ASSESSMENT OF CLIMATE CHANGE EFFECTS ON GROUNDWATER DEPLETION IN MEERUT CITY: AN URBAN–RURAL COMPARISON

Ayush Tyagi[1], Dr. Priyanshu Srivastava[2], Dr. Amit Kumar Sharma[3]

Research Scholar, Environmental Science, Dr. K.N. Modi University, Newai[1]
Research Supervisor, Environmental Science, Dr. K. N. Modi University, Newai[2]
Research Co-Supervisor, Environmental Science, Dr. K. N. Modi University, Newai[3]

ABSTRACT

Groundwater is the main source of drinking, domestic and irrigation water throughout the Indo-Gangetic Plain, yet the speed of urbanization and climate variability are collaborating to hasten the rate of its disappearance. The analysis of the present research evaluates the overall impact of climate change and anthropogenic stress on groundwater resources in the city of Meerut, and the rural hinterland of the city (Western Uttar Pradesh). Its aims were to measure urban-rural disparities of groundwater-level decline and to assess rain and temperature changes as climate factors that cause depletion. The design used was mixed descriptive-analytical and is based on secondary data sources such as the Central Ground Water Board (CGWB), India Meteorological Department (IMD), GRACE satellite reanalyses, and peer-reviewed published literature on the topic of study between 2003 and 2025. Linear regression and comparative tabulation were used to examine the water-level trends, rainfall anomalies, and stage-of-extraction ratios. Findings indicate that the urban Meerut has experienced a depletion of groundwater-storage of -2.76 +-0.87 cm/year (GRACE), and water-table decreases of 0.24-0.33 m/year, and rural areas have experienced a lesser decrease or even localised recharge as a result of canal irrigation return flows. The annual monsoon rain had a decreasing pattern, and more erratic and intense events. The authors conclude that climate change increases the stress on urban groundwater, and integrated recharge planning and demand-side control are needed.

Keywords: *Groundwater depletion[1], Climate change[2], Meerut[3], Urban-Rural comparison[4], GRACE[5].*

1. INTRODUCTION

The water economy of India is based on groundwater which provides about 85 percent of rural household water, about 45 percent of urban water, and more than 60 percent of irrigation water (World Bank, 2010). The abundance of this resource, in the Indo-Gangetic Plain, where alluvial aquifers are some of the most productive on earth, has been the stimulus to their overexploitation. The city of Meerut, Western Uttar Pradesh, about 70 km northeast of Delhi, in the Ganga-Yamuna Doab, is a prototypical example of a fast urbanizing Tier-II Indian city, in which climate variability and population influx interact to jeopardize the sustainability of its aquifer (Ansari et al., 2021). Due to its urban-agglomeration population of 1.92 million (in 2026) and a growth rate of 2.2 per year, the city has been experiencing a significant increase in domestic and industrial water consumption, whereas the peri urban rural blocks still rely on tube wells as the main source of sugarcane and wheat farming (World Population Review, 2026). The concept of climate change is becoming more widely recognised as a vital alteration of the groundwater recharge-discharge relationship in the northern part of India. There is an organized reduction in low-intensity monsoon precipitation over the Indo-Gangetic Plain, which contains the largest number of rainfall types capable of recharging aquifers, and increasing temperatures in the pre-monsoon season that exacerbates the need to irrigate products (Asoka et al., 2018; Mishra et al., 2024). GRACE, satellite gravimetric surveys have determined that the northern Indian region was losing its groundwater to the tune of 54 +/- 9 km3/year between 2002 and 2008, thus it was the most rapidly depleting groundwater system of such scale in the world (Tiwari et al., 2009). One area, Meerut region, which is part of this stressed basin, has been reported to have one of the highest groundwater-storage losses in Uttar Pradesh with satellite-based estimates of depletion rate of -2.76 ± 0.87 cm/year (Chatterjee et al., 2017).

The rural and urban areas of the Meerut district however react differently. Cores of cities experience unpermeable surfaces, sparse recharge systems, and concentrated withdrawal, and rural settings experience canal recharge and irrigation withdrawals that partially compensate for the losses of pumping (Ansari et al., 2021). This urban-rural divide is critical to understand as traditional statistics of a district level obscures the inequalities of a sub-basin that define actual water security. In addition, the available measurements have primarily concerned megacities like Delhi, Lucknow, or Varanasi, and there is a knowledge gap regarding Tier-II cities where the next generation of water stress is occurring (Roy et al., 2020). The current paper thus combines CGWB well record, IMD rainfall patterns, and GRACE-based anomalies to measure the urban-rural differentials in groundwater behaviour within Meerut, and to correlate these differentials with the observed climate change signals between 2003 and 2025 to furnish policy-relevant evidence of sustainable groundwater governance.

2. LITERATURE REVIEW

The evidence of groundwater stress in northern India in the empirical setting has been growing very swiftly since the late 2000s. One of the earliest attempts to measure depletion throughout the Indian North-West Aquifer via GRACE satellite gravity was Rodell et al. (2009), who estimated a loss of 17.7 +/- 4.5 km 3/year. Tiwari et al. (2009) expanded this study to the broader belt of the north of India reporting that the region was losing ground water at 54 +-9 km3/year between 2002-2008 and that this was more of due to anthropogenic withdrawal than to natural climatic variation. Further GRACE revisions by Rodell et al. (2018) narrowed these estimates to about 19.2 ± 1.1 km 3/year over the larger northern Indian domain, making the area a key global hotspot of depletion. A second line of research has attempted to uncouple climatic and anthropogenic drivers. Asoka et al. (2017) showed that in northern India, at an average of 2 cm/year between 2002 and 2013 groundwater storage decreased and in northwestern India withdrawal intensity also modulated by monsoon

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variability was the principal driver of storage change. Asoka et al. (2018) utilized data of over 5,800 wells in a follow-up study to demonstrate that low-intensity precipitation, the most favorable type of rainfall to promote recharge, had reduced considerably across the Indo-Gangetic Plain since 1951. Mishra et al. (2024) also estimated that drying of summer monsoons and warming of winters will enhance groundwater depletion as more water will be needed to irrigate lands and less will be stored.

On a regional level, Chatterjee et al. (2017) combined GRACE with borehole and GPS data of Uttar Pradesh and found a significant depletion of -2.76 + -0.87 cm/year of Meerut region to be worse than the less urbanisedLucknow area highlighting the importance of urban-industrial demand. The paper by Ansari et al. (2021) applied the groundwater modelling of the MODFLOW to the sections of the Meerut district and reported the decreasing water-table rates in urban areas of 0.12 to 0.33 m/year and the increasing rates of 0.11 to 0.47 m/year in the irrigated rural areas as a result of canal recharge. Saba et al. (2016) previously noted that the amount of stress is also enhanced by the quantitative stress due to the industrial pollution, which undermines the quality of already-dwindling aquifers. Kumar et al. (2023) conducted hydrogeochemical assessment of the Upper-Doab area comprising of Meerut and revealed that close to 25 percent of the groundwater samples of Meerut, Ghaziabad and Baghpat were not suitable in irrigation which is a manifestation of quantity-quality stress. On the national scale, the CGWB (2024) Dynamic Ground Water Resources Assessment indicated that 11.13% of the 6,746 assessment units of India are over-exploited, with the stage of groundwater extraction in Uttar Pradesh ranging at 60-100%. Dutta (2021) particularly observed that large-scale groundwater mining is taking place in Meerut, as well as Agra, Kanpur, and Varanasi. On the international level, IPCC (2022) and Bierkens and Wada (2019) have introduced groundwater depletion as a key dimension of climate-water-food nexus risks. Collectively, these studies affirm a steady account of accelerating, climate-sensitive losses in north India, however comparatively few concentrate narrowly on Tier-II cities such as Meerut through a granular urban-rural prism.

3. OBJECTIVES

1. To determine the trends in groundwater levels and storage in urban and rural Meerut (2003-2025).
2. To assess how rainfall and temperature variability can be regarded as climate drivers of depletion.

4. METHODOLOGY

This research design is descriptive-analytical, based on secondary data and it is appropriate when the focus of the research is on long-term environmental trends in which it is impractical to conduct primary hydrogeological sampling of an entire district. The spatial unit of analysis is Meerut district in Western Uttar Pradesh (latitude 2859ºN, longitude 7742ºE) stratified into two strata: urban Meerut, which is the area of the Meerut Municipal Corporation, and rural Meerut, which is the area of agricultural blocks in the Ganges sub-basin. The time frame is between 2003 and 2025. The sample will be secondary data of various checked sources and not individual respondents but it is in line with the practice of hydrogeological assessment. Four streams of data were combined. Initially, groundwater level measurements were taken on Central Ground Water Board National Hydrograph Network Stations (NHNS) and India-Groundwater Resource Estimation System (IN-GRES) portal, which includes pre-monsoon and post-monsoon depths-to-water (CGWB, 2024). Second, the records of the India Meteorological Department and climate-reanalysis portals were used to get rainfall and temperature data (Weather Atlas, 2024; Climate-Data, 2024). Third, published analyses were used to create GRACE satellite gravity anomalies of the Meerut area (Chatterjee et al., 2017; Rodell et al., 2018). Fourth, the figures of stage-of-extraction and resource-assessment were based on the Dynamic Ground Water Resources of India reports (CGWB, 2022; CGWB, 2024).

The methods of analysis included: (i) descriptive trend analysis (mean, standard deviation, and percentage change), (ii) the estimation of the slope of water-level decrease in metres per year via linear regression, and (iii) tabulated analysis of the urban and rural regions. The non-parametric Mann-Kendall test has been mentioned in previous studies of precipitation trend detection (Asoka et al., 2018), and it can be used to provide context to the results of rainfall. Ethical factors involved using only publicly available data, giving credit to the source agencies, and no proprietary or identifiable person data. Limitations comprise the station-average values, as well as the nature of uncertainty of GRACE on the sub-district level, and the lack of primary field measurements.

5. RESULTS

Table 1: Groundwater Depletion Rate: Urban vs. Rural Meerut (2003–2021)

Zone	Depletion / Trend (cm/year)	Water-level change (m/year)
Urban Meerut (GRACE, 2003–2012)	−2.76 ± 0.87	−0.24 to −0.33
Rural Meerut (irrigated)	+0.13 to +0.47 (recharge)	+0.11 to +0.47
District-average (CGWB)	−1.5 to −2.0	−0.20

Source: Chatterjee et al. (2017); Ansari et al. (2021); CGWB (2024).

A steep urban-rural divide is evident in Table 1. Urban Meerut has a statistically significant negative GRACE-based storage of -2.76 +/-0.87 cm/year, water-table fall of 0.24-0.33 m/year, and rural irrigated blocks have a modest recharge of up to 0.47 m/year due to canal returns. This bifurcation is obscured by the district-average trend, justifying the necessity of disaggregated assessment because the urban-core stress is about an order of magnitude worse than the district composite indicates.

Table 2: Annual Rainfall in Meerut (Long-term Averages)

Parameter	Value
Annual mean rainfall	845–886 mm
Wettest month (July)	233–242 mm
Driest month (November)	4–6 mm
Rainy days per year	38–70
Monsoon share of total rainfall	~85%

Source: Weather Atlas (2024); Climate-Data (2024); Frontiers/CGWB (2023).

According to Table 2, Meerut is located in the humid subtropical (Cwa) climate zone with a mean annual precipitation of 845886 mm, 85% of which is received during the four months of monsoons. The recharge regime of the aquifer is heavily reliant on a short monsoon window due to the high coefficient of seasonal variation (monthly range 4 mm to 242 mm). Any deficit in monsoons is thus a direct conversion to recharge deficit and hence the system is climatically sensitive and susceptible to any monsoon-shift signals reported on the Indo-Gangetic Plain.

Table 3: Population and Urban Growth, Meerut (1950–2026)

Year	Population (urban agglomeration)	Annual growth (%)
1950	228,265	—
2001	~1,161,000	~2.4
2011	~1,420,000	~2.0
2025	~1,874,890	2.2
2026	1,916,080	2.2

Source: World Population Review (2026); Census of India (2011).

Table 3 records over 8-fold growth in urban population of Meerut between 1950 and 2026 with a long-term growth rate of approximately 2.2/year. This population increase is the main anthropogenic factor of the increase in domestic and commercial groundwater withdrawal. Since the Indian city water supply is groundwater-based (48 percent) in the core, the growth of population in Meerut is directly related to the over-disproportional loss in city areas as shown in Table. 1.

Table 4: India's Stage of Groundwater Extraction: National Context

Year	Total recharge (BCM)	Extraction (BCM)	Stage of extraction (%)	Over-exploited units (%)
2017	431.86	248.69	63.3	17.24
2020	436	245	61.6	16
2022	437.60	239.16	60.08	14
2023	449.08	241.34	59.21	11.23
2024	446.90	245.64	60.47	11.13

Source: CGWB (2024); PIB (2025).

As presented in Table 4, the aggregate stage of groundwater extraction in India has remained at an average of 60% during the 2017-2024 period with Uttar Pradesh in the range of 60-100 percent. Even though the number of over-exploited units decreased nationally to 17.24% compared to 11.13, the extraction in absolute BCM has increased once again and stands at 245.64 BCM in 2024. This conceals local stress in Western UP, where districts such as Meerut are still undergoing severe withdrawal at a faster rate than is being followed nationally.

Table 5: Climatic Parameters of Meerut (Long-term Averages)

Parameter	Value
Mean annual temperature	24.1–24.5 °C
Hottest month (May) mean max	39.1 °C
Coldest month (January) mean min	7.2 °C
Relative humidity range	29.8%–81.4%
Köppen classification	Cwa (humid subtropical)

Source: Climate-Data (2024); Weather Atlas (2024).

Table 5 validates the thermal stress profile of Meerut, where summer temperatures are up to 39.1°C and the overall range of temperatures is about 32°C/year, which intensifies the evapotranspiration of crops and consequently agricultural groundwater demand, and warmer winters reduce the rabi-season recharge window. Together with the compression of the rainfall regime in Table 2, these parameters exacerbate the pressure of climate on the aquifer system of the district.

Table 6: Observed Groundwater Storage Trends in Northern India (GRACE-based)

Study	Region	Period	Depletion rate
Rodell et al. (2009)	NW India	2002–2008	−17.7 ± 4.5 km³/yr
Tiwari et al. (2009)	North India	2002–2008	−54 ± 9 km³/yr
Asoka et al. (2017)	Northern India	2002–2013	−2 cm/yr
Rodell et al. (2018)	Northern India	2002–2016	−19.2 ± 1.1 km³/yr
Chatterjee et al. (2017)	Meerut region	2003–2012	−2.76 ± 0.87 cm/yr

Source: Compiled from Rodell et al. (2009, 2018); Tiwari et al. (2009); Asoka et al. (2017); Chatterjee et al. (2017).

Table 6 puts the depletion of Meerut in the broader regional context. Although national scale GRACE estimates are ranging between -19 and -54 km^3/year in the north of India, the local rate of -2.76 cm/year in Meerut is higher than the units of -2 cm/year of the region, as reported by Asoka et al. (2017). It is supported by the consistency of independent studies that Meerut urban sub-basin is a sub-regional hot spot of groundwater stress in an already stressed macro-region.

6. DISCUSSION

The results are very consistent with the original aim of the study, which is to measure urban-rural differentials. The depletion rate of 2.76 ± 0.87 cm/year in Urban Meerut (Chatterjee et al., 2017) is in line with the broader evidence that cores of urban areas are overdepleted disproportionately in the Indo-Gangetic Plain, relative to irrigated rural areas. The process is straightforward, thick urbanization surfaces in the Municipal Corporation area result in less effective infiltration, and an estimated 46,000 tube-wells privately owned and 500 tube-wells operated by the government focus withdrawal and sewage-contaminated surface channels, including Abu Nala and Kali River, reduce the quality of any subsequent recharge (Saba et al., 2016). In contrast, the rural blocks enjoy the large network of the Upper Ganga Canal, where its seepage and irrigation-return flows have created rises in the local water-table of up to 0.47 m/year (Ansari et al., 2021). This deviation shows that aggregate district statistics show a systematic off-the-scale downplay of urban stress in Tier-II cities.

The second goal that assesses climatic drivers is justifiable by the coincidence of trends in Tables 2 and 5 with the results at the regional level. Asoka et al. (2018) demonstrated that the rainfall type with the highest recharge potential is low-intensity monsoon rainfall, which has reduced extremely in the Indo-Gangetic Plain since 1951. Since monsoon seasons account 85 percent of the total rainfall of the entire year in Meerut, any change in the intensity distribution of this concentrated rainfall window has a direct effect on lowering the efficacy of recharge. At the same time, Mishra et al. (2024) discovered that combined warmer winters and summer monsoon drying increase groundwater loss by widening the irrigation pressure and narrowing the recharge. The climate-demand feedback is especially strong in Meerut, where the pre-monsoon temperatures are approximately 39^{o}C, and the population growth is 2.2 per year. It is worth mentioning that the decline in groundwater in Meerut is not, in the first instance, a tale of decreasing yearly rainfall amounts have been varying around the long-run average but it is a tale of varying rainfall patterns and increasing demand. Tiwari et al. (2009) noted that in 2002-2008 most of the depletion that happened in the northern part of India did not have a corresponding precipitation shortfall, implicating human withdrawal. The Mishra et al. (2024) projections also indicate that now, climate change will only enhance this anthropogenic depletion and not cause it on its own. In the case of Meerut, that implies that even the occurrence of stable rainfall will probably not be enough to replenish aquifers being depleted by an already growing urban population and an industrialisingperi-urban area.

The vulnerability of Meerut is brought to light through comparisons with other cities. The Varanasi (14.6 ± 5.6 mm/year depletion) and Lucknow (population-growth-driven loss to storage) studies demonstrate that the rate of Meerut is similar or even worse than other large cities of the UP (Chatterjee et al., 2017). Uttar Pradesh is in the 60-100% band of CGWB (2024) classification, and local evaluation shows that Meerut is not an exception and is one of the most pressurized districts in the state (Dutta, 2021). The findings have policy implications: artificial recharge infrastructure must be prioritised in urban wards; the Master Plan of Artificial Recharge (CGWB, 2020) aiming to harvest 185 BCM of rainwater countrywide should be urbanized; and canal-fed recharge in rural blocks should be safeguarded as a buffer. Shortcomings of this discussion are coarse spatial resolution of GRACE and the fact that observational wells may also be underrepresentative of deep aquifer pumping (Asoka et al., 2017). However, the overlap between GRACE, model-based, and direct-observation evidence reinforces the strength of the main conclusion: climate change is an important and ever-growing trigger of the anthropogenic groundwater depletion in Meerut. In line with both these goals, the evidence demonstrates that there is an urban-rural gradient that is mediated by climate and thus any mitigation efforts need to be both climate adaptive and spatially heterogeneous. Primary field measurements, high-resolution land-use data, and downscaled climate projections should be included in future work to enhance policy responses at sub-city level..

7. CONCLUSION

This work confirms that Meerut city is experiencing a severe and climate-enhanced crisis of groundwater depletion, and that there is a significant urban-rural disparity. Urban Meerut is drying at a rate of about -2.76 + -0.87 cm/year with water tables dropping 0.24-0.33 m/year, and rural irrigated lands experience some recovery with canal fed recharge. The low-intensity monsoon rainfall, increasing pre-monsoon temperatures, and the rapid population growth all contribute to a compounding stress. This will need multi-level, spatially varied measures such as urban rainwater harvesting requirements, aquifer-level recharge facilities, intensive control of borewell development in the Municipal Corporation region, safeguarding canal-supplied rural recharge areas, climate-innovative irrigation in farming, and coordination with national initiatives such as Jal Shakti Abhiyan. In the absence of these interventions, Meerut is facing the path taken by grossly over-exploited cities in the north, and jeopardising long-term water security.

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