SPATIOTEMPORAL ANALYSIS OF GROUNDWATER RESOURCE DYNAMICS AND EXTRACTION TRENDS IN GADCHIROLI DISTRICT, MAHARASHTRA, INDIA

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Abstract
The official dataset of Dynamic Groundwater Resources of Maharashtra (2022–23) from GSDA-CGWB has been used to study the groundwater resource dynamics in Gadchiroli district. The article evaluated taluka wise recharge, annual extractable groundwater resource, groundwater extraction and future availability and stage of extraction in hard rock terrain of the district. The method adopted was descriptive in nature using secondary data and the analysis was restricted to manual tabulation and interpretation of the official values at taluka level. The total annual groundwater recharge for the 12 assessment units was 109,025.62 ham and the total annual extractable groundwater resource was 102,863.42 ham. Overall extraction pressure of groundwater was 24.37% with total extraction of 25,064.3 ham. The lowest extraction stage recorded was at Bhamragad (7.8%) and the highest at Sironcha (35.0%) with all the other units being safe. The highest future groundwater availability was found in Etapalli, Chamorshi and Aheri. The results show that there is good groundwater balance in the present condition in Gadchiroli, while talukas with relatively high extraction levels should be monitored. To ensure long-term groundwater security in the hard-rock aquifer system of the district, recharge protection, controlled groundwater use and district-specific planning are recommended.

Keywords: *Groundwater Recharge, Hard-Rock Aquifer, Groundwater Extraction, Gadchiroli District, Groundwater Resource Dynamics.*

1. Introduction

Groundwater is one of the most vital natural resources for Rural Water Supply, Irrigation and Livelihood security. It is more significant in areas of hard rock where surface water is often limited in availability and groundwater storage is determined by the physical properties of the underlying rocks. Hard-rock aquifers typically do not have continuous and highly porous water-bearing layers. They are primarily dependent on weathered zones, fractures, joints, faults, slope, drainage pattern and local recharge opportunities for their groundwater potential. Hence, in such regions, groundwater assessment is not just based on the total amount of rainfall received in a region, but also the availability of the groundwater resources and the pressure being exerted by groundwater extraction (Sajil Kumar et al., 2022).

Hard rock areas are a complex hydrogeological environment since the occurrence of groundwater is not always the same throughout space. Within the same district, there could be some talukas with good recharge and future groundwater availability, and others with comparatively limited groundwater availability due to topography, drainage control, thickness of the aquifer and/or poor fracture connectivity. In hard-rock provinces, recent studies have revealed that geology, slope, rainfall, drainage density and lineament distribution are significant factors affecting the groundwater potential and hence, a spatially sensitive assessment of groundwater potential is necessary for sustainable groundwater management planning (Pragadeeshwaran et al., 2026). Other studies have also highlighted the importance of considering geomorphology, terrain variation and structural features in hard-rock groundwater systems to account for the infiltration, storage and groundwater movement (Murugesan et al., 2025).

With the increasing demand for groundwater in India, it is imperative to assess the recharges, extraction and future availability of the groundwater periodically. Over-reliance on groundwater for irrigation and domestic use can slowly turn what may appear to be a safe aquifer into a stressed aquifer, particularly when there is no consideration of recharge planning and borewell drilling increases. As seen in the case of Indian hard-rock aquifers, the stress on the aquifer can be high when the rate of groundwater abstraction is greater than the natural recharge rate and when the deepening of borewells is a reaction to the depletion of shallow aquifers (Kulkarni et al., 2021). Therefore, groundwater-resource studies are not only valuable for determining the amount of water available, but also to determine if current groundwater removal is occurring at a safe rate.

In hard rock regions, rainfall, landform, drainage, and soil cover and the degree of weathering or fracturing of the bedrock are all significant factors in groundwater recharge (Subramani & Kamaraj, 2024). In these kinds of terrain, recharge is frequently localized and can be found at locations where surface runoff is reduced, fractures are present to allow infiltration into the subsurface, and infiltration is facilitated. In Indian hard rock basins, studies have indicated that soil type, fracture network, faults, drainage and geomorphological environment are important factors that influence recharge and groundwater potential (Arumugam et al., 2023). Thus, the assessment of the dynamics of groundwater resources should not assume that recharge is occurring uniformly across the district, but rather that it is a spatially variable process.

The sustainable management of groundwater also needs to be related to actual groundwater use. If extraction is relatively low compared to the annual extractable groundwater resources, an area could be deemed safe, but this should be viewed as a planning opportunity not a licence for uncontrolled development. The dynamics of groundwater, its storage change, and periodic assessment are important to assess whether an area is becoming more stable, depleted or stressed in the future (Mondal et al., 2022). Managed aquifer recharge and water-harvesting are important strategies to enhance groundwater security in the face of increased demand and climate variability in this context (Gebreslassie et al., 2025; Sufyan et al., 2024).

The study of groundwater resource dynamics in hard-rock environment is suitable in Gadchiroli district of Maharashtra. The district is different from the areas in Maharashtra dominated by the Deccan Trap and is correlated to the older hard-rock geology. Archean gneisses and dongargarh granite of Proterozoic age is the major lithounits of this area. In Maharashtra, groundwater planning at the district scale and taluka scale is of critical importance as the availability of groundwater is vital for rural drinking water security and local development, and the protection of groundwater recharge and responsible groundwater extraction (Wescoat & Murty, 2021). Groundwater studies in recent past have also revealed that potential-zone mapping can be done using lithology, slope, lineament, drainage, geomorphology and rainfall in complex terrains to assist in better water-resource planning (Sud et al., 2023).

The present study thus investigated the dynamics of groundwater resources and status of groundwater extraction in the hard-rock terrain of Gadchiroli district on the basis of the official dataset on Dynamic Groundwater Resources of Maharashtra 2022-23 provided by GSDA–CGWB. The study was based on taluka-wise recharge, extractable groundwater resource for annual recharge, groundwater extraction, stage of extraction, future availability and category of extraction. The main objective of the article was to understand the current state of groundwater and to determine if the groundwater system in hard rock is within safe extraction limits for the assessment conditions in 2022-23 in Gadchiroli district.

2. Methodology

2.1 Research Design and Data Source

This study was of descriptive type with secondary data approach. The analysis has been carried out only on the Report on the Dynamic Groundwater Resources of Maharashtra (Groundwater Surveys and Development Agency, Pune & Central Ground Water Board, 2024). The report gave a snapshot of the status of groundwater resources in Maharashtra as on March 2023 and gave the groundwater recharge, annual extractable groundwater resource, groundwater extraction, future availability, stage of extraction and categorization taluka-wise. In the current study, no primary field survey, processing of the remote sensing data, GIS modelling and any specialised software-based analysis was undertaken.

2.2 Study Area and Geological Basis

The study area was chosen as Gadchiroli district as it was identified as one of the non-Deccan Trap geological setting of Maharashtra from the report. According to the report, volcanic lava flows of Deccan Trap occurred in all districts of Maharashtra except Bhandara, Gondia and Gadchiroli. It also recognized the Precambrian rocks of the Sakoli Series, Iron Ore Series and Peninsular Basement Complex, Archean gneisses and dongargarh granite of Proterozoic age is the major lithounits of this area.(Groundwater Surveys and Development Agency, Pune & Central Ground Water Board, 2024). For this groundwater-resource interpretation, the district was considered to be a hard rock terrain. The assessment units at the taluka level provided in the official dataset of the Gadchiroli district have been used in the study.

2.3 Variables Extracted from the Dataset

The variables were selected as given in Annexure B and Annexure C of the data set (Groundwater Surveys and Development Agency, Pune & Central Ground Water Board, 2024). The total recharge-worthy area, recharge from rainfall during monsoon, recharge from other sources during monsoon, recharge from rainfall during non-monsoon, recharge from other sources during non-monsoon, total annual groundwater recharge, natural discharge and annual extractable groundwater resource were used from Annexure B. The data used for the purpose were: irrigation extraction, domestic extraction, industrial extraction, total extraction, net groundwater availability for future use, stage of groundwater extraction and category from Annexure C. Units of the report were the main units, which were units of value, and in this case, those units were the units of ham.

2.4 Manual Analytical Procedure

Only manual tabulation, comparison and interpretation of official taluka-wise values has been done. A new groundwater recharge and extraction model was not created. The 12 talukas of Gadchiroli assessment units were tabulated and district level totals were calculated by adding up the reported taluka totals. The stage of extraction was interpreted based on the official categorisation rule: safe (up to 70%), semi-critical (above 70% to 90%), critical (above 90% to 100%) and over-exploited (above 100%). This guaranteed that the methodology was in line with the data set.

3. Results

3.1 Recharge and Extractable Groundwater Resource

The total groundwater recharge of the 12 Gadchiroli assessment units was 109,025.62 ham per year and total extractable groundwater resource was 102,863.42 ham per year. Chamorshi had the maximum groundwater recharge (14,467.64 ham) and groundwater extractable (13,563.93 ham) in the year. Etapalli was next with 12,972.18 ham recharge and 12,288.72 ham extractable resource. The lowest value was recorded in Bhamragad with 3,840.94 ham recharge and 3,522.07 ham extractable resource. Kurkheda had a total of 10,468.75 ham recharge and 9,945.30 ham extractable resource (Groundwater Surveys and Development Agency, Pune & Central Ground Water Board, 2024).

Table 1. Taluka-wise groundwater recharge and extractable resource in Gadchiroli district

Taluka / Assessment unit	Total annual groundwater recharge (ham)	Annual extractable groundwater resource (ham)
Aheri	11,730.80	10,957.43
Korchi	5,009.66	4,758.21
Gadchiroli	6,892.19	6,512.50
Wadsa	6,847.05	6,455.63
Etapalli	12,972.18	12,288.72
Armori	9,365.19	8,872.79
Bhamragad	3,840.94	3,522.07
Chamorshi	14,467.64	13,563.93
Dhanora	9,545.95	9,046.55
Kurkheda	10,468.75	9,945.30
Mulchera	7,912.65	7,506.91
Sironcha	9,972.62	9,433.38
Total	**109,025.62**	**102,863.42**

3.2 Groundwater Extraction Pattern

The total groundwater extraction of Gadchiroli district is 25,064.30 ham based on 12 assessment units reported. Chamorshi had the maximum extraction of 3,318.4 ham, followed by Sironcha with 3,306.0 ham and Kurkheda with 3,183.7 ham. The lowest extraction was recorded at Bhamragad with 275.9 ham. The data revealed that the extraction was primarily from irrigation and domestic sources, and industrial extraction was either not present or was minimal in these Gadchiroli units (Groundwater Surveys and Development Agency, Pune & Central Ground Water Board, 2024). The overall groundwater development pressure was low, as the district-level extraction was far less than the annual extractable resource.

Table 2. Taluka-wise groundwater extraction status in Gadchiroli district

Taluka / Assessment unit	Irrigation extraction (ham)	Domestic extraction (ham)	Total extraction (ham)
Aheri	1,131.1	342.6	1,473.7
Korchi	1,045.5	182.1	1,227.6
Gadchiroli	1,437.2	296.3	1,733.5
Wadsa	1,292.9	378.1	1,671.0
Etapalli	1,640.4	345.3	1,985.6
Armori	2,296.8	464.8	2,761.8
Bhamragad	206.2	69.7	275.9
Chamorshi	2,587.8	729.3	3,318.4
Dhanora	2,131.4	311.6	2,443.1
Kurkheda	2,923.6	260.1	3,183.7
Mulchera	1,523.4	160.6	1,684.0
Sironcha	2,938.8	367.2	3,306.0
Total	**22,155.1**	**3,907.7**	**25,064.3**

3.3 Stage of Groundwater Extraction and Category

The calculated district-level extraction pressure, obtained by comparing total extraction with annual extractable groundwater resource, was approximately 24.37%. All twelve Gadchiroli assessment units were categorized as safe in the dataset. Sironcha had the highest stage of groundwater extraction at 35.0%, followed by Kurkheda at 32.0% and Armori at 31.1%. Bhamragad had the lowest stage at 7.8% (Groundwater Surveys and Development Agency, Pune & Central Ground Water Board, 2024). Since all values were below the official 70% safe-category threshold, no Gadchiroli taluka was classified as semi-critical, critical or over-exploited.

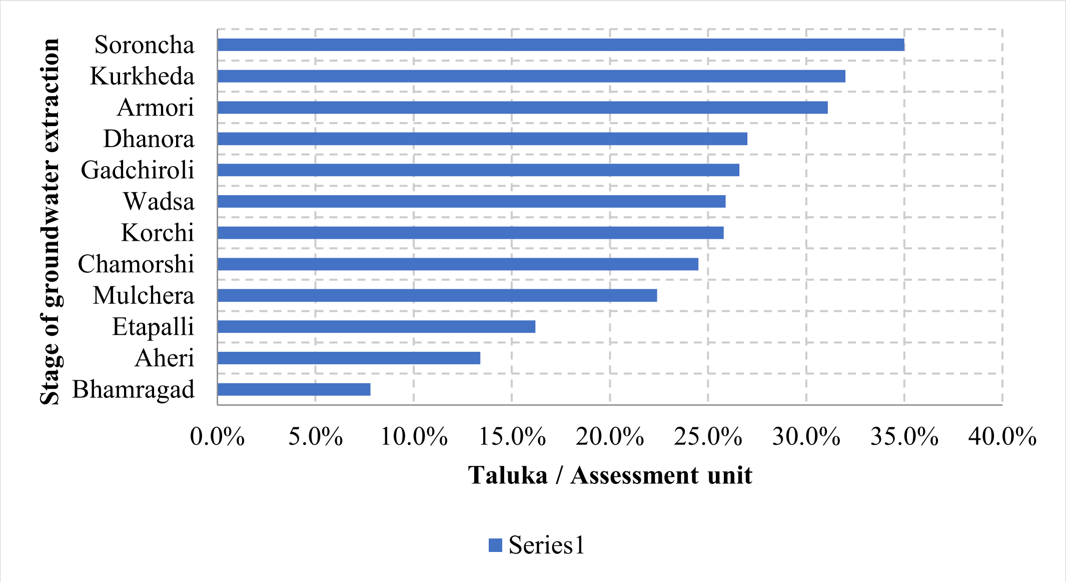

Figure 1. Stage of groundwater extraction in Gadchiroli assessment units

3.4 Future Groundwater Availability

The total net groundwater availability for future use in Gadchiroli district was 77,799.10 ham. Etapalli had the highest future groundwater availability at 10,303.1 ham, followed by Chamorshi at 10,245.5 ham and Aheri at 9,483.7 ham. Bhamragad showed the lowest future availability at 3,246.1 ham, mainly because of its smaller reported extractable resource. Kurkheda retained 6,761.6 ham for future use despite having one of the higher extraction stages. Overall, the results showed that Gadchiroli's hard-rock terrain had substantial remaining groundwater availability under the 2022–23 assessment conditions.

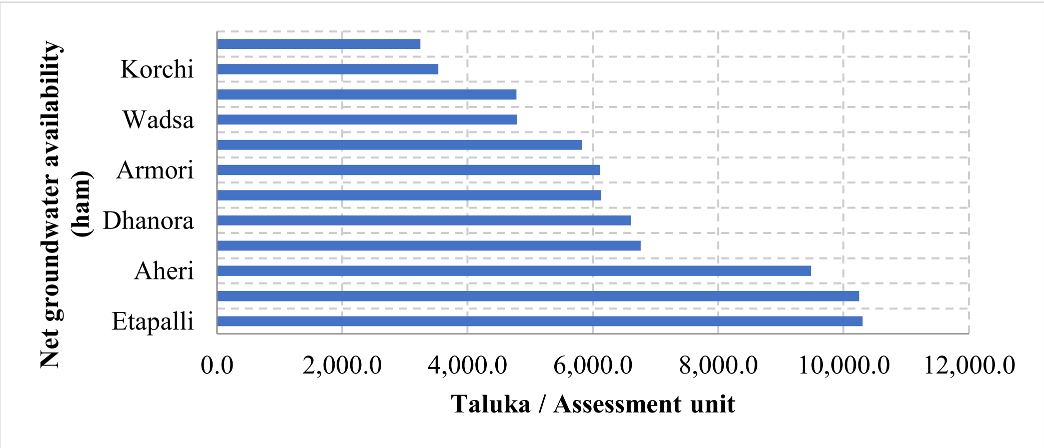

Figure 2. Net groundwater availability for future use in selected Gadchiroli units

4. Discussion

The outcomes showed that the groundwater development pressure in the district of Gadchiroli was still in low to moderate category during the assessment period 2022-23. The total annual groundwater extraction from the twelve assessment units was much lower than the extractable groundwater resource, thus providing an overall extraction pressure of approximately 24.37%. This indicates that the groundwater balance in the district was good at taluka level. Bhamragad had the lowest extraction stage at 7.8% while the highest was at 35.0% in Sironcha. All the assessment units were categorized in the safe zone. But the difference in the groundwater use between talukas also indicated that the groundwater use was not uniform across the taluka. The extraction stage in the case of Kurkheda, Armori and Sironcha were comparatively higher while Bhamragad and Aheri showed comparatively lower development. This pattern indicates that not only the recharge volume influenced the groundwater availability in Gadchiroli, but local demand, settlement pattern, groundwater dependence and the availability of groundwater-bearing zones in hard rock terrain also influenced the groundwater availability.

The results are in agreement with earlier research which indicates that in hard rock terrain, weathering and fractures/structural discontinuities are likely to control groundwater occurrence, rather than uniform aquifer conditions (Chandra et al., 2019). The observed spatial variation in recharge and extraction also supports the studies which highlighted the importance of the terrain, slope, drainage density and lineament conditions on the groundwater potential in hard rock terrain (Arulbalaji et al., 2019). The relatively safe status of Gadchiroli can be explained with the distributed recharge conditions that exist in crystalline and hard rock aquifers, where recharge may be different in different areas but remains sustainable under low extraction pressure (Fauzia et al., 2021). The same study that was conducted in Maharashtra on hard-rock has also revealed that the groundwater behaviour is closely related to groundwater flow paths, aquifer geometry and local resource planning requirements (Pande et al., 2022). The importance of monsoon recharge is highlighted as the tropical hard rock aquifers are recharged by monsoon rainfall in most cases instead of continuous recharge (Goswami & Sekhar, 2022). Further, the use of recharge, extraction and water-balance indicators in the current analysis is justified by the general Indian groundwater literature which considers recharge estimation as a key requirement for groundwater-resource assessment (Sajil Kumar et al., 2021). The hard rock nature of the Gadchiroli setting is complemented by the studies on fractured basement aquifers where the response of the aquifer is influenced by the rainfall recharge and weathering and rock–water interaction (Pradhan et al., 2022). The findings also indicate the importance of local recharge zones to be identified in hard-rock aquifers for future groundwater conservation (Subramani et al., 2024).

These results suggest that there is scope for planned groundwater usage in the area of Gadchiroli presently, however, it should not be construed as 'unlimited'. The safe categorization offers a positive management baseline particularly for talukas with high availability in the future like Etapalli, Chamorshi and Aheri. Talukas with relatively higher extraction stages such as Sironcha, Kurkheda and Armori, on the other hand, should be monitored closely as their agricultural expansion or dependence on borewells in the future could increase extraction pressure. The results further indicate that groundwater management should not be district generalized but should be taluka specific. In hard-rock areas where storage in the aquifer is limited to fractures and weathered zones, recharge supporting measures like farm ponds, check dams, percolation tanks and preservation of natural drainage channels would be particularly beneficial. The district's safe status should be treated as a time to preventively manage, not delay.

The major constraint of the study is that it was based solely on secondary data at the taluka level provided in the official groundwater-resource assessment. Thus, the analysis was unable to account for variations in well behavior, differences between villages, or variations in water-levels between seasons and aquifer specific hydraulic properties. The study also failed to account for the field based measurements of fracture density, lineament distribution, transmissivity, permeability or borewell yield. The results were interpreted at taluka level, so that the groundwater stress at local level may not be apparent at larger level of safe category. Another constraint is that the analysis was based on official estimates of recharge and extraction, rather than measurements made by the researchers. However, the data was useful for policy makers and provided a good basis to understand the dynamics and status of groundwater resources in the hard-rock terrain of Gadchiroli.

5. Conclusion

The overall resource position of groundwater in Gadchiroli district is favourable as per the assessment of 2022-23. The annual extractable groundwater resource was significantly higher than the total extraction and the overall extraction pressure was ~24.37%, which meant that groundwater use was within safe limits at the taluka level. The 12 assessment units were all considered safe with extraction stages varying from 7.8% in Bhamragad to 35.0% in Soroncha. The findings indicate that the hard rock terrain of the district still has a good amount of groundwater resources, especially in the villages of Etapalli, Chamorshi, Aheri and Kurkheda.

However, the safe category should not be considered a long-term secure category. Local fracture conditions, recharge variability and dependence on borewells are sensitivities of hard-rock aquifers. To monitor the extraction of talukas, regular monitoring is required for talukas like Sironcha, Kurkheda and Armori as their extraction level is comparatively higher than other talukas. The findings are in favour of taluka-wise groundwater planning, protection of recharge zones and investments in water-conservation structures. Water-level observations, fracture and lineament mapping, borewell-yield data, and seasonal monitoring at the village level should be carried out in the future to enhance local groundwater management. Overall, the groundwater base is fairly stable in Gadchiroli, however, preventive management is still necessary.

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