Spatio-Temporal Assessment (2016-2025) of Groundwater Level and Wheat Productivity in Hardoi District, Uttar Pradesh: A Geographical Analysis Based on GIS Techniques

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***Abstract*—Groundwater is the principal source of irrigation for wheat crop growing across the Indo-Gangetic Plain and its level is shaped by the balance between monsoon recharge and Rabi-season abstraction. This study examines the spatio-temporal groundwater level dynamic range in Hardoi District, Uttar Pradesh between 2016-2025 and their relationship with wheat productivity, using a Geographic Information System (GIS) framework built on secondary data. Central Ground Water Board (CGWB) well records for both pre- and post-monsoon seasons, GRACE/GRACE-FO Terrestrial Water Storage Anomaly (TWSA) data, Landsat 8/9 imagery for three Rabi seasons processed to NDVI, and Directorate of Economics and Statistics (DES) wheat yield records. District-mean pre-monsoon groundwater level fluctuated between 4.81 and 6.89 mbgl across the decade without a statistically meaningful linear trend ($R^2 = 0.05$), while GRACE-derived regional water storage showed a moderate improving trend ($R^2 = 0.60$) and wheat yield rose from 3.64 to 3.91 t/ha over the years ($R^2 = 0.57$). District mean NDVI likewise rose across the three dates examined, from 0.587 in 2016 to 0.664 in 2020 and 0.672 in 2025. District-level correlation between groundwater level and wheat yield was close to zero (r = -0.10) and between GRACE and yield was weakly positive (r = +0.30). The principal finding of concern is a severe, corroborated localised decline at Mallawan block, where well readings deepened from 12 mbgl to over 21 mbgl across pre- and post-monsoon survey. These findings point toward spatially targeted monitoring at identified hotspots such as Mallawan block rather than a uniform district-wide groundwater decline.**

***Index Terms*—Groundwater Level, Wheat Productivity, GIS, Remote Sensing, NDVI, GRACE, CGWB, Hardoi District, Indo-Gangetic Plain.**

I. INTRODUCTION

Groundwater underwrites food security across South Asia, working as the buffer that allows farmers to keep cultivating through months when rainfall is absent. Rodell et al. (2009) were among the first to use satellite gravimetry to demonstrate how heavily northern India draws on this buffer and Famiglietti (2014) later described the resulting strain as a crisis extending well beyond any single river basin. The Indo-Gangetic Plain, home to some of the densest agricultural populations on Earth to be placed at the centre of this concern. Its rice-wheat systems depend on near-continuous pumping during the dry season and decades of agricultural intensification have changed the balance between recharge and abstraction across much of the region.

India's own experience reflects this global pattern closely. Asoka et al. (2017) showed that pumping rather than rainfall variability alone drives most of the groundwater level change recorded across the country's grain belt, a conclusion repeated by CGWB (2022) assessments that identify large zones of Uttar Pradesh as gradually water-stressed. Wheat, sown at the start of winter and irrigated repeatedly through tillering, flowering, and grain filling is particularly exposed to any disruption in water supply. Where canal networks remain untrustworthy, farmers turn to private tube wells for self-assurance and this shift has steadily increased dependence on groundwater storage that recharges only once each year. Uttar Pradesh contributes a significant share of India's total wheat

production and much of its productivity growth over recent decades rests on expanding tube-well irrigation. Canal supply remains seasonal and often unpredictable which pushes a growing portion of the irrigation burden onto groundwater storage even during years of near-normal rainfall. Hardoi District, situated within the Middle Gangetic Alluvial Plain of central Uttar Pradesh, shows this with particular clarity. Its fertile alluvial soils and mixed canal-tube well system have long supported dense rice-wheat cultivation and reports from within the district describe uneven groundwater conditions with some areas under considerably more pressure than others. Rainfall irregularity adds a further layer of complexity.

1.1 Objectives

- To analyse spatio-temporal trends in groundwater level in Hardoi District during 2016-2025
- To assess wheat productivity using NDVI and district-level agricultural statistics.
- To examine the relationship between groundwater level and wheat productivity using GIS-based correlation analysis.

II. REVIEW OF LITERATURE

Global-scale assessment of groundwater change became possible with the launch of the GRACE satellite mission and Rodell et al. (2009) provided one of the first quantitative demonstrations that northern India, spanning Punjab, Haryana, Rajasthan, and western Uttar Pradesh were losing groundwater at a rate that could not be explained by rainfall variability alone. Tiwari et al. (2009) reached a similar conclusion using an independent gravity-field analysis over the same region and both studies were widely read as establishing that Indo-Gangetic groundwater decline was a structural, pumping-driven process rather than a short-term climatic anomaly. Famiglietti. (2014) later placed these regional findings within a global context describing groundwater depletion as an emerging crisis affecting most of the world's major irrigated agricultural basins and Gleeson et al. (2012) formalised this with the groundwater footprint concept showing that global groundwater withdrawal already exceeded sustainable recharge in a small number of heavily irrigated aquifer systems of which the Indo-Gangetic Plain is one of the largest.

A parallel strand of work has examined why groundwater is being depleted rather than simply documenting that it is. Wada et al. (2012) quantified the share of global irrigation sustained by non-renewable groundwater abstraction and Bierkens and Wada. (2019) reviewed the drivers of unsustainable use, pointing to cheap or unmetered electricity for pumping, water-intensive cropping choices, and weak local regulation as recurring factors across affected regions. Within India specifically, Asoka et al. (2017) directly tested the relative contribution of monsoon rainfall variability against irrigation pumping in explaining groundwater storage change and found that pumping was the dominant factor in most of the country's agriculturally intensive districts, a finding with direct bearing on how groundwater trends in a wheat-growing district such as Hardoi should be interpreted. Siebert et al. (2010) provided the underlying global inventory of groundwater-irrigated area that much of this literature draws on confirming that South Asia accounts for a disproportionate share of the world's groundwater-dependent irrigation.

Official Indian assessments corroborate this picture at a coarser administrative scale. CGWB's periodic Dynamic Ground Water Resource Assessments and Ground Water Year Books classify blocks and districts by the ratio of extraction to recharge and recent rounds have consistently placed Punjab, Haryana, and western Uttar Pradesh among the country's most over-exploited areas, while central and eastern Uttar Pradesh including districts such as Hardoi, have generally been classified as safe or semi-critical rather than over-exploited. This administrative classification suggests that the well-documented depletion narrative from the north-western Indo-Gangetic Plain may not transfer uniformly to central Uttar Pradesh.

A smaller body of work has applied GIS and remote sensing methods at finer spatial scale to link groundwater conditions with agricultural outcomes. Jha et al. (2010) demonstrated how remote sensing, GIS, and multi-criteria decision analysis could be combined to assess groundwater potential at the block level in West Bengal, illustrating the kind of sub-district analysis that district-averaged studies cannot provide. Kumar et al. (2005) reviewed India's water resources more broadly situating groundwater within the wider context of surface water availability and interstate allocation. Relatively few studies however, combine authenticated well-level groundwater

records, satellite-derived water storage anomalies, remote-sensing vegetation indices and official crop statistics within a single district-level GIS framework and fewer still test rather than assume a productivity relationship before reporting one. This is the specific gap the present study addresses for Hardoi District.

III. STUDY AREA

Hardoi District occupies a central position within Uttar Pradesh's Middle Gangetic Alluvial Plain, extending approximately between 26°53'N to 27°46'N latitude and 79°41'E to 80°46'E longitude, covering roughly 5986 square kilometres, the district lies within a transition zone where both canal irrigation and groundwater extraction shape agricultural life. Shahjahanpur borders it to the north-west, Sitapur to the north-east with Kheri also meeting the district along a short stretch of its northern boundary between the two. Lucknow and Unnao lie to the east, Kannauj and Kanpur to the south and Farrukhabad to the west. This central position gives Hardoi strong hydrological and economic connectivity with the surrounding agricultural belt.

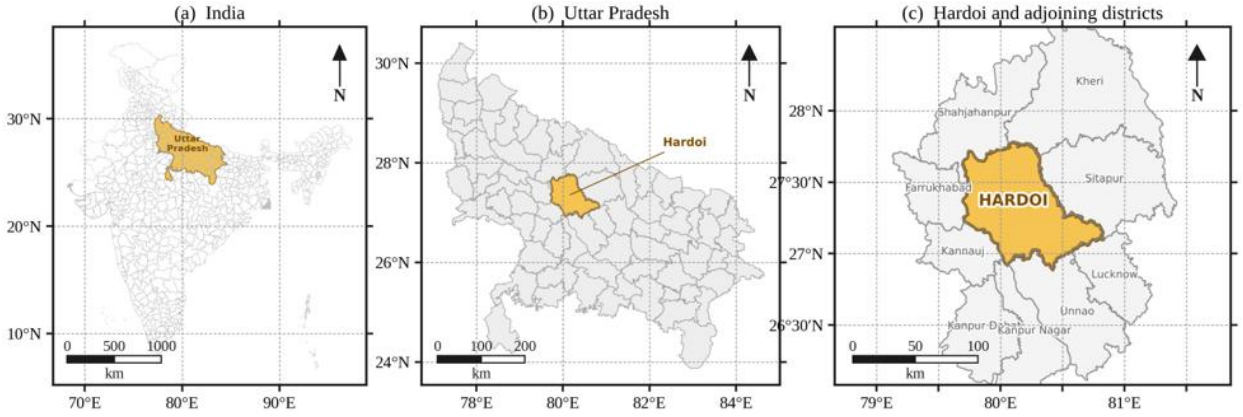

Figure 1 - Location of Hardoi District (26°53'N-27°46'N, 79°41'E-80°46'E) within Uttar Pradesh and India. Left: India, with Uttar Pradesh highlighted. Centre: Uttar Pradesh, with Hardoi District highlighted. Right: Hardoi District and its neighbouring districts.
Source: Census of India 2011 district boundary shapefile

Physio graphically, the district is built on Quaternary alluvial deposits comprising sand, silt, clay, and kankar layers, forming an unconfined to semi-confined aquifer system that responds readily to both recharge and withdrawal. These sediments have produced fertile alluvial soils generally sandy loam to clay loam in texture, well suited to intensive cultivation but dependent on regular irrigation to offset seasonal moisture deficits. Drainage is provided by minor tributaries of the Ganga river system together with seasonal streams that carry limited flow outside the monsoon months. Climatically, Hardoi experiences a sub-humid to semi-arid monsoon regime. Published climate normals put annual rainfall between roughly 850 mm and 1,050 mm, concentrated tremendously in the June-September monsoon window, while summer maximum temperatures frequently exceed 40°C and winter minimums fall to around 5-7°C. This seasonal concentration of rainfall means that groundwater recharge occurs within a narrow annual period, leaving the aquifer system reliant on that single window to offset a full year of extraction. Agriculture controls the district's economy, organised around a rice-wheat cropping system in which wheat serves as the principal Rabi crop alongside pulses, oilseeds and sugarcane. Irrigation combines canal networks with groundwater extraction though canal reliability varies across seasons and has pushed cultivators toward growing dependence on private tube wells and pumping sets. This combination of a narrow recharge window and extensive Rabi-season irrigation demand forms the hydro-agricultural backdrop against which the present analysis is conducted

IV. RESEARCH METHODOLOGY

This study follows a mixed method approach, integrating data collected from government agencies and satellite programmes with a common GIS

environment. Groundwater level records for the pre-monsoon and post-monsoon seasons were obtained from the Central Ground Water Board and used to establish annual fluctuation and multi-year level patterns at the district scale. Regional water storage change was assessed through GRACE and GRACE-FO Terrestrial Water Storage Anomaly products (CSR RL06.3 mascon solutions), providing an independent satellite-based cross-check on the well-based observations. Landsat 8/9 OLI imagery for three Rabi seasons (4 March 2016, 12 February 2020, and 1 February 2025) was processed to compute NDVI. Wheat area, production and yield statistics were obtained from the Directorate of Economics and Statistics, Government of Uttar Pradesh and the administrative boundary was sourced from the Census of India 2011 district shapefile.

Table 1 - Data Sources Used in the Study

Data Type	Source	Period	Purpose
Groundwater Level (pre/post monsoon)	CGWB	2016-2025	Groundwater level trend analysis
GRACE/GRACE-FO TWSA	CSR RL06.3 Mascon	2016-2025	Regional water storage assessment
Landsat 8/9 OLI (SR bands 4, 5; QA_PIXEL)	USGS Earth Explorer	2016, 2020, 2025	NDVI computation
Wheat Area, Production & Yield	DES, Government of Uttar Pradesh	2016-17 to 2022-23	Wheat productivity assessment
Administrative Boundary	Census of India 2011 (2011_Dist)	2011	Base map and GIS analysis

Source: compiled by author from CGWB, NASA/CSR (GRACE-FO), USGS Earth Explorer (Landsat), DES Government of Uttar Pradesh, and Census of India 2011, as detailed in the text above.

Groundwater depth observations from CGWB monitoring wells were spatially interpolated using Inverse Distance Weighting (IDW) over district boundary to generate pre-monsoon surfaces for 2016 and 2025, computed in Python (geopandas, scipy) after screening well records for missing or inconsistent readings. Statistical evaluation relied on linear regression to detect temporal trends in groundwater level, GRACE TWSA and wheat yield (reporting R^2) together with Pearson correlation coefficients (r) to examine relationships between these series at the 95 percent confidence level ($p < 0.05$). All spatial layers were projected to WGS 84 (EPSG:4326) for the district boundary and to UTM Zone 44N (EPSG:32644) for raster processing, ensuring consistent registration across datasets from different sources. Remote sensing inputs were processed as follows: GRACE and GRACE-FO mascon data were averaged monthly across the district polygon to derive an annual mean Terrestrial Water Storage Anomaly for each year (Table 3). NDVI was computed from Landsat 8/9 OLI Collection 2 Level-2 surface reflectance for three Rabi-season dates (4 March 2016, 12 February 2020 and 1 February 2025) using NDVI = (NIR - Red)/(NIR + Red) with USGS scale and offset factors, QA_PIXEL cloud masking and classification into Low, Moderate and High vigour bands. Land use/land cover (LULC) was classified for the same three dates using unsupervised k-means clustering (k = 6) on Landsat reflectance bands and derived spectral indices with clusters labelled post-hoc by spectral signature. I used Python based (Anthropic, Geopandas, Scipy, Rasterio, Matplotlib) to help process the satellite and groundwater datasets used in this study including NDVI computation, unsupervised LULC classification, spatial interpolation and statistical correlation analysis.

V. RESULTS AND DISCUSSION

5.1 Spatio-Temporal Groundwater Level Trends (2016-2025)

Groundwater remains the principal source of Rabi crop season irrigation in Hardoi District. CGWB well-level pre-monsoon (May) records drawn from 8 to 23 monitoring wells per year depending on the season show a district mean level that changed between 4.81 mbgl (2021) and 6.89 mbgl (2025) across the decade without settling into a steady and monotonic trend. Depth stood at 6.25 mbgl in 2016, eased to a low of 4.81 mbgl in 2021 and then rose across four consecutive years to reach 6.89 mbgl by 2025. Linear regression across the available series (2016-2025, excluding 2020, for which no validated CGWB reading was obtained) yields $R^2 = 0.05$, meaning a simple straight-line trend explains almost none of the year-to-year variation at district scale. Based on broader Indo-Gangetic literature a steady multi-year decline might have been expected for a groundwater-

dependent district such as Hardoi, the well-level record instead shows a district average that has moved within a comparatively narrow band. A second pattern, visible only at the level of individual wells rather than the district mean tells a more concerning story. The deepest single-well reading in the district rose sharply across the decade from 11.8 mbgl in 2016 to 21.6 mbgl in 2025, almost doubling even as the district-wide average moved only modestly. Mallawan block records the most extreme readings in both earliest and most recent years for which data exist, indicating a chronic, localised zone of decline rather than a uniformly worsening district. These two patterns describe a district where groundwater conditions have diverged spatially, a small number of severely stressed hotspots deepening considerably surrounded by a much larger area where average conditions have remained comparatively stable.

Post-monsoon (November) records, available for 2016-2023, add an important cross-check to the pre-monsoon picture. Seasonal recharge, calculated as the pre-monsoon mean minus the post-monsoon mean for each year with both readings, ranged barely between 0.70 m (2017) and 1.94 m (2018) with no meaningful trend across the seven years for which both seasons are available (R^2 = 0.02). This weak-trend finding for recharge shows the weak-trend finding for pre-monsoon depth itself, strengthening the reading that Hardoi's groundwater system at district-average scale, has not go through a consistent multi-year weakening of monsoon recharge.

Table 2 - District-Level Pre- and Post-monsoon Groundwater Depth Summary, Hardoi District (2016-2025)

Year	Pre-monsoon n	Pre-monsoon Mean (mbgl)	Post-monsoon n	Post-monsoon Mean (mbgl)	Seasonal Recharge (m)
2016	8	6.25	25	4.80	1.45
2017	18	5.83	23	5.13	0.70
2018	18	6.00	24	4.06	1.94
2019	17	5.59	15	4.01	1.58
2020	NA	NA	20	3.88	-
2021	18	4.81	16	3.46	1.35
2022	23	5.53	22	4.46	1.07
2023	23	5.85	21	4.60	1.25
2024	20	6.25	NA	NA	-
2025	18	6.89	NA	NA	-

Source: CGWB pre-monsoon (May) and post-monsoon (November) well-level records, Hardoi District. Pre-monsoon covers 2016-2019 and 2021-2025 (2020 unavailable); post-monsoon covers 2016-2023 (2024-2025 not available in November form; August/monsoon-season readings exist for 2024-2025 separately and are discussed in the text below). Recharge = pre-monsoon mean minus post-monsoon mean.

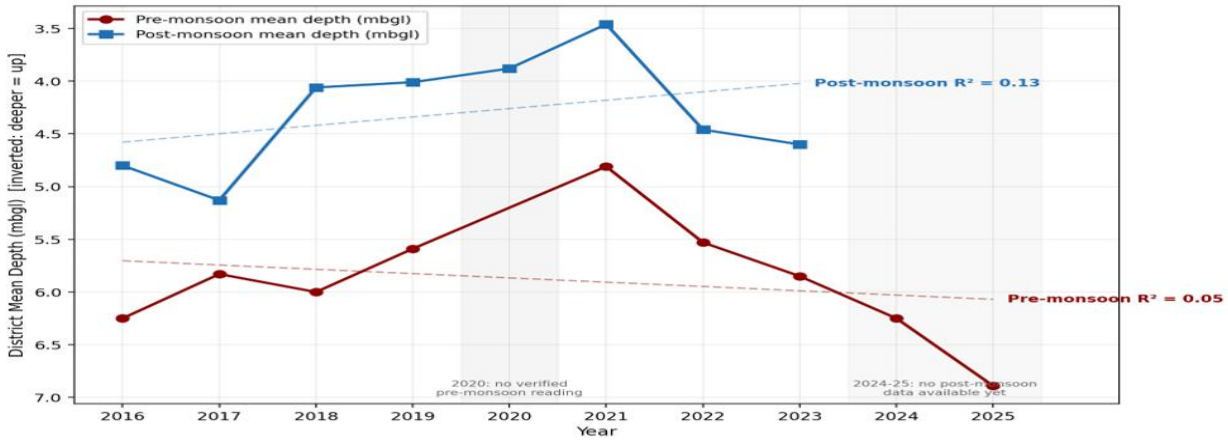

Figure 2 - District-mean pre-monsoon and post-monsoon groundwater level, Hardoi District with data gaps shown for 2020 (pre-monsoon) and 2024-2025 (post-monsoon). Y-axis inverted (deeper = upward). Linear regression trend lines are shown for reference (Pre-monsoon R^2 = 0.05; Post-monsoon R^2 = 0.13)

Source: CGWB pre-monsoon and post-monsoon well-level records

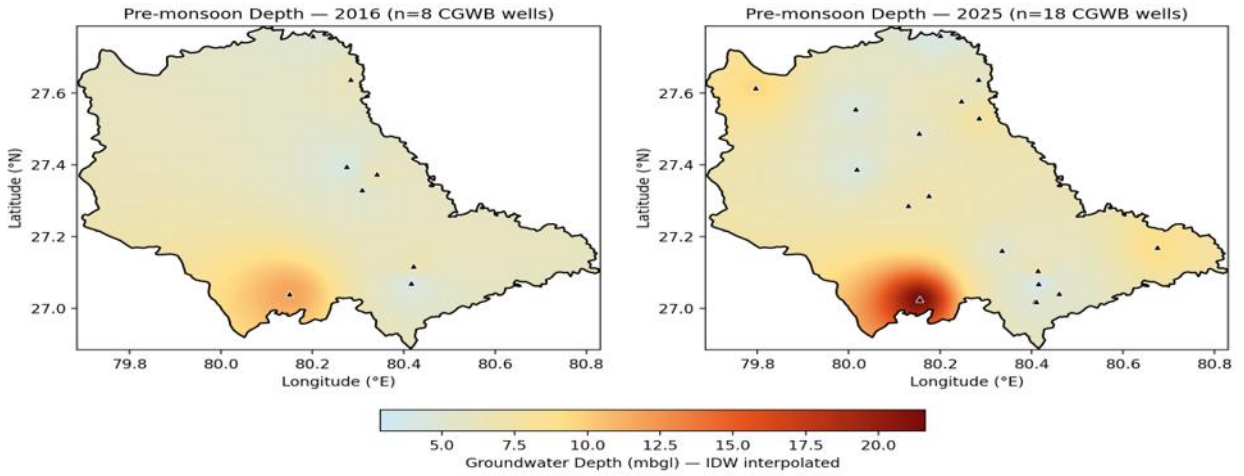

Figure 3 - IDW-interpolated pre-monsoon groundwater depth in Hardoi District for 2016 (n = 8 wells) and 2025 (n = 18 wells), Coordinate system: WGS 84 (EPSG:4326). The concentrated dark-red zone near the district's southern boundary (Mallawan block) is visible in both years and intensifies by 2025
Source: CGWB groundwater level observations (pre-monsoon) for Hardoi District

The post-monsoon data also confirms the Mallawan hotspot identified from pre-monsoon readings. Mallawan block records post-monsoon depths of 12.2 mbgl in 2018 rising to 14.8 mbgl in 2022 and 15.1 mbgl in 2023, a trajectory that closely parallels the pre-monsoon deepening at the same location. Because these findings come from separately conducted CGWB survey rounds, their agreement is meaningful corroborating proof that Mallawan is a genuine, persistent zone of decline rather than an artefact of a single survey round. August (monsoon-season) readings for 2024 and 2025, a third seasonal round distinct from both pre- and post-monsoon timing, show district means of 3.76 mbgl (n = 16) and 3.64 mbgl (n = 20) respectively, these are noted here as available context for those two years rather than merged into the pre/post-monsoon structure of Table 2, since monsoon-season and post-monsoon readings are not directly comparable.

The interpolated surfaces in Figure 3 support this reading spatially. The 2016 panel though based on a sparse eight-well sample, already shows a pronounced deep-groundwater patch in the district's south coincident with Mallawan block. By 2025, this same patch deepens significantly, consistent with the single-well maximum rising from 11.8 to 21.6 mbgl, while much of the remaining district area shows comparatively modest change between the two panels. This spatial pattern, corroborated across two independent seasonal datasets, characterises Hardoi's groundwater challenge as a deepening localised zone of decline within an otherwise comparatively stable landscape with direct implications for how monitoring and management should be targeted.

5.2 GRACE/GRACE-FO Terrestrial Water Storage Anomaly (2016-2025)

Well-based observations describe local aquifer behaviour, while GRACE/GRACE-FO data provide a regional cross-check on total terrestrial water storage, covering groundwater alongside soil moisture and shallow subsurface water. CSR RL06.3 mascon data for the Hardoi polygon show an annual mean Terrestrial Water Storage Anomaly (TWSA) that was most negative in 2018 (-31.76 cm equivalent water height) and has since improved, reaching -9.31 cm by 2025, the least negative value in the ten-year record. Linear regression across the full 2016-2025 series yields $R^2 = 0.60$ with a positive slope of +1.63 cm per year, indicating a statistically recognizable improvement in regional water storage over the decade. Two years in the middle of the series 2017 and 2018 carry lower confidence, only 5 of 12 months were observed in each of those years, compared with full 12-month coverage from 2019 onward. The particularly negative 2018 value should be read with this in mind, since it may partly reflect which, months happened to be observed rather than peak stress alone. From 2019 onward, where the monthly record is complete, the improving trend rests on firmer ground.

Table 3 - Annual Mean GRACE/GRACE-FO TWSA, Hardoi District (2016-2025)

Year	Annual Mean TWSA (cm)	Months Observed	Confidence
2016	-22.38	9 / 12	Good
2017	-27.80	5 / 12	Low - majority of months missing
2018	-31.76	5 / 12	Low - majority of months missing
2019	-27.56	12 / 12	Full
2020	-18.44	12 / 12	Full
2021	-23.31	12 / 12	Full
2022	-18.48	12 / 12	Full
2023	-19.92	12 / 12	Full
2024	-17.85	12 / 12	Full
2025	-9.31	12 / 12	Full

Source: CSR GRACE/GRACE-FO RL06.3 Mascon Grids. Missing months are excluded from annual means, not interpolated.

This result runs counter to the assumption, common in groundwater-stress literature on the wider Indo-Gangetic Plain (Rodell et al., 2009; Asoka et al., 2017), that terrestrial water storage in this part of Uttar Pradesh has been steadily declining. It does not contradict that literature's broader finding for the region as a whole, since GRACE's coarse native resolution means a single district can behave differently from the regional average and since the improvement recorded here follows a genuinely poor period in 2017-2019. It does mean that regional-scale literature cannot be cited as confirmation of local decline in Hardoi specifically, the district-level GRACE signal points the other way.

The GRACE and CGWB records agree on one point and diverge on another. Both show that Hardoi's groundwater and water-storage situation is not one of uniform, quickening decline.

Where they diverge is in direction at the district-average scale, CGWB pre-monsoon depth shows a weak, non-significant fluctuation with only a modest deepening between endpoints (R^2 = 0.05), while GRACE shows a moderate, improving trend (R^2 = 0.60). A weak-to-moderate correlation between the two series (r = 0.49, computed on overlapping years) suggests they are not measuring exactly the same signal at this spatial scale, which is expected given GRACE integrates a much larger area and includes soil moisture and surface water alongside groundwater.

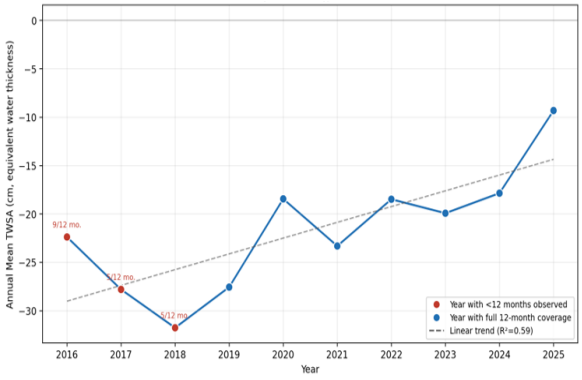

Figure 4 - Annual mean TWSA trend, Hardoi District (2016-2025), with years of incomplete monthly coverage flagged.
Source: CSR GRACE/GRACE-FO RL06.3 Mascon dataset

The persistent exception in both frameworks remains the Mallawan hotspot identified from well-level data, which a district-averaged satellite signal cannot resolve on its own.

5.3 NDVI-Based Assessment of Rabi-Season Vegetation Condition

NDVI was computed from Landsat 8/9 OLI surface reflectance for three Rabi-season dates, 4 March 2016, 12 February 2020, and 1 February 2025, using cloud-masked pixels within the Census 2011 Hardoi shape file boundary. Cloud-free coverage was high in all three years (87.0 percent in 2016, essentially complete in 2020 and 2025), giving confidence in the district-wide statistics reported below.

District mean NDVI rose from 0.587 in 2016 to 0.664 in 2020 and 0.672 in 2025 with median values following the same pattern (0.607, 0.706, and 0.726 respectively). This is an increasing trend in vegetation greenness across the decade, not a declining one and it is consistent with the rising wheat yield and the improving GRACE water-storage trend. The classification into vigour bands shows the same pattern the High class (NDVI ≥ 0.60) covered 51.4 percent of the district in 2016, rising to 69.2 percent in 2020 and 72.1 percent in 2025 while the Low class (below 0.45) fell from 21.7 percent to 12.8 percent and 13.1 percent over the same years.

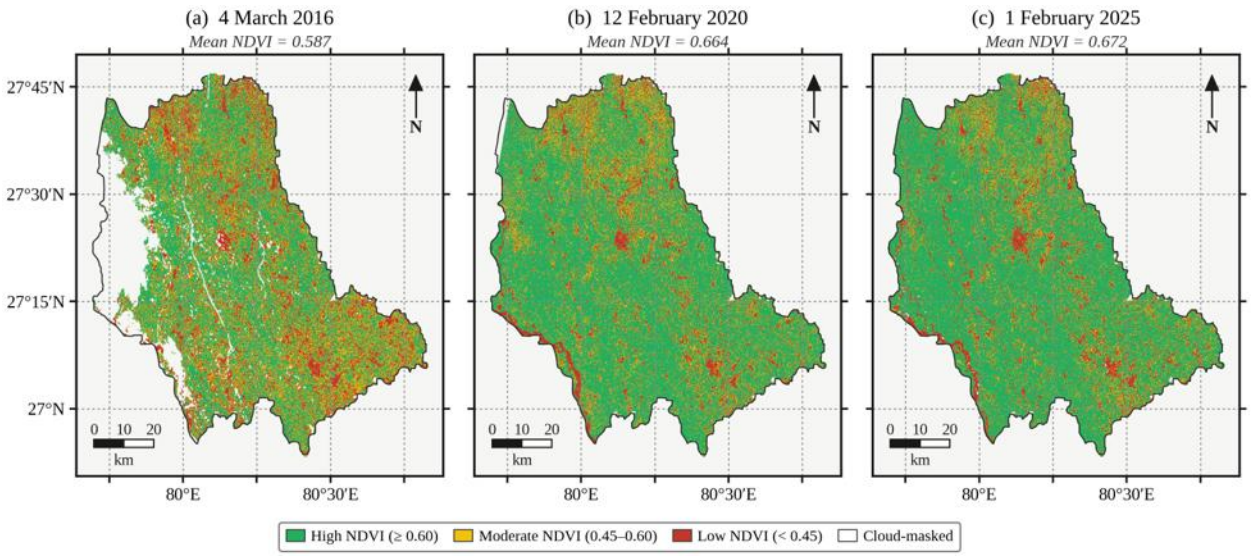

Figure 5 - NDVI classification of Hardoi District, Landsat 8/9 OLI, Rabi seasons 2016, 2020, and 2025. NDVI computed as (NIR-Red)/(NIR+Red) from Collection 2 Level-2 surface reflectance, cloud-masked using QA_PIXEL, and classified into Low (<0.45), Moderate (0.45-0.60), and High (>=0.60) vigour bands.
Source: Landsat 8/9 OLI Collection 2 Level-2 Surface Reflectance data (USGS Earth Explorer)

Two comparison dates fall close in the calendar to the imagery used (12 February and 1 February, rather than early March as in 2016) which means part of the apparent rise between 2016 and the later years could reflect earlier-season imagery capturing crops at a slightly different growth stage rather than vegetation vigour alone, this is a genuine limitation of comparing scenes that are not perfectly matched in day-of-year. Even allowing for this, the direction of change across all three authenticated datasets, NDVI, GRACE, and wheat yield, is consistently upward rather than downward, which strengthens confidence that the improvement is real rather than an artefact of any single measurement.

With these three authenticated dates now available, a district mean NDVI series can be compared descriptively against groundwater level and wheat yield though three points are too few to compute a statistically meaningful correlation coefficient. Pre-monsoon groundwater depth was 6.25 mbgl in 2016 and 6.89 mbgl in 2025 (2020 unavailable) while NDVI rose across the same two years, this pairing does not suggest that deeper groundwater coincided with lower vegetation vigour, consistent with the near-zero groundwater-yield. A longer NDVI series, ideally annual rather than three points a Rabi season apart, would be needed before this relationship could be tested formally.

5.4 Wheat Productivity Trend (2016-17 to 2022-23)

DES records for Hardoi District, available for Rabi seasons 2016-17 through 2022-23, show a clear increasing yield trend. District average yield rose from 3.64 t/ha in 2016-17 to 3.91 t/ha in 2022-23, an increase of 7.4 percent over seven years. Linear regression across these seven years yields $R^2 = 0.57$ with a positive slope of about +0.039 t/ha per year, a modest but statistically recognizable upward trend.

Table 4 - District-Level Wheat Area, Production and Yield, Hardoi District (2016-17 to 2022-23)

Rabi Season	Wheat Area (ha)	Production (tonnes)	Yield (t/ha)
2016-17	314,474	1,143,427	3.64
2017-18	314,432	1,155,223	3.67
2018-19	311,849	1,159,455	3.72
2019-20	315,210	1,125,615	3.57
2020-21	320,441	1,200,052	3.75
2021-22	329,234	1,248,455	3.79
2022-23	305,898	1,196,979	3.91

Source: Directorate of Economics and Statistics (DES), Government of Uttar Pradesh. 2023-24 and 2024-25 data were not available at the time of writing.

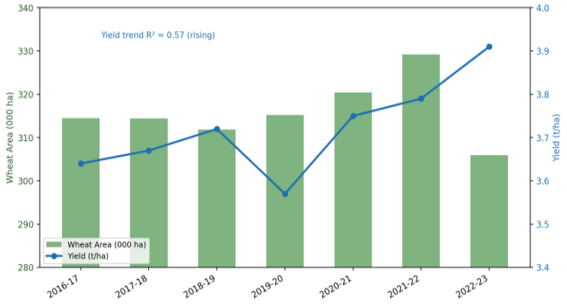

Figure 6 - Bar and line combination chart, wheat area (bars, primary Y-axis, 000 ha) and yield (line, secondary Y-axis, t/ha) in Hardoi District, Rabi seasons 2016-17 to 2022-23

Source: Directorate of Economics and Statistics (DES), Government of Uttar Pradesh. 2023-24 and 2024-25 data were not available at the time of writing.

Wheat area fluctuated without a strong trend across the seven years, from a high of 329,234 ha in 2021-22 to a low of 305,898 ha in 2022-23, while production followed the rising yield from 1,143,427 tonnes in 2016-17 to 1,196,979 tonnes in 2022-23, despite area production falling slightly in the final year. This confirms that yield improvement rather than area expansion, drove the production gain.

5.5 Land Use / Land Cover Classification (2016, 2020, 2025): Land use/land cover (LULC) classification was performed using Landsat 8 surface reflectance bands (Blue, Green, Red, NIR, and SWIR) along with NDVI, NDWI and NDBI as additional inputs.

Due to the absence of field-based data samples, an unsupervised k-means clustering approach (k = 6) was applied and the resulting clusters were assigned to land cover classes based on their spectral characteristics. Built-up and bare/fallow land were combined because they showed similar spectral responses, while agricultural classes were differentiated using NDVI-based vegetation intensity. The classification indicates a clear increase in high vigour agricultural land rising from 59.7% in 2016 to 73.5% in 2020 and 74.6% in 2025. In contrast, moderate vigour agricultural land declined from 30.3% to 15.3% and 14.0% during the same period. This pattern agrees with the NDVI-based vegetation assessment, which also indicates increasing vegetation vigour across the district.

Built-up and bare/fallow land remained relatively stable, showing only a marginal increase from 10.0% in 2016 to 10.6% in 2025, suggesting gradual land transformation rather than major agricultural land loss. Water bodies were identified in 2020 (1.0%) and 2025 (0.7%), while a separate water class was not detected in the 2016 classification likely due to the limited extent of water features during the dry-season image acquisition.

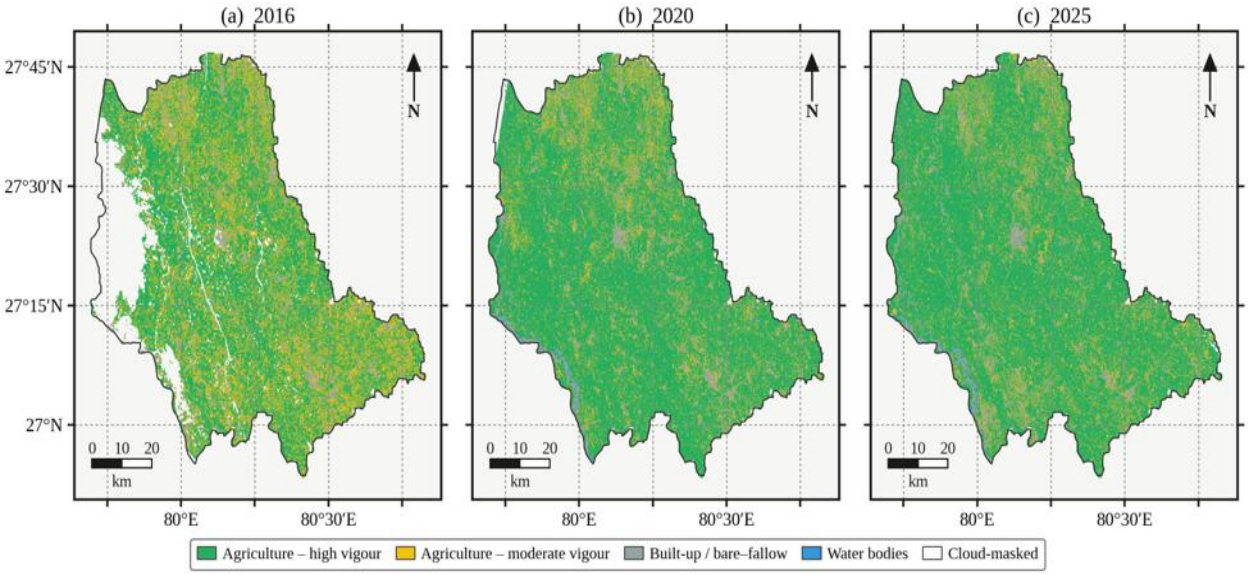

Figure 7 - Land use/land cover classification, Hardoi District: 2016, 2020, 2025.

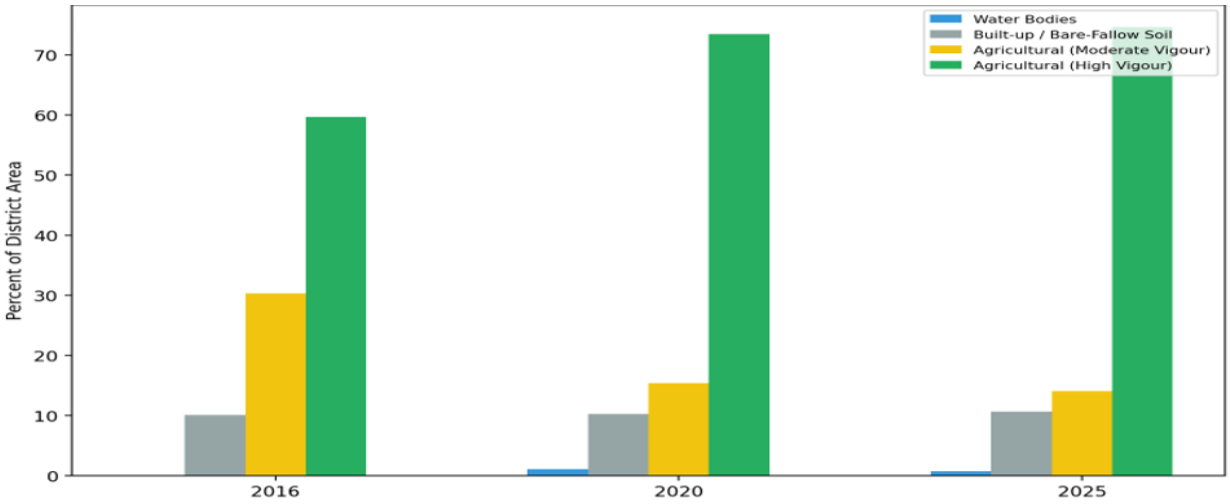

Figure 8- LULC Class Composition, Hardoi District: 2016, 2020, 2025
Source: USGS Landsat 8 OLI Collection 2 Level-2 Surface Reflectance imagery, class composition analysis and graphical representation

A validation check using eleven reference locations showed an overall agreement of 64%. The classification performed better for larger and clearly identifiable classes such as major towns and agricultural areas while small settlements and narrow water bodies features showed greater uncertainty due to spatial limitations and single-date imagery.

5.6 Relationship Between Groundwater Level and Wheat Productivity

The relationship between groundwater conditions and wheat productivity was assessed using groundwater, GRACE-based TWSA and wheat yield datasets. NDVI was not included in the correlation analysis because only three observations (2016, 2020, and 2025) were available which is insufficient for reliable statistical interpretation.

The correlation between pre-monsoon groundwater level and wheat yield for six overlapping years (2017–2019 and 2021–2023) was very weak negative (r = -0.10), indicating no clear district-level relationship during the study period. Similarly, GRACE-derived annual mean TWSA showed a weak positive relationship with wheat yield (r = +0.30) across seven overlapping years (2017–2023), indicating that improved water storage conditions were associated with slightly higher yields.

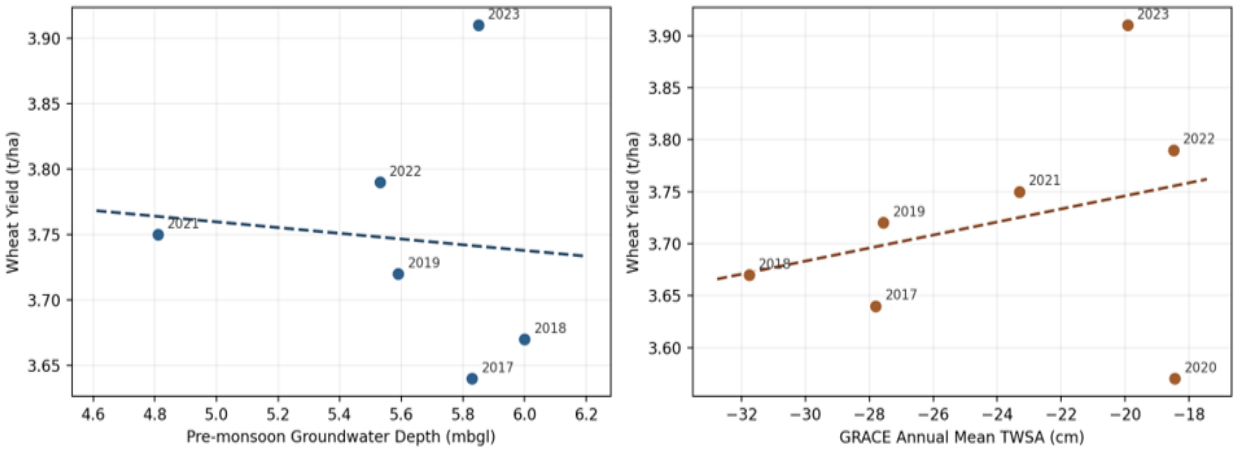

Figure 9 - (A) pre-monsoon groundwater depth vs wheat yield, r = -0.10 across six overlapping years; (B) GRACE annual mean TWSA vs wheat yield, r = +0.30 across seven overlapping years.
Source: Tables 2, 3, and 4 of this study

The direct relationship between groundwater level and GRACE-based TWSA produced a moderate correlation (r = 0.49) reflecting that both datasets capture related but different aspects of water availability. GRACE represents regional water storage, including soil moisture and surface water whereas groundwater observations reflect local aquifer conditions and capture areas such as the Mallawan hotspot. These findings do not indicate that groundwater has no role in agricultural productivity. Rather, at the district scale, groundwater changes and wheat yield variations did not follow a consistent pattern during 2016–2023. A more detailed and micro level assessment would require block or village-level yield data linked spatially with groundwater-stressed areas, especially like Mallawan block, as district averages may hide localized impacts.

5.7 Integrated Discussion

The mutual analysis of groundwater, GRACE-based TWSA, NDVI, LULC and wheat productivity shows a more complex pattern than a simple groundwater decline–yield reduction relationship. Pre-monsoon groundwater levels indicate a weak district-level trend (R^2 = 0.05) although a persistent decline hotspot is observed in Mallawan blocks. In contrast, GRACE-based TWSA shows an improving trend (R^2 = 0.60) and wheat yield also increases during the study period (R^2 = 0.57). The weak correlation between groundwater depth and yield (r = -0.10) and between TWSA and yield (r = +0.30) suggests no clear evidence of district-wide groundwater-based productivity decline. The results do not imply that groundwater stress is insignificant. The Mallawan hotspot represents a localized area of concern but its influence is not reflected in district-level yield averages. Therefore, groundwater management should focus on targeted monitoring, efficient irrigation practices and recharge measures in stressed areas rather than applying uniform interventions across the district. The findings should be interpreted considering data limitations like missing recent yield data, uncertainty in LULC classification(unsupervised) and limited overlapping years for correlation analysis.

VI. CONCLUSION

This study aims to examine groundwater level dynamic range in Hardoi District between 2016 and 2025 and their relationship with wheat productivity. Pre-monsoon groundwater level fluctuated without a statistically meaningful trend across the decade (R^2 = 0.05), GRACE-derived regional water storage improved moderately (R^2 = 0.60) and wheat yield rose from 3.64 to 3.91 t/ha across the years with available data (R^2 = 0.57). District-level correlation between groundwater level and wheat yield was close to zero (r = -0.10) and between GRACE and yield was weakly positive (r = +0.30). None of these results supports a hypothesis of district-wide groundwater driven wheat productivity decline of the kind that broader regional literature might have suggested for a groundwater-dependent district such as Hardoi.

The finding of genuine and validated concern is the Mallawan block hotspot, where independent pre-monsoon and post-monsoon CGWB survey rounds both show severe deepening from 12 mbgl to over 21 mbgl across the decade. Because this signal appears consistently across two separately conducted seasonal surveys, it should be treated as real and demands targeted attention even though it has not been large enough to move the district-wide yield average in a noticeable direction. This dissimilarity between a genuine localised zone of decline and not supported district-wide narrative is the central primary finding of this analysis.

Addressing the Mallawan hotspot pattern calls for spatially targeted action rather than uniform district-wide measures. Irrigation efficiency improvements and artificial recharge structures should be prioritised first around Mallawan block specifically rather than spread evenly across a district where most areas show comparatively stable groundwater and rising wheat yield. The approach demonstrated here testing rather than assuming a relationship between groundwater level and productivity and reporting results honestly when they different from initial expectations, offers a model that could be extended to other districts of the Middle Gangetic Plain.

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