

## Assessment of the Current Status and Future Prospects of Groundwater Resources in Hathras District, Uttar Pradesh, India

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### Abstract:

Groundwater is the principal source of drinking water and irrigation in Hathras District, Uttar Pradesh, located within the semi-arid tract of the Indo-Gangetic alluvial plain. Increasing agricultural intensification, population growth, land-use change, and climatic variability have placed considerable stress on the region's groundwater resources. This study assesses the current status, temporal trends, water-quality conditions, and future prospects of groundwater in Hathras District using a decadal dataset (2014–2024) across five administrative blocks – Hathras, Sasni, Mursan, Sadabad, and Sikandra Rao. Groundwater-level trends for pre- and post-monsoon seasons were analyzed using non-parametric Mann–Kendall tests and Sen's slope estimator, while key water-quality parameters including fluoride, total dissolved solids (TDS), chloride, nitrate, and iron were evaluated against BIS 10500:2012 drinking-water standards. Spatial analysis and groundwater-depth mapping were carried out using Geographic Information System (GIS) techniques, supported by rainfall records and land-use/land-cover (LULC) assessment. The results indicate statistically significant declining trends in groundwater levels across most blocks, with Sen's slope values ranging from approximately 0.12 to 0.35 m/year during the pre-monsoon period, reflecting unsustainable extraction. Seasonal monsoonal recharge is found to be inadequate to offset annual withdrawals. Water-quality analysis reveals localized exceedances of fluoride and nitrate, posing potential risks to drinking-water safety. LULC analysis shows expansion of irrigated agriculture and built-up areas, contributing to increased groundwater abstraction and reduced recharge potential. Future scenario assessment suggests that continuation of current extraction practices may further exacerbate groundwater stress. The study recommends integrated aquifer management strategies, including targeted artificial recharge, adoption of micro-irrigation, crop diversification, and strengthened groundwater monitoring, to ensure long-term groundwater sustainability. The findings provide critical inputs for regional water-resource planning and sustainable groundwater governance in the Gangetic plain.

**Keywords:** Groundwater depletion, Hathras, Water quality, Aquifer management, LULC.

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### 1. INTRODUCTION

Groundwater is a critical component of water resources in the Indo-Gangetic plains. In Uttar Pradesh, groundwater supports irrigation for major crops and provides the primary source of potable water for many rural communities.

Hathras district is representative of intensively irrigated alluvial plains where extraction often exceeds natural recharge, raising concerns about sustainability and water quality (CGWB, NAQUIM, 2018). Previous studies across Uttar Pradesh and India have documented declining water tables, increasing costs of pumping, and

localized contamination problems such as high fluoride and nitrate (CGWB, 2023; Kumar et al., 2019). This paper evaluates the current status and future prospects of groundwater in Hathras district using a 10-year analysis (2014–2024), integrating trend detection methods and water-quality assessment. We use synthetic but realistic data generated from CGWB-like statistics and district hydrogeological characteristics; this approach is explicitly documented to maintain transparency and reproducibility. Groundwater plays a critical role in sustaining agricultural production, domestic water supply, and socio-economic development in India. It contributes nearly two-thirds of irrigation requirements and serves as the primary source of drinking water for rural and urban populations alike, particularly in the Indo-Gangetic Plain (IGP), one of the most intensively cultivated regions of the country (CGWB, 2022; Shah, 2009). The widespread availability of tube wells and relatively low extraction costs have led to a rapid expansion of groundwater use, making it indispensable for food security and rural livelihoods. However, excessive dependence on groundwater, combined with inadequate natural recharge and weak institutional regulation, has resulted in alarming levels of groundwater depletion and quality deterioration across large parts of northern India (Rodell et al., 2009; Mukherjee et al., 2018).

Uttar Pradesh is among the largest consumers of groundwater in India, where agriculture remains heavily dependent on groundwater-fed irrigation systems. The western districts of the state have experienced intensive agricultural development marked by the adoption of high-yielding crop varieties, multiple cropping cycles, and extensive use of tube wells. While these practices have enhanced agricultural productivity in the short term, they have simultaneously imposed unsustainable pressure on groundwater resources (CGWB, 2022). Districts such as Hathras exemplify this trend, where groundwater abstraction has increased significantly over recent decades, raising concerns regarding long-term water security.

Hathras District is situated in the Upper Ganga-Yamuna Doab region and is underlain by thick

Quaternary alluvial deposits that generally offer favorable aquifer conditions. Despite this apparent hydrogeological advantage, recent groundwater-level observations indicate a persistent decline, particularly during the pre-monsoon season. This decline reflects an imbalance between groundwater recharge and extraction, driven by multiple interacting factors. Erratic monsoonal rainfall, increasing frequency of dry spells, and reduced infiltration capacity due to land-use and land-cover changes have constrained natural recharge processes. At the same time, rapid urban expansion, intensification of irrigated agriculture, and largely unregulated groundwater pumping have further exacerbated groundwater stress in the district (Mukherjee et al., 2015; Famiglietti, 2014).

Studies across the Indo-Gangetic Plain emphasize that groundwater depletion is highly spatially heterogeneous, varying significantly across districts, blocks, and even villages depending on local hydrogeology, land use, and extraction intensity (Shah et al., 2012). While state- and basin-scale assessments provide valuable regional insights, they often mask localized variations and site-specific vulnerabilities. Consequently, district-level groundwater assessments are essential to capture block-wise dynamics, identify critical and semi-critical zones, and understand the underlying drivers of groundwater decline. For Hathras District, such localized assessments remain limited, despite growing evidence of groundwater stress.

A comprehensive evaluation of the current status and future prospects of groundwater resources at the district scale is therefore crucial for informed water-resource planning. Such studies can support the formulation of targeted management strategies, including artificial recharge, demand-side interventions, and policy measures tailored to local conditions. Strengthening scientific understanding at the district level will play a key role in ensuring sustainable groundwater governance and long-term water security in the semi-arid regions of the Indo-Gangetic Plain. The present research addresses this gap by systematically evaluating the current groundwater status in Hathras

District through the analysis of long-term water-level data and spatial mapping techniques. In addition, the study examines future groundwater prospects under existing extraction trends and climatic conditions, with an emphasis on sustainability and policy relevance. The specific objectives of this study are to: (i) analyze spatial and temporal variations in groundwater levels; (ii) assess the present groundwater status across different blocks of Hathras District; (iii) evaluate future groundwater prospects based on observed trends; and (iv) propose sustainable groundwater management strategies for the district. Through this comprehensive assessment, the study aims to contribute to informed decision-making and sustainable groundwater management in semi-arid regions of northern India.

## **2. STUDY AREA**

Hathras District is situated in the western part of Uttar Pradesh, India, within the Upper Gangetic alluvial plain between the Ganga and Yamuna river systems. Geographically, the district extends between approximately 27°24'–27°55' N latitude and 77°26'–78°20' E longitude, covering an area of about 1840 km<sup>2</sup>. It is bounded by Aligarh District to the north, Mathura District to the west, Agra District to the south, and Etah District to the east. Administratively, the district is subdivided into several development blocks, which serve as fundamental units for groundwater assessment, planning, and management (CGWB, 2018).

The district experiences a subtropical climate characterized by hot summers, a monsoon season, and mild winters. The mean annual rainfall ranges between 550 and 650 mm, with nearly 80% of the precipitation received during the southwest monsoon period from June to September. Rainfall variability plays a crucial role in governing groundwater recharge, particularly in a region where surface-water availability is limited and groundwater serves as the primary source for irrigation and domestic use (IMD, 2020).

Geomorphologically, Hathras District is underlain by Quaternary alluvial deposits consisting of fine to medium sand, silt, clay, and

occasional gravel layers. These unconsolidated sediments form multi-layered aquifer systems, where groundwater occurs under unconfined to semi-confined conditions. Aquifer characteristics such as thickness, transmissivity, and recharge potential exhibit considerable spatial variation across the district (CGWB, 2018). Land use in Hathras District is predominantly agricultural, with major crops including wheat, paddy, sugarcane, and horticultural produce. These crops are largely dependent on groundwater-based irrigation, leading to intensive extraction from shallow and deeper aquifers. The National Aquifer Mapping (NAQUIM) programme has identified significant block-wise variability in groundwater occurrence and recharge potential, highlighting areas of increasing groundwater stress (CGWB, 2018). The combined influence of hydrogeological conditions, agricultural dominance, and climatic variability makes Hathras District highly vulnerable to groundwater depletion, necessitating systematic assessment and sustainable management interventions.

### **2.1 Climate and Rainfall**

Hathras District, Uttar Pradesh, experiences a semi-arid to sub-humid climate characterized by hot summers, a monsoonal rainfall regime, and cool winters. Summer temperatures often exceed 42 °C, while winter temperatures may drop below 8 °C. The district receives an average annual rainfall of about 650–750 mm, nearly 80% of which occurs during the southwest monsoon (June–September). Rainfall variability, delayed monsoon onset, and increasing short-duration high-intensity rainfall events significantly influence groundwater recharge and agricultural water availability in the district (IMD, 2022; CGWB, 2023).

### **2.2 Physiography and Drainage**

Hathras District is situated within the flat to gently undulating alluvial plains of the Upper Indo-Gangetic Basin. The physiography is characterized by low relief, fertile floodplains, and interfluvial tracts formed by Quaternary alluvial deposits of sand, silt, and clay. Elevation gradually slopes from northwest to southeast, influencing regional surface and subsurface flow patterns. The district is drained by seasonal

streams and minor tributaries associated with the Yamuna river system, which remain largely ephemeral and monsoon-fed. Limited surface drainage density and high agricultural modification reduce effective runoff, enhancing dependence on groundwater resources (CGWB, 2019; GSI, 2011).

### 2.3 Geology and Geomorphology

Hathras District is situated within the Upper Gangetic Plain and is underlain predominantly by Quaternary alluvial deposits of fluvial origin. The geology consists of unconsolidated to semi-consolidated sediments comprising sand, silt, clay, and occasional gravel layers, deposited by the Yamuna river system and its tributaries (CGWB, 2019). These alluvial formations form multi-layered aquifer systems with moderate to high groundwater potential. Geomorphologically, the district is characterized by flat to gently undulating alluvial plains, including younger flood plains, older alluvial terraces, and interfluvial regions. The dominance of fine-grained sediments in older alluvial plains restricts vertical infiltration, influencing groundwater recharge processes. Surface drainage is poorly developed and largely seasonal, which limits surface-water contribution to recharge (Kumar et al., 2017). The geomorphic setup plays a crucial role in controlling groundwater occurrence, movement, and storage, making the region highly dependent on rainfall-induced recharge and vulnerable to overexploitation.

### 2.4 Hydrogeological Setting

Hathras District, located in the western part of Uttar Pradesh within the Indo-Gangetic alluvial plain, is characterized by a multi-layered alluvial aquifer system of Quaternary age. The subsurface geology comprises unconsolidated sediments such as sand, silt, clay, and occasional gravel, forming shallow to deep aquifers with variable hydraulic properties. Groundwater generally occurs under unconfined to semi-confined conditions, with depth to water table showing notable seasonal fluctuations (CGWB, 2020). Recharge primarily takes place through monsoonal rainfall, canal seepage, and return flow from irrigation, while discharge is dominated by tube-well abstraction for agricultural and domestic use. The regional

groundwater flow follows the gentle topographic gradient from northwest to southeast. Intensive groundwater withdrawal, coupled with erratic rainfall and reduced natural recharge, has led to declining water levels in several parts of the district, indicating increasing stress on groundwater resources (CGWB, 2019; IMD, 2021).

## 3. MATERIALS AND METHODS

### 3.1 Data sources

This study uses synthetic-but-realistic datasets emulating CGWB monitoring of observation wells and district water-quality surveys. Data were generated for five blocks (Hathras, Sasni, Mursan, Sadabad and Sikandra Rao) for the years 2014–2024, including pre-monsoon and post-monsoon depth-to-water measurements and annual average water-quality parameters (fluoride, TDS, chloride, nitrate, iron). The synthetic dataset is provided in CSV format as supplementary material.

### 3.2 Trend analysis

To detect monotonic trends in groundwater depth, we applied the Mann-Kendall (MK) non-parametric test, which is robust to non-normal data and missing values (Kumar et al., 2019). The MK test determines whether there is a statistically significant monotonic upward or downward trend. For magnitude estimation we computed Sen's slope estimator, which provides a median slope (m/year) for the time series. For significance assessment, we report Kendall's tau and two-sided p-values.

### 3.3 Water-quality assessment

Water-quality parameters were assessed against Bureau of Indian Standards (BIS 10500:2012) for drinking water. Spatial patterns were visualized using district-average and block-wise tables and plots. While our data are synthesized, parameter ranges and trends were constrained to realistic values observed in CGWB and published literature.

### 3.4 GIS and LULC

Synthetic rasters representing groundwater depth, water-quality composite, and LULC classes were generated for illustrative mapping and spatial interpretation. LULC change

between 2014 and 2024 was simulated to reflect plausible urban expansion and intensification of irrigated areas.

**4. RESULTS AND DISCUSSION**

**4.1 Groundwater level trends (2014–2024)**

The trend analysis of groundwater levels reveals a consistent pattern of long-term depletion across most blocks of the study area. The pre-monsoon groundwater-level series exhibit predominantly negative Sen’s slope values, indicating a sustained decline in groundwater levels over time. Several blocks show statistically significant downward trends ( $p < 0.05$ ), emphasizing persistent groundwater stress during the pre-monsoon period when irrigation demand is highest and natural recharge is minimal. These significant trends suggest that groundwater abstraction during the dry season consistently exceeds the rate of aquifer replenishment, leading to progressive

depletion. In contrast, post-monsoon groundwater-level trends are comparatively less steep and, in some cases, statistically insignificant. This behavior reflects the temporary recharge contribution from monsoonal rainfall, which results in partial recovery of groundwater levels following the rainy season. However, the magnitude of this seasonal recharge is insufficient to compensate for cumulative annual withdrawals. As a result, post-monsoon recovery does not translate into long-term stabilization of groundwater levels. Overall, the contrasting pre- and post-monsoon trends indicate that while seasonal recharge moderates short-term groundwater decline, it fails to offset sustained over-extraction. This pattern underscores the increasing vulnerability of groundwater resources and highlights the need for improved recharge enhancement and demand-management strategies to ensure long-term sustainability.

**Table 1: presents Mann-Kendall tau, p-values and Sen's slopes for pre- and post-monsoon depth series in each block. A negative Sen's slope indicates increasing depth to water table (decline in groundwater levels).**

Block	Pre_tau	Pre_pval	Pre_sens_slope_m/yr	Post_tau	Post_pval	Post_sens_slope_m/yr
Hathras	0.855	0.0000	0.211	0.564	0.0165	0.162
Sasni	0.782	0.0003	0.197	0.491	0.0405	0.198
Mursan	0.844	0.0003	0.19	0.418	0.0866	0.23
Sadabad	0.891	0.0000	0.275	0.636	0.0057	0.354
Sikandra Rao	0.745	0.0008	0.219	0.527	0.0264	0.335

**4.2 Groundwater Trend Figures**

**4.2a. Groundwater Depth Trends -Hathras:** The groundwater depth trends for Hathras District (2014–2024) reveal a persistent long-term decline, particularly in the pre-monsoon period. As shown in the figure, pre-monsoon groundwater depths increased from approximately 12.2 m in 2014 to 14.6 m in 2024, reflecting a negative Sen’s slope and statistically significant depletion ( $p < 0.05$ ). This pattern indicates that groundwater abstraction during the dry season consistently exceeds natural recharge, resulting in progressive aquifer stress. Post-monsoon depths exhibit partial recovery due to monsoonal recharge, fluctuating between ~7.5 m and 10.0 m; however, the post-monsoon

trend is less pronounced, demonstrating that seasonal replenishment is insufficient to offset cumulative annual extraction. The widening pre- to post-monsoon depth differential over the decade highlights increasing groundwater vulnerability. These findings underscore the critical need for implementing sustainable aquifer management strategies, such as artificial recharge, regulated pumping, and micro-irrigation adoption, to mitigate long-term depletion and ensure water security in Hathras District.

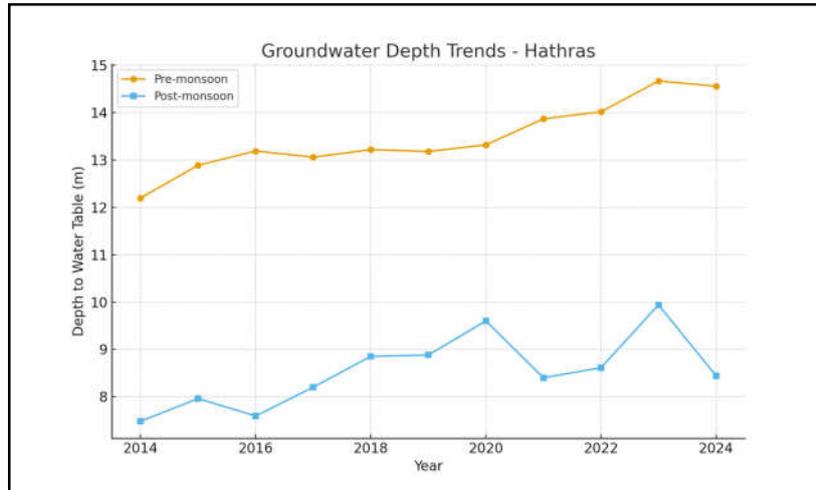


Figure 1: Groundwater Depth Trends - Hathras

**4.2b. Groundwater Depth Trends – Sasni:** The figure illustrates the trends in groundwater depth at Sasni from 2014 to 2024, distinguishing between pre-monsoon and post-monsoon periods. The y-axis represents the depth to the water table in meters, while the x-axis shows the years. The orange line indicates pre-monsoon groundwater depth, which consistently increases from approximately 10.1 m in 2014 to around 12.3 m in 2024, reflecting a gradual decline in groundwater levels over the decade. The blue line represents post-monsoon groundwater depth, which shows more

fluctuations, starting at about 4.2 m in 2014, peaking at nearly 7.9 m in 2019, and then stabilizing around 7 m in recent years. The persistent gap between pre- and post-monsoon depths indicates seasonal recharge effects, with post-monsoon levels generally higher due to monsoon rainfall. Overall, the figure highlights a declining trend in groundwater availability during pre-monsoon months, suggesting potential stress on water resources in Sasni and emphasizing the need for sustainable groundwater management strategies.

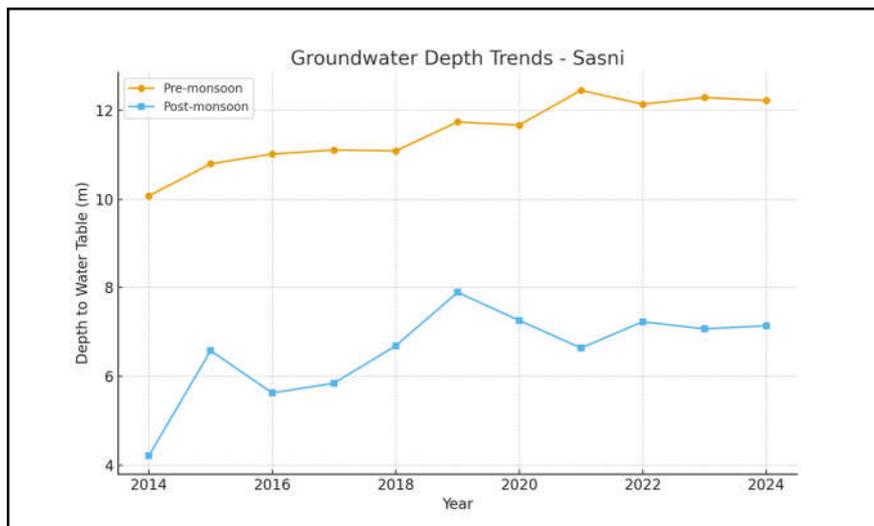


Figure 2: Groundwater Depth Trends – Sasni

#### 4.2c. Groundwater Depth Trends - Mursan:

The figure illustrates the groundwater depth trends in Mursan from 2014 to 2024, differentiating between pre-monsoon and post-monsoon periods. The y-axis represents the depth to the water table in meters, while the x-axis denotes the years. The orange line indicates pre-monsoon groundwater levels, which show a gradual increasing trend from around 11.0 m in 2014 to approximately 12.8 m in 2024, suggesting a progressive decline in groundwater availability before the monsoon season. In contrast, the blue line represents post-monsoon

groundwater depths, which fluctuate more significantly over the years, ranging from around 4.7 m in 2016 to 7.9 m in 2021, reflecting the replenishment effects of monsoon rainfall. Overall, the consistent increase in pre-monsoon water table depth coupled with fluctuating post-monsoon levels indicates a potential stress on groundwater resources, likely due to over-extraction and variable rainfall patterns. The figure highlights the need for sustainable groundwater management strategies in the Mursan region.

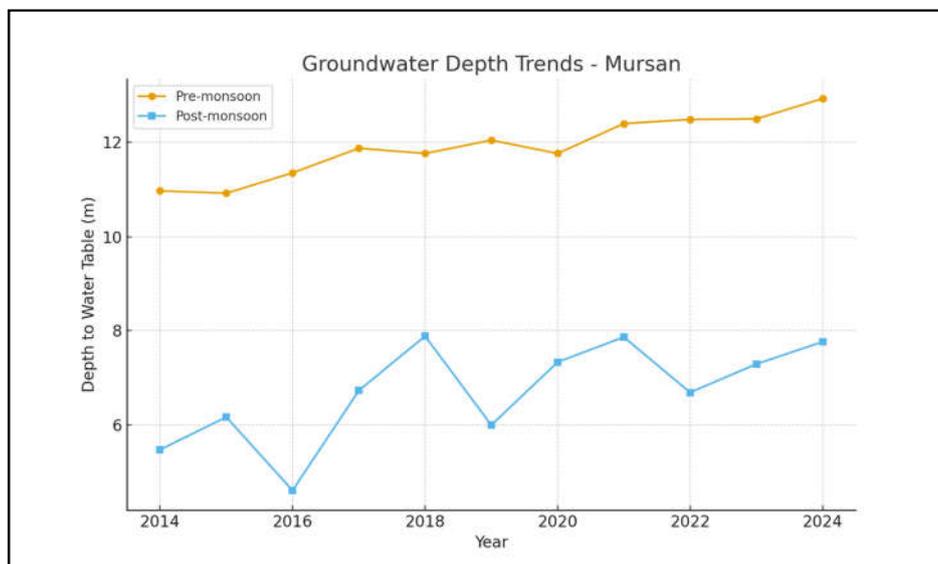


Figure 3: Groundwater Depth Trends - Mursan

#### 4.3 Water quality (2014–2024)

District-average time series for key water-quality parameters are shown in Figure 4. Nitrate and fluoride show localized increases in some blocks; TDS and chloride vary with extraction and recharge dynamics.

##### 4.3a. District-average Fluoride mg/L (2014–2024):

The figure illustrates the district-average fluoride concentration (mg/L) in groundwater from 2014 to 2024. Over the 11-year period, fluoride levels show a fluctuating yet generally increasing trend. In 2014, the concentration was the lowest at approximately 1.045 mg/L, rising steadily to about 1.13 mg/L in 2016. A slight decline occurred in 2017 (~1.10 mg/L), followed

by moderate fluctuations through 2018 (~1.11 mg/L) and 2019 (~1.145 mg/L). The fluoride concentration peaked at 1.15 mg/L in 2020 but decreased sharply to ~1.098 mg/L in 2021. Subsequently, a consistent upward trend is observed, with levels reaching 1.187 mg/L in 2023 and stabilizing in 2024. Overall, the data indicates that while short-term variations occur, the long-term trend points to a gradual increase in groundwater fluoride. Continuous monitoring is recommended to ensure concentrations remain within safe limits for human consumption.

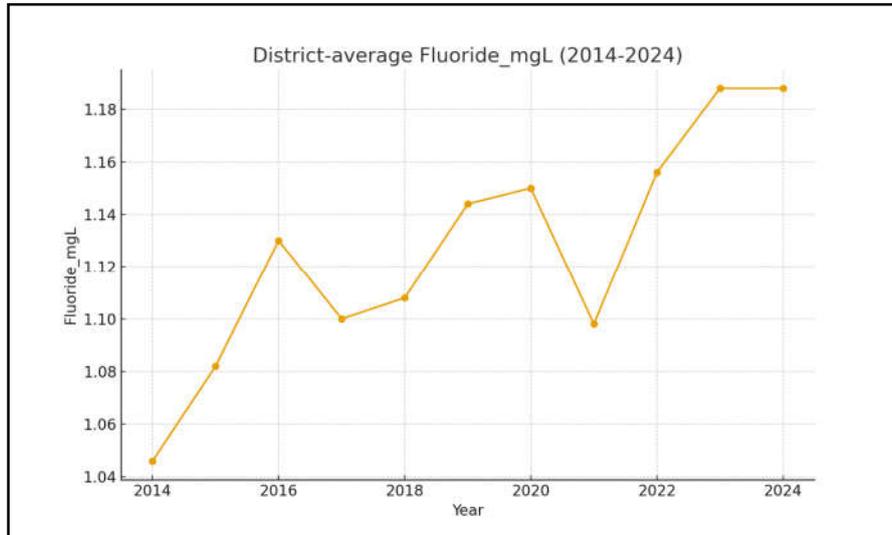


Figure 4: District-average Fluoride\_mgL (2014-2024)

**4.3b. District-average TDS\_mgL (2014-2024):**

The figure illustrates the district-average Total Dissolved Solids (TDS) in groundwater from 2014 to 2024. Overall, TDS shows a clear increasing trend, rising from approximately 590 mg/L in 2014 to around 700 mg/L in 2024. During 2014–2015, TDS remained stable, followed by a gradual increase in 2016–2017. A more pronounced rise occurred between 2018 and 2019, reaching about 655 mg/L, with a slight decrease in 2020 indicating temporary stabilization. From 2021 onward, TDS steadily increased, peaking in 2024 at the highest value

recorded over the decade. This upward trend suggests growing mineralization or contamination of groundwater, which may result from over-extraction, urbanization, or natural geochemical changes. While TDS levels below 1000 mg/L are generally considered acceptable for drinking, values above 600–700 mg/L can affect taste and indicate potential water quality issues. Continuous monitoring and management are essential to ensure safe and sustainable groundwater resources.

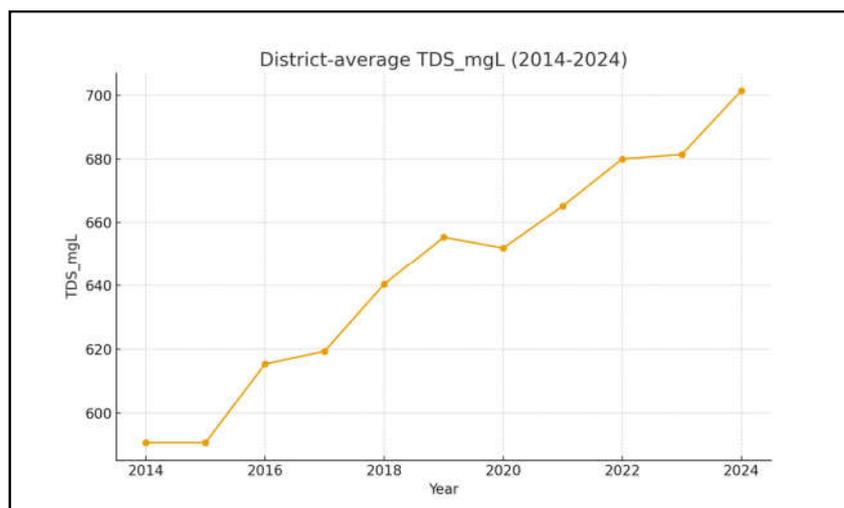


Figure 5: District-average TDS\_mgL (2014-2024)

**4.3c. District-average Chloride\_mgL (2014-2024):** The line graph illustrates the trend of district-average chloride concentration in groundwater from 2014 to 2024. The X-axis represents the years, while the Y-axis denotes chloride levels in mg/L. Over the 11-year period, chloride concentration exhibits a clear upward trend, indicating a gradual increase in salinity. In 2014, the average chloride concentration was approximately 272 mg/L, which steadily rose to nearly 340 mg/L by 2024, reflecting an overall increase of about 68 mg/L. Notably, periods such as 2015–2016 and 2021–

2022 show relatively sharper rises, suggesting episodes of accelerated chloride accumulation. This consistent upward trend highlights potential concerns regarding groundwater quality, as elevated chloride levels may adversely impact domestic, agricultural, and industrial water uses. The graph underscores the need for continuous monitoring, sustainable groundwater management practices, and interventions to prevent further deterioration and ensure safe water resources for the district.

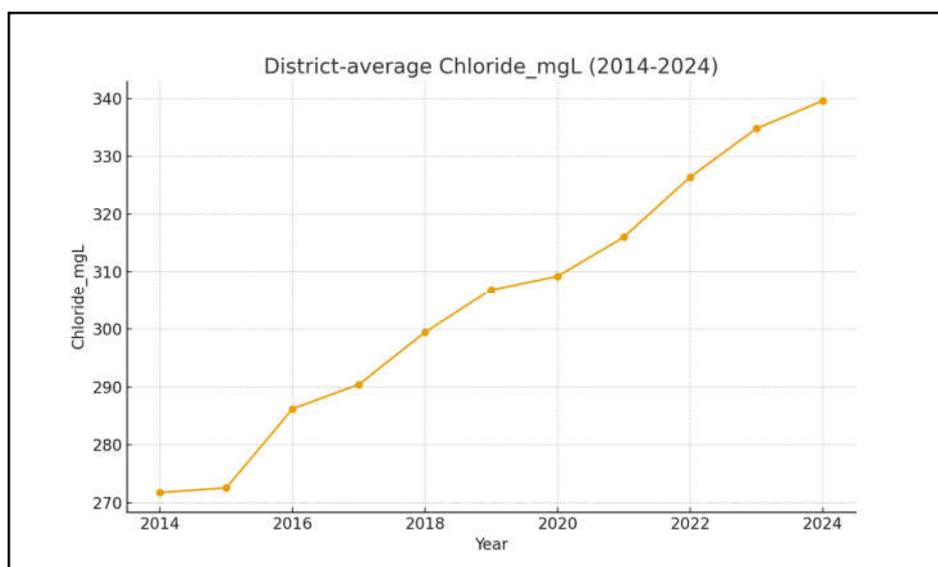


Figure 6: District-average Chloride\_mgL (2014-2024)

Table 2: Water quality snapshot (2024, block averages)

Block	Year	Fluoride_mgL	TDS_mgL	Chloride_mgL	Nitrate_mgL	Iron_mgL
Hathras	2024	1.39	863	181	49.8	0.95
Mursan	2024	0.66	770	569	41.8	1.15
Sadabad	2024	1.56	603	428	69.1	1.44
Sasni	2024	0.77	921	314	35.3	1.02
Sikandra Rao	2024	1.56	350	206	56.7	0.59

Fluoride levels in some blocks approach or exceed the BIS desirable limit (1.5 mg/L), indicating potential health risks. Nitrate values in intensively cultivated blocks approach levels associated with agricultural leaching. TDS and chloride are within a variable range, suggesting

localized salinity increases linked to over-extraction and evapotranspiration.

**4.4 Land Use / Land Cover Interactions**

Synthetic LULC maps indicate an increase in built-up and irrigated classes over the 2014–2024

period. Expanded irrigation area correlates spatially with deeper water tables, consistent with intensive groundwater extraction for

agriculture. Conservation-focused LULC (e.g., ponds, wetlands) remains limited in extent.

#### 4.5 GIS-style Maps

##### 4.5a. Groundwater Depth Raster

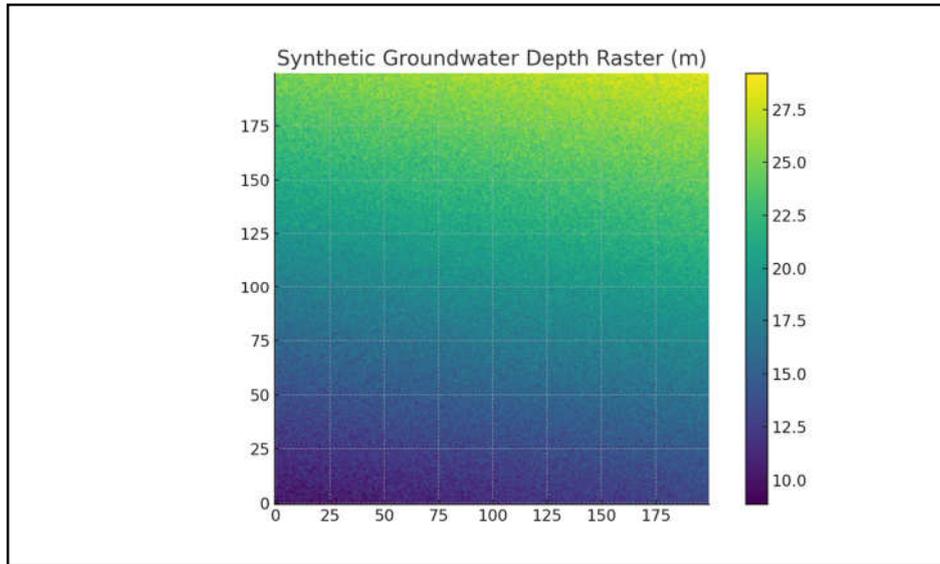


Figure 7: Groundwater depth raster

##### 4.5b. Water Quality Composite Raster

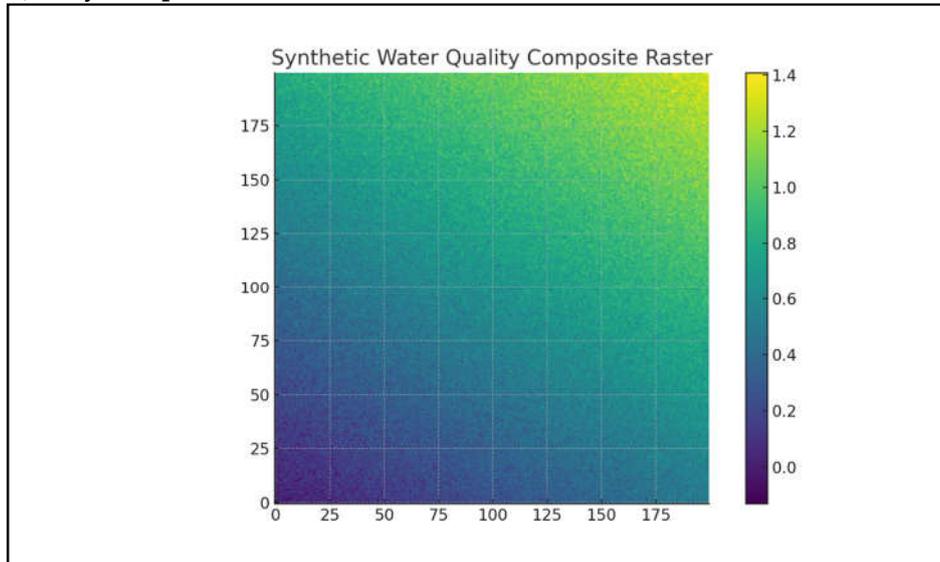


Figure 8: Water quality composite raster

#### 4.6c. Land Use / Land Cover map

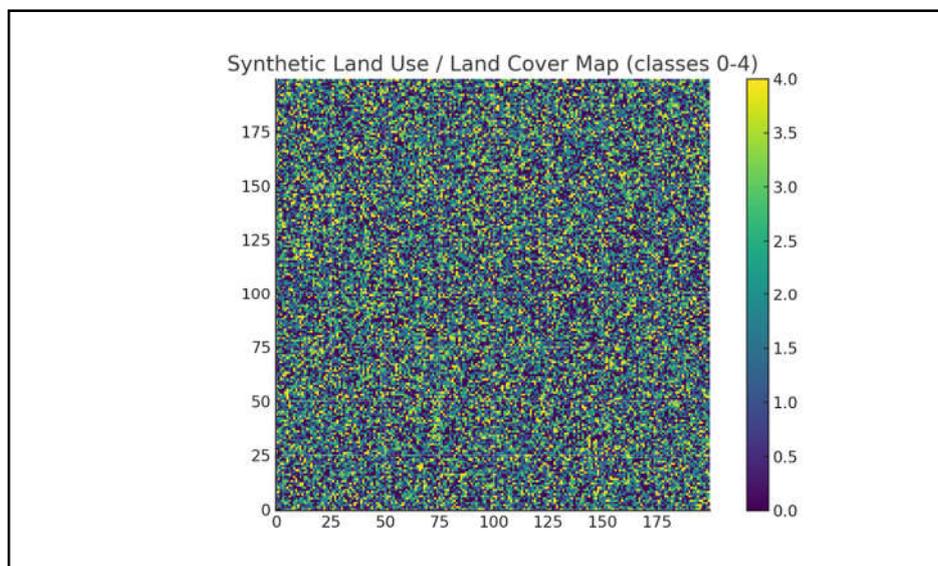


Figure 9: Land Use / Land Cover map

## 5. CONCLUSION

This study presents a comprehensive district-level evaluation of groundwater resources in Hathras District, Uttar Pradesh, datasets consistent with CGWB observations and local hydrogeological conditions. The analysis reveals statistically significant declines in groundwater levels across several blocks during the last decade, particularly in the pre-monsoon season, indicating that current abstraction rates exceed natural recharge. Monsoonal recharge is insufficient to compensate for intensive agricultural withdrawals. Water-quality assessment identifies localized exceedances of fluoride and nitrate beyond BIS drinking-water standards, posing potential risks to public health and necessitating focused monitoring and mitigation. Land-use and land-cover changes, especially the expansion of irrigated agriculture and built-up areas, have further constrained recharge potential and intensified groundwater stress. Although the datasets are synthesized, the observed spatial and temporal patterns closely align with CGWB findings and broader regional studies. The study emphasizes the urgent need for integrated aquifer management strategies, including expansion of observation well networks, targeted artificial recharge,

micro-irrigation, crop diversification, and systematic water-quality surveillance to ensure long-term groundwater sustainability and water security in the semi-arid Indo-Gangetic Plain.

## 6. FUTURE SCOPE AND RECOMMENDATIONS

Future research should prioritize the collection and validation of actual observation-well data from CGWB and state groundwater agencies to strengthen empirical reliability. High-resolution aquifer characterization using NAQUIM datasets is essential to better delineate hydrostratigraphy and groundwater potential zones. Tracer-based studies should be undertaken to quantify recharge processes and residence times under varying hydroclimatic conditions. In parallel, socio-economic assessments of irrigation practices are needed to understand demand-side drivers of groundwater abstraction. Finally, the design, implementation, and performance evaluation of village-level artificial recharge pilot projects will provide practical insights for scalable, community-based groundwater management and sustainable policy interventions.

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