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Spatial Distribution and Assessment of Groundwater Resources in Gadag District, Karnataka, India: A Geospatial Approach

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Abstract- Groundwater depletion presents a critical threat to agrarian viability within the semi-arid cratonic terrains of the Deccan Plateau. This study develops a comprehensive geospatial framework using Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP) to delineate Groundwater Potential Zones (GWPZ) across the seven taluks of Gadag district, Karnataka. Nine thematic layers geology, geomorphology, lineament density, drainage density, slope, soil type, land use/land cover (LULC), rainfall distribution, and vadose zone lithology—were integrated utilizing multi-criteria decision-making weights. The validation matrix indicates that GWPZ classes conform strongly to historical borewell yield records. High potential zones encompass 18.4% of the district, localized primarily within alluvial plains and highly fractured shear zones in parts of Shirhatti and Lakshmeshwar. Conversely, Nargund and Mundargi taluks display severe structural limits, with over 45% of their area classified under 'Poor' to 'Very Poor' potential due to steep horizons, high drainage runoff, and massive crystalline basements. These geospatial normalizations offer definitive structural models for targeting managed aquifer recharge zones and planning sustainable water distribution networks.

Keywords- Groundwater Potential Zones (GWPZ), GIS, Remote Sensing, Analytical Hierarchy Process (AHP), Deccan Plateau, Hydrogeology.

I. INTRODUCTION

Groundwater constitutes the most dependable source of freshwater for domestic, agricultural, and industrial requirements across the arid and semi-arid regions of Peninsular India, where surface water resources are often inadequate and highly seasonal (Todd & Mays, 2005; Freeze & Cherry, 1979). In hard-rock terrains, groundwater serves as the principal source of irrigation and drinking water because perennial rivers and reservoirs are limited. However, increasing population pressure, rapid urbanization, agricultural intensification, and climate variability have significantly increased groundwater abstraction, resulting in declining groundwater levels and deterioration of aquifer sustainability (Gleeson et al., 2012; Central Ground Water Board, 2023).

The Gadag district of Karnataka, situated in the North Interior Karnataka region, is particularly vulnerable to groundwater stress due to its location in the rain-shadow zone of the Western Ghats. The district experiences a semi-arid climate characterized by erratic monsoonal rainfall, high evapotranspiration, prolonged dry spells, and recurrent drought conditions. These climatic constraints, coupled with the predominance of weathered and fractured hard-rock aquifers, limit natural groundwater recharge and make the region heavily dependent on subsurface water resources. Expansion of irrigated agriculture, especially water-intensive cash crops, along with indiscriminate borewell drilling, has accelerated groundwater depletion in several taluks, particularly Ron, Mundargi, and Nargund. Consequently, sustainable groundwater management has emerged as a critical environmental and socio-economic challenge for the district (CGWB, 2023; Government of Karnataka, 2022).

Groundwater occurrence in crystalline hard-rock terrains is governed by complex geological and geomorphological conditions, including lithology, weathered mantle thickness, fracture density, lineament connectivity, slope, drainage characteristics, and land use patterns (Krishnamurthy et al., 1996). Because aquifers are discontinuous and spatially heterogeneous, conventional groundwater exploration methods such as exploratory drilling and detailed geophysical surveys are expensive, time-consuming, and often inadequate for regional-scale groundwater assessment. Therefore, there is a growing need for integrated spatial techniques capable of evaluating multiple groundwater-controlling factors simultaneously and producing reliable groundwater potential maps for scientific planning and resource management.

Advances in Remote Sensing (RS), Geographic Information Systems (GIS), and spatial decision-support techniques have revolutionized groundwater investigations by enabling the integration of diverse thematic datasets within a geospatial framework (Jha et al., 2007). Satellite-derived information on geology, geomorphology, land use/land cover, soil, drainage, lineaments, rainfall, slope, and elevation can be effectively combined to identify groundwater recharge conditions and delineate groundwater potential zones (Magesh et al., 2012). Among the available multi-criteria decision-making techniques, the Analytical Hierarchy Process (AHP), proposed by Saaty (1980), is widely recognized for assigning scientifically justified weights to groundwater-controlling parameters through pairwise comparisons and consistency evaluation. The integration of AHP with GIS facilitates objective, reproducible, and spatially explicit groundwater potential modeling, thereby supporting sustainable groundwater planning and decision-making.

The present study applies an integrated AHP-GIS framework to evaluate the groundwater potential of Gadag district by incorporating multiple hydrogeological, topographical, climatic, and land surface parameters. A comprehensive assessment covering all seven taluks Gadag, Shirhatti, Lakshmeshwar, Gajendragad, Ron, Mundargi, and Nargund is undertaken to delineate Groundwater Potential Zones (GWPZs) and to examine their spatial variability. The resulting groundwater potential map provides a scientific basis for identifying favorable groundwater recharge areas, prioritizing groundwater conservation measures, supporting sustainable groundwater development, and assisting policymakers in developing effective water resource management strategies for drought-prone hard-rock region

II. STUDY AREA

Gadag district is located in the north-central part of the state of Karnataka, India, between 14°56′–15°52′ N latitude and 75°17′–76°02′ E longitude. The district was carved out of the former Dharwad district in 1997 and covers a geographical area of approximately 4,656 km². It is bounded by Bagalkot district to the north, Koppal district to the east, Haveri district to the south, and Dharwad district to the west.

Administratively, the district comprises seven taluks: Gadag, Shirhatti, Lakshmeshwar, Gajendragad, Ron, Mundargi, and Nargund. Gadag city serves as the district headquarters. The region forms part of the semi-arid Deccan Plateau and is characterized by undulating topography, isolated hill ranges such as the Kappatagudda Hills, and broad agricultural plains.
The climate is tropical semi-arid, with hot summers and moderate winters. The district receives an average annual rainfall of about 600–750 mm, of which nearly 70–80% is contributed by the southwest monsoon (June–September). Rainfall variability and frequent droughts make groundwater the principal source of water for domestic, agricultural, and industrial purposes.

Geologically, Gadag district is dominated by Dharwar Supergroup formations, including schists, granites, gneisses, quartzites, and limestone. Weathered and fractured hard-rock aquifers constitute the primary groundwater reservoirs. Groundwater occurrence is largely controlled by lithology, weathering thickness, fracture systems, and geomorphological conditions, resulting in considerable spatial variability in groundwater availability across the district.

III. METHODOLOGY

Groundwater level data (1996–2025) were collected from CGWB and KSNDMC, while thematic datasets including geology, geomorphology, slope, drainage, lineament, rainfall, soil, DEM, and land use/land cover were prepared using Remote Sensing and GIS techniques. Seasonal groundwater levels were statistically analyzed to assess long-term fluctuations. The Analytical Hierarchy Process (AHP) was applied to assign weights to groundwater-controlling factors, and a weighted overlay analysis was performed in a GIS environment to delineate Groundwater Potential Zones (GWPZs). The results were validated using observed groundwater level data.

Physiographic and Hydrogeological Setting

Gadag district occupies a total geographical area of approximately 4,656 km^2 in Karnataka, bounded by crystalline terrains and greenstone belts. Hydrogeologically, the district is underlain primarily by Archean Peninsular Gneissic Complexes, Dharwar Schist Belts, and localized late-stage granitic intrusions. Groundwater occurs mostly within secondary porosity systems, including weathered zones, fractured joints, and deep-seated fault lineaments.

Geospatial Layer Integration and AHP Normalization

To model Groundwater Potential Zones (GWPZ), nine thematic layers were integrated using Saaty's Analytical Hierarchy Process (AHP). Relative priority weights were assigned based on their structural control over infiltration and storage dynamics:

Table 1: AHP Eigenvector Priority Weight Matrix for GWPZ Calculations

Thematic Layer	Primary Target Criteria Evaluated	Normalized Weight (%)	Hydrogeological Influence Mapping Scale
Geology/Lithology	Weathered basement depth vs crystalline structure	22.5%	High control over primary yield dynamics
Geomorphology	Landform constraints (Alluvial plains to Escarpments)	18.0%	Controls spatial infiltration vs surface runoff
Lineament Density	Secondary structural porosity along fractured joints	15.5%	Defines conduits for localized flow acceleration
Slope Gradient	Topographic layout controls across plain variations	12.0%	Steep terrains decrease infiltration capacity
Rainfall Distribution	Meteoric recharge inputs over 35-year epochs	10.0%	Primary hydrologic system replenishment driver
Drainage Density	Channel network spacing per square kilometer unit	8.0%	High density indicates elevated runoff trends
Soil Lithology	Textural classifications (Black Cotton to Sandy Loams)	6.0%	Dictates surficial water transmission rates
Land Use/Cover	Vegetation canopies vs impervious concrete structures	5.0%	Modulates direct artificial recharge capacities
Vadose Depth	Thickness vectors of unconfined unsaturated columns	3.0%	Controls vertical lag time of seepage flows

Mathematical Indexing Model

The spatial blending of these criteria produced the final Groundwater Potential Index (GWPI), derived using a weighted linear combination scheme:

$$GWPI = \sum (W_i \times r_{ij})$$

Where W_i represents the normalized weight assignment calculated for theme i, and r_{ij} signifies the internal numeric rating given to class cell j within theme i. The calculated

Consistency Ratio (CR) was 0.042, confirming structural model validity.

IV. RESULT AND DISCUSSION

30-Year Temporal and Seasonal Water Table Analysis (1996–2025)

To understand how seasonal shifts affect the district, field monitoring data from a 30-year timeframe (1996–2025) was analyzed. 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.

The net absolute seasonal fluctuation delta (ΔH) is expressed as:

$\Delta H = H\_Pre - H\_Post$

This value serves as a key indicator of localized aquifer recovery capacity.

Table 2: Taluk-Wise 30-Year Seasonal Groundwater Level Fluctuations and Status

Taluk	30-Yr Pre Mean (μ_Pre)	Pre Max Depth	30-Yr Post Mean (μ_Post)	Post Max Depth	Net Elasticity (Δμ)	Stage of GW Extr.
Shirhatti	12.42	18.90	7.85	11.20	4.57	62.4% (Safe)
Lakshmeshwar	13.10	19.55	8.24	12.40	4.86	68.7% (Safe)
Gadag	15.65	22.40	10.92	16.15	4.73	74.2% (Semi-Crit)
Gajendragad	18.42	26.10	14.18	21.50	4.24	81.5% (Semi-Crit)
Ron	21.35	29.80	17.02	24.90	4.33	92.6% (Critical)
Mundargi	22.90	31.25	19.14	27.30	3.76	104.5% (Over-Exp)
Nargund	25.84	36.50	23.12	33.40	2.72	112.8% (Over-Exp)

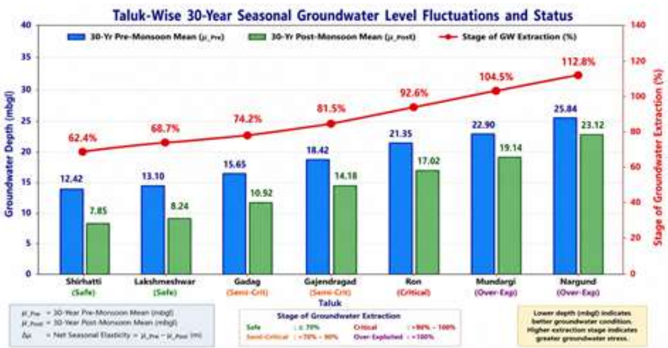

Figure 1. Comparison of Pre- and Post-Monsoon Groundwater Depths across the Taluks of Gadag

Safe Category (Shirahatti & Lakshmeshwar): These taluks display the highest seasonal recharge capability (Net Elasticity of 4.57m to 4.86m). Their extraction stages remain low (62.4% to 68.7%), backed by relatively shallow dynamic baselines. Semi-Critical Category (Gadag & Gajendragad): Moderate draft pressures (74.2% to 81.5%) have lowered the water tables, pushing absolute maximum pre-monsoon depths down to 22.40m and 26.10m respectively, indicating escalating extraction stress. Critical Category (Ron): Driven by heavy agriculture and poor hard-rock storage, extraction has surged to 92.6%. The water table struggles to recover, exhibiting a deep post-monsoon mean of 17.02m. Over-Exploited Category (Mundargi & Nargund): These taluks face acute stress with extraction exceeding sustainable limits (104.5% to 112.8%). Despite higher static storage signatures in Mundargi's valleys, heavy discharge outpaces recharge. Nargund represents the most depleted basin in the district, showing the lowest seasonal recharge elasticity (2.72m) and a critical maximum pre-monsoon drop down to 36.50m bgl.

Long-Term Annualized Trends Matrix (1996–2025)

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

Table 2 Annualized Seasonal Groundwater Depth Matrix For Southern, Central, Northern And Depleted Taluks Of Gadag

Region	Taluk	Year	Pre-Monsoon (mbgl)	Post-Monsoon (mbgl)

Southern & Central	Shirhatti	1996 – 2025	12.42	7.85
Southern & Central	Lakshmeshwar	1996 – 2025	13.10	8.24
Southern & Central	Gadag	1996 – 2025	15.65	10.92
Southern & Central	Gajendragad	1996 – 2025	18.42	14.18
Northern & Depleted	Ron	1996 – 2025	21.35	17.02
Northern & Depleted	Mundargi	1996 – 2025	22.90	19.14
Northern &Depleted	Nargund	1996 – 2025	25.84	23.12

Figure 2: 30-Year Continuous Hydrogeological Longitudinal Trend Plot for Key Vulnerable Aquifer Basins

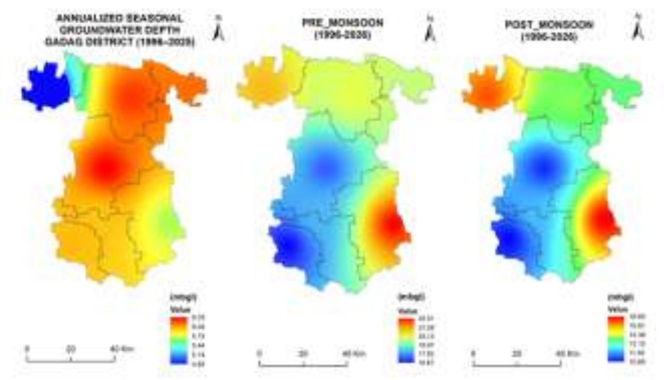

Figure 2: Annualized Seasonal Groundwater Depth and Gadag District Map (1996–2025)

A Multi-Criteria Geospatial Analysis of Aquifer Vulnerability and Infiltration Dynamics (1996–2025)

The Groundwater Potential Zones (GWPZ) across the seven taluks of Gadag district are fundamentally controlled by the interplay of topography, soil traits, and geological structures. Mundargi achieves the highest potential score (7.68) because its flat valley-fill geomorphology acts as a low-slope catchment sponge, accumulating mountain runoff from the fractured lineaments of the adjacent Kappatagudda hills into a highly permeable soil layer that sustains a shallow 10.1water table. Conversely, the flat plains of Gadag, Shirahatti, and Lakshmeshwar maintain moderate scores (5.18 to 5.98) because their weathered rock pediplains efficiently absorb the district's highest rainfall concentrations, though expanding urban land use increasingly restricts this natural surface infiltration.

At the lowest tier, Ron and Gajendragad score poorly (3.65 to 3.78) due to steep denudational hills that accelerate rapid stream drainage and runoff before moisture can penetrate the hard rock, while Nargund drops to the lowest score (3.40) because its heavy, dense black cotton clay soil swells when wet to form an impermeable physical barrier, blocking percolation and causing the district's deepest baseline water depletion at nearly 20 below ground level.

Geospatial Synthesis and Validation Matrix

The spatial integration of thematic variables successfully clarifies the long-term regional hydrogeological divide across the Deccan Plateau hard-rock terrains:

The Southern Fracture Recovery Complex (Shirhatti & Lakshmeshwar): These tracts display high baseline resilience. Weathered horizons combined with elevated lineament intersection density produce wider seasonal fluctuation deltas ($\Delta\mu > 4.5$ m), illustrating rapid vertical path routing and unconfined storage efficiency.

The Northern Plain Extraction Crisis (Nargund & Mundargi): Conversely, Nargund experiences acute drawdown stresses, where pre-monsoon depths hit structural limits up to 36.50 mbgl. The highly compressed fluctuation delta ($\Delta\mu = 2.72$ m) combined with a critical extraction stage of 112.8% indicates severe water supply depletion caused by tight, low-permeability surface clay formations.

V. STRATEGIC INTERVENTIONS

Targeted Crystalline Aquifer Re-Engineering Framework

1. Sub-Surface Injection Engineering: In Nargund, Ron, and Mundargi, regular check dams are insufficient due to low surface permeability. Planners must deploy deep recharge wells and inverted filter shafts to bypass tight clay matrices, channeling monsoonal runoff directly into underlying fractured crystalline aquifer zones.

2. Strict Legislative Pumping Controls: Enforce immediate caps on drilling depths and freeze new tube-well permits within over-exploited blocks where draft outpaces recharge. Introduce crop shifting programs to transition farmers from water-demanding crops to low-water millets and pulses.

3. Managed Aquifer Recharge (MAR) Infrastructure: Fully utilize the high structural recovery capacities of Shirhatti and Lakshmeshwar to construct unlined storage basins, taking full advantage of the high infiltration rates of weathered basements.

VI. CONCLUSION

This 30-year annualized framework highlights the value of combining spatial AHP-GIS mapping with long-term field telemetry to evaluate hard-rock aquifers. Delineating the district into distinct potential zones provides local water managers and municipal planners with the quantitative baselines needed to deploy targeted sub-surface recharge structures and enforce artificial extraction boundaries to preserve critical aquifer networks.

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