

A STUDY OF CLIMATE CHANGE EFFECTS ON GROUNDWATER RESOURCES IN MEERUT: URBAN vs RURAL CONTEXT

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Abstract

Climate change has significantly reshaped the dynamics of groundwater in the Upper Ganga Plain, and the Meerut district of Uttar Pradesh is an interesting place to study urban-rural differentials, as it is a place of intensive sugarcane agriculture alongside the rapid urbanisation. This paper examines the relationship between changes in rainfall, temperature and anthropogenic pressure, and their comparison and contrast in terms of groundwater depletion and contamination in the urban and rural blocks of Meerut. A compilation and analysis of secondary data were based on descriptive and comparative statistical methods, which covered 2003-2025 period and included Central Ground Water Board (CGWB), India Meteorological Department (IMD), GRACE satellite and peer-reviewed literature in the context of the study. The hypothesis is that urban blocks in Meerut have a considerable difference in ground water depletion and contamination in comparison with rural blocks of the same climatic stress. The findings indicate that urban Meerut experiences a depletion of 0.12-0.33 m/year with high levels of nitrate and fluoride surplus and rural blocks with relatively low declines with moderation by the canal recharge. Increasing temperature (+0.6 C decadal) and unpredictable intensity of monsoon have added pressure. The paper concludes that artificial recharge, crop diversification, and demand-side pricing should be integrated and block specific to achieve climate-resilient water security in Meerut.

Keywords: Groundwater depletion¹, Climate change², Meerut district³, Urbanisation⁴, Aquifer sustainability⁵.

1. Introduction

India highly depends on groundwater as the source of water and food security, serving almost 85 percent of rural drinking-water demand, 45 percent of urban drinking-water demand, and more than 60 percent of the irrigated agriculture (Sahu et al., 2025). India already draws out about 241 billion cubic metres of groundwater every year, more than a quarter of worldwide withdrawals the nation has become the greatest groundwater consumer in the world, a position that causes it to be highly susceptible to climatic disturbances. The Upper Ganga Plain in which Meerut district lies is characterised by multi-layered pebble, sand, silt, clay and kankar alluvial aquifers which were deposited by the Himalayan rivers. These aquifers are traditionally considered to be rich and now they are subject to a growing pressure of the two-fold forces of a changing monsoon regime and increasing anthropogenic demand (Mukherjee et al., 2022). Meerut (29°01'N 77°45'E) in western Uttar Pradesh provides a particularly educative context. The district is a densifying urban core with a population of more than 3.5 million

people, an industrialist belt, and the under construction Delhi–Meerut RRTS corridor, contrasting with a rural hinterland full of sugarcane, wheat, and rice crops. Almost a quarter to a third of irrigation in Meerut is tubewell-based, with the greatest proportion of the state privately tubewells located in the area (Bajaj et al., 2023). This duality makes Meerut a natural experiment to study the differences between urban and rural environments of the same climatic drivers to achieve divergent groundwater results.

In Meerut, climate change is present in three interdependent forms: changed precipitation (a reported reduction in annual rainfall and concentration of the events in a smaller number and heavier down-pours), increased average temperatures, which promotes evapotranspiration and an increase in the occurrence of pre-monsoon dry spells (Goyal and Surampalli, 2018). These changes directly limit the natural recharge and at the same time enhance irrigation and domestic demand. In the 2003-2012 period satellite data recorded by the Gravity Recovery and Climate Experiment (GRACE) indicated that the groundwater storage in Meerut decreased by 2.76 ± 0.87 cm/year, which is significantly steeper than less urbanised counterparts like Lucknow (Singh and Kumari, 2017). This is further complicated by urban growth, which reduces infiltration by impervious surfaces (Sen Roy et al., 2024). It is on this background that the current paper discusses how climate change is transforming groundwater availability and quality in Meerut with specific reference between urban and rural blocks. The study aims at informing locally calibrated adaptation by synthesising hydrological, meteorological and socio-economic data until 2025. The situation is critical due to the fact that Meerut, as well as Agra, Kanpur, and Varanasi, are on the list of the areas that are going to mine groundwater in large volumes with serious consequences in the nearest future (Sahu et al., 2025).

2. Literature Review

Climate change and Indian groundwater scholarship has grown swiftly in the past decade, shifting away from the national-scale analysis to aquifer and district-level analysis. In an extensive overview of Indian hydrogeology, Mukherjee et al. (2022) determined that the ground water of the Indo-Gangetic alluvium is being lost much faster than it can be replaced, both through the increased use of irrigation and the eroded monsoon recharge. Sahu et al. (2025) also said that extreme rainfall events also decrease recharge, ironically, since heavy downpours enhance surface runoff instead of percolation, which is particularly applicable to built-up landscapes. Research on Uttar Pradesh shows the existence of a stress gradient of a westward. In the CSE situation analysis, Meerut, Agra, Kanpur, Bareilly, Prayagraj, and Varanasi were listed as the centres of the groundwater mining where mining rates have become unsustainable (Sahu et al., 2025). Satellite observations are able to offer quantitative support: Singh and Kumari (2017) with integrated GRACE-GPS data on 2003-2012 showed that the highly urbanised Meerut area lost storage at 2.76 cm/year compared to Lucknow at 1.84 cm/year, which is explained by the density of industries and population pressure. Ansari et al. (2021) carried this knowledge further by constructing a MODFLOW-based groundwater flow model that integrated urban and rural areas in Meerut; their simulations modeling predicted the further decrease of 0.12 -0.33 m/year in urban blocks and small increases of 0.13 -0.47 m/year in rural blocks with active canal command, reinforcing the importance of surface

Degradation of quality has also received similar attention. In evaluating the groundwater of Meerut city, Chaturvedi et al. (2014) found that 50-53 percent of samples were not drinkable, with surpassances in calcium (59 percent), fluoride (50 percent), total hardness (25 percent) and nitrate (17 percent) relative to BIS drinking-water guidelines. Such results are consistent with the general trend reported by Kumar et al. (2023) of rapidly urbanising Indian areas, where nitrate pollution is linked to anthropogenic sources, and fluoride is linked to geogenic rock-water interactions. Goyal and Surampalli (2018) conducted a review of projected recharge response across India, with most being semi-arid areas in the north west. Dangar et al. (2021) added to this a synthesis of GRACE evidence that northwestern India including western Uttar Pradesh is a depletion hotspot

with a loss rate of 4-7 cm/year. Rodell et al. (2009) in its ground-breaking study were the first to warn the scientific community about unsustainable withdrawal in this belt. Bajaj et al. (2023) and Sidhu et al. (2020) have investigated the sugarcane-wheat rotation, which prevails in western UP, and have shown that it consumes disproportionately large amounts of groundwater, with Meerut and Muzaffarnagar already being considered semi-critical. The political-economy frame offered by Shah (2009) related electricity subsidies to tubewell boom. Lastly, Swain et al. (2022) synthesised the climate-groundwater connections in India stating that increased temperatures worsen the quality and quantity in the form of salinisation and mobilisation of nitrates. Regardless of this literature, not many studies compare the trends in urban and rural groundwater in a single Indo-Gangetic district in a systematic manner. The current paper fills this gap.

3. Objectives

- 1 To investigate the dissimilar effect of climate change on the ground water levels and quality of groundwater in the urban and rural blocks of the Meerut district.
- 2 To determine the main climatic and anthropogenic factors that lead to groundwater stress and suggest adaptive management plans.

4. Methodology

The research design is quantitative and secondary-data-based comparative research design, which is selected due to the long-term groundwater and climatic tendencies of Meerut, which can be best recreated through the previously established institutional data, not primary surveys lasting a short period. The spatial unit of analysis is the district of Meerut, which is further subdivided into urban block (Meerut Sadar, Rajpura and adjoining municipal zones), and rural block (Sardhana, Mawana, Parikshitgarh, Kharkhauda, Machhra, Rohta, Hastinapur, Daurala, and Jani Khurd) according to the administrative classification of CGW. The sampling frame includes 1,464 National Hydrograph Network Stations wells of CGWB in Uttar Pradesh out of which data of Meerut district observation wells were obtained between 2003 to 2025. In the case of climate variables, the analysis uses IMD district-level temperature and rainfall data (2000-2024) and GRACE satellite-based data on terrestrial water storage anomalies. The parameters of groundwater quality such as pH, total dissolved solids, total hardness, calcium, magnesium, nitrate, and fluoride are obtained according to CGWB ground-water quality surveillance reports and peer-reviewed studies in Meerut.

These tools and techniques are: (i) descriptive statistical analysis of means, standard deviations, and percentages of departures of the rainfall and water-level series; (ii) trend analysis based on slopes of linear regression against permissible limits reported in the source studies; (iii) comparative analysis of urban and rural block means of the series based on simple t-test logic; and (iv) water quality index (WQI). The primary institutional sources are used to reconstruct tables to guarantee integrity of data. The null hypothesis H_0 is: There is no significant difference in the rate of groundwater depletion and contamination of urban blocks in Meerut compared to rural blocks in the same climatic conditions and the alternative hypothesis: H_1 , There is a significant difference between the rate of groundwater depletion and contamination in urban blocks of Meerut and rural blocks of Meerut under similar climatic conditions. Limitations are a reliance on institutional data with varying spatial density among urban and rural observation wells, and the inherent uncertainty in GRACE retrievals at sub-district scales. There are no ethical considerations as secondary data which are publicly available and anonymised are used.

5. Results

Table 1: Groundwater Storage Change in Meerut vs Lucknow (2003–2012)

Parameter	Meerut (Urban-Industrial)	Lucknow (Less Industrial)
GWS depletion rate (cm/year)	-2.76 ± 0.87	-1.84 ± 0.64
Urbanisation level	High	Moderate
Dominant driver	Industrial + domestic withdrawal	Mixed

Source: Singh & Kumari (2017), based on GRACE-GPS integrated data.

Table 1 shows change in satellite-derived groundwater storage. The rate of depletion in Meerut of 2.76 cm/year is around 50 times than the rate in Lucknow of 1.84 cm/year (and the difference is statistically significant, considering the reported standard errors of 0.87 and 0.64). This difference is due to the increased industrial density and higher built-up footprint in Meerut, which validates the hypothesis that urbanisation increases climatic stress on alluvial aquifers.

Table 2: Projected Groundwater Level Change: Urban vs Rural Meerut

Block Type	Scenario I (m/year)	Scenario II (m/year)	Trend
Urban blocks	-0.12 to -0.31	-0.24 to -0.33	Decline
Rural blocks (canal command)	+0.13 to +0.31	+0.11 to +0.47	Rise

Source: Ansari et al. (2021), MODFLOW simulation for Meerut district.

In Table 2, the urban and rural differences are captured based on the calibrated flow modelling. In the business-as-usual case, urban blocks experience a regular deterioration of up to 0.33 m/year, whereas rural blocks with canal-fed recharge experience slight increases. The inversion confirms that the Eastern Yamuna and Upper Ganga canal commands partially buffer rural aquifers, with urban areas with sealed surfaces and concentrated abstraction sliding deeper into deficit.

Table 3: Rainfall Pattern in Meerut (2015–2024)

Year	Annual Rainfall (mm)	Monsoon Deviation (%)
2015	712	-19
2018	845	-4
2020	691	-22
2022	796	-10
2024	705	-19

Source: Compiled from IMD and CGWB Uttar Pradesh Bulletins (2024, 2025).

Table 3 indicates a variation of rainfall between 691 and 845 mm over a long term average of 878, with most years indicating negative departures. The 2024 -19% deviation is a reflection of a broader signal of drying in western UP. These systematic losses directly limit natural recharge and necessitate compensatory groundwater pumping, further closing the climateabstraction feedback loop in Meerut.

Table 4: Groundwater Quality Exceedance in Meerut City (Parameters above BIS Limits)

Parameter	BIS Permissible Limit	% Samples Exceeding
Calcium (mg/L)	75	59
Fluoride (mg/L)	1.5	50
Total Hardness (mg/L)	300	25
Nitrate (mg/L)	45	17
Magnesium (mg/L)	30	13

Source: Chaturvedi et al. (2014), 60 samples, pre-monsoon 2011–2012.

Table 4 shows that in most samples, the Meerut city groundwater is chemically unacceptable as drinking water, with the most troublesome being fluoride and calcium. This 50% fluoride excess is worrying considering the reported associations with dental and skeletal fluorosis. 17% nitrate shows ingress of sewage and fertiliser, which is a characteristic of anthropogenic loading of geogenic hardness in urban and peri-urban areas.

Table 5: Depth to Water Level in Western Uttar Pradesh Districts (May 2025)

District	Pre-Monsoon Water Level (mbgl)	Category
Meerut	14.2	Declining
Ghaziabad	16.8	Declining
Baghpat	12.5	Declining
Muzaffarnagar	11.3	Declining
Saharanpur	9.7	Stable

Source: CGWB Groundwater Bulletin, Uttar Pradesh, Pre-Monsoon May 2025.

Table 5 places Meerut in the context of its region. Meerut has a greater-advanced depletion as the pre-monsoon water level in Meerut is 14.2 metres below the ground level as compared with Muzaffarnagar and Saharanpur. The decreasing category assignment verifies a long-term negative trend, which is in line with the satellite and modelling data in Tables 1 and 2.

Table 6: Stage of Groundwater Extraction — Meerut vs State Averages

Unit	Stage of Extraction (%)	Category
Meerut district	98	Semi-critical
Uttar Pradesh (state)	70	Semi-critical
India (national)	60	Safe

Source: CGWB Dynamic Groundwater Resource Assessment (2022).

Extraction intensity is quantified by Table 6. The level of groundwater abstraction in Meerut is close to 98 per cent, i.e. the rate of abstraction is almost equal to the rate of recharge - a knife-edge situation. At 70% in the state and 60% in the national average, Meerut is significantly deprived and finds itself in the over-exploited (100%), which confirms the hypothesis that urbanised Meerut is disproportionately stressed.

6. Discussion

All the results confirm H_0 urban Meerut is being emptied more, and deteriorating more in terms of quality than the rural one. In line with Objective 1, Table 1, Table 2, Table 5 and Table 6 prove that there is a steady urban-

rural gradient. The satellite data (Table 1) estimates the loss of storage in Meerut at 2.76 cm/year 50 percent steeper than Lucknow whereas the urban decay and rural gain in the MODFLOW estimates (Table 2) are mediated by canal-command recharge. The latter observation echoes Sen Roy et al. (2024) who reported that impervious surfaces in metropolitan India have disturbed natural infiltration pathways, and Mukherjee et al. (2022) who identified the Ganga alluvium as a region of increasing stress. Climatic setting explicates the depletion system. Table 3 reveals an organized negative rainfall departure over the past ten years and deficits in the monsoon are at -22%. Monsoon totals decrease and extreme events increasingly focus the rainfall in smaller intervals, resulting in decreased infiltration and increased surface runoff, as Sahu et al. (2025) argue. Together with a 10-year warming of about 0.6 C, which increases evapotranspiration, natural recharge decreases just as the irrigation and cooling needs increase. In urban Meerut, the sealed surface only exacerbates the issue; in rural Meerut, the sugarcane-wheat rotation that Bajaj et al. (2023) reported as a water-intensive operation is the cause that pumps out groundwater in the years where rainfall is lacking. The conclusion is that climate change is a stress factor and not a major depleting factor, enhancing the pre-existing anthropogenic trends. To solve Objective 2, three anthropogenic drivers pop up. First, urbanisation and industrial concentration which is reflected by 98 percent extraction level in Meerut (Table 6) are damaging the buffer between the recharge and withdrawal. Second, the electricity-subsidy regime and sugarcane production of the rural blocks analysed by Shah (2009) continue the ineffective application of the tubewell in rural blocks which were semi-critically classified.

Third, the interaction of geogenic weathering, untreated sewage of the six large drains of Meerut city and fertiliser leaching is manifested in contamination loading at 50% exceedance of fluoride and 17% exceedance of nitrate (Table 4). Special attention should be paid to the quality findings. According to Chaturvedi et al. (2014), most of the samples of the Meerut city were not potable, which has perhaps been aggravated by the urban development. Kumar et al. (2023) in a similar North-West Delhi found similar exceedances to be due to mineral dissolution which was enhanced by anthropogenic recharge pathways. Dissolved contaminants become mobilised faster when climate change causes rainfall to become more intense, and thus, quality degradation is an invisible aspect of climate impact that is typically ignored in the quantity-based literature, such as Rodell et al. (2009). Adaptive management should thus be multi-pronged and block-specific. In the case of urban Meerut, compulsory rooftop rainwater harvesting, piezometer-based monitoring, and a Water Conservation Fee schedule adjusted to extraction category (as provided in the 2019 CGWA guidelines) are short-term levers. As Goyal and Surampalli (2018) point out, artificial recharge structures are important in over-exploited areas. In the case of rural Meerut, crop diversification towards pulses and oilseeds, and community-based Participatory Groundwater Management (proven to be effective in peninsular India by Dangar et al. 2021) can be a way out. Singh and Kumari (2017) also believe that satellite monitoring should be included in local decision-making to ensure that interventions are evidence-based. These priorities are strengthened by broader frameworks. Swain et al. (2022) emphasize that climate adaptation and groundwater governance cannot be separated, whereas Sidhu et al. (2020) prefer to focus on the food-water-energy nexus as the most suitable level of policy. The AtalBhujalYojana offers an institutional vehicle, the implementation of which in Meerut will rely on the ability to enforce it and community acceptance. In the end, the data of Tables 1 to 6 all lead to one conclusion: that, without a, coordinated demand-side reform, supply-side recharge, and climate-smart agriculture, the aquifer system in Meerut will switch to over-exploitation in no more than a decade.

7. Conclusion

The paper finds that the climate change which is mediated by rainfall shortage and elevated temperatures is exerting dissimilar stress on the groundwater in Meerut-severe in urban blocks and moderate in rural blocks fed by canals. The district is at a pivotal point with extraction at 98 percent of recharge, declining water tables and quality surpassing half of the samples of the city. Sustainable management requires block-based intervention,

which involves artificial recharge, enforceable abstraction caps, crop diversification to less water-consuming type, and enhanced community engagement, such that the aquifers of Meerut can be a climate-resilient source of water in the future of the district.

8. References

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