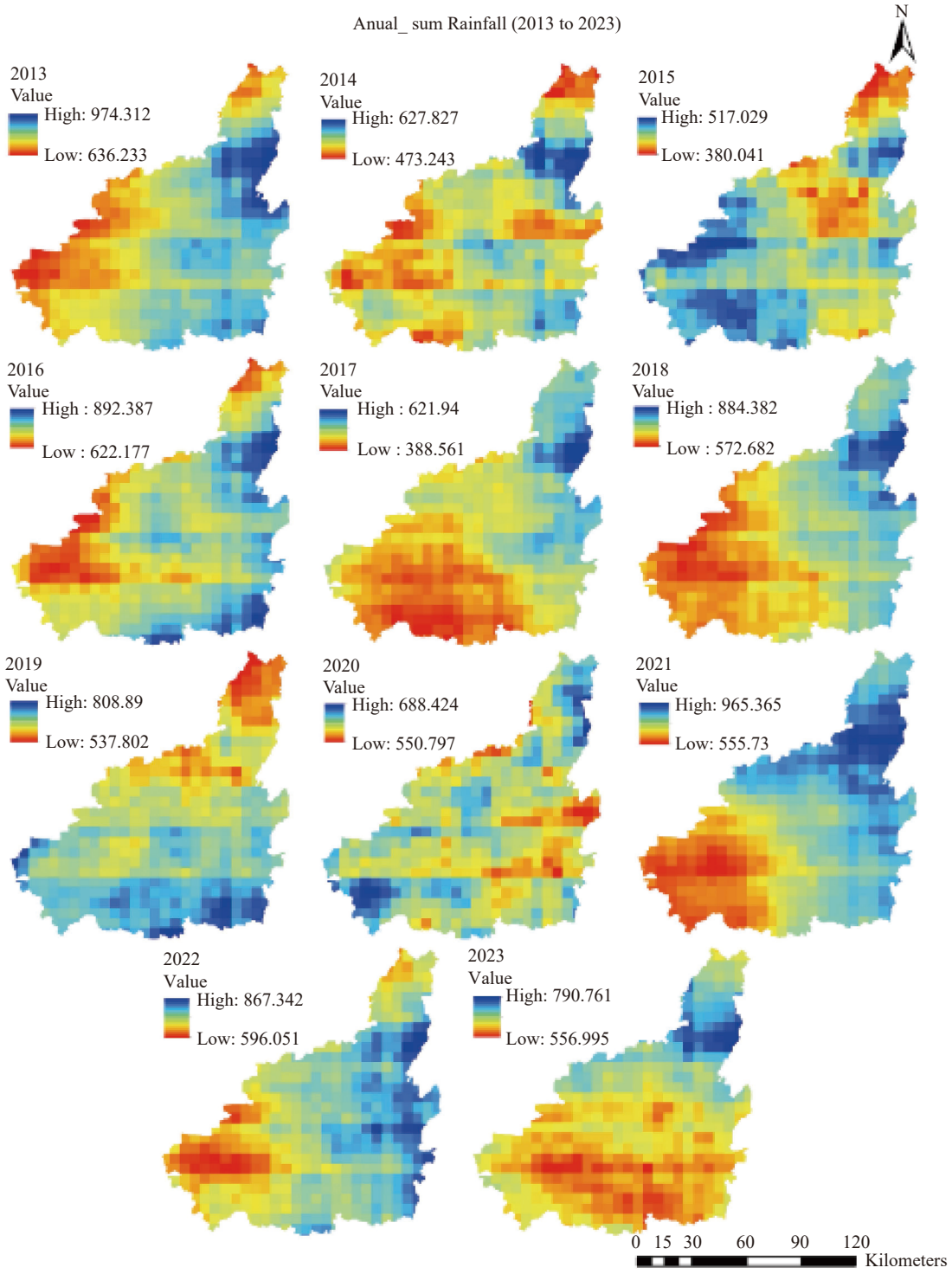


Fig. 7 Spatial distribution of annual mean rainfall in the study area (2013–2023)

regions) indicate relatively higher vegetation density or water availability, while areas of low ET (red regions) correspond to urbanized, arid, or sparsely vegetated areas with limited water availability. The spatial coverage of high and low ET areas varied over time, with 2020 and 2022 showing elevated ET values, possibly due to favorable climatic conditions and higher vegetation activity, and 2018 and 2023 showing more extensive low-ET areas, potentially attributable to reduced precipitation, augmented thermal stress, and intensified anthropogenic activity. These patterns are consistent with studies demonstrating that variability in evapotranspiration exerts a dominant influence on groundwater recharge processes in semi-arid regions (Turkeltaub and Bel, 2024; Hou et al., 2023). Increased evapotranspiration reduces effective recharge by diverting more water to the atmo-

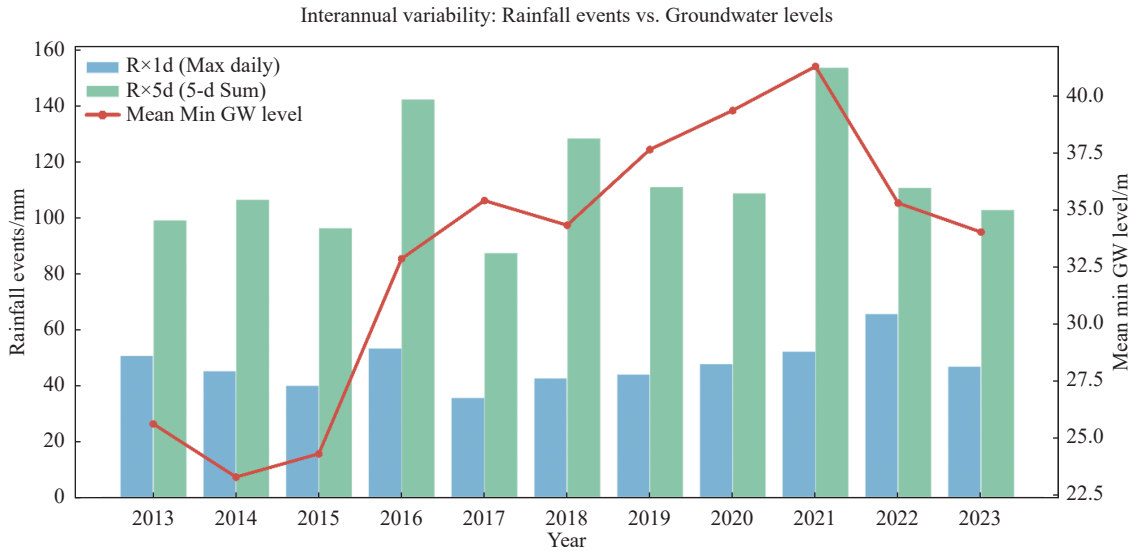


Fig. 8 Interannual variability of event-based rainfall indices (R×1d and R×5d) and corresponding mean groundwater levels (2013–2023)

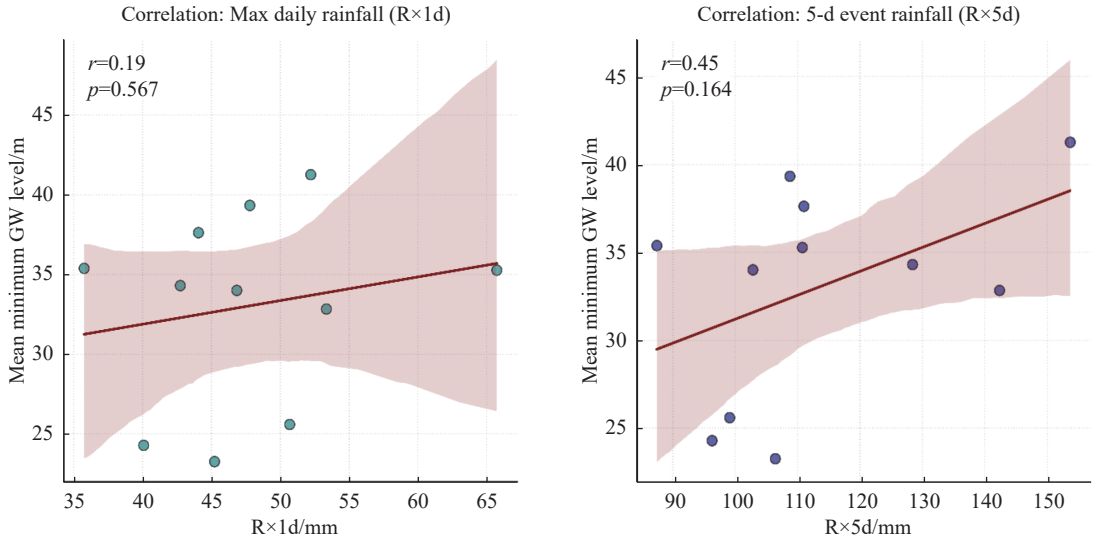


Fig. 9 Correlation between maximum 1-d rainfall (R×1d) and groundwater levels, and between 5-d cumulative rainfall (R×5d) and groundwater levels

sphere, thereby compounding groundwater stress alongside abstraction (Turkeltaub and Bel, 2024; Hou et al., 2023).

2.2.3 Relative humidity

The spatiotemporal variability of Relative Humidity (RH) from 2013 to 2023 is presented in Fig. 11. Blue colors indicate higher RH and red colors indicate lower RH. Generally, the spatial distribution of high-RH regions appears relatively consistent over the study period, possibly reflecting the influence of land use pattern, vegetation cover, and local climatic conditions on atmospheric moisture concentration. Conversely, regions with lower RH are drier and may be further affected by urbanization, reduced vegetation, and low precipitation. High interannual variability is observed, with some years showing increased high RH coverage, indicating wetter conditions, and others showing lower RH values, indicating drier conditions and higher atmospheric moisture demand. This is consistent with findings from arid and semi-arid regions, where relative humidity is strongly negatively correlated with evapotranspiration, reflecting its role in vapor pressure deficit and evaporative demand (El-Shirbeny et al., 2025; Sammen et al., 2023). Variations in relative humidity serves as a direct indicator of evapotranspiration rates and an indirect indicator of groundwater stress in the semi-arid urban environment of Jaipur (Eltarabily et al., 2023).

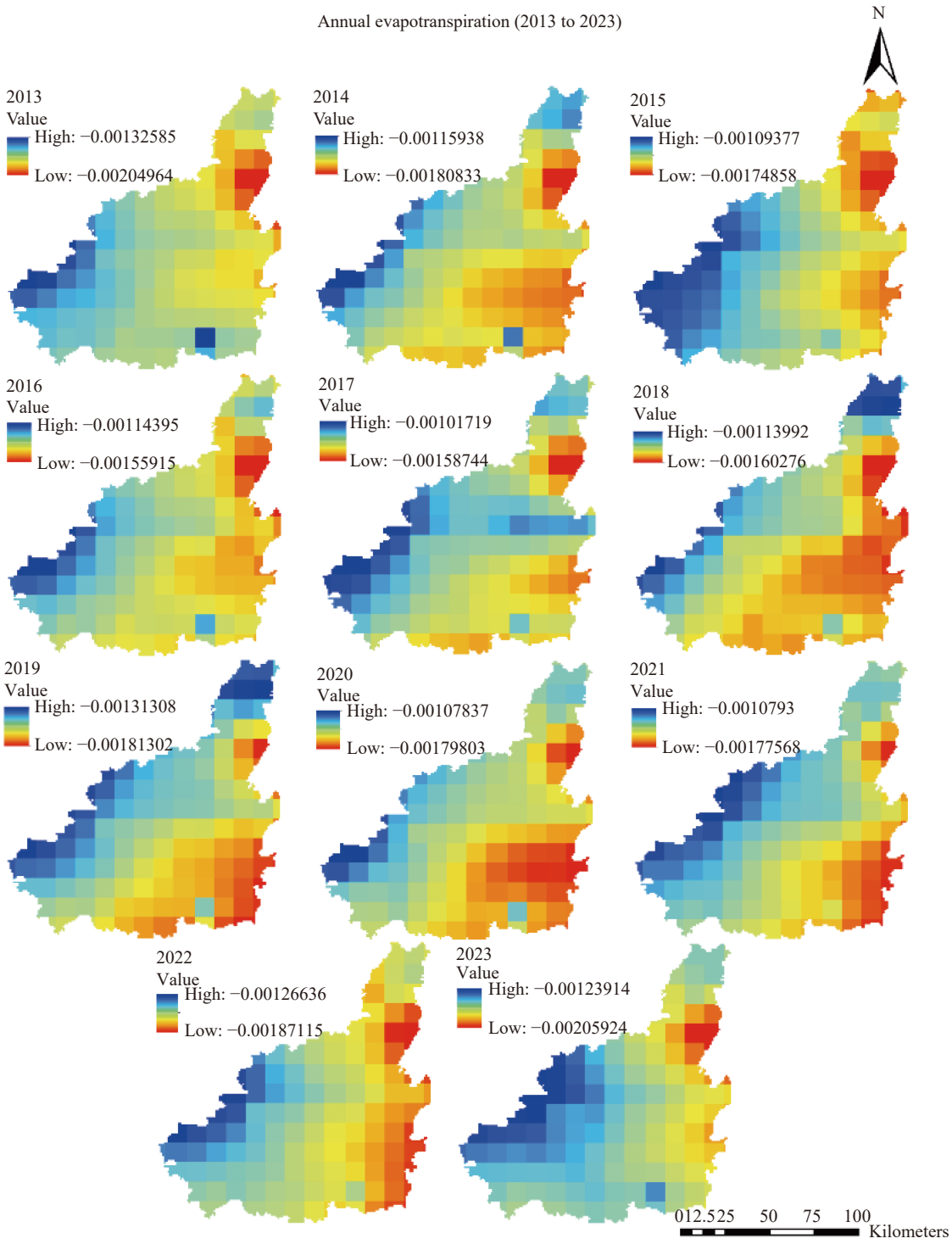


Fig. 10 Annual evapotranspiration in the study area (2013–2023)

2.3 Correlation analysis

Pearson correlation analysis was utilized to quantify the relationship between relative humidity and evapotranspiration in Jaipur, examining the role of atmospheric moisture conditions in regulating evapotranspiration dynamics under semi-arid conditions. Pearson, Spearman, and Kendall correlation coefficients between annual rainfall and groundwater levels were calculated to assess the strength of the climate-groundwater relationship under both linear and nonlinear assumptions (Fig. 12). The findings show weak to moderate correlations, with rank-based methods (Spearman and Kendall) yielding slightly higher coefficients than Pearson correlation. These findings indicate that the rainfall–groundwater relationship is characterized by nonlinear recharge behavior rather than

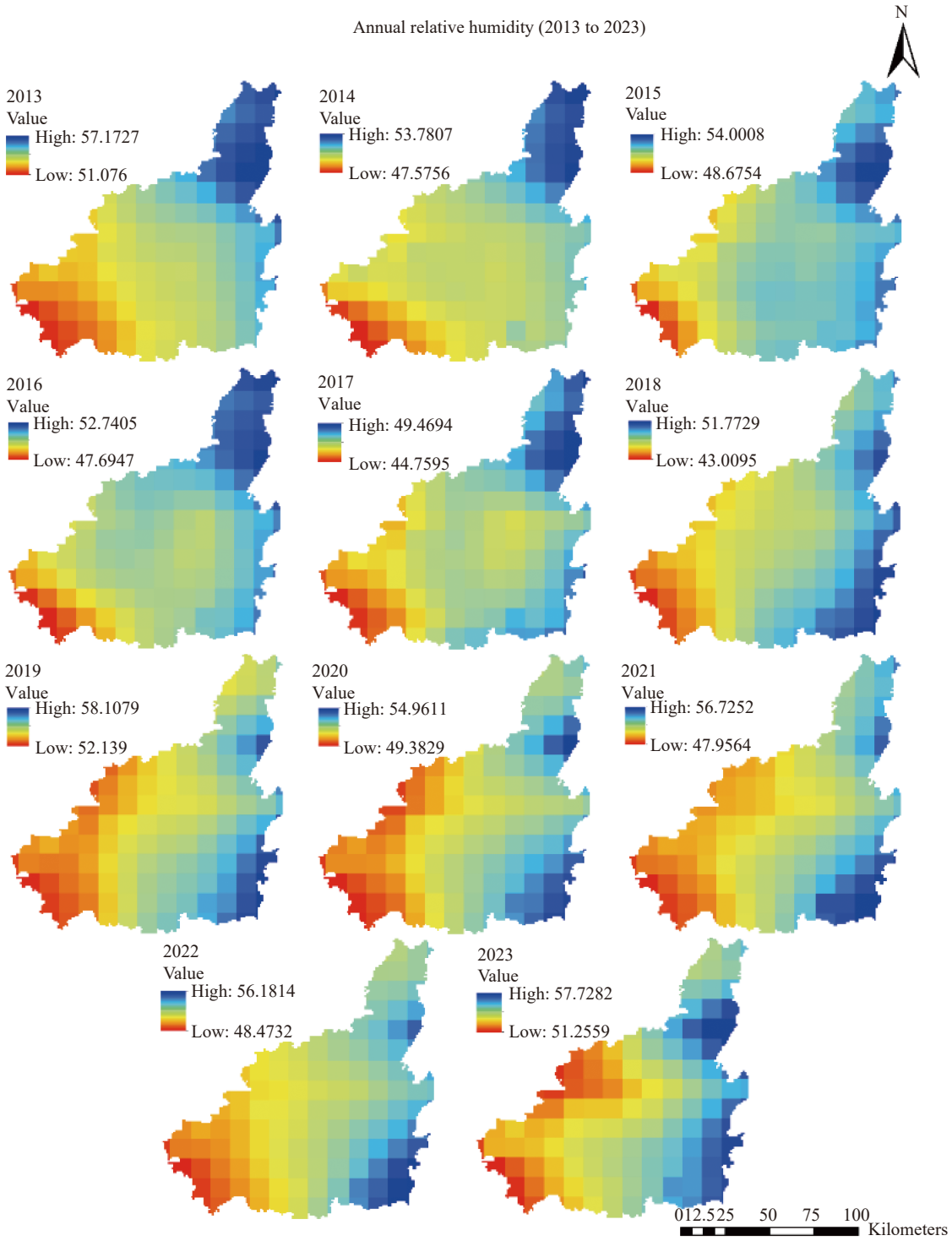


Fig. 11 Annual relative humidity in the study area (2013–2023)

simple linear interaction. The weak correlations may therefore reflect a delayed system response rather than the absence of a hydrological connection. Groundwater levels may respond to cumulative or antecedent rainfall over multiple seasons rather than to immediate annual precipitation, consistent with reported delayed groundwater responses in aquifer systems (Meng et al., 2023).

The differing correlations between annual maximum and minimum groundwater levels and rainfall variability provide valuable physical insight. Annual maximum groundwater levels show significantly lower correlations with rainfall, while annual minimum levels show relatively stronger, though still moderate, correlations. These patterns suggest that rainfall events may temporarily influence shallow or seasonal groundwater storage, although the response remains spatially heteroge-

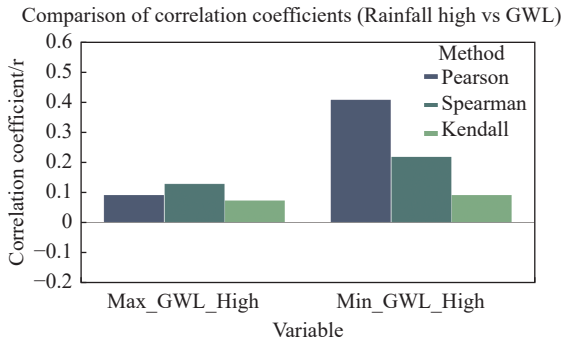


Fig. 12 Comparison of correlation coefficients between rainfall and groundwater levels using Pearson, Spearman, and Kendall methods

neous and temporally delayed. This behavior is typical of hard-rock aquifer systems, where recharge is intermittent, spatially heterogeneous, and rapidly lost through fractures and abstraction (Goswami and Sekhar, 2022). A lagged correlation analysis suggests improved association between rainfall and groundwater levels with a one-year delay, supporting the presence of delayed recharge processes.

The low correlation coefficient ($r < 0.5$) suggests that only a limited portion of inter-annual rainfall variability is directly reflected in groundwater-level changes at Jaipur. This does not imply that climate exerts no influence; rather, it indicates that recharge occurs through complex, non-linear and time-delayed processes. The results for annual mean relative humidity and evapotranspiration over 2013–2023 reveal a strong negative correlation ($r = -0.9272$, $p < 0.0001$). This strong negative relationship reflects the physical dominance of atmospheric moisture over evapotranspiration: Higher humidity reduces vapor pressure deficit and thereby suppresses evapotranspiration rates (Eftekhari and Khashei-Siuki, 2025; Goteti and Famiglietti, 2024).

Table 2 Annual mean values of relative humidity and evapotranspiration

Year	Mean_RH	Mean_ET
2013	54.0554	0.2917
2014	50.6243	0.9915
2015	51.7037	0.8814
2016	50.4135	0.9814
2017	47.1167	1.1913
2018	47.4670	1.1714
2019	54.6859	0.2516
2020	52.1585	0.7915
2021	51.8610	0.8314
2022	51.9684	0.8616
2023	54.4699	0.2316

The regression analysis of annual rainfall and groundwater-level changes (Fig. 13) demonstrates a weak positive correlation, indicating that groundwater levels do not rise proportionally with annual rainfall. The weak relationship between rainfall and groundwater variability suggests that groundwater dynamics in Jaipur are governed by additional hydrogeological and anthropogenic factors beyond climatic variability alone. The wide confidence intervals further demonstrate that rainfall variability alone cannot adequately explain groundwater-depth variations in the urban area.

This is further supported by the regression equation $ET=7.4436-0.1296\times RH$, indicating that a 1% increase in RH is associated with a decrease in ET of 0.1296 $mm\cdot a^{-1}$, with an R^2 of 0.8598, meaning RH accounts for 85.98% of the variance in ET. These findings are consistent with studies from semi-arid regions, where ET is primarily controlled by atmospheric humidity and temperature (Sandeep et al., 2021).

The Coefficient of Variation (CV) of RH was 4.90%, indicating relatively stable humidity over

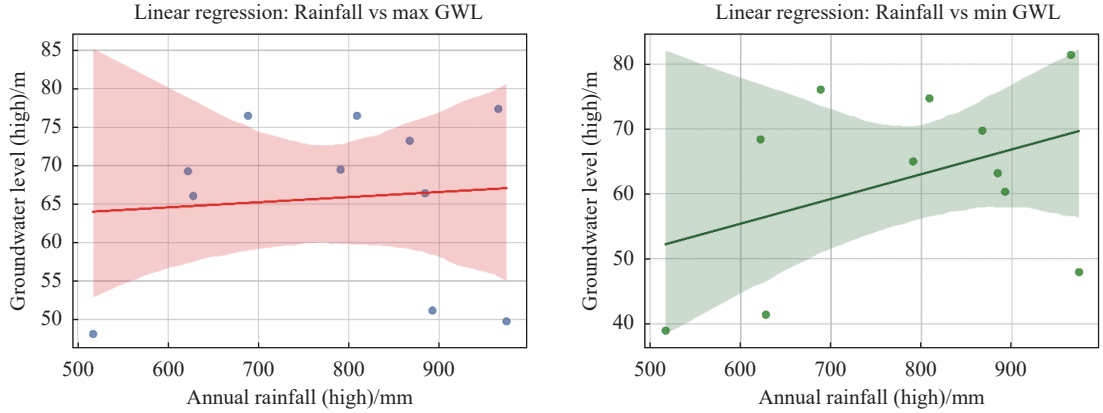


Fig. 13 Linear regression relationship between rainfall and groundwater level

the study period, whereas the CV of ET was considerably higher at 45.79%, reflecting the influence of seasonal variation, land-use change, and climatic variability in Jaipur. Similar seasonal patterns in ET have been reported previously in Rajasthan, where monsoon months suppress ET and arid summer months drive sharp increases (Saxena et al., 2024).

The observed ET values, ranging from 0.2316 mm·a^{-1} and 1.1913 mm·a^{-1}, are consistent with the climatic conditions of Jaipur, where evaporation rates peak during dry summers and are lowest during the monsoon due to elevated atmospheric moisture (Kumar et al., 2010). The decline in ET observed in 2018 may be attributable to land cover change, reduced groundwater availability, or variations in monsoonal rainfall intensity. These trends are consistent with the broader literature showing that urbanization and declining groundwater levels can alter evapotranspiration dynamics in semi-arid regions. The correlation analysis presented here identify statistical associations rather than causal relationships; any hypothesis regarding the controlling factors of the groundwater dynamics must therefore be interpreted within the broader hydrogeological and anthropogenic context of the study area.

Direct spatial data on groundwater extraction intensity were not available for the study area. The potential influence of anthropogenic abstraction was therefore evaluated indirectly, using spatial groundwater depletion patterns in conjunction with land-use characteristics and urban expansion trends, supported by the existing literature. Persistent groundwater depletion over large parts of the area, particularly in central and western Jaipur, broadly, corresponds to areas of high population density, suggesting that elevated demand and groundwater extraction are major contributing factors. Although this approach does not provide quantitative estimates of groundwater extraction, the spatial agreement between depletion patterns and urban pressure provides indirect evidence of anthropogenic influence on groundwater variability.

While the analysis indicates weak correlations between climatic variables and groundwater levels, the interpretation of anthropogenic influence is based on indirect evidence derived from spatial depletion patterns and regional land-use characteristics. Due to the absence of direct groundwater abstraction or pumping data, the relative contributions of anthropogenic and climatic drivers cannot be quantitatively separated, and the conclusions should be interpreted within this limitation.

3 Conclusions

This study provides a city-scale evaluation of groundwater dynamics and climatic variability in Jaipur during 2013 to 2023. The findings indicate that the central and western sections of the city have experienced pronounced groundwater depletion, driven by rapid urbanization, high population density, and agricultural activities, all of which have resulted in abstraction rates exceeding natural replenishment.

Groundwater conditions in the northern and northeastern regions appear relatively stable, suggesting localized recharge benefits and comparatively lower anthropogenic pressure. Interannual and spatial rainfall variability during the study period was substantial; however, the pattern of groundwater response to rainfall variations was subdued, suggesting low recharge efficiency under prevailing hydrological and anthropogenic conditions. This mismatch is attributable to the threshold-dependent nonlinear recharge behavior of semi-arid hard-rock aquifer systems, in which cumulative rainfall must exceed infiltration and evapotranspiration losses before effective recharge occurs, a process that does not produce an immediate groundwater response.

The correlation analysis revealed a strong negative relationship between relative humidity and evapotranspiration, confirming that atmospheric moisture conditions are a significant control on evapotranspiration processes in Jaipur's semi-arid climate. The relationship highlights the sensitivity of atmospheric water loss to humidity fluctuations in urban, water-limited environments. The event-based analysis using extreme rainfall indices suggested that short-duration extreme rainfall events contribute little to groundwater recharge, whereas multi-day accumulated events show a somewhat stronger, though still limited, influence, highlighting the importance of rainfall persistency over intensity.

The observed evapotranspiration patterns reflect the semi-arid climate of Jaipur, characterized by high atmospheric demand during dry summers and suppressed ET during the monsoon. Long-term changes in ET likely reflect the combined effects of land cover change, declining groundwater availability, and shifting monsoonal patterns.

Overall, groundwater dynamics in Jaipur are influenced by the interplay of climatic variability, hydrological constraints, and anthropogenic pressures, with observed spatial patterns suggesting a particularly strong association with groundwater extraction. While the findings suggest that anthro-

pogenic abstraction is a dominant driver, the absence of direct extraction or water-use data means this interpretation rests on inference spatial and hydroclimatic evidence rather than explicit quantification. Consequently, the relative contributions of climatic variability and anthropogenic pumping cannot be quantitatively partitioned within the scope of this study. The findings highlight the need to integrate hydrogeological constraints, climatic variability, and urban water demand into groundwater management strategies. Future research should incorporate groundwater abstraction data, recharge potential mapping, and advanced modeling approaches to improve the robustness of groundwater management in rapidly urbanizing semi-arid regions.

4 Limitations

This study has several limitations that should be considered when interpreting the findings. Groundwater dynamics were assessed using depth-to-water-level measurements rather than elevation-corrected hydraulic head data, limiting the ability to analyze groundwater flow gradients and directions. The study was conducted at an annual temporal scale, which may not adequately capture seasonal or event-scale recharge dynamics typical of fractured hard-rock aquifers. The absence of high temporal resolution (daily) rainfall and groundwater level data restricts the ability to explicitly quantify short-term recharge processes and event-based system responses. Detailed aquifer-screen information and well-depth metadata were not consistently available for all monitoring wells; the analysis therefore focuses on regional groundwater-depth variability rather than aquifer-specific hydraulic responses. Potential variations in screened aquifer horizons among monitoring wells could not be explicitly evaluated.

Direct spatial data on groundwater abstraction were not available, and anthropogenic influences were inferred indirectly from groundwater trends, land-use patterns, and supporting regional studies rather than from quantified well-level pumping data. The statistical analysis primarily relied on linear and rank-based correlation methods, which may not fully capture the non-linear and time-lagged relationships between climatic variables and groundwater response. Additionally, spatial interpolation using kriging may introduce localized uncertainties, particularly in areas with sparse monitoring well distribution, potentially resulting in interpolation artifacts that should be interpreted with caution. Despite these limitations, the study provides a regional-scale assessment of groundwater variability and its interaction with climatic factors, offering useful insights for groundwater management in semi-arid urban environments.

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