Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Will climate change worsen the groundwater situation in India?

R K Ray

ranjanray-cgwb@gov.in

Rajiv Gandhi National Ground Water Training and Research Institute (RGNGWTRI), Central Ground Water Board, Ministry of Jal Shakti, Government of India

Rumi Mukherjee

Rajiv Gandhi National Ground Water Training and Research Institute (RGNGWTRI), Central Ground Water Board, Ministry of Jal Shakti, Government of India

Article

Keywords:

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11037756/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Will climate change worsen the groundwater situation in India?

R K Ray* and Rumi Mukherjee

Rajiv Gandhi National Ground Water Training and Research Institute (RGNGWTRI), Central Ground Water Board, DoWR, RD&GR, Ministry of Jal Shakti, Government of India, Sector 23, Nava Raipur, Chhattisgarh, India. Email: ranjanray-cgwb@gov.in

*Corresponding author email: ranjanray-cgwb@gov.in

Abstract

Groundwater is the major source of water for irrigation and domestic use in India, and increasing groundwater stress has raised concerns about the potential effects of climate change on groundwater resources. This study assesses whether projected changes in precipitation could adversely affect natural groundwater recharge across India. Daily precipitation data from the INDRA-CMIP6 dataset, based on 14 CMIP6 climate models and a multi-model ensemble at 0.1° × 0.1° resolution, were analysed under the SSP2-4.5 scenario. Changes in rainfall amount and the number of rainy days were assessed for all the 800 districts in India by comparing 2050–2059 with the baseline period 2020–2029. The analysis was carried out separately for annual, monsoon and non-monsoon periods, and districts were classified into six categories according to the combined changes in rainfall and rainy-day frequency. The results indicate a generally favourable annual precipitation regime, with mean annual rainfall projected to increase by 6.36% and rainy days by 2.93%. During the monsoon, 681 districts (85.1%) show improved recharge conditions, while none shows deterioration. However, 158 districts show potentially declining recharge conditions during the non-monsoon period, particularly in Uttar Pradesh, Haryana, Punjab, Rajasthan, Delhi and the Bundelkhand Region.

1. Introduction

Groundwater remains a major source of freshwater worldwide; however, dependence on groundwater in India is considerably higher than the global average. Globally, groundwater is estimated to provide approximately 42% of the water used for irrigated agriculture and about 36% of potable water supplies [1]. In India, more than 80% of domestic water supplies are served by groundwater [2]. Similarly, wells constituted the largest source of irrigation in India, accounting for approximately 60.5% of the country's net irrigated area in 2021–22, compared with 24.7% supplied by canals [3]. This heavy dependence on groundwater, however, has come at a considerable cost.

The emerging concern over groundwater stress in India is not new. Groundwater stress as a potential challenge for India was recognised as early as 1979, when the Groundwater Overexploitation Committee was constituted [4]. Over the past five decades, groundwater depletion and overexploitation have emerged as one of the most discussed topics in the field of groundwater research in India. Early assessments by the Central Ground Water Board [5] documented growing pressures on groundwater resources, while subsequent studies have highlighted the extent, drivers and implications of groundwater depletion across the country [6–9]. Satellite-based observations have provided compelling evidence of substantial groundwater losses in northwestern India [6], while more recent studies have highlighted the implications of groundwater depletion for agricultural sustainability and food and water security [9].

The latest assessment of the Dynamic Ground Water Resources of India for 2025 indicates that nearly one-fourth (24.98%) of the assessment units in the country are classified as semi-critical, critical or over-exploited, reflecting the widespread pressure on groundwater resources across the country [10].

Climate change is expected to alter multiple factors governing groundwater recharge, withdrawal and quality. Changes in precipitation amount and the number of rainy days may directly affect groundwater recharge, while rising temperatures may increase irrigation demand and, consequently, groundwater abstraction. Sea-level rise may further increase the risk of seawater intrusion and salinisation of coastal aquifers. These processes are closely interconnected, creating a complex interplay of climate and groundwater responses (Fig. 1).

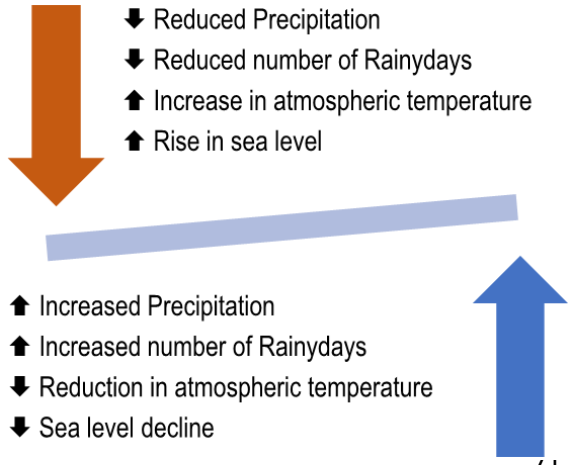


Fig.1.Possible impacts of climate change on groundwater regine

Numerous studies have examined the potential impacts of climate change on groundwater systems. Green et al. [11] reviewed groundwater responses to changes in precipitation, evapotranspiration and recharge, while Amanambu et al. [12] provided a comprehensive assessment of climate–groundwater interactions and future research needs. Davamani et al. [13] further reviewed the application of simulation models for assessing climate-change impacts on groundwater. For India, Krishnan et al. [14] provide the most comprehensive assessment of observed and projected climate change over the Indian region, including changes in temperature, precipitation and the monsoon; however, the assessment does not explicitly quantify the implications for groundwater recharge. Swain et al. [15] similarly highlighted the complex and uncertain effects of climate variability on groundwater systems. Bhattarai et al. [16], using historical groundwater, climate and crop-water-stress data, projected that net groundwater loss during 2041–2080 could reach approximately three times the current depletion rate. Conversely, Abeysingha et al. [17] found that increased rainfall could reduce irrigation requirements for rice despite higher evapotranspiration under future climate scenarios. Collectively, these studies demonstrate that climate change can affect groundwater through multiple and sometimes opposing pathways, but provide limited clarity on the likely direction and magnitude of changes in natural groundwater recharge across India. Further, most studies on the impacts of climate change consider multiple pathways and interacting parameters, making it difficult to derive clear policy directions or establish priorities. Despite the inherent uncertainties in climate projections, clearer and more focused assessments are essential for informed mitigation and adaptation planning.

The central question, therefore, is: will climate change worsen the groundwater situation in India? Recognising the complexity and uncertainty involved, we narrow this question to a more specific and measurable one: will climate change reduce natural groundwater recharge in India? As a deliberate simplification to provide clearer policy guidance, man-made water-related interventions and factors such as sea-level rise are excluded from the analysis. Using the most probable climate scenario, we categorise Indian districts into six categories based on projected changes in groundwater recharge, comparing conditions during 2050–2059 with the baseline period of 2020–2029. This simplified approach aims to provide a scientifically defensible and policy-relevant assessment of the likely direction of change in groundwater recharge across India.

2. Materials and Methods

2.1 Climate Projection Dataset

The study uses the INDRA-CMIP6 dataset developed by Mandal et al. [18], titled Indian Subcontinent high Resolution Downscaled pRecipitation and Air temperature data from CMIP6.
The dataset provides daily precipitation and maximum and minimum temperature data based on 14 CMIP6 general circulation models (GCMs), together with a multi-model ensemble. The dataset was

developed using the Daily Bias Correction with Constructed Analogs (DBCCA) approach at a spatial resolution of 0.1° × 0.1°.

The INDRA-CMIP6 dataset provides high-resolution climate projections for the Indian subcontinent and was used as the primary climate-projection dataset for assessing projected changes in precipitation characteristics. The dataset has also been endorsed by the Government of India through a Press Information Bureau release dated 15 May 2026.

2.2 Parameters and SSP Selection

The analysis focuses on precipitation volume and its temporal distribution, represented by two parameters: rainfall volume and the number of rainy days. A rainy day was defined as a day receiving at least 2.5 mm of rainfall [19].

Among the multiple Shared Socioeconomic Pathway (SSP) scenarios, SSP2-4.5 was selected for the analysis. SSP2 represents a middle-of-the-road socioeconomic development pathway [20]. Baldassare and Reichler [21] proposed a framework for identifying likely climate projections and applied it using SSP2-4.5, while Huard et al. [22] assessed the likelihood of greenhouse-gas concentration scenarios using probabilistic integrated assessment model simulations. SSP2-4.5 was therefore considered a plausible representation of the future emissions trajectory for the present assessment.

Although climate-driven warming may affect groundwater recharge through increased evaporative demand [23], temperature was not explicitly included in the present assessment. Analyses using the FAO-56 Penman–Monteith method show that, at Akola, a 1°C increase in mean air temperature increased annual ET_0 by approximately 2.2% [24]. CMIP6 projections indicate an additional 1.2–1.3°C warming over India by mid-century under SSP2-4.5 relative to 1995–2014 [25]. The corresponding warming relative to the 2020–2029 baseline is expected to be substantially smaller; hence, the associated increase in ET_0 is likely to be modest.

2.3 Categorisation Scheme and Computational Procedure

This study compares the ten-year average rainfall and the average number of rainy days during 2050–2059, representing the near-future period, with those during 2020–2029, considered the baseline period. The overall data-processing workflow adopted in the study is presented in Fig. 2. The INDRA-CMIP6 dataset, available as a single NetCDF (.nc) file, contains daily precipitation data at the grid-cell level.

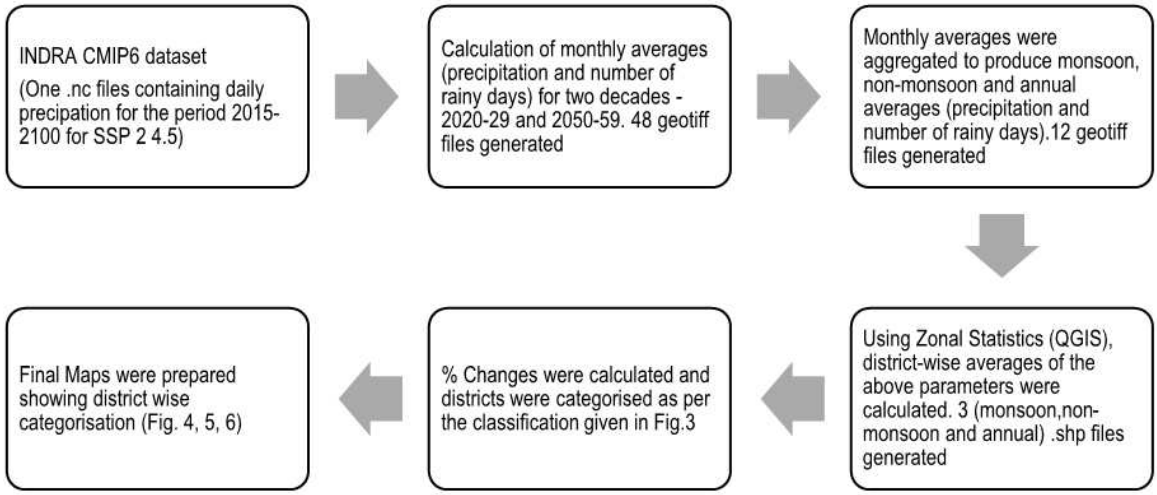


Fig.2 Data-processing workflow adopted in the study

These data were processed to aggregate daily precipitation records and generate ten-year monthly average rainfall datasets in GeoTIFF format. Monthly maps representing the ten-year average number

of rainy days were also prepared from the daily precipitation data. The resulting gridded datasets were subsequently spatially aggregated to derive district-wise average rainfall and average number of rainy days, allowing projected changes to be assessed at the district level. The analyses were performed using Python [version] within the Spyder IDE [version], using the Anaconda distribution [version]. Geospatial data processing and spatial analysis were performed using QGIS 3.40

For each district, the percentage change in precipitation and the number of rainy days between the near-future period (2050–2059) and the baseline period (2020–2029) was calculated. A threshold of ±5% was adopted to distinguish relatively small changes from those considered significant. Changes exceeding +5% or falling below −5% were considered significant, whereas changes within ±5% were considered not significant. Based on the direction and significance of changes in precipitation and the number of rainy days, nine possible combinations were identified, as shown in Fig. 3. These combinations represent the different ways in which the two parameters may change simultaneously and were used to assess their potential implications for groundwater recharge.

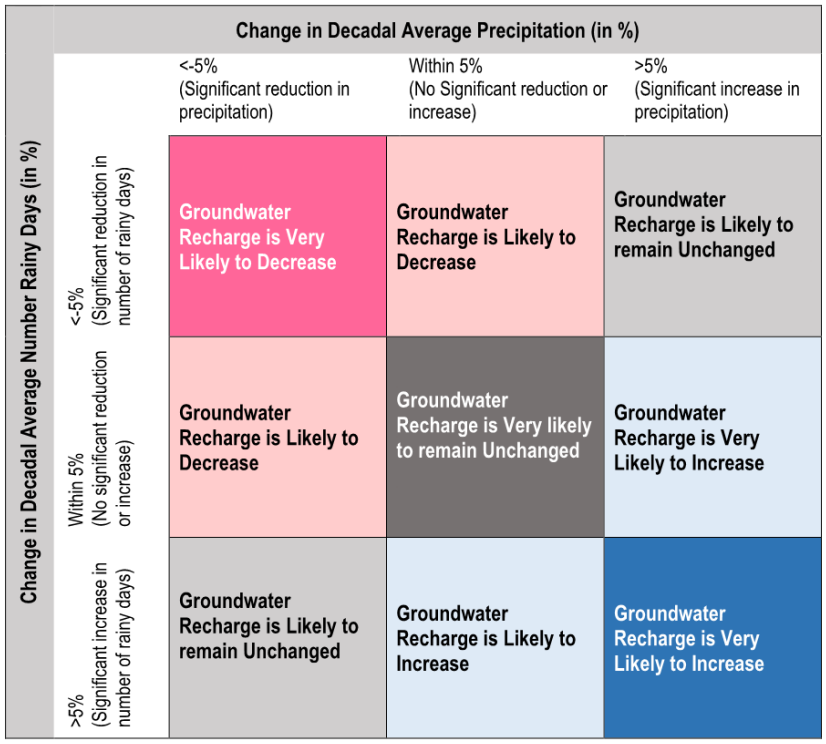


Fig.3: Criteria for categorisation of districts

The nine combinations were subsequently regrouped into six broader categories based on the expected combined influence of precipitation and rainy-day frequency on groundwater recharge. Where both precipitation and the number of rainy days remain within ±5% of the baseline values, groundwater recharge is considered very likely to remain unchanged. Where one parameter increases while the other decreases, the opposing effects are considered likely to offset one another, and groundwater recharge is classified as likely to remain unchanged. Where both precipitation and the number of rainy days increase, the combined effect is expected to favour recharge, and groundwater recharge is considered very likely to increase. Where one parameter increases while the other remains within the ±5% range, groundwater recharge is considered likely to increase, reflecting the positive influence of the increasing parameter. Conversely, where both precipitation and the number of rainy days decrease, the combined effect is expected to adversely affect recharge, and groundwater recharge is considered very likely to decrease. Finally, where one parameter decreases while the other remains within the ±5% range, groundwater recharge is classified as likely to decrease.

Accordingly, the six categories used in the study are: (i) Groundwater Recharge is **Very Likely to Remain Unchanged**—both precipitation and rainy days remain within ±5%; (ii) Groundwater Recharge is **Likely to Remain Unchanged**—precipitation increases while rainy days decrease, or vice versa; (iii) Groundwater Recharge is **Very Likely to Increase**—both precipitation and rainy days increase; (iv) Groundwater Recharge is **Likely to Increase**—one parameter increases while the other remains within ±5%; (v) Groundwater Recharge is **Very Likely to Decrease**—both precipitation and

rainy days decrease; and (vi) Groundwater Recharge is **Likely to Decrease**—one parameter decreases while the other remains within ±5%.

The analysis was carried out separately for the annual, monsoon and non-monsoon periods to capture seasonal differences in precipitation and rainy-day frequency. In accordance with the seasonal classification adopted by the India Meteorological Department [19], the monsoon period was defined as June, July, August and September (JJAS). The remaining months, namely October to May, were collectively considered the non-monsoon period. For simplicity and to maintain a consistent two-season framework, the winter monsoon was not treated as a separate season in this analysis. This classification was applied consistently to both precipitation and rainy-day calculations for the baseline and near-future periods.

3. Results and Discussions

3.1 Changes during monsoon

The change in mean monsoon rainfall between the two periods ranges from +0.82% in Srinagar, Jammu and Kashmir, to +20.32% in Devbhumi Dwarka, Gujarat. Notably, all 800 district observations show either an increase in mean monsoon rainfall or no significant change. Thus, not a single district in the dataset is projected to experience a significant decline in mean monsoon rainfall between 2020–2029 and 2050–2059. The pattern of change in rainy-day frequency is somewhat different, with percentage changes ranging from −1.96% in Sant Ravidas Nagar, Uttar Pradesh, to +23.15% in Devbhumi Dwarka, Gujarat. However, the decline in rainy-day frequency remains relatively small, with no district showing a reduction exceeding 5%.

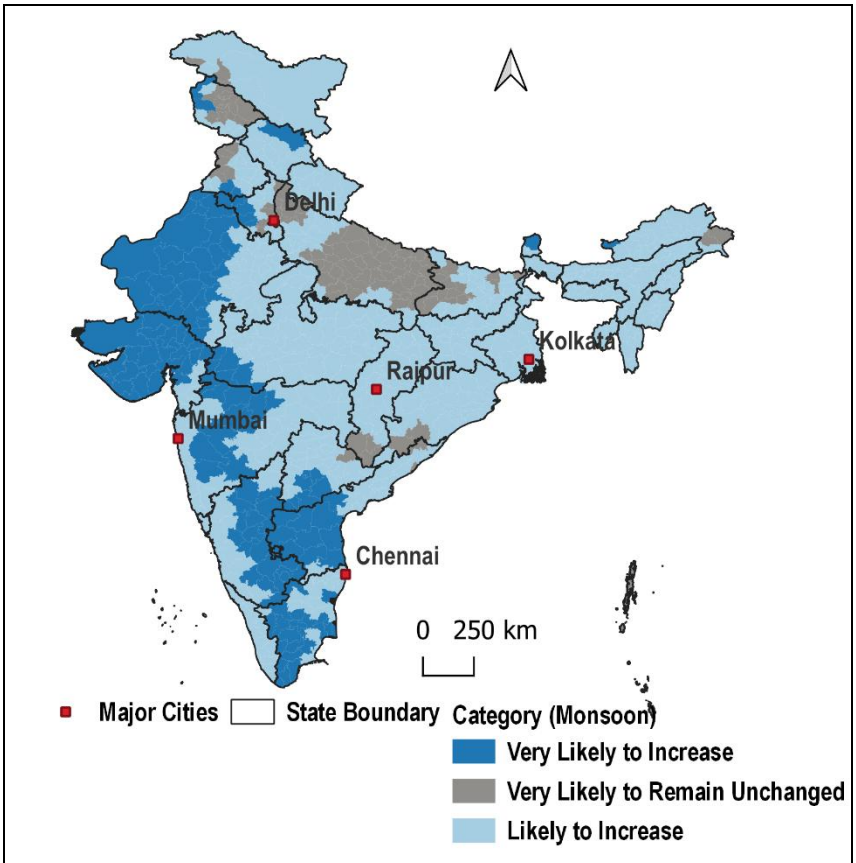


Fig. 5:Projected changes in groundwater recharge in monsoon seasib during the period 2050-59

When changes in rainfall amount and rainy-day frequency are considered together, 681 districts, representing 85.1% of the 800 observations, fall into one of the two categories indicating improved groundwater-recharge conditions. The remaining 14.9% of districts show no significant change. Notably, no district is classified as experiencing deterioration in groundwater-recharge conditions during the monsoon period.

The analysis of data for the monsoon period therefore indicates that projected changes in precipitation under SSP2-4.5 are broadly favourable for the climatic conditions associated with groundwater recharge during India's principal rainy season. This finding is particularly relevant because monsoon

precipitation constitutes the dominant source of natural groundwater recharge across large parts of the country (Table 1).

3.2 Changes during non-monsoon

The non-monsoon results reveal substantially greater spatial variability than those observed during the monsoon period.

The non-monsoon analysis identifies 383 districts as having a potential increase in groundwater-recharge conditions, while a further 255 districts show no significant change. In contrast, 158 districts are classified as showing a potential decrease in groundwater-recharge conditions. Two districts show an uncertain recharge response because changes in rainfall amount and rainy-day frequency do not provide a consistent indication of the direction of change.

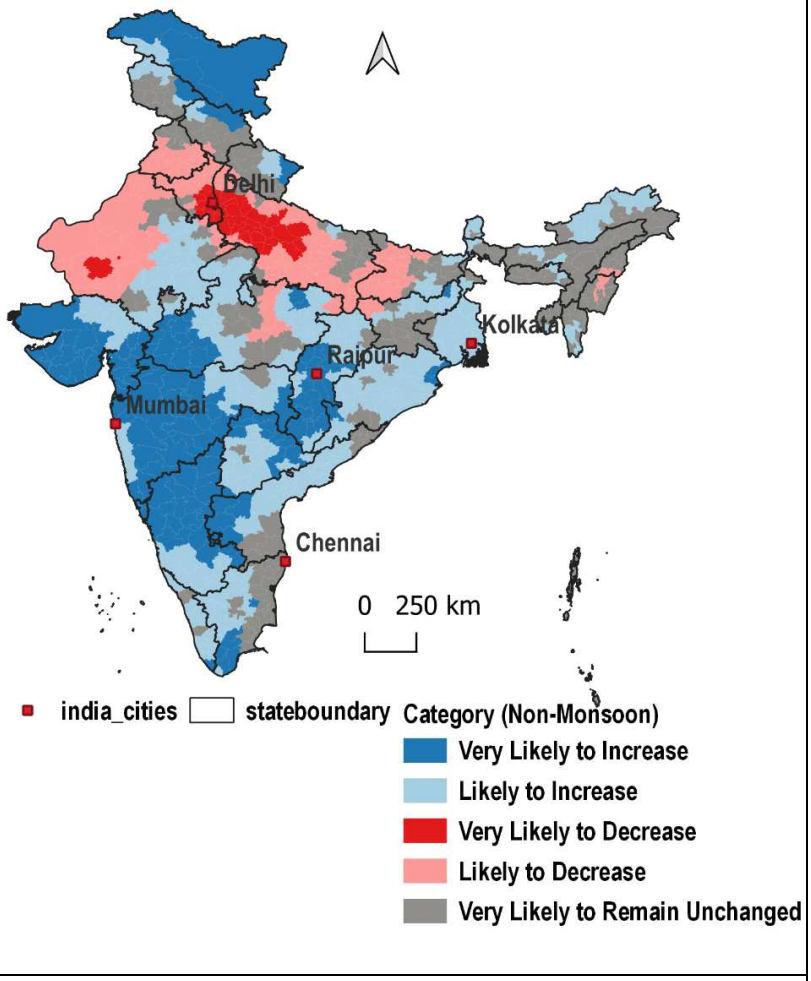


Fig. 6:Projected changes in groundwater recharge in non-monsoon seasib during the period 2050-59

The magnitude of change in non-monsoon rainfall is considerably more variable than that observed during the monsoon. Rainfall change ranges from −8.73% in Farrukhabad, Uttar Pradesh, to +20.05% in South Goa, Goa. Variation in rainy-day frequency is even more pronounced, ranging from −66.08% in Balotra, Rajasthan, to +89.62% in Anand, Gujarat. Thus, changes in the frequency of rainfall events during the non-monsoon period are substantially larger, in relative terms, than changes in total rainfall.

The strongest concentration of districts showing potential decreases in recharge occurs in Uttar Pradesh, Haryana, Punjab, Delhi, Bihar and Chandigarh. These areas are particularly significant because many are already characterised by substantial dependence on groundwater and, in several cases, serious groundwater depletion. The spatial coincidence between existing groundwater stress and projected deterioration in non-monsoon recharge conditions is therefore an important finding of the analysis.

The significance of these projected changes is, however, moderated by the relatively small contribution of non-monsoon rainfall to annual rainfall-derived groundwater recharge. According to CGWB [10], rainfall contributes about 269.17 BCM to the total annual groundwater recharge in India, of which approximately 245.36 BCM occurs during the monsoon and only 23.81 BCM during the non-monsoon period. Thus, non-monsoon rainfall accounts for less than 10% of the country's annual rainfall-derived groundwater recharge. The contribution is particularly small in Rajasthan (2.4%), Uttar Pradesh (2.0%)

and Delhi (8.3%), while it is higher in Haryana (16.4%) and Punjab (13.3%). In Bihar, Jharkhand, Nagaland and Manipur, non-monsoon rainfall contributes approximately 5.5%, 8.7%, 25.0% and 16.3%, respectively, of rainfall-derived annual groundwater recharge. Consequently, projected deterioration in non-monsoon recharge conditions is unlikely to substantially offset the favourable changes projected for the monsoon period in Rajasthan, Uttar Pradesh, Delhi, Bihar and Jharkhand, where the non-monsoon contribution is relatively small. In contrast, the relatively greater contribution of non-monsoon rainfall in Haryana, Punjab, Nagaland and Manipur suggests that adverse changes during this period could have a more appreciable influence on overall rainfall-derived groundwater recharge.

3.3 Annual Changes

At the annual scale, the results indicate an overall improvement in the precipitation regime across the country between the two periods.

The increase in recharge potential is supported by projected increases in both precipitation and the number of rainy days. Mean annual precipitation increases from approximately 1,410 mm during 2020–2029 to 1,498 mm during 2050–2059, representing an increase of approximately 88 mm (6.36%). Over the same period, the mean number of rainy days increases from 144.2 to 147.7 days, an increase of approximately 3.5 days (2.93%). Thus, the projected increase in rainfall amount is considerably greater, in relative terms, than the increase in the number of rainy days.

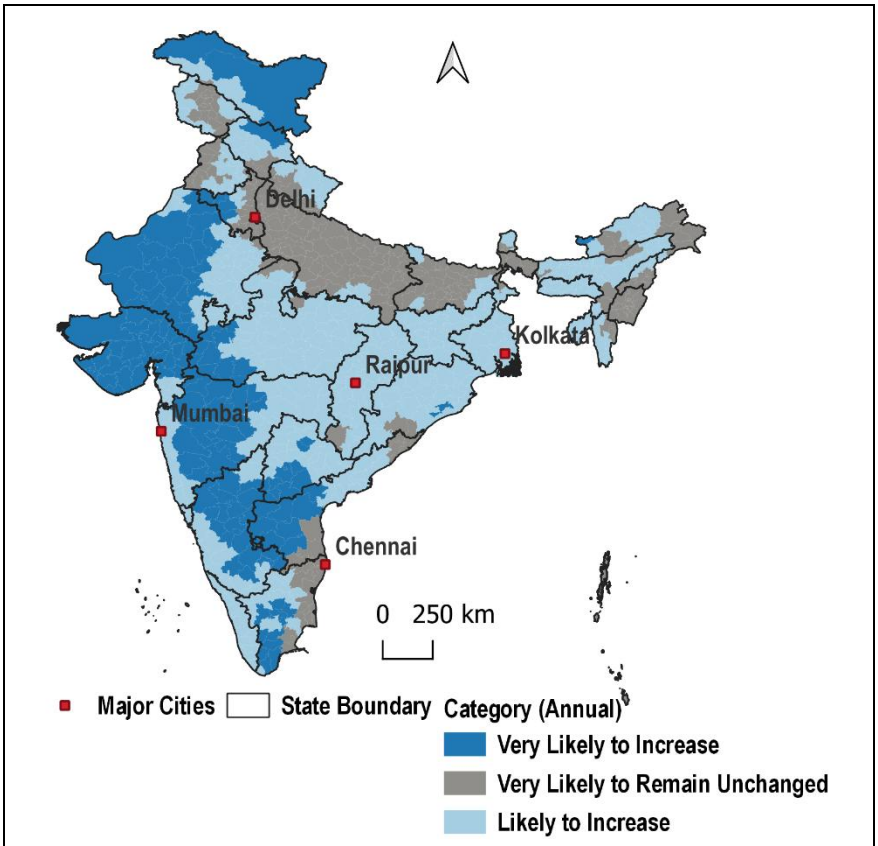


Fig. 6:Projected annual changes in groundwater recharge during the period 2050-59

At the district level, the annual percentage change in rainfall ranges from a minimum of −0.54% in Chennai district, Tamil Nadu, to a maximum of nearly 20% in Devbhumi Dwarka district, Gujarat. A similar spatial variation is observed in the number of rainy days, with percentage changes ranging from approximately −4% in Rupnagar, Punjab, to approximately 24% in Devbhumi Dwarka, Gujarat.

Of the 800 districts considered in the analysis, 537 (67.1%) are classified as showing some improvement in groundwater-recharge conditions, while approximately one-third show no significant change. Importantly, none of the observations is classified as showing deterioration in groundwater-recharge conditions at the annual scale.

The annual analysis therefore presents a predominantly favourable picture when changes in precipitation amount and rainy-day frequency are considered together. Although some districts show deterioration in recharge conditions during the non-monsoon period, the magnitude of these changes is

likely to have a limited influence on the annual recharge regime because non-monsoon rainfall contributes only a relatively small proportion of rainfall-derived groundwater recharge in most parts of the country. In contrast, the projected increase in precipitation and rainy-day frequency during the monsoon period, which is the principal season of groundwater recharge across much of India, provides a stronger positive contribution to the annual precipitation regime. Thus, the favourable changes projected for the monsoon period are likely to offset, at the annual scale, the less favourable changes observed during the non-monsoon period. The annual results consequently suggest that, despite localised deterioration during the non-monsoon period, the overall climatic conditions influencing groundwater recharge are likely to remain favourable or improve under SSP2-4.5.

Table 1: Summary of Districts showing changes in groundwater recharge in 2050-59

	Number and Percentage of Districts in different periods.		
Category	**Monsoon**	**Non Monsoon**	**Annual**
Groundwater Recharge is Very Likely to Increase	141 (18%)	141 18%)	138 (17%)
Groundwater Recharge is Likely to Increase	540 (67%)	238 30%)	399 (50%)
Groundwater Recharge is Very Likely to Remain Unchanged	119 (15%)	248 (31%)	263 (33%)
Groundwater Recharge is Likely to remain Unchanged	0	2 (1%)	0
Groundwater Recharge is Very Likely to Decrease	0	48 (6%)	0
Groundwater Recharge is Likely to Decrease	0	110 (14%)	0

3.4 Implications for Groundwater Management

The results have important implications for groundwater management and policy in India. The projected increase in precipitation during the monsoon period, together with the predominance of districts showing improved or unchanged annual recharge conditions, indicates that climate change is unlikely to adversely affect groundwater recharge uniformly across the country. However, the concentration of districts showing potentially less favourable recharge conditions during the non-monsoon period in several groundwater-stressed regions indicates that existing groundwater-management challenges may become more difficult in these areas.

The northern and northwestern parts of the country require particular attention in this context. Punjab, Haryana, Delhi, Uttar Pradesh, Rajasthan and parts of Bihar contain a large number of districts where the projected non-monsoon precipitation regime is less favourable. Similar conditions are projected in the Bundelkhand region of Uttar Pradesh and Madhya Pradesh, as well as parts of Jharkhand. These regions already experience substantial dependence on groundwater and, in several cases, persistent groundwater depletion. A less favourable precipitation regime during the non-monsoon period, when groundwater dependence for irrigation and other uses is generally high, could therefore add further pressure on already stressed aquifers. The results reinforce the need to sustain and, where necessary, intensify groundwater-conservation and demand-management measures in these regions. District-level prioritisation can be guided by the detailed results provided in the Supplementary Information.

The projected changes in Nagaland and Manipur require a somewhat different interpretation. Although some districts in these states show significant changes in non-monsoon precipitation or rainy-day frequency, the potential implications for groundwater recharge are likely to be less severe than in the drier northern and northwestern regions. These states receive substantially higher rainfall, and the relatively limited reduction in precipitation or rainy-day frequency projected in the non-monsoon period is unlikely, by itself, to result in a substantial deterioration of annual groundwater-recharge conditions. Nevertheless, local variations in hydrogeological conditions and groundwater dependence should be considered when developing state- or district-level management strategies.

An important positive implication of the analysis is the projected increase in annual precipitation even in several traditionally low-rainfall regions, including Rajasthan, Haryana, Punjab, Delhi and the

Bundelkhand region of Uttar Pradesh and Madhya Pradesh. These areas are also characterised by substantial groundwater stress and have considerable potential for artificial groundwater recharge. A major constraint to artificial-recharge planning in these regions, however, is the limited availability of surplus or non-committed source water [26]. The projected increase in precipitation, particularly during the monsoon period, could potentially improve the availability of source water for recharge interventions and thereby increase the feasibility of artificial-recharge measures.

4. Conclusion

The answer to the question, "Will climate change worsen the groundwater situation in India?", is likely to be more definite the less one understands the complexities of climate change and groundwater dynamics. Having said that, our analyses indicate that, in comparison with the current situation (2020–2029), in the near future (2050–2059), under the most probable climate scenario (SSP2-4.5), annual recharge conditions are likely to improve in 537 of 800 districts (67.1%), with the remaining districts largely showing no significant change and none showing deterioration. During the monsoon, 681 districts (85.1%) show improved recharge conditions, again with no district showing deterioration.
These findings represent changes in recharge conditions rather than projections of groundwater levels or availability, as abstraction, irrigation demand, land-use change and aquifer characteristics were not explicitly considered. The projected improvement should therefore not be interpreted as a basis for relaxing the ongoing groundwater-management efforts.

The principal concern emerges during the non-monsoon period, when 158 districts show potentially less favourable recharge conditions. These are concentrated particularly in Punjab, Haryana, Delhi, Uttar Pradesh, Rajasthan and Bundelkhand, where high groundwater dependence and existing groundwater stress could make seasonal reductions in recharge more consequential. These areas therefore warrant continued emphasis on groundwater conservation, demand management and district-level prioritisation.
An important management opportunity is the projected increase in precipitation, particularly during the monsoon, even in several groundwater-stressed and relatively low-rainfall regions such as Rajasthan, Haryana, Punjab, Delhi and Bundelkhand. Greater monsoon rainfall could increase the availability of surplus source water, currently a major constraint on artificial recharge, and thereby improve opportunities for managed aquifer recharge where suitable hydrogeological conditions exist.

Funding Declaration

No funding was received for this research.

Data Availability

The output datasets produced as a part of this study and the python codes are provided as supplementary material along with this manuscript.

References

1. Food and Agriculture Organization of the United Nations. Why 'groundwater governance' matters now. FAO, Rome (2015).
2. World Bank. World Bank signs agreement to improve groundwater management in select states of India. Press release, 17 February 2020.
3. Central Water Commission. Water and Related Statistics – 2023. Basin Planning & Management Organisation, Central Water Commission, Ministry of Jal Shakti, Government of India, New Delhi (2023).
4. Mukherji, A. & Shah, T. Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeol. J. 13, 328–345 (2005).
5. Central Ground Water Board. Ground Water Resource Estimation Methodology, 1984. Ministry of Water Resources, Government of India, New Delhi (1984).

6. Rodell, M., Velicogna, I. & Famiglietti, J. S. Satellite-based estimates of groundwater depletion in India. Nature 460, 999–1002 (2009).
7. Saha, D. & Ray, R. K. Groundwater resources of India: potential, challenges and management. In Groundwater Development and Management: Issues and Challenges in South Asia (ed. Sikdar, P. K.), 19–42 (Springer, Singapore, 2019).
8. Saha, D., Marwaha, S. & Mukherjee, A. Groundwater resources and sustainable management issues in India. In Clean and Sustainable Groundwater in India (eds Saha, D., Marwaha, S. & Mukherjee, A.), 1–11 (Springer, Singapore, 2018).
9. Devineni, N., Perveen, S. & Lall, U. Solving groundwater depletion in India while achieving food security. Nat. Commun. 13, 3374 (2022).
10. Central Ground Water Board. National Compilation on Dynamic Ground Water Resources of India, 2025. Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India, New Delhi (2025).
11. Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., Treidel, H. & Aureli, A. Beneath the surface of global change: impacts of climate change on groundwater. J. Hydrol. 405, 532–560 (2011).
12. Amanambu, A. C. et al. Groundwater system and climate change: present status and future considerations. J. Hydrol. 589, 125163 (2020).
13. Davamani, V. et al. A critical review of climate change impacts on groundwater resources: a focus on the current status, future possibilities, and role of simulation models. Atmosphere 15, 122 (2024).
14. Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A. & Chakraborty, S. (eds). Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India. Springer, Singapore (2020).
15. Swain, S., Taloor, A. K., Dhal, L., Sahoo, S. & Al-Ansari, N. Impact of climate change on groundwater hydrology: a comprehensive review and current status of the Indian hydrogeology. Appl. Water Sci. 12, 120 (2022).
16. Bhattarai, N. et al. Warming temperatures exacerbate groundwater depletion rates in India. Sci. Adv. 9, eadi1401 (2023).
17. Abeysingha, N. S. et al. Climate change impacts on irrigated rice and wheat production in Gomti River basin of India: a case study. SpringerPlus 5, 1250 (2016).
18. Mandal, J. et al. INDRA-CMIP6: Indian subcontinent high resolution Downscaled pRecipitation and Air temperature data from CMIP6. Sci. Data 13, 1038 (2026).
19. India Meteorological Department. Rainfall Trends over India during 1901–2020. Climate Research and Services, Ministry of Earth Sciences, Government of India, Pune (2024).
20. Intergovernmental Panel on Climate Change. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds Masson-Delmotte, V. et al.). Cambridge University Press, Cambridge (2021).
21. Baldassare, D. & Reichler, T. A simple framework for likely climate projections applied to tropical width. Clim. Dyn. 62, 8441–8451 (2024).
22. Huard, D., Fyke, J., Capellán-Pérez, I., Matthews, H. D. & Partanen, A.-I. Estimating the likelihood of GHG concentration scenarios from probabilistic integrated assessment model simulations. Earth's Future 10, e2022EF002715 (2022).
23. Banerjee, C., Sharma, A. & Kumar, N. D. Decline in terrestrial water recharge with increasing global temperatures. *Sci. Total Environ.* **764**, 142913 (2021). https://doi.org/10.1016/j.scitotenv.2020.142913.
24. Priya, A., Nema, A. K., Islam, A. & Sikka, A. K. Assessing sensitivity of reference evapotranspiration to changes in climatic variables: a case study of Akola, India. *Mausam* **66**, 777–784 (2015). https://doi.org/10.54302/mausam.v66i4.585
25. Dhara, C., Deshpande, A., Roxy, M. K., Dalpadado, P. & Shrestha, M. S. A post-AR6 update on observed and projected climate change in India. *PLOS Clim.* **4**, e0000724 (2025). https://doi.org/10.1371/journal.pclm.0000724

505 26. Central Ground Water Board. Master Plan for Artificial Recharge to Groundwater in India –
506 2020. Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga
507 Rejuvenation, Government of India, New Delhi (2020)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- OutputMapsRayandMuherjee.zip