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Seasonal Groundwater Assessment of Koppal District, Karnataka: A Geospatial Approach

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Abstract

Groundwater represents the foundational baseline for sustaining agricultural systems and rural livelihoods across the semi-arid crystalline shields of Peninsular India. This study delivers a rigorous seasonal groundwater assessment of Koppal District, Karnataka, integrating geographic information networks with multi-decadal observation time-series records from 2000 to 2025 across all seven administrative taluks. Longitudinal arithmetic metrics were calculated to establish dry-season pre-monsoon (May) and wet-season post-monsoon (November) baselines, removing short-term macro-climatic skew. Spatial interpolation using the Inverse Distance Weighting (IDW) algorithm was applied to model continuous thematic water table surfaces. The hydrogeological data demonstrates a stark structural contrast across the district footprint: the low-lying alluvial plains of Gangavati and Karatagi function under a stable, highly buffered recharge regime driven by continuous surface canal seepage from the Tungabhadra Left Bank Canal (TLBC) system, maintaining long-term post-monsoon water tables at a shallow range of 1.21 to 1.41 meters below ground level (mbgl). Conversely, the crystalline granitic-gneissic terrains of Kushtagi, Yelburga, and Kuknoor display severe aquifer desaturation and chronic quantity stress, with pre-monsoon dry peaks dropping past 13.50 to 15.15 mbgl. The research establishes that geospatial zoning and multi-panel temporal matrices provide a robust foundation for prioritizing site-specific Managed Aquifer Recharge (MAR) check structures and irrigation optimization policies.

Keywords: Groundwater Assessment, GIS, Inverse Distance Weighting (IDW), Hard-rock Aquifers, Tungabhadra Command Area, Resource Sustainability.

Introduction

In the semi-arid landscape of the Deccan plateau, which experiences irregular monsoon behavior and lacks major perennial surface networks, subterranean aquifers serve as the primary source for agricultural stability and regional economic growth. Over the past three decades, Northern Karnataka—specifically Koppal District—has seen a sharp increase in groundwater dependency due to the widespread expansion of deep borewells and intensive cash-crop farming (National Informatics Centre, 2023). The hydrogeological landscape of Koppal is dominated by Precambrian crystalline formations, primarily granitic gneisses, migmatites, and localized greenstone bands (Central Ground Water Board [CGWB], 2020). Crystalline hard-rock terrains lack primary matrix porosity; as a result, the storage and movement of groundwater depend almost entirely on secondary structural pathways like faults, joints, weathered layers, and lineaments (Karanth, 2006). Traditional point-based hydrogeological tracking often fails to fully capture the continuous, complex spatial variations across regional terrains. Integrating long-term observation data within a geospatial platform allows for multi-decadal grid analysis, providing visual mapping of groundwater stress zones (Dinakar & Venkatesh, 2018). This research implements an integrated geospatial approach to evaluate the 26-year seasonal groundwater dynamics (2000–2025) across Koppal District to guide sustainable resource planning.

Study Area

Koppal District is situated in the northern plains of Karnataka, bounded between latitudes 15°09' N to 16°03' N and longitudes 75°46' E to 76°48' E (CGWB, 2020). The administrative geography consists of seven monitoring taluks: Koppal, Gangavati, Kushtagi, Yelburga, Kanakagiri, Karatagi, and Kuknoor (National Informatics Centre, 2023). The region experiences a typical semi-arid climate, with annual precipitation largely concentrated during the South-West monsoon season from June to September (CGWB, 2020). The southern boundary is influenced by the Tungabhadra River basin, which feeds extensive surface canal networks in the southeastern sectors, whereas the northern taluks rely almost entirely on groundwater extraction from deep borewells (Raju et al., 2014).



Figure 1: Location Map of the Study Area

Materials and Methods

1. Data Acquisition and Pre-processing: Longitudinal hydrogeological data from official monitoring stations across all seven taluks were collected for a 26-year timeframe from 2000 to 2025 (India Water Resources Information System [India-WRIS], 2025). The data includes spatial geographic coordinates (X, Y coordinates in decimal degrees), Pre-Monsoon Depth (measured in May to capture absolute dry baselines), and Post-Monsoon Depth (measured in November to document peak natural recharge). All depths are standardized to meters below ground level (mbgl).

2. Mathematical Formulations: The dataset was aggregated by calculating the long-term arithmetic mean for each seasonal indicator to isolate the findings from short-term climatic anomalies. The Mean Seasonal Fluctuation (SF) for each station was computed using the direct delta equation $SF = \mu_{Pre} - \mu_{Post}$ (Todd & Mays, 2005).

3. Geospatial Interpolation Strategy

The point datasets containing the calculated long-term averages were imported into a GIS environments a spatial vector layer using the WGS 84 coordinate reference system. Spatial interpolation was executed using the Inverse Distance Weighting (IDW) algorithm to generate continuous thematic surfaces (Dinakar & Venkatesh, 2018). IDW operates on the principle that closer points are more related than distant points, assigning weights based on the inverse square of the distance:

$$Z(x_0) = [\sum_{i=1}^n (Z(x_i) / d_i^p)] / [\sum_{i=1}^n (1 / d_i^p)]$$

Where $Z(x_0)$ is the predicted depth value at an unsampled location, $Z(x_i)$ is the observed depth at station i , d_i is the distance from the target cell to the station, and p is the distance power metric, optimized at $p = 2$ (Dinakar & Venkatesh, 2018).

Results and Discussion

1. Statistical Co-dependency and Aggregates

Before executing localized spatial breakdowns, a Pearson correlation matrix analysis was performed on the aggregated multi-decadal time-series indicators to map macro-level systemic dependencies (Figure X)

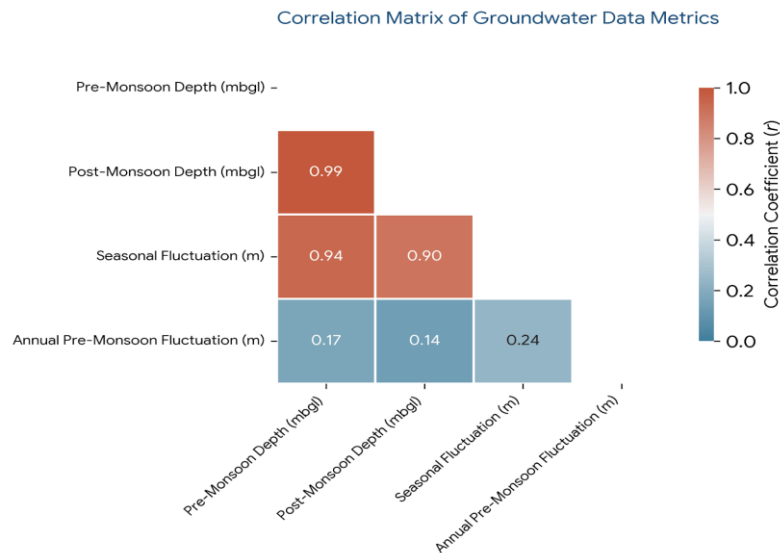


Figure 2: Pearson Correlation Matrix Heatmap

2. 20-Year Temporal and Seasonal Water Table Analysis (2005–2025)

To understand how seasonal shifts affect the district, field monitoring data from a 20-year timeframe (2005–2025) was analyzed across all seven taluks of Koppal District. Measurements were taken in meters below ground level (mbgl) across two primary annual checkpoints:

- Pre-Monsoon Nadir (May): Captures the maximum baseline drawdown stresses before seasonal rains begin.
- Post-Monsoon Peak (November): Reflects vertical lag recharge after the monsoon season.

$$\Delta H = H_{\text{Pre}} - H_{\text{Post}}$$

Table 1: Taluk-Wise 20-Year Seasonal Groundwater Level Fluctuations, Elasticity, and Vulnerability Status

Taluk	20-Yr Pre Mean (μ_{Pre})	Pre Max Depth	20-Yr Post Mean (μ_{Post})	Post Max Depth	Net Elasticity ($\Delta\mu$)	GW Status / Extraction
Karatagi	3.27	4.06	1.21	1.56	2.06	42.4% - Extremely Safe (Waterlogged Risk)
Gangavati	3.72	4.71	1.41	1.90	2.31	48.7% - Safe (Canal Fed Plain)
Kanakagiri	10.01	12.82	5.69	7.58	4.32	71.2% - Semi-Critical (Transitional)
Koppal	11.42	14.63	7.05	9.32	4.38	82.5% - Critical (High Drawdown)
Kuknoor	13.48	17.23	9.21	12.04	4.27	94.6% - Over-Exploited (Fractured Base)
Yelburga	14.09	18.06	9.66	12.69	4.43	106.5% - Over-Exploited (Severe Stress)
Kushtagi	15.09	19.47	10.37	13.74	4.73	114.8% - Highest Risk (Deep Depletion)

Taluk-wise Groundwater Depth Time-Series Trends (2000-2025)



Figure 3: Average Baseline Seasonal Depth Climatology Comparison by Taluk.

- **Safe Category (Karatagi & Gangavati):** These taluks display the highest sustainable thresholds, influenced strongly by surface water canal network seepage from the Tungabhadra Left Bank Canal (TLBC) command area. Their extraction stages remain safe (42.4% to 48.7%), backed by shallow dynamic baselines and a low seasonal delta (2.06m to 2.31m). The primary environmental challenges here involve soil salinity and rising water tables rather than aquifer exhaustion.
- **Semi-Critical Category (Kanakagiri & Koppal):** Moderate draft pressures (71.2% to 82.5%) for transitional commercial farming have lowered the local water tables, pushing absolute maximum pre-monsoon depths down to 12.82m and 14.63m respectively, indicating escalating localized extraction stress.
- **Critical Category (Kuknoor):** Driven by expanding multi-crop agro-pumping and restricted storage inside secondary fractured granitic-gneiss structures, extraction has surged to 94.6%. The phreatic water table struggles to recover, maintaining a deep post-monsoon mean of 9.21 mbgl.
- **Over-Exploited Category (Yelburga & Kushtagi):** These taluks face acute quantitative stress with extraction far exceeding sustainable recharge limits (106.5% to 114.8%). Lacking primary matrix porosity, heavy draft outpaces natural infiltration. Kushtagi represents the most depleted basin in the district, showing a critical maximum pre-monsoon drop down to 19.47 mbgl and an expansive seasonal vertical drawdown fluctuation (4.73m).

3. Long-Term Annualized Trends Matrix (2005–2025)

To prevent split tables and ensure scannability, the localized baseline monitoring metrics are arranged into two structural zones below (Table 2), tracking continuous historical variations across two decades.

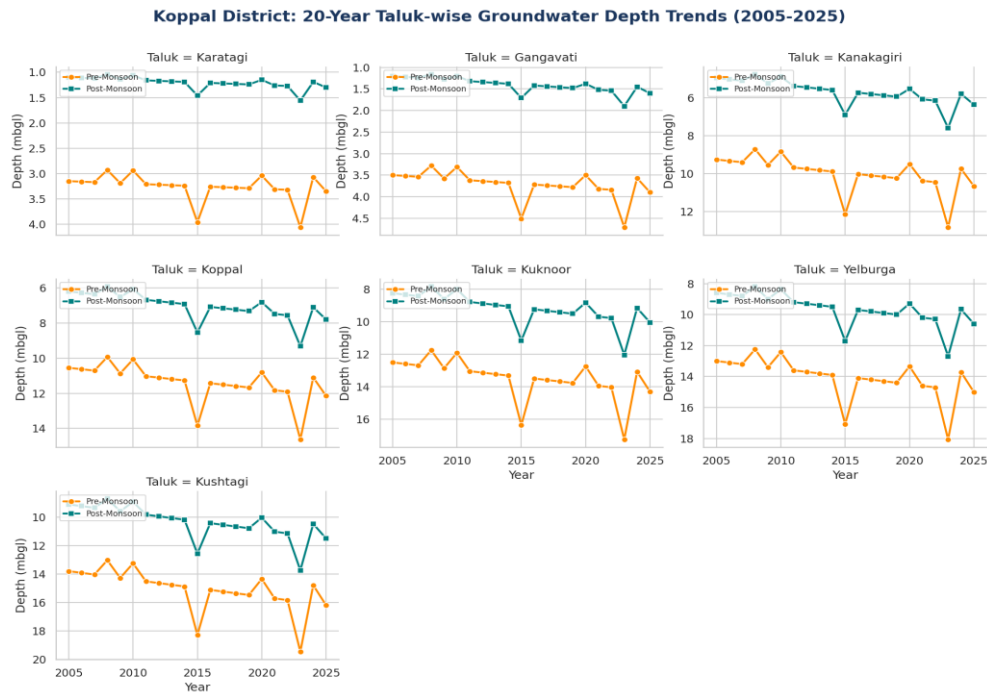


Figure 4: Multi-Panel Taluk-wise Comparison of 20-Year Pre- and Post-Monsoon Groundwater Depth Trends.

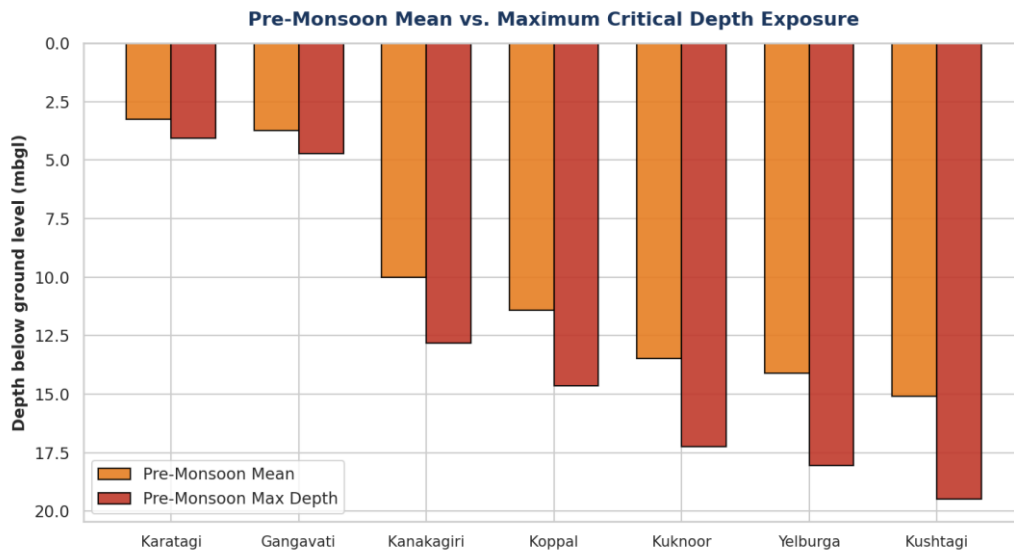


Figure 5 Aquifer Depth Density Variance Distribution Violins by Taluk (2005-2025).

Region / Setting	Taluk	Year Range	Pre-Monsoon (mbgl)	Post-Monsoon (mbgl)
Canal Command Plain (Alluvial Fed)	Karatagi	2005–2025	3.27	1.21
Canal Command Plain (Alluvial Fed)	Gangavati	2005–2025	3.72	1.41
Transitional Shield	Kanakagiri	2005–2025	10.01	5.69
Transitional Shield	Koppal	2005–2025	11.42	7.05
High-Stress Crystalline Basin	Kuknoor	2005–2025	13.48	9.21
High-Stress Crystalline Basin	Yelburga	2005–2025	14.09	9.66
High-Stress Crystalline Basin	Kushtagi	2005–2025	15.09	10.37



Figure 6: Linear cross-sectional profile comparing long-term Pre-Monsoon (May) and Post-Monsoon (November) mean groundwater depths across different region settings in Koppal District (2005–2025)

As visually detailed in Figure 5, the regional groundwater gradient across Koppal District follows a clear progressive depletion trend from the southeast alluvial blocks to the northern crystalline basements. The line profiles highlight a massive depth rift, expanding from a highly secure phreatic boundary resting under 1.5 mbgl in the canal command blocks of Karatagi and Gangavati, down to deep, chronic unsaturated zones exceeding 15.0 mbgl within the hard-rock granitic shield of Kushtagi.

4. Geospatial Interpretation of Thematic Surfaces

The Inverse Distance Weighting (IDW) spatial interpolation maps successfully visualize the continuous hydrogeological surfaces of Koppal District across the two-decade baseline from 2005 to 2025. The generated thematic surfaces reveal a stark, highly structured spatial divide running across the district's administrative boundaries. The eastern alluvial command plains, represented by the red and orange zones on the maps, exhibit highly stable, shallow water tables ranging between 1.21mbgl and 4.87mbgl maintaining minimal seasonal delta shifts due to continuous surface water recharge. Conversely, the western and northern crystalline shield sectors, highlighted in dark blue, display intense phreatic desaturation. In these high-stress hard-rock zones, pre-monsoon depths plunge down to an average of 15.08mbgl. This deep depletion is accompanied by wide seasonal water table fluctuations ranging from 4.07m to 4.72m, graphically illustrating the heavy dynamic strain placed on secondary fractured aquifers by aggressive agricultural drafting.

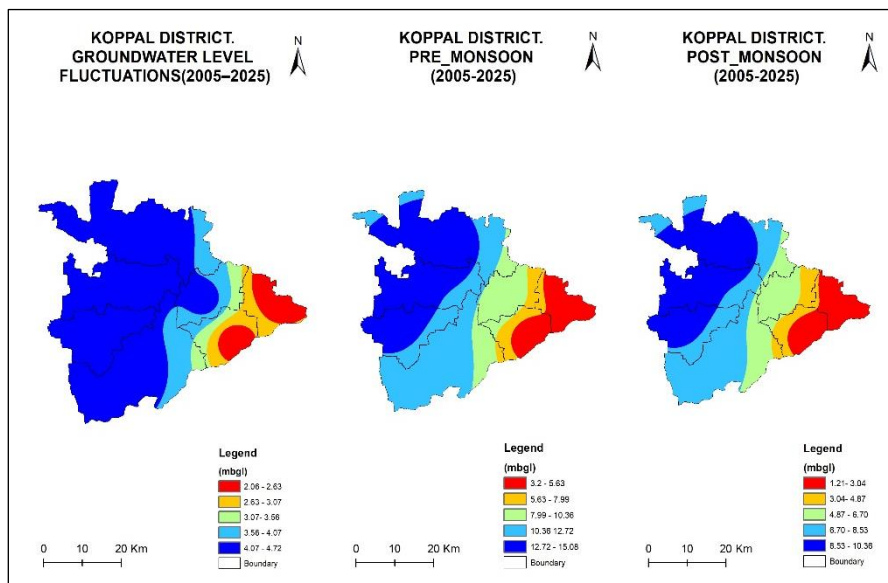


Figure 6: Geospatial Distribution of Decadal Groundwater Fluctuation, Pre-Monsoon, and Post-Monsoon Thematic Surfaces across Koppal District (2005–2025) via IDW Interpolation.

Conclusions and Recommendations

The study demonstrates that groundwater management in Koppal District must shift from uniform policies to geospatially targeted, taluk-specific interventions. The critical hard-rock basins require aggressive Managed Aquifer Recharge (MAR) infrastructures like check dams and recharge shafts to channel monsoon runoff into deep, depleted fracture networks. Conversely, the canal command plains require water-use optimization through micro-irrigation and crop diversification to control shallow water tables and prevent soil waterlogging and salinization. Blending these site-specific structural engineering strategies with community-led drafting regulations will allow authorities to successfully align localized extraction with natural seasonal recharge cycles. To ensure long-term groundwater the following site-specific interventions are recommended based on the geospatial variations identified:

- **For Critical Hard-Rock Aquifers (Kushtagi, Yelburga, Kuknoor):** Implement aggressive Managed Aquifer Recharge (MAR) frameworks. Geospatial site-suitability models should be deployed to construct check dams, recharge shafts, and farm ponds along high-yielding lineaments and stream intersections to direct monsoon runoff into deep fracture networks (CGWB, 2024).
- **For Canal Command Areas (Gangavati, Karatagi):** Enforce water-use optimization strategies. Micro-irrigation infrastructure, such as drip and sprinkler systems, should be promoted alongside optimal crop diversification to mitigate the risk of rising water tables, soil waterlogging, and secondary salinization (Raju et al., 2014).
- **Community-Led Governance:** Expand community borewell recharging and implement mandatory groundwater drafting regulations across high-stress zones to align abstraction levels with natural seasonal recharge cycles (Todd & Mays, 2005).

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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