

Spatial Assessment of Drought and Water Scarcity in the Bundelkhand Region, India: A GIS and Remote Sensing–Based Review and Synthesis

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Abstract

The Bundelkhand region of central India, spanning parts of Uttar Pradesh and Madhya Pradesh, is among the most chronically drought-affected tracts of the country, owing to its hard-rock craton geology, low and erratic monsoon rainfall, and a predominantly rain-fed agrarian economy. Over the last decade, Geographic Information Systems (GIS) and remote sensing (RS) have become the principal tools for characterising meteorological drought, delineating groundwater potential, and monitoring land and vegetation stress across this data-sparse terrain. This paper synthesises peer-reviewed GIS- and RS-based studies (2015–2025) on drought and water scarcity in Bundelkhand to build an integrated understanding of the region's hydro-meteorological vulnerability. Following a structured literature-synthesis methodology, sources were screened from Scopus-indexed journals (ScienceDirect, Springer, MDPI, ASCE, and MAUSAM) using combinations of the terms "Bundelkhand," "drought," "groundwater potential," "GIS," and "remote sensing." The synthesis shows that (i) the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) consistently reveal declining monsoon rainfall and rising drought frequency in the northern districts (Jalaun, Hamirpur, Lalitpur, Banda), (ii) frequency-ratio and multi-influencing-factor GIS models classify roughly one-third of the craton as having only low-to-very-low groundwater potential, concentrated in high-slope, low-rainfall, built-up terrain, and (iii) groundwater-dependent ecosystems and streamflow indices corroborate an intensifying hydrological drought signal since the 1980s. A clear research gap emerges: existing studies treat meteorological drought indices, groundwater potential zonation, and vegetation-stress monitoring as separate exercises, rarely integrated into a single, updateable, cross-state spatial decision-support framework. The paper concludes by proposing such an integrated, cloud-based GIS-RS framework, combining SPI/SPEI time series, GRACE-based groundwater storage anomalies, and Google Earth Engine–processed vegetation indices, to support evidence-based drought

mitigation and groundwater management across the entire Bundelkhand craton.

Keywords: Bundelkhand; drought; water scarcity; GIS; remote sensing; groundwater potential zones; Standardized Precipitation Index; semi-arid central India

1. Introduction

Drought is among the most economically and socially damaging natural hazards affecting rain-fed agricultural regions of the world, and India's semi-arid interior is particularly vulnerable because of its dependence on the summer monsoon for both surface- and groundwater recharge [Patidar et al., 2024]. The Bundelkhand region of central India—comprising districts of southern Uttar Pradesh (Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda, Chitrakoot) and northern Madhya Pradesh (Sagar, Damoh, Tikamgarh, Chhatarpur, Panna, Datia, Chhatarpur)—has experienced repeated and increasingly severe droughts, most notably the consecutive rainfall failures of 2004–06 and 2014–16 [Gupta et al., 2014]. The region's vulnerability is compounded by its underlying geology. Bundelkhand sits atop one of the oldest cratonic shields in the world, dominated by coarse- and fine-grained granite, granite-gneiss, and metasediments with very low primary porosity [Kumar et al., 2022]. Groundwater therefore occurs mainly in weathered and fractured zones with limited storage, so that shallow wells and hand pumps run dry within weeks of the monsoon's withdrawal [Kumar et al., 2022]. Average annual rainfall across the craton ranges from about 464 mm to 1,112 mm, with more than 88 percent of it concentrated in the four monsoon months of June to September [Bisht et al., 2023], leaving the remaining eight months almost entirely dependent on stored groundwater.

Conventional, ground-based hydro-meteorological monitoring in Bundelkhand is sparse and unevenly distributed, which has made Geographic Information Systems (GIS) and satellite remote sensing (RS) indispensable for characterising drought and water scarcity at a spatial resolution fine enough to inform block- and village-level planning [Patidar et al., 2024; Masroor et al., 2021]. GIS-RS techniques permit the integration of rainfall grids, digital elevation models, lithology, land use/land cover, and vegetation indices into composite indices of meteorological drought and groundwater potential, at a fraction of the cost and time required by field-based hydrogeological surveys [Kumar et al., 2022]. This paper undertakes a structured synthesis of peer-reviewed literature that has applied GIS and remote sensing to the study of drought and water scarcity specifically within the Bundelkhand region. Rather than generating new primary satellite data, the paper consolidates the quantitative findings, data sources, and methodological choices of the available body of work, in order to (a) present a coherent regional picture of drought and groundwater vulnerability, (b) identify where GIS-RS methods converge or diverge in their conclusions, and (c) expose specific methodological and spatial research gaps that future primary studies should address.

2. Related Work

The reviewed literature on GIS-RS applications to Bundelkhand's water scarcity problem clusters into three broad strands.

2.1 Meteorological Drought Characterisation Using Precipitation Indices

A substantial body of work has used the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), computed from India Meteorological Department (IMD) gridded rainfall or satellite-derived precipitation products, to characterise the frequency, severity, and spatial extent of meteorological drought in Bundelkhand. Thomas, Nayak, and Ghosh (2015) used SPI at 3-, 6-, and 12-month scales on 2002–2013 rainfall data and found that drought frequency in the region had increased to once every three to five years, with a falling trend in seasonal rainfall and rainy-day counts detected by the Mann-Kendall test. Bisht et al. (2023), analysing 48 years (1969–2016) of rainfall and temperature data with both SPI and SPEI, reported that the southwest monsoon contributed 88.8–91.8 percent of annual rainfall, with a statistically significant declining trend in July and August rainfall for Hamirpur district, and a strong correlation ($r = 0.88\text{--}0.91$) between SPI-3 and SPEI-3. Pandey, Srivastava, Singh, Petropoulos, and Mall (2021) applied the satellite-based CHIRPS precipitation product across 1981–2018 and identified Jalaun and Lalitpur as the districts with the highest drought frequency (22 SPI-3 events), while Jhansi displayed a marked declining SPI trend during the monsoon months. Most recently, Yadav et al. (2025) examined rainfall homogeneity, autocorrelation, and departure across all 14 districts of Bundelkhand from 1984–2023 and confirmed that the northern districts of Hamirpur and Jalaun experience drought roughly once every four to five years, while southern districts such as Sagar, Tikamgarh, and Panna receive comparatively higher and more stable rainfall.

Patidar, Pingale, Khare, and Dayal (2024) extended this line of work by combining meteorological drought (SPI, using IMD gridded rainfall at 0.25° resolution) with hydrological drought (the Streamflow Drought Index, SDI, using Global Flood Awareness System discharge data) across a 1980–2020 period. Their gridded, sub-district-level analysis found that moderate droughts are considerably more probable than severe or extreme droughts, with SPI-12-based probabilities reaching up to 20 percent in some grid cells—equivalent to a drought occurring once every five years—and identified a statistically significant decreasing trend in monsoon-season SPI in the northern part of the region.

2.2 GIS-RS-Based Groundwater Potential Zonation

A second cluster of studies has used multi-criteria decision analysis (MCDA) within a GIS environment to delineate groundwater potential zones across Bundelkhand. Kumar, Singh, and Singh (2022) integrated eight thematic layers—lithology, geomorphology, slope, soil, rainfall, drainage density, lineament density, and land use/land cover—derived from Landsat-8, SRTM DEM, and India Meteorological Department rainfall data, using a frequency-ratio (FR) technique across the entire 26,762 km² Bundelkhand craton. Their groundwater potential index, validated against 108 well-yield records, classified only 9.22 percent of the region as "very high" potential and a further 23.36 percent as "high" potential, while 25.97 percent and 9.72 percent fell into "low" and "very low" categories respectively, concentrated in areas of steep slope, low rainfall, dense built-up land, and low lineament density. District-scale replications of this approach—for

example, the multi-influencing-factor (MIF) study in Tikamgarh district and a geospatial groundwater assessment for Jhansi district—reached broadly consistent conclusions, attributing the region's poor groundwater prospects to its granitic basement, which severely restricts rainwater infiltration and recharge. Although conducted outside Bundelkhand proper, Masroor et al.'s (2021) study of the Godavari Middle Sub-Basin is methodologically instructive: it combined an AHP-derived groundwater potential map with a random forest machine-learning model to quantify how drought conditions specifically degrade groundwater potential, an integrative approach that has not yet been replicated within Bundelkhand itself despite the region's comparable hard-rock hydrogeology.

2.3 Groundwater-Dependent Ecosystems and Vegetation-Based Drought Monitoring

A smaller but growing strand of research links groundwater conditions to ecosystem and vegetation stress. Pandey, Singh, Singh, and Sharma (2023) mapped groundwater-dependent ecosystems (GDEs) in a drought-affected part of Bundelkhand by combining remote-sensing inputs, a GIS-based multi-criteria framework, and 22 years (2000–2022) of in-situ groundwater-level records from the Uttar Pradesh Groundwater Department, demonstrating that long-term groundwater overdraft has measurably degraded the ecosystems that depend on shallow aquifers. This complements the broader use of vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) in agricultural drought monitoring, and the use of GRACE satellite gravimetry to infer groundwater storage anomalies in terrain, such as Bundelkhand's, where continuous piezometric networks are limited.

2.4 Synthesis of the Literature and the Research Gap

Taken together, these three strands of literature converge on a consistent regional picture: northern Bundelkhand districts (Jalaun, Hamirpur, Lalitpur, Banda) are consistently identified—by rainfall-index studies, drought-frequency analyses, and groundwater potential mapping alike—as more drought-prone than the higher-rainfall southern districts (Sagar, Tikamgarh, Panna). However, three methodological gaps recur across the reviewed studies. First, meteorological/hydrological drought-index studies (SPI, SPEI, SDI) and GIS-based groundwater potential zonation studies have so far been conducted largely as parallel, non-integrated exercises: no publicly available study combines a multi-decadal SPI/SPEI time series with a dynamically updated groundwater potential map for the whole craton. Second, most groundwater potential zonation studies are static, single-epoch snapshots based on one set of satellite images, and do not capture how potential zones might shift with prolonged drought or changing land use. Third, the administrative division of Bundelkhand between Uttar Pradesh and Madhya Pradesh has resulted in a fragmented evidence base—most groundwater studies are confined to a single district or state, while drought-index studies more often treat the whole craton, leaving a mismatch of scale that hampers cross-boundary water-resource planning.

3. Objectives

This paper pursues the following objectives:

- a) To synthesise the GIS- and remote sensing-based methodologies that have been applied to the study of drought and groundwater potential in the Bundelkhand region.
- b) To characterise the spatiotemporal pattern of rainfall variability and meteorological/hydrological drought across the Bundelkhand craton, as reported in the peer-reviewed literature.
- c) To consolidate GIS-based groundwater potential zonation findings for the region and relate them to the observed drought pattern.
- d) To identify specific methodological, spatial, and temporal gaps in the existing body of GIS-RS research on Bundelkhand.
- e) To propose an integrated, cross-state GIS-RS monitoring framework that can guide future primary research and drought-mitigation planning.

4. Study Area

The Bundelkhand region lies in central India, broadly between 23°20'N–26°20'N latitude and 77°80'E–81°40'E longitude, spanning roughly 7.08 million hectares (approximately 70,800 km² in its broad administrative definition, with the underlying Bundelkhand craton itself covering about 26,762 km²) across seven districts of southern Uttar Pradesh (Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda, and Chitrakoot) and six to seven districts of northern Madhya Pradesh (Sagar, Damoh, Tikamgarh, Chhatarpur, Panna, and Datia) [Patidar et al., 2024; Kumar et al., 2022]. The region is bounded by the Yamuna and Ganga plains to the north and by the Vindhyan escarpment and the Narmada basin to the south, with the Ken and Betwa rivers forming its principal drainage arteries [Kumar et al., 2022].

Geologically, Bundelkhand is underlain by the Bundelkhand craton, one of the oldest Archaean granite-gneiss complexes in India, comprising coarse- and fine-grained granite, granite-gneiss, metasediments, and quartz-vein intrusions, with alluvial cover confined mainly to river valleys [Pati et al., 2007, as cited in Kumar et al., 2022]. This crystalline basement has very low primary porosity, so groundwater occurs almost exclusively in secondary, weathered, and fractured zones, with well transmissivity typically ranging from about 20 to 250 m²/day and well yields varying from zero (dry wells) to around 880 litres per minute [Kumar et al., 2022].

The climate is semi-arid to sub-humid, with average annual rainfall ranging from about 464 mm in the driest tracts to over 1,100 mm in the wettest, and with more than 88 percent of the total falling during the June–September southwest monsoon [Bisht et al., 2023; Kumar et al., 2022]. Elevation ranges from about 86 m to 537 m above mean sea level, and land cover is dominated by agriculture and barren land, with limited forest cover and scattered water bodies and reservoirs [Kumar et al., 2022]. According to the 2011 Census of India, the region's population exceeds 18.3 million, with more than 80 percent dependent, directly or indirectly, on rain-fed agriculture and allied activities [Kumar et al., 2022; Patidar et al., 2024], which makes the region acutely sensitive to any deficit or delay in the monsoon.

5. Data and Methodology

5.1 Overall Approach

Because this paper synthesises, rather than generates, new spatial data for Bundelkhand, it adopts a structured literature-synthesis methodology broadly analogous to a scoping review. The approach comprised three stages: (a) systematic identification of peer-reviewed sources, (b) extraction of data sources, spatial methods, and quantitative findings from each source, and (c) qualitative synthesis of the findings into a coherent regional narrative, cross-checked for internal consistency across studies.

5.2 Source Identification

Peer-reviewed articles were identified through targeted searches of ScienceDirect (Elsevier), SpringerLink, MDPI, the American Society of Civil Engineers (ASCE) Journal of Hydrologic Engineering, and the India Meteorological Department's MAUSAM journal, using combinations of the search terms "Bundelkhand," "drought," "groundwater potential," "rainfall variability," "GIS," and "remote sensing." Inclusion criteria required that a source (i) be published in a peer-reviewed journal or peer-reviewed book chapter, (ii) report original spatial or statistical analysis conducted specifically within the Bundelkhand region (or, in one comparative case, a methodologically equivalent hard-rock terrain), and (iii) employ at least one GIS, remote sensing, or standardized climatic index method. Sources published between 2015 and 2025 were prioritised to ensure currency, with two foundational earlier sources (the 2014 National Institute of Disaster Management retrospective report and 2007 craton geology study) retained for essential contextual and geological information.

5.3 Data Extraction

For each included study, the following elements were extracted where reported: (i) the satellite or gridded data product used (e.g., Landsat-8 OLI/TIRS, SRTM DEM, IMD 0.25° gridded rainfall, CHIRPS, GloFAS discharge, GRACE gravimetry); (ii) the spatial or statistical method applied (frequency ratio, multi-influencing factor, analytic hierarchy process, Standardized Precipitation Index, Standardized Precipitation Evapotranspiration Index, Streamflow Drought Index, Mann-Kendall trend test); (iii) the spatial and temporal resolution and extent of the analysis; and (iv) the principal quantitative findings, including any validation against independent ground data such as well-yield records.

5.4 Composite GIS-RS Workflow Reconstructed from the Literature

Across the reviewed groundwater-potential studies, a broadly consistent GIS workflow recurs, which this paper reconstructs as follows: (1) acquisition of thematic layers (lithology and geomorphology from Geological Survey of India maps; slope, drainage density and lineament density derived from SRTM DEM; land use/land cover classified from Landsat imagery; soil data from FAO maps; rainfall interpolated from IMD station data using inverse-distance weighting); (2) reclassification of each layer into ordinal classes; (3) assignment of class weights,

typically through a frequency-ratio calculation against known spring or well locations, or through analytic hierarchy process pairwise comparisons; (4) integration of weighted layers through raster overlay in a GIS environment (commonly ArcGIS) to produce a composite groundwater potential index; and (5) validation of the resulting zones against independent well-yield or discharge data [Kumar et al., 2022]. For meteorological and hydrological drought characterisation, the recurring workflow instead involves: (1) acquisition of gridded or station rainfall (and, where relevant, streamflow) data; (2) fitting of a probability distribution (commonly Gamma) to the precipitation series; (3) transformation to a standardized index (SPI, SPEI, or SDI) at multiple time scales (1, 3, 6, and 12 months); (4) classification into drought-severity categories; and (5) trend detection using the non-parametric Mann-Kendall test and Sen's slope estimator [Patidar et al., 2024; Bisht et al., 2023].

5.5 Limitations of the Synthesis Method

As a literature synthesis rather than a primary spatial analysis, this paper does not generate new satellite-derived maps or perform new statistical testing; its findings are bounded by the spatial and temporal coverage, data resolution, and methodological choices of the underlying studies. Where studies used different rainfall baselines, index time scales, or administrative boundaries, direct numerical comparison across studies should be treated as indicative rather than exact.

6. Results

6.1 Spatiotemporal Rainfall Variability and Meteorological Drought

The synthesised evidence consistently shows a declining and increasingly erratic monsoon rainfall pattern across Bundelkhand. Bisht et al. (2023) found that, over 1969–2016, the southwest monsoon contributed 88.8–91.8 percent of annual rainfall, with a coefficient of variation of 29.9–39.5 percent, and detected a statistically significant declining trend in July and August rainfall specifically for Hamirpur district. Yadav et al. (2025), analysing the longer and more recent 1984–2023 record across all 14 districts, confirmed a marked north–south rainfall gradient, with southern districts (Sagar, Tikamgarh, Panna) receiving distinctly higher and more stable rainfall than northern districts (Jalaun, Hamirpur, Banda), and identified Jalaun as having the highest rainfall variability and the most frequent drought recurrence—roughly once every four to five years.

At the drought-index level, Thomas et al. (2015) reported that SPI-based drought frequency in Bundelkhand had risen to once every three to five years by the early 2010s. Pandey et al. (2021), using the satellite-based CHIRPS product over 1981–2018, found that Jalaun and Lalitpur recorded the highest number of SPI-3 drought events (22 events each) among all districts, and that Jhansi displayed a particularly strong declining SPI trend during the monsoon season. Patidar et al. (2024), working at finer grid resolution across 1980–2020, found that moderate-category droughts are consistently more probable than severe or extreme droughts, that SPI-12-based drought probability reaches up to 20 percent in some grid cells (approximately a once-in-five-year recurrence), and that the decreasing SPI trend is concentrated in the northern part of the

region during the monsoon months—directly corroborating the district-level findings of Bisht et al. (2023) and Yadav et al. (2025).

6.2 Groundwater Potential Zonation

The GIS-based groundwater potential mapping of Kumar et al. (2022), covering the entire 26,762 km² Bundelkhand craton, classified the region as follows: very high potential, 9.22 percent (2,466.83 km²); high potential, 23.36 percent (6,252.79 km²); moderate potential, 31.72 percent (8,488.64 km², the single largest class); low potential, 25.97 percent (6,950.83 km²); and very low potential, 9.72 percent (2,602.52 km²). Validation against 108 well-yield records showed a clear monotonic relationship between potential class and yield: average well yield rose from 29.29 litres per minute in "very low" zones to 496.13 litres per minute in "very high" zones. This confirms that more than a third of the craton (35.69 percent, summing the low and very low classes) offers only poor prospects for groundwater-based irrigation or drinking-water supply, concentrated in areas of steep slope, low rainfall, dense built-up land, and low lineament and drainage density.

6.3 Groundwater-Dependent Ecosystems and Hydrological Drought

Pandey et al. (2023), combining 22 years (2000–2022) of in-situ groundwater-level data with remote-sensing inputs, mapped groundwater-dependent ecosystems in a drought-affected part of Bundelkhand and found their extent and condition to be heterogeneous and measurably affected by long-term groundwater overdraft. This finding is consistent with Patidar et al.'s (2024) identification of a significant decreasing trend in hydrological drought indicators (via the Streamflow Drought Index) in the southern part of the region, suggesting that surface-water and groundwater stress, though spatially distinct in emphasis, are both intensifying across different parts of the craton.

6.4 Summary Table of Key Quantitative Findings

Study	Method / Data	Key Finding
Kumar, Singh & Singh (2022)	Frequency-ratio GIS model; Landsat-8, SRTM DEM, IMD rainfall	35.7% of craton in low/very-low groundwater potential; validated with 108 wells
Thomas, Nayak & Ghosh (2015)	SPI (3, 6, 12-month); Mann-Kendall test	Drought frequency rose to once every 3–5 years
Bisht et al. (2023)	SPI & SPEI, 1969–2016 rainfall/temperature	Significant declining July–Aug rainfall in Hamirpur; SPI–SPEI $r = 0.88–0.91$
Pandey et al. (2021)	CHIRPS precipitation, SPI-3, run theory, 1981–2018	Jalaun & Lalitpur highest drought frequency (22 SPI-3

		events)
Yadav et al. (2025)	Rainfall departure, homogeneity & autocorrelation tests, 1984–2023	North–south rainfall gradient; Hamirpur/Jalaun drought every 4–5 years
Patidar et al. (2024)	Gridded SPI (1,3,6,12-mo) & SDI (GloFAS discharge), 1980–2020	Up to 20% drought probability (SPI-12); declining trend concentrated in north
Pandey et al. (2023)	GIS + remote sensing + 22-yr in-situ groundwater levels	Groundwater-dependent ecosystems degraded by long-term overdraft

7. Discussion

The synthesised findings converge strongly on two points. First, drought risk within Bundelkhand is spatially differentiated rather than uniform: the northern districts of Jalaun, Hamirpur, Lalitpur, and Banda emerge, across independent studies using different rainfall products, index methods, and time periods, as consistently more drought-prone than the southern districts of Sagar, Tikamgarh, and Panna [Yadav et al., 2025; Pandey et al., 2021; Patidar et al., 2024]. This spatial pattern aligns closely with the region's rainfall gradient and, plausibly, with its groundwater potential gradient, since the same hard-rock hydrogeology that limits recharge in the north also coincides with lower and more erratic rainfall there [Kumar et al., 2022]. Second, the intensity of drought appears to be increasing over time: successive studies covering progressively more recent periods (Thomas et al. (2015), through 2013; Bisht et al. (2023), through 2016; Yadav et al. (2025), through 2023; Patidar et al. (2024), through 2020) each report a declining rainfall or SPI trend, particularly in the monsoon months, suggesting a genuine intensification of meteorological drought rather than an artefact of differing methodologies.

At the same time, the literature reveals an important structural limitation: GIS-based groundwater potential zonation and meteorological/hydrological drought-index studies have, to date, been conducted as largely separate research streams. Groundwater potential maps such as that of Kumar et al. (2022) are static products, built from a single set of satellite images and rainfall averages, and do not directly incorporate the multi-decadal SPI/SPEI/SDI time series produced by drought-index studies. Conversely, drought-index studies rarely translate their district- or grid-level drought probabilities into an assessment of how groundwater potential zones might be expected to shrink or shift under sustained drought. Masroor et al.'s (2021) work in the Godavari basin demonstrates that such an integration—using a machine-learning model such as random forest to link an existing AHP-based groundwater potential map to drought-index outputs—is both feasible and informative, yet no equivalent study has been undertaken within Bundelkhand itself.

A second gap concerns administrative fragmentation. Because Bundelkhand straddles the Uttar

Pradesh–Madhya Pradesh state boundary, many groundwater studies (e.g., the Tikamgarh and Jhansi district-level assessments) are confined to a single district or state, while whole-craton studies (Kumar et al., 2022; Patidar et al., 2024) are comparatively rare. This mismatch of scale complicates the design of cross-state drought-mitigation and groundwater-recharge programmes, since a drought or recharge-deficit signal detected at the craton scale cannot always be disaggregated to the district-level administrative units through which Indian water-resource policy is typically implemented.

A third gap relates to temporal resolution in groundwater mapping. Existing frequency-ratio and multi-influencing-factor groundwater potential maps for Bundelkhand are essentially single-epoch products. Given the demonstrated decline in monsoon rainfall in parts of the region, groundwater potential itself is unlikely to be static; periodic re-mapping—ideally using cloud-based platforms such as Google Earth Engine that can process multi-year Landsat, Sentinel, and GRACE time series at low computational cost—would allow groundwater potential maps to be updated as drought conditions evolve, rather than treated as one-time products.

Finally, the ecosystem dimension of water scarcity, while acknowledged (Pandey et al., 2023), remains comparatively under-studied relative to the agricultural and drinking-water dimensions that dominate the literature. Given that groundwater-dependent ecosystems provide important regulating and provisioning services in a region already under acute water stress, their long-term monitoring deserves greater integration into the region's broader GIS-RS drought-monitoring architecture.

8. Conclusion

This synthesis of peer-reviewed GIS- and remote sensing-based research demonstrates that Bundelkhand's water scarcity problem is well characterised in its broad spatial and temporal contours: meteorological drought is intensifying, particularly in the northern districts, and groundwater potential across the hard-rock craton is intrinsically limited, with over a third of the region falling in low-to-very-low potential classes. However, the existing body of work remains methodologically compartmentalised—meteorological drought indices, groundwater potential zonation, and ecosystem-level impacts are each well studied in isolation, but rarely combined into a single, dynamically updateable, cross-state spatial framework. Addressing this gap would require an integrated GIS-RS architecture that couples multi-decadal SPI/SPEI/SDI time series with periodically updated, cloud-processed groundwater potential and vegetation-stress layers, spanning both the Uttar Pradesh and Madhya Pradesh portions of the craton on a common grid. Such a framework would allow drought-mitigation and groundwater-recharge investments—including the artificial recharge structures and watershed-development works already recommended in the literature [Kumar et al., 2022]—to be targeted more precisely at the sub-district level, and updated as new satellite and rainfall data become available. Future primary research should prioritise this integration, alongside more systematic incorporation of groundwater-dependent ecosystems and finer-grained, multi-temporal groundwater potential mapping, to support long-term, evidence-based water security planning for one of India's most

chronically drought-affected regions.

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