Hydrogeospatial and GRACE-Satellite Data Based Investigation of Groundwater Recharge Dynamics in Jalgaon, Maharashtra

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Abstract

Severe groundwater depletion has been reported in semi-arid regions of India due to intensive irrigation practices, declining rainfall trends, and limited natural recharge. In this context, Jalgaon district in North Maharashtra has been examined using GRACE satellite-derived groundwater storage anomalies (GWSA), which were integrated with hydrogeological, climatic, and geospatial datasets to assess groundwater recharge potential at a regional scale. A high-resolution recharge potential map was generated using the Analytic Hierarchy Process (AHP) within a GIS-based Multi-Criteria Decision Analysis (MCDA) framework. The results indicate that approximately 18.7% of the area was classified as having high recharge potential, mainly along the Tapi River alluvium, lineament corridors, and zones with moderate soil permeability. Around 42.5% of the area was identified with moderate recharge potential, while 38.8% was delineated as low to very low, particularly within basaltic plateau regions that exhibit poor infiltration capacity. Groundwater anomalies derived from GRACE satellite data have displayed a declining trend of −1.2 to −2.5 m/decade, indicating unsustainable extraction. Pediplains and valley fills containing artificial recharge structures, such as check dams and percolation tanks, were observed to show relatively improved resilience. This study has contributed a scientific basis for prioritising micro-watershed level recharge interventions under programmes such as Jal Yukta Shivar Abhiyan and Atal Bhujal Yojana, with an emphasis on structurally favourable and hydrogeologically responsive zones to strengthen groundwater sustainability.

1. Introduction

Groundwater is considered the largest distributed store of freshwater globally, and its role is regarded as essential for maintaining ecosystems, supporting agricultural productivity, and supplying drinking water (Scanlon et al., 2023). It has been reported that over 2.5 billion people depend on groundwater for daily needs, while aquifers are utilised for more than 40% of irrigation worldwide (Shah et al., 2023). In numerous regions, concerning declines in groundwater levels have been documented because of overexploitation, unpredictable rainfall, climate variability, and land-use changes (Dixit et al., 2022; Akhila et al., 2025). Significant negative groundwater storage anomalies have been detected across major aquifer systems located in Asia, North Africa, and North America during recent decades, and these trends have been associated with long-term socioeconomic and ecological consequences (Chandanpurkar et al., 2025). With the advent of satellite-based monitoring systems, particularly NASA's GRACE (Gravity Recovery and Climate Experiment) mission, subsurface water dynamics have been understood in far greater detail (Adams et al., 2022). Using GRACE data, regional-scale variations in groundwater storage are provided, enabling spatial and temporal tracking of depletion patterns (Karki et al., 2025). When integrated with geospatial and hydrogeological indicators, such satellite observations are believed to enhance the precision of groundwater recharge potential assessments, especially in water-scarce regions (Mostafa et al., 2025).

India has been reported as the world's largest groundwater extractor, accounting for more than 250 billion cubic meters annually, primarily for irrigation purposes. It has been noted that groundwater is utilized to meet over 65% of irrigation and 85% of rural domestic water demands. An acute and worsening groundwater crisis has been documented, based on assessments from the Central Ground Water Board (CGWB), which reveal that more than 260 districts have been classified as semi-critical, critical, or overexploited. Groundwater depletion has been exacerbated by climate variability, delayed monsoons, population increases, and unsustainable agricultural practices (Jana et al., 2021). Programs such as the Atal Bhujal Yojana (ABHY) and Jal Shakti Abhiyan have been introduced to promote participatory groundwater management and recharge activities (Sachdev and Panigrahi, 2023). Despite the presence of a substantial river network, widespread water scarcity has been observed, caused by uneven rainfall patterns, excessive groundwater abstraction, and limited natural recharge. Within this context, Jalgaon district in northern Maharashtra, bordered by the Satpura mountain range and predominantly drained by the Tapi River, has been considered. The district is recognised as an agricultural hub and often referred to as the "Banana Capital" of India due to banana cultivation over approximately 50,000 hectares (Kavita et al., 2022). A paradoxical situation has been identified, wherein water-intensive agriculture is practised within a drought-prone environment. Average annual rainfall of approximately 600–700 mm is received, which is characterised as highly seasonal and irregular, largely confined to the monsoon period (Kachkure and Algur, 2023).

The geological framework of the district consists predominantly of Deccan Basalt interspersed with alluvial zones along the Tapi basin, resulting in spatial variability in aquifer conditions. Deep confined aquifers are observed in the alluvial belt, whereas fractured and vesicular basalt formations are prevalent in other areas (Joshi and Kulkarni, 2022). A proliferation of dug-cum-borewells exceeding depths of 100–150 meters has been recorded, driven by the agricultural demand for assured irrigation. Consequently, groundwater levels have been declining at rates exceeding 1.5–2 meters per year, leading the district to be recognised as one of the emerging groundwater stress hotspots in Maharashtra (Kadam et al., 2025). Although check dams, percolation tanks, and micro-watershed interventions have been constructed, groundwater recharge remains insufficient to compensate for the volume abstracted annually.

Assessment of groundwater recharge potential in Jalgaon district has been considered essential due to its complex hydrogeological and agricultural setting. Traditional approaches such as aquifer testing and field-based surveys are acknowledged as useful, though their spatial coverage is often

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limited. A geographically distributed, data-driven approach has been presented as an effective alternative, wherein hydrogeological, topographic, and climatic indicators are combined with groundwater storage anomalies derived from GRACE satellites within a GIS framework. Spatial integration of diverse thematic layers is facilitated through Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP), enabling the ranking of locations based on recharge suitability.

By integrating satellite-derived groundwater storage trends with hydro-geospatial datasets, an evaluation and mapping of groundwater recharge potential zones in Jalgaon district has been undertaken in this study. A regional-scale analytical framework has been employed, incorporating GRACE data, hydrogeology, GIS, and remote sensing. The objectives of the investigation can be summarised as follows 1. GRACE satellite data are utilised to examine groundwater storage anomalies and evaluate temporal groundwater trends within the district. 2. Hydrogeological and geospatial factors influencing recharge—such as slope, land use/land cover, soil type, lineament density, and rainfall—are identified and classified. 3. Groundwater recharge potential is mapped using an AHP-based MCDA model within a GIS environment. 4. Zones of high, moderate, and low recharge suitability are delineated, allowing prioritisation of intervention efforts.

2. Study Area Overview

The study focusses on the Jalgaon district, which covers around 11,800 square km. The district is divided into 15 talukas, which include Jalgaon, Bhusawal, Yawal, Chopda, Amalner, and Erandol. The elevation fluctuates between 150 and 600 meters, and the environment is dominated by undulating basaltic uplands, pediplains, and the Tapi River's alluvial floodplain. Annual rainfall varies greatly across the area, with lower levels in the central and eastern talukas (figure 1). The aquifer system is composed primarily of fractured and weathered basalt, interspersed with alluvial deposits in the Tapi basin. Over the years, the number of borewells has significantly increased, with water levels during pre-monsoon often dipping below 25–30 meters below ground level (mbgl) in many locations. Recharge structures, though present, are often not aligned with the underlying hydrogeological framework, reducing their efficiency.

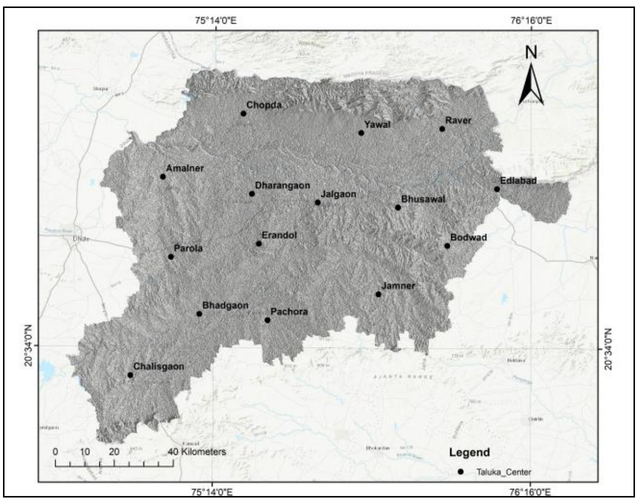

Figure 1: Location of study area

3. Material and Methodology

The methodology used in this work is an integrated strategy that combines remote sensing, satellite-based groundwater anomaly data, GIS-based spatial analysis, and a multi-criteria evaluation model to identify groundwater recharge potential zones in the Jalgaon area. The overall framework is structured into four major stages:

1. Data Collection and Preprocessing
2. Selection and Derivation of Thematic Layers
3. Application of Multi-Criteria Decision Analysis (MCDA) using Analytic Hierarchy Process (AHP)
4. Validation and Zonation of Recharge Potential Areas

3.1 Data Sources

Jalgaon district, located in the northern part of Maharashtra, was selected as the study area due to its growing water scarcity and agricultural dependence. The following datasets were collected and pre-processed for the analysis (Table 1):

Table 1: Geodatabase source

Data Type	**Parameter**	**Source**
Satellite Data	GRACE Monthly Groundwater Storage Anomalies (2002–2023)	NASA JPL/CSR
Topographic	GDEM (30 m resolution)	USGS Earth Explorer
Climate	Average Rainfall	TRMM
Soil and Land Use	Soil Texture, LULC classification	NBSS&LUP and NRSC Bhuvan
Geological	Lineament, Lithology, Slope	Geological Survey of India (GSI), NRSC
Administrative	Taluka Boundaries	Maharashtra Remote Sensing Application Centre (MRSAC)

3.2 Derivation of Thematic Layers

Eight key thematic layers were selected for their relevance in influencing groundwater recharge potential. Each layer was prepared in a GIS environment using ArcGIS and QGIS software:

1. **Rainfall**: Mean annual precipitation was derived from thematic mapping rainfall mission (TRMM) data
2. **Slope**: Derived from SRTM DEM. Gentle slopes (0–5%) favor infiltration; steep slopes lead to runoff.
3. **Soil Texture**: Soils were categorized into sandy, loamy, clayey, and gravelly based on infiltration capacity.
4. **Land Use/Land Cover (LULC)**: LULC classes such as agricultural land, forest, barren land, and built-up area were extracted using supervised classification.
5. **Drainage Density**: Calculated from hydrology tools in GIS. Lower drainage density generally indicates more infiltration potential.
6. **Lineament Density**: Lineaments extracted using edge-detection from DEM and geological maps; higher density implies more secondary porosity.
7. **Lithology**: Geological formations were classified into basaltic, alluvial, and mixed lithologies.
8. **Depth to Water Table**: Derived from CGWB pre- and post-monsoon well data; zones with deep water table indicate potential recharge targets.

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All thematic layers were resampled to a common spatial resolution (30 m) and projected to UTM Zone 43N for uniformity.

3.3 GRACE-Based Groundwater Storage Analysis

The GRACE (Gravity Recovery and Climate Experiment) satellite mission provides monthly terrestrial water storage anomalies (TWSA), which were used to derive groundwater storage anomalies (GWSA) using the water balance approach:

$$GWSA = TWSA - (\text{Soil Moisture} + \text{Surface Water}) \qquad (1)$$

Monthly GWSA data (2002–2023) were extracted for Jalgaon district using Google Earth Engine (GEE) and processed using Python-based scripts. Linear trend analysis and Mann-Kendall trend tests were applied to identify spatial trends in groundwater change.

3.4 Multi-Criteria Decision Analysis (MCDA) using AHP

The AHP technique was adopted to assign weights to each thematic layer and their respective classes based on their influence on groundwater recharge. The methodology followed these steps:

3.4.1 Step 1: Pairwise Comparison Matrix

A pairwise comparison matrix was developed among the selected parameters. The Saaty's 1–9 scale was used to represent relative importance. For example, rainfall may be rated more important than land use for recharge (Table 2).

Table 2: Pairwise Comparison Matrix

Criteria	Rainfall	Soil Texture	Lineament Density	LULC	Lithology	Slope	Drainage Density	Depth to WT
Rainfall	1	2	3	4	4	5	6	6
Soil Texture	1/2	1	2	3	3	4	5	5
Lineament Density	1/3	1/2	1	2	2	3	3	4
LULC	1/4	1/3	1/2	1	2	3	3	3
Lithology	1/4	1/3	1/2	1/2	1	2	2	2
Slope	1/5	1/4	1/3	1/3	1/2	1	2	2
Drainage Density	1/6	1/5	1/3	1/3	1/2	1/2	1	2
Depth to Water Table	1/6	1/5	1/4	1/3	1/2	1/2	1/2	1

3.4.2 Step 2: Normalization and Weight Derivation

The matrix was normalized, and eigenvectors were computed to derive weights for each criterion. The consistency ratio (CR) was checked to ensure logical consistency. A CR $\leq$ 0.1 was considered acceptable.

Table 3: Finalised weight of parameter

Parameter	Weight (%)
Rainfall	21
Soil Texture	18
Lineament Density	15
Land Use/Land Cover	13
Lithology	11
Slope	9
Drainage Density	7
Depth to Water Table	6

3.4.3 Step 3: Weighted Overlay Analysis

Each raster layer was reclassified into five suitability classes: Very High, High, Moderate, Low, and Very Low. Using the raster calculator in GIS, a final groundwater recharge potential map was generated by weighted summation of all layers.

3.5 Validation and Ground Truthing

To ensure the reliability of the groundwater recharge potential zones identified in the study, validation was carried out through the integration of well water level data from the Groundwater Surveys and Development Agency (GSDA) and the Central Ground Water Authority (CGWA). Pre-monsoon and post-monsoon groundwater level records from multiple observation wells across the district were analyzed to assess seasonal fluctuations and long-term recharge behavior. Areas categorized as having high to very high recharge potential in the GIS-based model were expected to show measurable water level recovery post-monsoon, aligning with field-recorded data.

4. Result and discussion

4.1 Rainfall

Precipitation is regarded as a key determinant of groundwater recharge potential, particularly in semi-arid basaltic regions such as Jalgaon. In this investigation, mean annual rainfall values were obtained and derived from TRMM datasets. Considerable spatial variability in precipitation patterns across the district was observed, with values ranging from approximately 650 mm in the southern talukas (Chalisgaon and Amalner) to more than 1,250 mm in the northern regions (Raver and Yawal). Talukas located in central and eastern parts of the district—such as Jalgaon (Figure 2), Pachora, and Jamner—were recorded as receiving moderate levels of rainfall between 750 and 850 mm. Variations in precipitation across the region have been shown to markedly influence infiltration processes; higher rainfall in northern zones has been associated with increased recharge potential, particularly in areas where favourable topography and soil permeability are present.

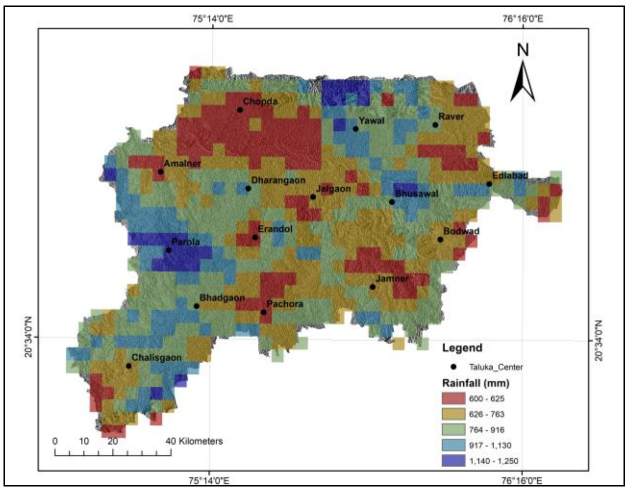

Figure 2: Soil texture map of study area

A strong relationship between higher precipitation zones and enhanced recharge suitability was identified once the interpolated rainfall map was overlaid with groundwater recharge potential zones. This correlation was further supported through the AHP-weighted model, in which rainfall was assigned the highest weightage (21%). Validation of these results was provided by groundwater level trends from CGWA

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and GSDA, where post-monsoon rises of approximately 2.0 to 3.5 meters were recorded in high-rainfall talukas such as Yawal and Raver. By contrast, seasonal rises of less than 1 meter were noted in areas with lower rainfall and hard rock terrain, such as Bodwad and Parola. In certain eastern pockets like Edlabad, limited recharge was observed even under favourable precipitation conditions, due to poor soil permeability and intense runoff on steep slopes.

4.2 Soil Texture

A diverse range of soil textures within Jalgaon district has been documented, including clay loam, clayey, sandy loam, gravelly clay loam, and sandy loam (Figure 3). Clayey and clay loam soils have been observed as dominant in central and eastern talukas such as Jalgaon, Erandol, and Pachora, whereas gravelly textures are present across the western upland regions of Chalisgaon and Amalner. These finer-textured soils have been assigned a ‘High’ category in the AHP evaluation (weight: 3%), as higher infiltration rates and recharge capacity are supported, particularly under favorable topographic and rainfall conditions (Bojer et al., 2024). Talukas characterised by significant clay loam coverage, including Bhusawal and Bodwad, were consistently classified within the High to Very High recharge potential zones in the weighted overlay analysis. Gravelly soils in upland areas were categorised as Moderate to Low recharge zones in most cases, unless additional favourable features such as high lineament density or gentle slopes were present. Borewell site observations within clay loam zones revealed noticeable increases in groundwater levels during the monsoon season, and such findings have underscored the critical role played by fine-textured soils in facilitating effective groundwater recharge.

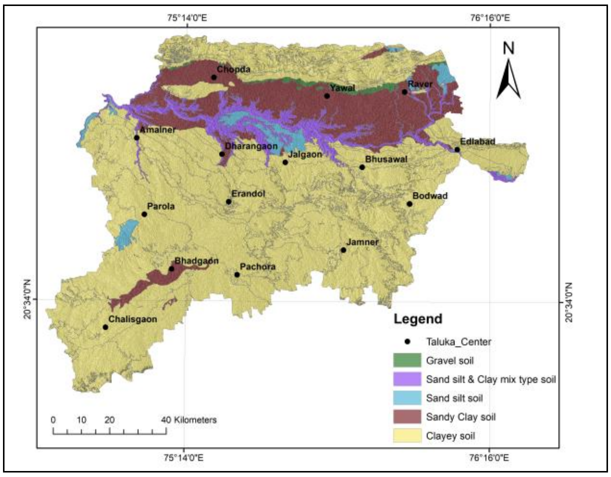

Figure 3: Soil texture map of study area

4.3 Lineament Density

Subsurface fracture networks, expressed through lineament density, have been recognised as critical contributors to vertical groundwater recharge, particularly within the hard-rock basaltic terrain of Jalgaon district. Moderate to high lineament densities around the Tapi floodplain—including areas near Bhusawal and Jalgaon town—have been identified in GSDA aquifer mapping. Accordingly, these features were assigned a weight of 7% within the AHP model. Enhanced aquifer connectivity was facilitated by dense lineaments, enabling both shallow and deep recharge pathways in basaltic formations.

Seasonal water table rises of approximately 2–3 meters were recorded in borewells located in regions such as Jalgaon and Pachora, compared to much lower recovery in areas with sparse lineament density. Such variations have illustrated the hydrological significance of lineament-rich zones and their potential for promoting infiltration. The association between lineament density and recharge capability has been further strengthened when combined with moderate to high rainfall and favourable soil textures.

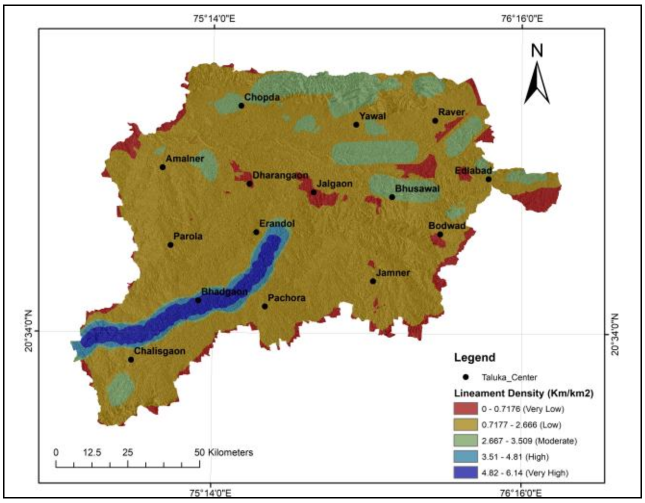

Figure 4: Lineament Density map of study area

4.4 Land Use/Land Cover (LULC)

Land use/land cover (LULC) composition in Jalgaon district—characterised by predominantly agricultural land (75–80%) with scattered forests, grasslands, and limited built-up areas—has been shown to exert a substantial influence on groundwater recharge. Within the AHP framework, agricultural lands and water bodies were allotted the highest weightage (5%), whereas wasteland and built-up areas were assigned minimal influence. Moisture retention and reduced surface runoff were supported by irrigated croplands, particularly those under banana cultivation, thereby promoting infiltration and groundwater recharge; conversely, built-up regions with impervious surfaces were associated with decreased infiltration potential. A close correspondence between high recharge potential zones and irrigated agricultural clusters was observed in the spatial overlay analysis, especially within talukas such as Bodwad and Bhusawal, where canal seepage and micro-irrigation techniques have been practised. Urbanised zones, including Jalgaon city, were delineated as Low to Very Low recharge potential areas owing to unfavourable LULC conditions that impede infiltration (Figure 5).

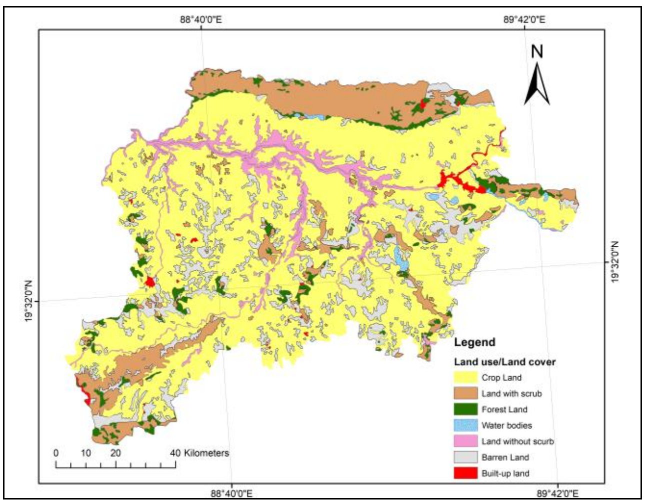

Figure 5: Land use/land cover map of study area

4.5 Lithology

Deccan Trap basalt has been identified as the dominant lithology across Jalgaon district. Minor Gondwana sediments and alluvium were observed along the Tapi River corridor. A weight of 16% was assigned to lithology in the AHP evaluation. Alluvial zones in the northern and central talukas were rated as high suitability due to higher porosity and permeability. Basaltic uplands, especially plateau regions, were classified as low suitability owing to low fracture density and porosity (Figure 6). Talukas such as Bhusawal, Yawal, and Jalgaon were mapped as High to Very High recharge zones. Borewell data showed notable post-monsoon water level rises, confirming effective recharge. In contrast, basalt plateau areas appeared largely as Low recharge zones. These results matched the limited recharge trends reported in CGWA monitoring data.

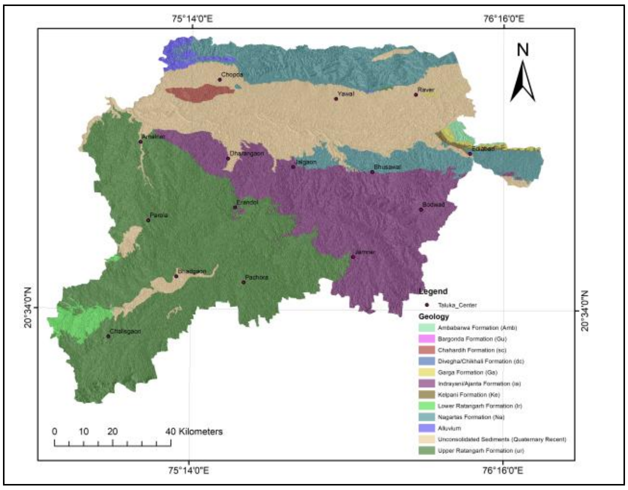

Figure 6: Lithology map of study area

4.6 Slope

Slope analysis using SRTM data identified gentle slopes (<5%) in the Tapi River floodplain as highly suitable for recharge. Slopes above 15% were classified as low suitability zones, while areas between 5% and 15% were placed in the moderate category (Figure 7). A weight of 24% was given to slope in the AHP model, indicating strong control over infiltration and runoff. High recharge zones were delineated in valley-fill areas of Pachora and Jamner, where slopes remained below 5%. In contrast, steep basaltic uplands and mountainous regions were marked as Low to Very Low suitability. This pattern matched field observations of runoff-dominated hydrology in those areas.

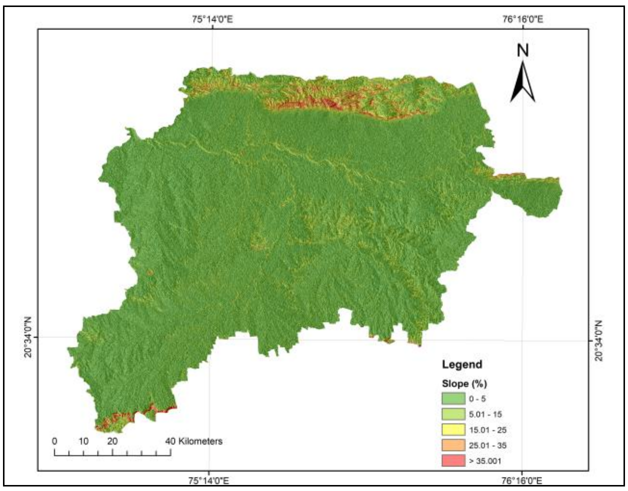

Figure 7: Slope map of study area

4.7 Drainage Density

Slope analysis based on SRTM data showed that gentle slopes (<5%) in the Tapi floodplain are considered highly suitable for recharge. Areas with slopes above 15% were marked as low suitability, while slopes of 5%–15% were placed in the moderate category. Slope received a weight of 24% in the AHP model due to its strong effect on infiltration and runoff. High recharge zones were observed in the flat valley-fill areas of Pachora and Jamner. Steep basaltic uplands and mountainous parts were classified as Low to Very Low suitability. These findings matched field reports indicating runoff dominance in those regions. (Figure 8).

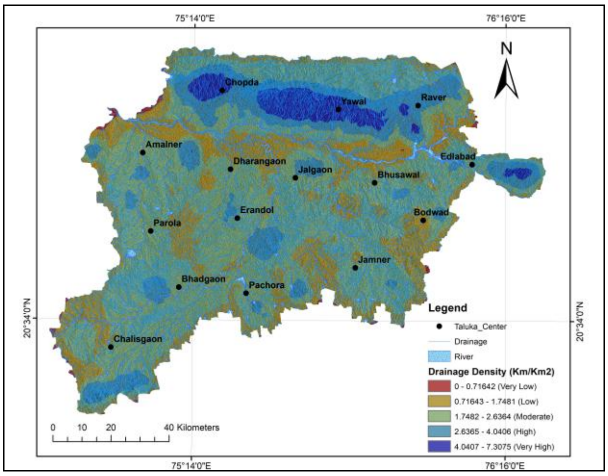

Figure 8: Drainage density map of study area

4.8 Depth to Water Table

Although the depth-to-water table received the lowest weight (6%) in the AHP model, it was still considered an important indicator for differentiating recharge suitability zones. Groundwater levels deeper than 20 meters in upland areas were classified as Low to Very Low recharge zones, while shallow water tables (<5 m) in the Tapi floodplain and central alluvial areas were assigned High suitability. Depths of 5 to 15 meters were placed in the Moderate category. This classification was validated through GSDA and CGWA monitoring records. The findings demonstrated that initial groundwater depth exerts strong control on recharge response. Areas with water tables less than 10 meters below ground level showed noticeable post-monsoon rise, whereas deeper wells in upland basaltic regions remained largely unaffected despite rainfall. These observations indicate that shallow aquifers respond more readily to recharge, while deeper hard-rock aquifers exhibit limited recharge due to restricted vertical percolation (Figure 9).

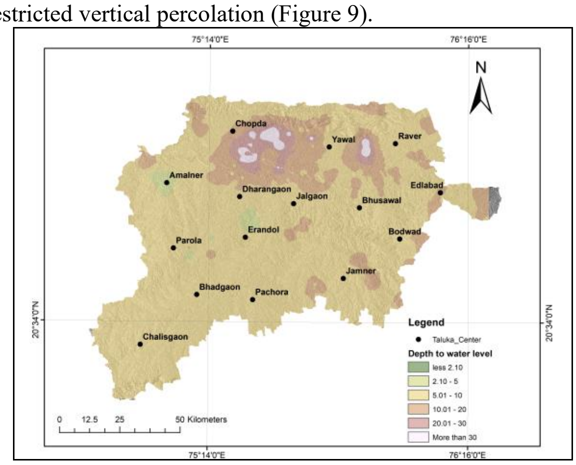

Figure 9: Depth to Water Table map of study area

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4.9 GRACE-Based Groundwater Storage Analysis

The Gravity Recovery and Climate Experiment (GRACE) satellite data is regarded as an advanced approach for monitoring terrestrial water storage (TWS) variations over time, which can be translated into groundwater storage fluctuations once surface water and soil moisture components have been accounted for. Within the Jalgaon district context, GRACE-derived data from 2003 to 2022 were analysed to assess groundwater storage trends at seasonal and interannual scales. Monthly GRACE-TWS anomalies, obtained from the NASA Jet Propulsion Laboratory (JPL), were processed using basin averaging techniques, and groundwater storage change (ΔGWS) was computed by subtracting soil moisture and surface water estimates from GLDAS data. The resulting time series indicated pronounced seasonal declines during pre-monsoon periods, and partial recovery during post-monsoon months, with notable deficits recorded during drought years such as 2014–15 and 2018–19.

A net declining trend of approximately –1.2 cm per year in groundwater storage anomalies (GWSA) was observed across the district, which has aligned with previous CGWB reports and has reinforced concerns about unsustainable extraction. This depletion trend was particularly pronounced in intensively irrigated talukas such as Jalgaon, Bhusawal, and Yawal, which are associated with large-scale banana cultivation and canal-based irrigation. Validation of GRACE results with GSDA monitoring well data showed strong agreement, especially in depicting interannual variability and progressive depletion. These findings have highlighted the necessity of integrating satellite-based information into groundwater management strategies, thereby enabling planners to identify over-extraction hotspots and prioritise appropriate recharge measures (Rodell et al., 2009; Long et al., 2015) (Figure 10).

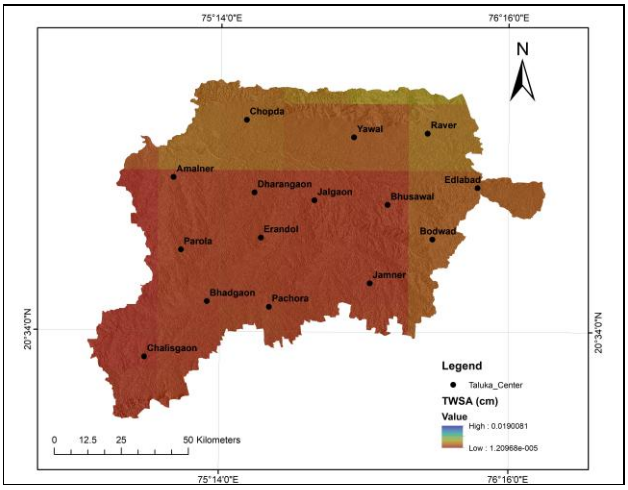

Figure 10: GRACE derived spatial distribution of TWSA (cm)

4.10 Multi-Criteria Decision Analysis (MCDA) Using AHP

Assessment of spatial variability in groundwater recharge potential in the Jalgaon area was carried out using the Analytical Hierarchy Process (AHP) together with a Multi-Criteria Decision Analysis (MCDA) approach. Seven thematic layers—soil texture, lineament density, land use/land cover (LULC), lithology, slope, drainage density, and depth to water table—were selected as key contributors to recharge dynamics. Pair-wise comparison matrices were developed using expert judgment and literature-derived scales (Saaty, 1980), with importance scores allotted from 1 (equal) to 9 (extremely important). An acceptable consistency ratio (CR < 0.10) was obtained, confirming the logical soundness of the AHP matrix. Rainfall (21%), lineament density (17%), and depth to water table (15%) were identified as the most influential factors under semi-arid Deccan basaltic settings.

A composite Groundwater Recharge Potential Index (GRPI) map was produced by combining the thematic layers through weighted overlay analysis in a GIS environment following normalization and weight assignment. Functioning as a spatial decision-support tool, this map classified the district into five categories: very high, high, moderate, low, and very low recharge potential. Validation based on CGWA-GSDA well data, GRACE trends, and field inspection confirmed High potential in zones such as Yawal, Raver, and Chopda—areas characterized by lineament intersections, deeper aquifers, and moderate slopes. Low potential areas, including Bodwad and Parola, were associated with steep gradients, less permeable lithology, and poor drainage interaction. Implementation of this AHP-based MCDA technique is considered beneficial under national schemes like Jal Shakti Abhiyan and Atal Bhujal Yojana, and has been recognised as an effective framework for regional-scale planning of artificial recharge structures.

4.11 Integrated Groundwater Recharge Potential Mapping Using AHP-GRACE Fusion

Generation of the final groundwater recharge potential map for Jalgaon district was accomplished through the integration of the AHP-derived Groundwater Recharge Potential Index (GRPI) and GRACE-derived Groundwater Storage Anomaly (GWSA) dataset, thereby merging surface-based and satellite-based assessments for enhanced spatial reliability. Weighted overlay analysis in a GIS environment was applied to create the GRPI map, using seven thematic layers—soil texture, lineament density, LULC, lithology, slope, drainage density, and depth to water table—each weighted according to the AHP methodology. In parallel, monthly GRACE-TWS data (2003–2022) were processed to isolate groundwater storage components, which were subsequently interpolated across the district using Ordinary Kriging geostatistical techniques. Through the combination of GRPI and GWSA layers, areas exhibiting both high recharge suitability and critical groundwater depletion were detected, indicating priority zones for intervention.

Significant spatial heterogeneity in recharge potential across the district was evident in the integrated output. Very high recharge potential zones (constituting 8.2% of the district) were recorded mainly in northern and northeastern portions—including parts of Yawal, Raver, and Chopda—characterised by low slopes, high lineament density, substantial drainage networks, and shallow water tables. These areas also displayed moderate-to-high GRACE-based depletion, making them strong candidates for artificial recharge measures. Considerable high-potential zones (37.6%) were distributed across Bhusawal, Jalgaon, and Erandol, featuring favourable lithological conditions but subject to slope or lineament constraints. Low and very low recharge areas (26.3%) were concentrated mainly in the southwestern regions such as Bodwad and Parola, marked by steep slopes, clay-rich soils, and limited fracture density; these matched stable or moderately improving GRACE groundwater trends, owing to lower rates of extraction.

Holistic prioritisation of recharge zones was enabled by this integrated methodology, as both surface-based recharge suitability and dynamic groundwater decline were evaluated simultaneously. Rather than relying solely on hydrogeological or LULC indicators, incorporation of GRACE data has introduced a time-sensitive validation element reflecting real-world aquifer stress. Provision of a robust decision-support tool has been achieved, aiding district and state authorities in programmes such as Jal Shakti Abhiyan, Atal Bhujal Yojana, and the GSDA Maharashtra Aquifer Management Plan. Emphasis has been placed not only on geologically favourable areas, but also on zones where urgent intervention is required based on depletion trends, thereby offering a scientific foundation for prioritised investment in recharge infrastructure (Figure 11).

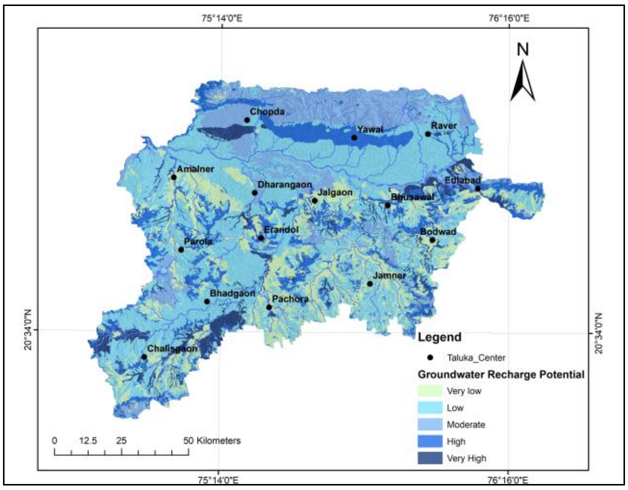

Figure 11: Groundwater Recharge Potential map study area

4.12 Model Validation Using ROC-AUC Analysis

Evaluation of the reliability and predictive strength of the integrated groundwater recharge potential map was performed using Receiver Operating Characteristic (ROC) curve analysis. This validation technique was applied to compare the predicted recharge suitability with actual field-based validation points, including observed well performance, existing recharge structures, and long-term trends of water-level rise. Validation points were compiled from GSDA-documented recharge wells, functioning check dams, and successful borewell locations distributed across Yawal, Chopda, and Bhusawal talukas.

Computation of the Area Under the ROC Curve (AUC) was carried out after binary classification of spatial zones into “Recharge” and “Non-Recharge” categories using prescribed threshold values. An AUC score of 0.89 was recorded, which indicates excellent predictive performance of the model. Values nearing 1.0 are considered highly accurate, while those approaching 0.5 represent random prediction capability. A strong correlation between the AHP-GRACE integrated model outputs and actual recharge behavior observed in the field is suggested by the high AUC value of 0.89.

Confirmation of high predictive accuracy has reinforced the robustness of the AHP-weighted multi-criteria overlay approach, which was further enhanced by incorporation of time-series GRACE satellite anomalies as a dynamic groundwater response indicator. Capability of the model to clearly differentiate between zones of high and low recharge potential has been validated, thereby providing a scientifically reliable tool for prioritization of groundwater recharge interventions at the regional level.

5. Conclusion

This study presents a comprehensive spatio-regional analysis of groundwater recharge potential in Jalgaon district, Maharashtra, using an integrated approach that combines hydrogeospatial parameters with satellite-derived GRACE data within a GIS-based AHP-MCDA framework. The methodology incorporated seven thematic layers—Soil Texture, Lithology, Slope, LULC, Drainage Density, Lineament Density, and Depth to Water Table—weighted using the Analytical Hierarchy Process (AHP). The final recharge potential map was classified into five zones, revealing that areas like Yawal, Chopda, Raver, and northern Bhusawal exhibit high to very high recharge suitability due to favorable geological structures, deeper aquifers, moderate slopes, and active water conservation measures.

The integration of GRACE-derived groundwater storage anomalies added a temporal and dynamic dimension, validating the spatial pattern of recharge potential across the district. The model's robustness was confirmed through field validation, CGWB-GSDA monitoring well data, and ROC-AUC analysis, which yielded a strong accuracy score of 0.89. This high AUC underscores the predictive reliability of the model in identifying and prioritizing zones for artificial recharge interventions.

The outcomes offer valuable scientific guidance for implementing programs like Jal Shakti Abhiyan and Atal Bhujal Yojana, especially in the water-scarce, agriculturally intensive areas of Jalgaon. The methodology is replicable for other semi-arid, basaltic terrains across India and can significantly assist in data-driven groundwater resource planning, helping to build climate resilience and water security for future generations.

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