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Article

Sustainale groundwater management in rajasthan: evidence from district – level analysis

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Abstract

The major source of freshwater in Rajasthan is ground water, being a state with arid or semi-arid climatic conditions, high variability in rainfall and low surface water. The growing reliance on groundwater as the source of irrigation, domestic and industry has resulted in massive depletion of aquifers within the state. The current research paper analyses groundwater recharge, extraction, and variability in rainfall in Rajasthan in the framework of a district-based analytical procedure and aims to evaluate groundwater stress and discuss the avenues of sustainable groundwater management. The official sources of secondary data on rainfall, groundwater recharge, extractable resources, and sector-wise groundwater extraction were used to gather data on the period till March 2023, such as the Central Ground Water Board and the Government of Rajasthan. As the analysis shows, although periodically the precipitation is above the normal level and large amounts of monsoon-driven recharge are observed, the total stage of groundwater extraction in Rajasthan is in the field of excess and, in such a manner, most of the districts and assessment units are over-exploited or critical. The most prevalent cause of groundwater depletion is irrigation, whereas the stress is comparably less in the areas of irrigation via canals. There are notable spatial differences, as western and central districts have been considerably over-extracted, and selected areas of the southern Rajasthan have a relatively favourable recharge situation. The paper emphasises the inadequacy of availability and use of groundwater and the necessity of district-based management approaches, higher irrigation efficiency, artificial recharge, and better groundwater control. The results are empirical data to endorse policy interventions to guarantee the sustainability of groundwater and water security in Rajasthan in the long term.

Keywords: *Groundwater sustainability, Rainfall variability, Groundwater recharge, Groundwater extraction, Water resource management, Rajasthan*

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1 INTRODUCTION

The most important source of fresh water in Rajasthan is groundwater which serves drinking water, agriculture, industry and rural livelihood of one of the most arid and water-rationed states in India. Low and highly variable rainfall, extreme climatic conditions, and common droughts are some of the characteristics of Rajasthan; the state relies on groundwater to support its increasing water demand. The pressures on groundwater resources have increased over the decades due to the overpopulation growth, development of irrigated agriculture, urbanisation, and low availability of surface water. This has led to the development of ground water as the source of the water economy in the state especially in the rural and semi-urban regions.

The rainfall in Rajasthan is low as well as redistributed both spatially and on time. Whereas the monsoon rainfall is relatively higher in the southern and southeastern districts, the western and northwestern districts are always under water scarcity. In recent years, there have been instances of excessive rainfalls in the state; but this has not been so translated into sustainable groundwater situations. The reliance on the monsoon rainfall in the recharge of ground waters predisposes the aquifers to the effects of climatic fluctuations and even brief periods of low rainfall severely impact on the availability of the groundwater. It is this structural reliance on an unpredictable monsoon system that makes ground water management in Rajasthan particularly hard.

Groundwater assessment data on the district level indicates that there is an alarming state of over-extraction. Assessment units are mostly over-exploited, critical or semi-critical in nature, and the stage of groundwater extraction is over by far safe levels. The highest proportion of water withdrawal is through irrigation due to the patterns of cropping that are water intensive, and the use of inefficient irrigation methods. Already in those districts which had a relatively high potential of recharge, the levels of extraction are unsustainable, which means that there is an imbalance between the available resource and its utilisation pattern. Conversely, some canal-irrigated areas demonstrate the lower stress of groundwater, which demonstrates the importance of surface water in eliminating reliance on groundwater.

Ongoing excessive utilisation of ground water has dire environmental, economic and social effects. Drying water tables escalate the costs of pumping and diminish well yields and the water quality issues like salinity and fluoride pollution. Due to the marginal farmers and small farmers, rural vulnerability and inequity are exacerbated. In terms of the long term, further depletion of the groundwater risks agricultural output, drinking water security and climate change resilience in general. These problems explain why it is necessary to address the need to move extractive groundwater utilisation to the sustainability-based management model.

The district level analysis will prove essential in this context in order to know the spatial differences in rainfall, recharge, extraction and ground water stress. The Hydrogeological diversity and regional contrast in Rajasthan require a localised planning system and not a uniform policy intervention. The analysis of the groundwater dynamics on the district level has some useful information about priority areas, developing the targeted recharge, controlling extraction, and promoting the efficient utilisation of water. This form of evidence-based approach is fundamental in matching groundwater governance with the concept of sustainability.

The objective of the current research is to understand the dynamics of rainfall, groundwater recharge, and extraction in the district of Rajasthan to determine the degree of ground water stress and the ways to achieve sustainable groundwater management. Through analysing differences in amount of rainfall, groundwater resources, groundwater extraction and groundwater development stages across the different districts, the research aims to produce empirically validated data, which can be utilised in the process of making informed policy decisions, groundwater management approaches and environmental sustainability of long term groundwater in Rajasthan.

2 REVIEW OF LITERATURE

Goyal, Gaur, and Paul (2025) performed an overall evaluation of the groundwater degradation in the Jhunjhunun district, where the slope tests were performed using the MannKendall and Sen slope tests to identify the rates of decline between the years 1984 and 2020. Findings showed a shocking overall drop of 27.3 metres of the water table mainly attributed to the practises such as irrigation that were intensive and lack of recharge. Models of ARIMA forecasting suggested that the groundwater table may continue to decrease to 82 metres without any

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intervention by the year 2050. According to the study, use of water-efficient cropping systems and artificial recharge structures are important in curbing depletion.

Meenu (2025) examined the national groundwater abstraction and discovered that Rajasthan is experiencing the most serious water-levels drop among other states, Punjab and Haryana, because of over-extraction of groundwater to irrigate their lands and mismanagement. The paper is a proponent of a multi-pronged strategy which incorporates policy changes, rain water extraction, and effective irrigation. Significantly, it puts the crisis of Rajasthan in the context of the overall failure of water governance in India, where participative and decentralised management is needed.

Saikia and Chetry (2020) used the MannKendall test as a spatio-temporal approach to examine ground water changes in the districts of Rajasthan. The cases of critical depletion occurred in Alwar, Jaipur, Jaisalmer, and Jhunjhunun which depicts dependence and lack of recharge. The paper also indicated that the traditional monitoring networks were not sufficient to capture local-level changes, which implies GIS-based interpolation when managing sustainability.

In the article by Sharma, Ram, and Sharma (2022), the authors studied the quality of groundwater in Bikaner and found that it contained high salinity, fluoride, and nitrate. The research established that the salt level escalated after monsoon because of leaching and evaporation. It suggested desalination and artificial recharge through pits using boreholes as the methods which are sustainable. The results indicate the interdependence between the reduction in water quantity and quality and the importance of integrated water-quality management approaches.

The groundwater draught of irrigation in Rajasthan was estimated by Rajasthan (2023), and it showed that there is extraction of inordinate amount of ground water, estimated at 1.52 million hectare-metres per year. They showed in their calculation that more than 10 percent of the draught is based on diesel pumping, which results in unsustainable energy and water use. This paper will demonstrate the institutional failures of ground water management in India, especially in semi-arid Rajasthan.

The study by Chinnasamy, Maheshwari, and Prathapar (2015) took advantage of GRACE satellite information to determine the estimates of groundwater storage that existed in the agroclimatic regions of Rajasthan over time. The researchers observed that variability in rainfall, and pre-existing moisture condition have a significant influence on recharges. GRACE data was found to be effective in capturing the large scale trends as well as demonstrate decreasing total water storage in line with increasing demand of irrigation. The authors propose strategic recharge zoning that is grounded on indicators of satellite-based data.

Garg et al. (2024) groundwater potential zones were outlined in eastern Rajasthan by means of combined RS-GIS and the Analytical Hierarchy Process (AHP). The experiment found out that the recharge potential is significantly influenced by the texture of the soil, geomorphology, and drainage density. The model was proven to be reliable by validation with decadal groundwater fluctuation data, which demonstrated that GIS-AHP is effective in the development of the model as an aquifer recharge project planning tool.

In Maheshwari et al. (2014), a participatory framework of groundwater management was introduced as a part of the MARVI project in the Udaipur and Aravalli districts of Gujarat. Transdisciplinary approaches were highlighted in the study where farmers, non-governmental organisations and researchers worked to manage groundwater at the watershed level. The monitoring had been enhanced and community ownership had been created through the introduction of Bhujal Jankaars (local groundwater volunteers). This model of participation can be viewed as a model to be replicated in the governance of sustainable ground water.

The study by Ram, Lamba, and Kumar (2022) checked the groundwater status in the Sikar, Neemkathana, and Khandela areas and found out that

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there is a high level of fluoride and nitrate that is beyond WHO standards. These were linked to geological weathering and industrial effluent as pointed out by the study. It related water quality degradation with the rising levels of fluorosis and methaemoglobinemia, with the necessity of strict control of regulation and periodic remediation.

Sunita et al. (2025) used geostatistical and the PCA to examine hydrogeochemical properties of 36 locations in eastern Rajasthan groundwater. The results showed predominance of mineralization processes of Na–Cl-water and evaporation. High levels of EC, Na + and TDS proved salinity stress. The research established that semi-arid areas need regular hydrochemical monitoring and water distribution on a demand basis in order to have sustainable groundwater management.

Dabaria (2024) has looked at the relationship between groundwater parameters in Jaipur to determine the major causes of water quality degradation. The abstract is relatively brief; however, the study reveals the statistical correlation of such important hydrochemical indicators as pH, hardness and salinity. Such correlations provide a useful base to build predictive water quality models, allowing to avoid contamination patterns early and focus on mitigation areas.

In assessing sustainability of groundwater at the subnational level, Srivastava, Singh, and Shirsath (2018) used the Sustainable Development Goals (SDG 6 and 13). Rajasthan, Punjab and Haryana were known to be hotspots of depletion, which was persistent, and it needed to be rationalised and encouraged to use water-saving technologies, according to the authors. They emphasised on integrated water resources management (IWRM) in order to achieve equilibrium between socio-economic growth and aquifer health. It is remarkable that the study has connected the local hydrological realities with the global sustainability agenda.

Yadav (2023) thoroughly examined fluoride pollution in Sikar with the concentration of 0.1 to 9.94 mg/L, which is significantly above the WHO standards. Geological leaching and long residence period of groundwater were found to be major causes. The paper suggested the artificial recharge facilities to blend fluoride concentration and relieve the pressure on the deep aquifers. It is important since the study integrates the public health consequences with hydrogeochemical mechanisms, which is a transition between environmental and medical aspects.

Chouhan (2023) examined the effect on the groundwater availability in the Jhunjhunu district due to the climate. The study revealed that alteration in rainfall patterns of intensity combined with anthropogenic extraction has increased water scarcity. The author stated that there is a necessity of local adaptation plans, better rain-gathering, and at the policy level, integrating climate resilience in groundwater management. The paper will connect climate change studies to the groundwater policy, with arid zones being susceptible to hydroclimatic changes.

Rizvi, et al. (2025) introduced a review on a national scale, highlighting the problem of unsustainable use of agricultural groundwater resources, which is one of the factors that cause the depletion of the resources, especially in the state of Rajasthan and Punjab. The paper highlighted policy implementation failure, lack of education and decentralisation of water. It also suggested that groundwater conservation should be introduced into the agricultural policy and modern irrigation practises such as drip and sprinkler irrigation systems should be adopted. The review spans the systems in hydrology, governance and socio-economics.

Vaishnava (2023) provided a historic and cultural overview of the native water conservation systems used in Rajasthan like baoris, tankas, and johads. These non-centralized organisms show arid long-term viability and adaptation to arid environments by communities. The paper proposes the need to revive these ancient methods and update them with the latest hydrological approaches in order to be resilient in the face of climate change. It highlights the fact that the concept of sustainability in Rajasthan has a strong connexion with the cultural continuity.

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In assessing the ground water potential of the aquifer systems in India, Santosh et al. (2025) discovered that Rajasthan is among the most overexploited areas especially in sedimentary aquifer of the Indo-Gangetic basin. The proposed study hypothesised the use of managed aquifer recharge (MAR) and effective irrigation schemes to meet SDGs 6 (Clean Water) and 13 (Climate Action). The results point to the extent of overextraction and necessity of the technological interventions.

Narisetty et al. (2023) used the sophisticated GIS-based vulnerability models (DRASTIC and SINTACS) in the semi-arid areas of Rajasthan to assess the vulnerability to pollution. The analysis identified more than 30 percent of the region as being in the very high vulnerability category in the region of Jalore, Pali, and Jodhpur. The use of both land-use and temperature data as an integrative approach increased sensitivity, which increased the accuracy of hazard prediction. The results are used as scientific grounds in prioritising monitoring and conservation policies.

3 METHODOLOGY OF THE STUDY

The current research gets its research approach to be descriptive and analytical research so as to investigate the changes in rainfall, ground water availability, and extraction rates across the Rajasthan districts with the aim of evaluating ground water stress and ways of ground water management leading to sustainability. The research design combines the analysis of secondary data and the district-level comparative evaluation that helps to guarantee a thorough understanding of spatial and temporal change.

3.1 Data Sources

The research is primarily founded on secondary data which has been gathered through the authoritative government sources. Published Government of Rajasthan records provided district-wise data of rainfall, long-term normals and yearly changes. The data related to groundwater resources, including monsoon and non-monsoon rainfall recharge, other sources of recharge, natural discharge, extractable groundwater resources, which were assessed on a yearly basis, and the classification of the assessment units were found in reports on the Central Ground Water Board (CGWB) and the State Ground Water Department, Rajasthan. Reports on the CGWB groundwater assessment reports were also used to compile data on the current annual groundwater extraction used in irrigation, domestic and industrial purposes. All the data are related to the latest period of assessment possible, mostly to 31 March 2023.

3.2 Spatial Unit of Analysis

To make it easier to analyse the situation, the district was chosen as the major unit of analysis where it included all 33 districts of Rajasthan. The scale was selected because it brings regional heterogeneity in the distribution of rainfalls, hydrogeological, recharge potential, and depth of groundwater extraction. The district level can be compared sensibly between the varied climatic and physiographic areas like the western arid areas, eastern plains, and South humid areas.

3.3 Analytical Framework

Rainfall analysis was done by looking at the normal long-term rainfall and the annual rainfall changes in the past years and calculating the departure of normal rainfall (percentage) to detect deficit years, normal years and surplus years. Resource assessment was done on the groundwater through the calculation of the total recharge of the ground water per district per year including that which was contributed by the monsoon and non-monsoon recharge and that which was contributed by other sources like the canals and irrigation return flows. To estimate the annual extractable ground water resource, natural discharge was subtracted on total recharge.

The use of groundwater was measured in terms of the district-level information on irrigation, domestic and industrial groundwater use. The extraction of the ground water stage was determined by the summation of the ground water extracted divided by the total ground water that could be extracted annually as a

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percentage of the extractable ground water resources. According to standard CGWB classification the districts and assessment units had been grouped into safe, semi-critical, critical, over-exploited and saline.

The relative method was used to examine the spatial differences between groundwater availability and stress among the districts. Temporal comparison was also conducted in case there is an available data on several years, especially to compare the groundwater extraction level and classification of the assessment unit between the years 2022 and 2023. This aided in the determination of the emerging trends, areas of improvement, and zones of persistent stress.

Interpretation of the results was done with regards to the climatic variability of Rajasthan, irrigation and reliance on ground water. The focus was placed on the connexion between rainfall variability and patterns of recharges and the intensity of extraction in order to describe the groundwater stress. Synthesis of the findings was made to draw policy relevant findings that are based on the sustainable management of groundwater, demand management, and recharge management.

4 DECADAL GROUNDWATER LEVEL VARIATIONS IN PRATAPGARH

Gautam et al. (2022) used statistical analysis of data on 76 wells to evaluate the changes in the level of ground water in Pratapgarh. The statistical analysis included data collected between 2009 and 2019. They noticed that the rate of decrease was constant in both pre-monsoon and post-monsoon periods which was caused by uncertainty in terms of rainfall and excess exploitation of the aquifer. Although it is a hard-rock landscape, seasonal recharge was visible implying that recharge interventions can be done with management.

Cansi and Moreno (2019) investigated the history of groundwater policies by comparing the two cases and providing the conceptual understanding which can be applied to India and Rajasthan. Even though the analysis is about Brazil, when it comes to the governance failures, disparities in access, and sustainability the discussion is relevant to the policy problems facing Rajasthan. The authors advocate fair water management that incorporates both economical exploitation and ecological rights, which is the solution that is directly applicable to the water-deficient situation in Rajasthan.

Table-1: Average annual Rainfall (2022)

S. No.	District	Normal (1901-70)	2017-18	2018-19	2019-20	2020-21	2021-22
1	Ajmer	437	428	799	528	606	573.1
2	Alwar	626	565	462	509	765	615.8
3	Banswara	870	813	1281	1055	878	998.3
4	Baran	895.3	1004	1320	652	1363	1049.2
5	Barmer	260	130	390	345	274	476
6	Bharatpur	675.1	802	593	539	779	572.7
7	Bhilwara	603.3	578	967	581	705	675.2
8	Bikaner	249.8	254	307	298	320	437.4
9	Bundi	715.8	636	1199	511	1106	920.5
10	Chittorgarh	772.3	730	1243	711	1029	785.8
11	Churu	337.9	341	476	485	593	508.7
12	Dausa	625.7	595	740	545	750	784.2
13	Dhaulpur	717.5	757	812	496	810	696.3
14	Dungarpur	610.4	788	1144	892	710	829.5
15	Ganganagar	171.6	182	231	240	201	400.5
16	Hanumangarh	237.5	206	353	359	377	317.9
17	Jaipur	526.8	537	744	623	715	652.8

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18	Jaisalmer	158.6	121	252	351	302	346.7
19	Jalore	400.6	148	544	597	391	626.4
20	Jhalawar	884.8	966	1783	789	1294	1317.1
21	Jhunjhunu	459.5	471	684	410	613	406.5
22	Jodhpur	296.7	211	436	414	324	457.5
23	Karauli	616.2	571	584	559	871	582
24	Kota	808.7	755	1282	577	1319	1150.8
25	Nagaur	363.1	351	652	504	616	510.8
26	Pali	484.5	325	753	585	512	540.6
27	Pratapgarh	806	1152	1978	1068	1346	1129.6
28	Rajsamand	556.1	544	918	693	679	617
29	Sawai Madhopur	655.8	919	898	623	1014	749
30	Sikar	459.8	581	712	524	680	490.4
31	Sirohi	606.3	359	903	922	692	1074.7
32	Tonk	598.2	527	863	480	818	802.4
33	Udaipur	632.7	565	1069	778	788	889.5
	Rajasthan	549.1	519.3	542.7	829	583	735

According to the rainfall statistics of Rajasthan, it can be clearly seen that the 20212022 year was very wet as compared to normal years across the state. The average yearly precipitation of Rajasthan (190170) is 549.1 mm and the state received approximately 735mm in 202122, which is approximately 34 times higher than the average (long-term). This reflects a high monsoon state performance. There was however very uneven rainfall distribution across the districts. The high rainfall experienced in the deeply monsoon-active areas of the Hadoti and Mewar regions was very high in the Southern and south-eastern areas including Jhalawar (1317.1 mm), Pratapgarh (1129.6 mm), Kota (1150.8 mm), Baran (1049.2 mm), Sirohi (1074.7 mm), and Udaipur (889.5 mm). These were conducive to agriculture, reservoirs and ground water recharge, which also enhanced the chances of floods. The normal rainfall in the central and north-eastern regions, such as Ajmer, Jaipur, Alwar, Bhilwara, Rajsamand and Tonk were moderate and were almost equal to their average, showing the relative stability of monsoon conditions to support rain-fed agriculture. Conversely, in western desert areas like those of Jaisalmer, Barmer, Bikaner, and Ganganagar, comparatively low rainfall was also still being received in absolute terms, but even these areas are a good monsoon year in arid Rajasthan, as well. On the whole, the data points at the extremely fluctuating character of rainfall in Rajasthan and the necessity of water management, prevention of flood in the high-rainfall state, and preparedness to drought in the west of the state.

Table-2: Departure from Normal Rainfall (%) - Rajasthan Districts

S. No.	**District**	**2017-18**	**2018-19**	**2019-20**	**2020-21**	**2021-22**
1	Ajmer	-2.09	45.31	17.17	27.92	23.75
2	Alwar	-10.82	-35.45	-22.87	18.18	-1.66
3	Banswara	-6.99	32.06	17.5	0.85	12.85
4	Barmer	10.85	32.15	-37.24	34.31	14.67
5	Barmer	-99.59	33.32	24.54	5.16	45.38
6	Bharatpur	15.78	-13.78	-25.15	13.38	-17.88
7	Bhilwara	-4.4	37.59	-3.86	14.37	10.65
8	Bikaner	1.65	18.57	16.14	21.96	42.89
9	Bundi	-12.64	40.28	-40.22	35.29	22.24
10	Chittorgarh	-5.76	37.88	-8.65	24.91	1.72

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11	Churu	0.86	29.08	30.33	43	33.58
12	Dausa	-5.16	15.42	-14.73	16.6	20.21
13	Dhausa	5.18	11.66	-44.66	11.46	-3.04
14	Dungarpur	22.49	46.66	31.6	14.08	26.41
15	Ganganagar	5.95	25.87	28.57	14.62	57.15
16	Harumangarh	-15.29	32.63	33.9	36.92	25.29
17	Jaipur	1.83	29.21	15.39	26.3	19.30
18	Jaisalmer	-31.44	37.02	54.81	47.51	54.25
19	Jalore	-170.68	26.38	32.47	-2.54	36.05
20	Jhalawar	8.41	50.38	-12.14	31.62	32.82
21	Jhunjhunu	2.34	32.81	-12.04	25.04	-13.04
22	Jodhpur	-40.62	31.9	28.41	8.4	35.15
23	Karauli	-7.89	-5.59	-10.21	29.22	-5.88
24	Kota	-7.08	36.94	-40.06	38.7	29.73
25	Nagaur	-3.56	44.34	27.96	-41.08	28.92
26	Pali	-49.3	35.64	17.14	5.33	10.33
27	Pratapgarh	30.06	59.26	24.5	40.14	28.65
28	Rajsamand	-2.22	39.39	19.74	18.15	9.87
29	Sawai Madhopur	28.61	26.93	-5.29	35.33	12.44
30	Sikar	20.83	35.41	12.31	32.42	6.24
31	Sirohi	-69.01	32.87	34.21	12.38	43.58
32	Tonk	-13.62	30.68	-24.53	26.89	25.45
33	Udaipur	-11.94	40.84	18.68	19.7	28.87
RAJASTHAN	-12.6	29.5	5.6	23.3	21.16	

The departure-normal rainfall (%) data indicate that Rajasthan had a significant inter-annual and inter-spatial variability in rainfall between 201718 and 202122 with a general tendencies towards surplus conditions over the recent years. On the state level, Rajasthan had a negative rainfall of -12.6 percent in 201718 and thereafter, a high excess of 29.5 percent in 201819. The year 2019 20 was near normal with a slight surplus of 5.6 percent and years 2020 2021 were distinctly wet with positive departures of 23.3 and 21.16 percent. This shows that the deficits have been recovered and the overall monsoon trend has been improving over the past two years of the period.

Western and arid districts in 202122 had very high positive departures at the district level (and sometimes more than 4055 percent) including Jaisalmer, Bikaner, Jodhpur, Ganganagar and Barmer, which is particularly favourable in desert areas where even 4055 percent is a significant positive change. Pratapgarh, Jhalawar, Kota, Udaipur, Dungarpur, and Sirohi, southern and south-eastern districts, always registered high annual departures, frequently above 25-40 percent, which proves them to be of high-rainfall regions with frequent conditions of surplus. Contrarily, there were also mixed trends in some north-eastern and central districts like Alwar, Bharatpur, Karauli, Jhunjhunu and Dhaulpur where deficits and surpluses interchanged, and rainfall was quite unreliable. Altogether, the statistics show that although Rajasthan as a region on the whole recorded excess rainfall in the recent years, particularly in 202021 and 202122, distribution is highly skewed which demonstrates the necessity of region-specific water management measures to address both flood-prone and drought-prone zones.

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Table-3: Number of Assessment Units in Rajasthan

S. No.	Category	No. of Blocks	S. No.	Category	No. of Blocks
1	Safe	38	3	Critical	22
2	Semi-critical	28	4	Over Exploited	216
5	Saline	3		Total	302

This classification of ground water blocks depicts a highly stressed ground water scenario. Only 38 blocks out of the available 302 blocks are of the Safe category and this means that the extraction of groundwater in these areas is neither beyond the sustainable limits. The other 28 blocks come under Semi-critical which includes the groundwater utilisation that learns towards the limit of sustainability and should be monitored closely. Conversely, there are also 22 Critical blocks, and the extraction of groundwater has already reached unsafe levels, and there is a high threat of its extinction. The worst aspect of the data is that there are up to 216 blocks, which are represent the overwhelming majority, which are Over-Exploited, indicating the extraction of groundwater to a level much higher than the recharge rate. Moreover, salinity affects 3 blocks rendering ground water unfit to drink and irrigate even though it is available. All in all, the data suggests the existence of severe levels of groundwater stress, with close to four-fifths of the blocks registered as being under critical, over-exploited, or salty, which provides a clear illustration of the importance of regulating groundwater, artificial recharge, and implementing sustainable water management practises.

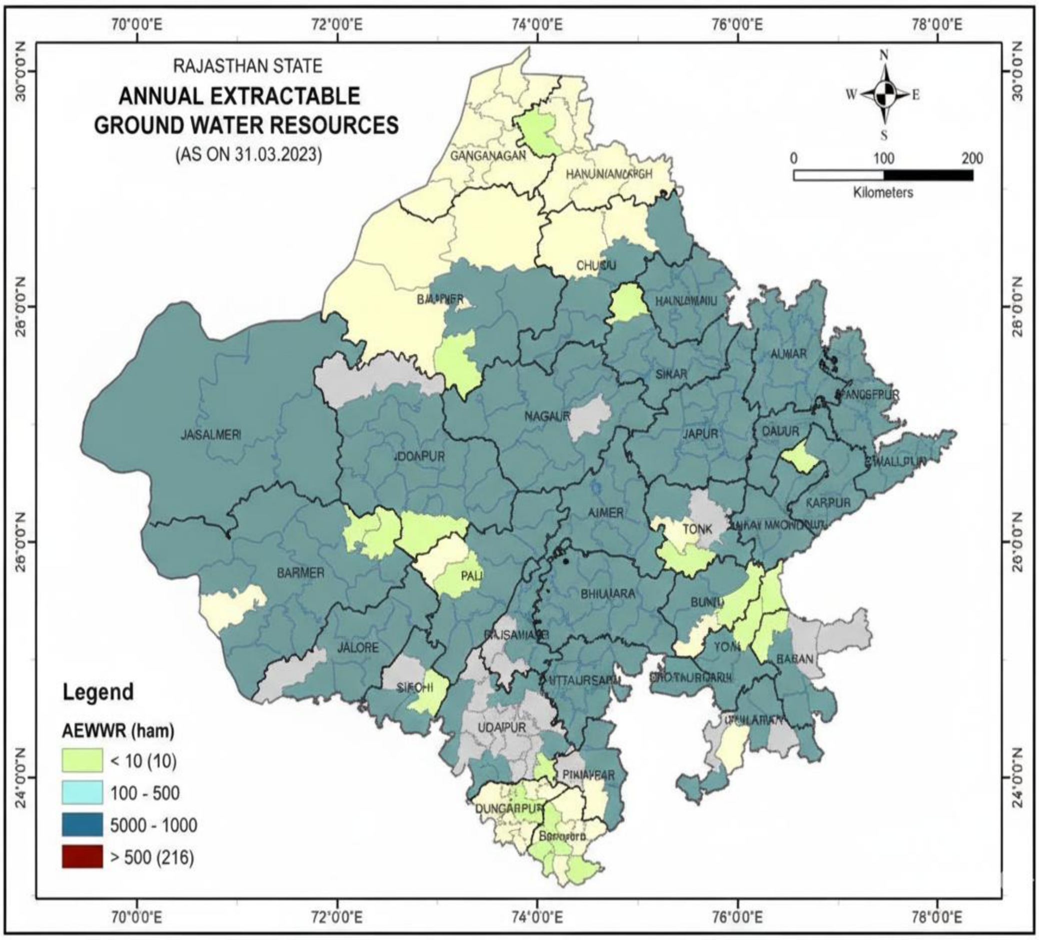

Figure 1 – Annual Extractable ground water resources

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Table-4: Comparison of Groundwater Resources 2022 and 2023

Particulars	2023	2022
Total Annual Ground Water Extraction	10793.64 ham	10695.55 ham
Stage of Ground Water Extraction (% of Assessment Units)	151.07%	151.96%
Safe Assessment Units	38	30
Semi-critical Assessment Units	28	28
Critical Assessment Units	22	23
Over Exploited Assessment Units	216	217
Saline Assessment Units	3	3
Total Assessment Units	302	302

Groundwater assessment data of 2022 and 2023 show the situation with groundwater is continuously over-exploited, and the changes have been marginal between the two years. The total annual groundwater extraction recorded 10,695.55 ham in 2022 and 10,793.64 ham in 2023 indicating that there is still excessive reliance on groundwater sources. The groundwater abstraction rate was also very high in the two years at 151 percent implying that groundwater abstraction is higher than 151 percent of the rate of recharge and this is a clear indication of unsustainable usage.

The classification of assessment units is slightly improved. In 2022, there were 30 units of Safe and in 2023, the number of units has grown to 38, which could be a signal of a localized improvement in the conditions of groundwater, potentially because of increased rainfall, recharge, or a decrease in extraction in certain regions. The Semi-critical units were not altered in terms of numbers with 28 being the same figure but Critical units slightly reduced by a margin of 23 to 22. On the same note, Over-exploited units declined a notch to 217 to 216 however they still make an overwhelming majority of the 302 assessment units. Saline units did not vary and it means that there are still water quality problems in definite regions.

Generally, although there are slight positive changes made in some of the assessment units, the statistics indicate that groundwater resources in Rajasthan are under extreme pressure. High level of ground water extraction and the preponderance of over-exploited units are the reasons why the tightening of ground water regulation, increase of artificial recharge, higher irrigation efficiency, and abandonment of water-intensive agricultural practises are essential measures in ensuring the long-term sustainability of the ground water.

Table-5: District wise Resources of Rajasthan (ham)

Name of District	Monsoon Rainfall Recharge	Monsoon Other Sources	Non-Monsoon Rainfall Recharge	Non-Monsoon Other Sources	Total Annual GW Recharge	Total Natural Discharges	Annual Extractable GW Resource
Ajmer	28350.64	1938.3	107.28	7562.79	37959.01	3795.9	34163.11
Alwar	71055.06	1061.76	2824.96	4734	79675.78	7967.58	71708.2
Banswara	10143.43	276.91	0	12748.07	23168.41	2316.85	20851.56
Baran	39760.35	5153.94	0	20068.11	64982.4	6054.71	58927.68
Barmer	35541.7	683.04	74.74	2054.72	38354.2	3835.44	34518.77
Bharatpur	31346.36	1691.88	1028.4	5602.54	39669.18	3402.44	36266.73
Bhilwara	31320.03	100.1	0	13689.26	45109.39	4494.81	40614.58
Bikaner	25174.63	694.75	3238.11	1775.08	30882.57	3012.06	27870.51

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Bundi	17768.55	1295.54	0	14001.81	33065.9	2643.75	30422.15
Chittaurgarh	23505.07	1642.48	0	9405.73	34553.28	3455.31	31097.97
Churu	13980.01	21.8	1479.1	512.82	15993.73	1204.22	14789.51
Dausa	24381.35	998.83	180.59	2366.68	27927.45	2792.76	25134.69
Dhaulpur	19964	1279.83	1078.04	5187.68	27509.55	2470.04	25039.51
Dungarpur	9063.13	1338.68	0	12064.61	22466.42	2224.83	20241.59
Ganganagar	4771.87	16249.07	1003.31	25942.51	47966.76	4796.65	43170.1
Hanumangarh	5212.91	7924.31	1029.84	8323.2	22490.26	2249.05	20241.22
Jaipur	61524.41	2204.25	1088.9	7769.56	72587.12	7258.72	65328.4
Jaisalmer	8488.83	380.23	538.02	1140.69	10547.77	1054.78	9492.99
Jalor	38666.31	1201.21	0	8081.32	47948.84	4166.86	43781.98
Jhalawar	39717.12	2899.9	0	13010.71	55627.73	5332.33	50295.4
Jhunjhunun	21046.63	294.98	1734.62	1474.86	24551.09	2455.11	22095.98
Jodhpur	35479.98	994.78	736.55	2993.98	40205.29	3471.68	36733.61
Karauli	28079.55	472.76	205.27	5060.02	33817.6	3254.58	30563.02
Kota	29039.29	3102.49	0	19433.4	51575.18	5157.51	46417.67
Nagaur	56744.71	1077.11	1523.73	3330.84	62676.39	6032.61	56643.77
Pali	27655.63	467.85	0	4027	32150.48	3215.07	28935.41
Pratapgarh	15650.44	170.1	0	6943.7	22764.24	2275.87	20488.37
Rajsamand	8531.5	219.35	18.7	2815.47	11585.02	1158.54	10426.48
Sawai Madhopur	31728.1	2121.39	0	10378.56	44228.05	4422.8	39805.24
Sikar	31523.1	1794.93	1535.21	2046.21	36899.45	3689.92	33209.52
Sirohi	25608.25	172.5	0	3996.6	29777.35	2977.72	26799.63
Tonk	29191.09	3843.85	0	11194.13	44229.07	4197.53	40031.53
Udaipur	21418.1	548.72	0	10287.18	32254	3225.43	29028.56
Total	901432.13	64317.62	19425.37	260023.84	1245198.96	120063.46	1125135.44

According to the district-wise groundwater resource information of Rajasthan as on 31.03.2023, the general groundwater recharge structure and availability across the state with a significant regional variation can be seen. On the state level, the estimated figure of the total ground water recharge is approximately 1245199 ham, out of which almost 72 percent is recharged by monsoon rainfall (901432ham). Non-monsoon rainfall also contributes a small portion to the recharge (19,425 ham) whereas other contributors include canals, tanks, and irrigation return flows, which contribute a large portion especially in the canal irrigated districts. When natural discharges (120,063 ham) have been taken into consideration, the extractable groundwater resource per annum of Rajasthan is approximately 1,125,135 ham, which means the amount that can be taken under the ideal conditions.

The difference between districts indicates that the extractable resources and annual recharge of groundwater are relatively high in the east and south-eastern districts like Jaipur, Alwar, Nagaur, Baran, Kota, Jhalawar, and Tonk because they have better rainfall and surface water input. As an illustration, Jaipur (65,328 ham), Nagaur (56,644 ham) and Jhalawar (50, 295 ham) have some of the largest extractable ground water resources in the state. There are also moderate to great recharge in the southern districts such as Udaipur, Bhilwara, Chittorgarh, and Rajsamand that is mainly contributed by monsoon rainfall and subsurface inflows. Contrastingly, west arid regions such as the Jaisalmer, Barmer, Bikaner, and Jodhpur have relatively low natural rainfall recharges, although canal and other sources significantly improve recharge in the districts like

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Ganganagar and Hanumangarh, where other source prevails over the recharge structure.

The information also shows clearly that Rajasthan is extensively relying on the monsoon to replace groundwater, which means the state is extremely susceptible to the changes and fluctuations in monsoon patterns as well as climate change. Although there has been significant recharge in some of the districts, the general over exploitation of the ground water, as observed in the previous assessment data, implies that the extraction is way beyond the sustainable levels in most locations. Generally, the resource evaluation highlights the necessity of enhancing rainwater collection, artificial recharge of water, and conjunctive utilisation of surface and underground water, especially high extraction, and low-recharge districts, to make sure that groundwater is sustainable in the long term in Rajasthan.

Table-6 Current Annual Ground Water Extraction (Ham)

Name of District	Irrigation Extraction (ham)	Industrial Extraction (ham)	Domestic Extraction (ham)	Total Extraction (ham)	Stage of GW Extraction (%)
Ajmer	47462.83	176	1184.34	48823.19	142.91
Alwar	113255.21	3413.35	14469.75	131138.28	182.88
Banswara	11598.17	4.02	2417.18	14019.38	67.23
Baran	67411.74	102.57	8364.65	75878.95	128.77
Barmer	37805.31	438	7406.28	45649.61	132.25
Bharatpur	37331.9	71.85	6391.83	43795.62	120.76
Bhilwara	60213.29	735.87	5372.48	66321.65	163.3
Bikaner	28462.85	71	9705.94	38239.79	137.21
Bundi	27292.16	66	3723.39	31081.54	102.17
Chittaurgarh	46512.33	107.23	2028.21	48647.78	156.43
Churu	15419.69	4.76	3185.95	18610.4	125.84
Dausa	47521.68	3.19	11095.15	58620.01	233.22
Dhaulpur	29417.68	15.73	4615.56	34048.97	135.98
Dungarpur	11227.75	1.11	885.25	12114.12	59.85
Ganganagar	16989.18	39	38.57	17066.75	39.53
Hanumangarh	11247.76	200	914.9	12362.66	61.08
Jaipur	107004.97	1662.63	38927.03	147594.63	225.93
Jaisalmer	30418.32	5.84	3941.1	34365.26	362.01
Jalor	75036.44	2.58	4408.2	79447.23	181.46
Jhalawar	54683.43	0.41	3956.82	58640.65	116.59
Jhunjhunun	35396.64	564.16	11912.02	47872.82	216.66
Jodhpur	78476.56	677.58	15154.96	94309.12	256.74
Karauli	43466.39	0.07	4836.85	48303.32	158.04
Kota	40190.84	180.93	8572.76	48944.54	105.44
Nagaur	88158.52	1147.65	13604.42	102910.61	181.68
Pali	41633.64	17.58	4366.05	46017.27	159.03
Pratapgarh	25665.32	19	643.83	26328.16	128.5
Rajsamand	10057.26	391.64	2416.81	12865.72	123.39
Awai Madhopur	56358.79	0.22	7836.38	64195.43	161.27

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Sikar	51368.58	221.34	12208.95	63798.89	192.11
Sirohi	29160.36	340.77	1840.64	31341.77	116.95
Tonk	29959.39	36	10828.93	40824.35	101.98
Udaipur	24219.28	2059.79	3449.6	29728.67	102.41
Total	1430424.28	12777.86	230704.79	1673907.14	148.77

The statistics of the volume of groundwater that is being extracted on an annual basis clearly show intensive and extensive stress on the groundwater resources in Rajasthan. On the state level, approximately 1,673,907 ham is extracted annually as ground water, with irrigation taking the largest percentage (approximately 1,430,424 ham), then domestic use (230,705 ham) and industrial extraction is comparatively small because of the large percentage (12,778 ham). The general level of groundwater abstraction is 148.77 percent, which implies that the amount of groundwater abstracted in the state is almost one and a half times of the extractable resource, which proves the unsustainable level of use.

The district-wise analysis reveals that there are very high levels of ground water removal in a number of districts. Some of the highly exploited districts include Jaisalmer (362 percent) and Jodhpur (256.74 percent) as well as Dausa (233.22 percent) and Jaipur (225.93 percent) and Sikar (192.11 percent) where the extraction is much higher than the recharge. The districts are mostly relying on ground water to irrigate and supply domestic needs, which depicts high pressure on the aquifers. There are also other districts like Alwar, Nagaur, Jalor, Bhilwara, Chittorgarh, Karauli and Pali that are at stages of extraction well above 150 percent and thus found in category of over-exploited or critical.

Conversely, the stage of groundwater extraction is quite low in some of the districts, including Ganganagar (39.53 percent), Hanumangarh (61.08 percent), Banswara (67.23 percent), and Dungarpur (59.85 percent). This is attributed to the fact that there is the availability of surface water and canal irrigation hence fewer people rely on groundwater. On the whole, this information points out the fact that groundwater deprivation in Rajasthan is primarily caused by irrigation, and unless some powerful strategies, including regulated pumping, encouragement of micro-irrigation, diversification of crops, artificial recharge, and conjunctive use of surface and groundwater are taken, the process of groundwater loss is bound to accelerate further and the water security of the state will be endangered in the long run.

5 CONCLUSION

A comparison of rainfall patterns, groundwater resources, and the level of extraction in Rajasthan provides a clear indication of a paradoxical situation whereby there is a relatively good rainfall in the recent years coupled with extremely high rates of groundwater over-extraction. Despite the fact that a number of districts reported a higher than normal rainfall and large amounts of ground water recharge especially during monsoon season, the general level of ground water abstraction is of critical concern of over 148 percent at the state level. Preponderance of irrigation as the main ground water consumer and, the uneven spatial distribution of ground water recharge and abstraction have created the prevalence of over-exploitation, particularly in central, eastern and western districts like Jaipur, Jodhpur, Jaisalmer, Dausa, Sikar and Nagaur. The percentage of assessment units that are still in the safe range is minimal, thus demonstrating that most of the water used in the state of Rajasthan is not sustainable even during the years when the rainfall is excessive.

6 STUDY IMPLICATIONS

This investigation's ramifications are practical and scholarly, emphasizing human resource strategies (HRS) centrality in molding entity internal dynamics, as favorable HRS, workplace environment, and employee loyalty ties imply HR exceeds administrative to integrated tools for settings where staff excel (Agarwala, 2003; Paul & Anantharaman, 2004). Choices on hiring, skill building, review, benefits, and info thus require long-term atmospheric fabric and staff-entity relation investments. Practically, entities pursuing positive, team-oriented, creativity-assistive environments should embrace aligned HR approach clusters focused on principle-aligned choice, ongoing education, and progressive

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input (Martins & Terblanche, 2003; Shipton et al., 2005). When staff see HRS as equitable, clear, and truly progressive, they display stronger loyalty, stressing backing and equity importance (Meyer & Smith, 2000; Giauque et al., 2010). Discoveries also imply for leadership and shift, as leaders must match HR guidelines to desired atmospheric principles and employ review, benefit, and progression systems to indicate team, info exchange, and creativity valuation (Lau & Ngo, 2004; Valle & Jiménez, 2005). Thus, HR frameworks serve as tangible tools converting leadership aims to daily encounters, backing views that environment, atmosphere, and HRS form unified behavior/output systems (Gelade & Ivery, 2003; Ordaz et al., 2011). At strategy and oversight levels, the investigation suggests entities targeting lasting rivalry edge view HRS as strategic personnel/social asset builders (Bontis, 2001; Birasnav & Rangnekar, 2009). Robust, progressive, cooperative HR framework investments likely produce resilient environments and devoted workforces, creativity/output prerequisites in shifting settings (Tan & Nasurdin, 2011; Özbağ et al., 2013). Lastly, the investigation urges future probes on how/when HRS convert to stronger environments/higher loyalty, and how these affect creativity/entity success across varied settings (Preacher et al., 2007; Sarstedt et al., 2011).

7 STUDY IMPLICATIONS

The results of this paper have significant relevance in the water resource planning and management in Rajasthan. First, they note that there is an urgent need to have district-wide groundwater management plans, because rainfall, recharge potential, and extraction pressures are too diverse throughout the state. Second, the findings indicate the importance of irrigation efficiency and crop planning, which are especially urgent in over-exploited areas where crops that are water-consuming still prevail. Third, monsoon rainfall is a significant recharge source and thus is very sensitive to climatic changes, thus supporting the need of groundwater harvesting, artificial recharge facilities, and surface groundwater conjunctive use. These insights can help policymakers to ensure groundwater control, focus on stressed blocks and sustainable water use in agriculture and urban areas.

8 FUTURE SCOPE OF THE STUDY

Future studies can extend this study by using long-term climatic change forecasts to evaluate their effect on fluctuation of rain fall and ground water recharge in Rajasthan. Local aquifer-scale investigations might offer a clearer understanding of local groundwater processes, recharge, storage of water, and water quality problems such as salinity and fluoride pollution of groundwater. Incorporation of remote sensing and a GIS-based analysis would assist in mapping out the areas of groundwater stress and in tracking out the changes over time. Also, subsequent research can assess the usefulness of governmental solutions, including micro-irrigation systems, canalization, and recharge initiatives, in enhancing the sustainability of groundwater. Socio-economic aspects such as the behaviour of farmers, what farmers do, and how these institutions govern farmers can also be considered to create more comprehensive and participatory systems of managing groundwater.

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