Water Resources Development and Management in Hard Rock Terrains: A Review of Sagar District, Madhya Pradesh, India

Manish K. Soni
Assistant Professor, Civil Engineering Department, Indira Gandhi Engineering College Sagar, M.P.

***Abstract*—Hard rock terrains pose significant challenges for sustainable water resources management due to their limited primary porosity and complex hydrogeological characteristics. This study presents a comprehensive analysis of water resources management strategies in Sagar district, Madhya Pradesh, India. Sagar district, predominantly underlain by Precambrian crystalline rocks of the Bundelkhand Massif, represents a typical hard rock terrain with acute water scarcity issues. Through detailed hydrogeological assessment, groundwater trend analysis, and evaluation of management interventions implemented in the area, this research identifies key challenges and successful strategies for sustainable water resources development. The study reveals declining groundwater levels, spatial heterogeneity in aquifer properties, and the critical importance of artificial recharge and community-based water management approaches. The findings demonstrate that integrated management strategies combining geological understanding, artificial recharge programs, demand management, and community participation can effectively address water security challenges in hard rock terrains. This case study provides valuable insights for similar hydrogeological settings across the Indian subcontinent and other hard rock regions globally.**

***Index Terms*—Hard rock aquifers, groundwater management, Sagar district, Bundelkhand Massif, artificial recharge, water scarcity, crystalline rocks.**

1. INTRODUCTION

Hard rock terrains constitute approximately 65% of India's geographical area and provide water supply to nearly 60% of the population. These geological formations, characterized by crystalline rocks with limited primary porosity, present unique challenges for water resources management. The Bundelkhand region of central India, including Sagar district in Madhya Pradesh, exemplifies these challenges with persistent water scarcity, declining groundwater levels, and complex hydrogeological conditions.

The region experiences a semi-arid climate with highly variable monsoon rainfall, making groundwater the primary source of water supply for domestic, agricultural, and industrial uses. Historical data from the Central Ground Water Board (CGWB) and State Water Resources Department indicate increasing stress on groundwater resources, with many areas showing declining water table trends and deteriorating water quality.

This research aims to analyse the hydrogeological characteristics and groundwater resources of Sagar district, evaluate groundwater level trends and resource availability, assess water resources management strategies implemented in the district, identify successful interventions and their replication potential and develop recommendations for sustainable water resources management in hard rock terrains.

Sagar district represents a microcosm of water challenges faced by hard rock terrains across India. The district's experience with various management interventions, including traditional water harvesting, artificial recharge programs, and community-based initiatives, provides valuable lessons for water resources management in similar geological settings. Understanding the effectiveness of different strategies in this specific context contributes to the broader knowledge base for sustainable groundwater development in crystalline rock aquifers.

2. THE STUDY AREA

Sagar District, covering an area of 10,252 km², is located in the northern part of Madhya Pradesh between 23°10' to 24°27' North latitude and 78°19' to 79°21' East longitude.

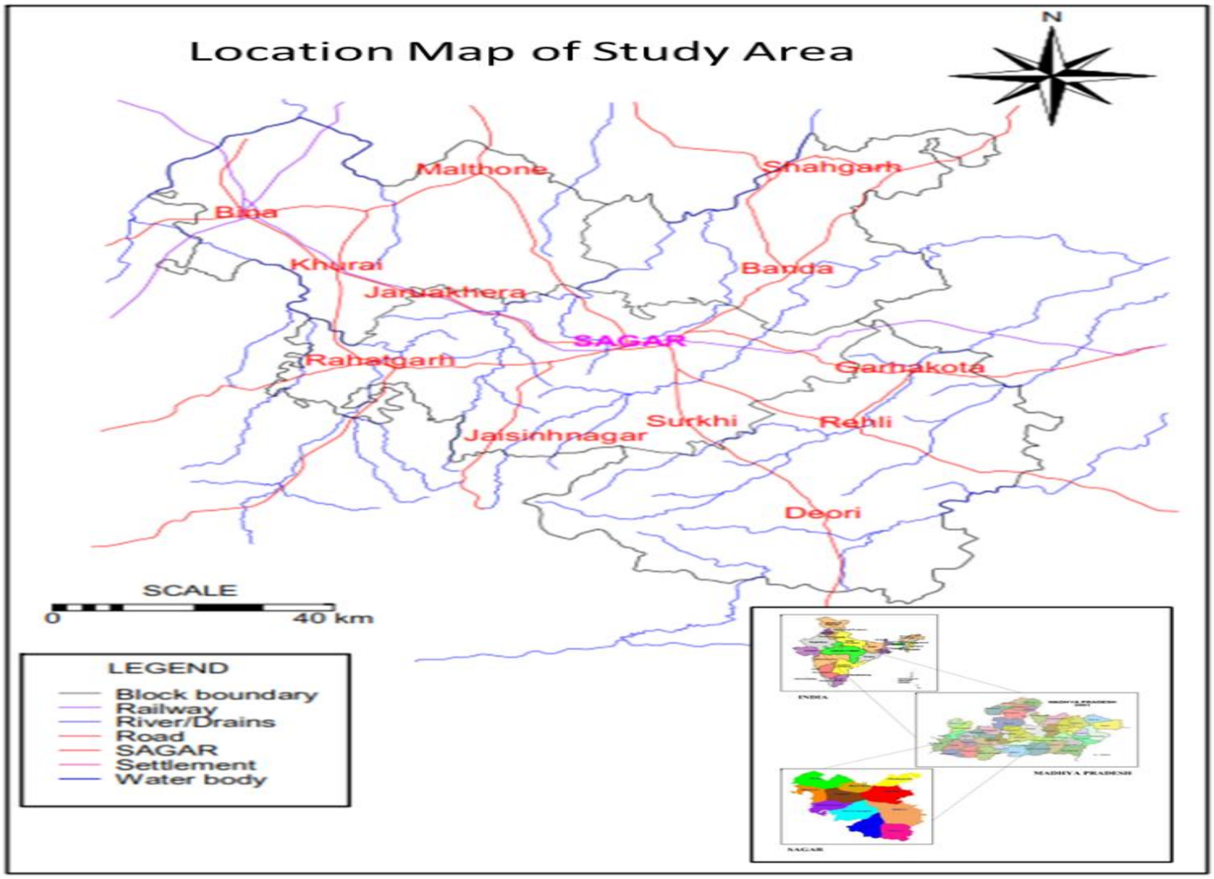

Fig:1, Location Map of Study Area

The district falls within the Bundelkhand Massif, one of India's oldest geological formations, composed predominantly of Archaean granite-gneiss complex with intrusions of younger granite and basic rocks. This geological setting creates a typical hard rock terrain with groundwater occurrence primarily controlled by structural features, weathering patterns, and secondary porosity development.

Sagar district is strategically located in the northern part of Madhya Pradesh, serving as a gateway to the Bundelkhand region. The district comprises ten tehsils: Sagar, Khurai, Rehli, Banda, Deori, Malthone, Shahgarh, Garhakota, Rahatgarh, and Kesli. The topography is characterized by undulating terrain with elevations ranging from 300 to 600 meters above mean sea level. The district is drained by several rivers including Sunar, Bina, Bewas, and their tributaries, all belonging to the Yamuna River system. The drainage pattern is predominantly dendritic, controlled by the underlying geological structure and weathering characteristics of the crystalline rocks.

Sagar district experiences a subtropical climate with three distinct seasons: summer (March-June), monsoon (July-September), and winter (October-February). The average annual rainfall ranges from 800 to 1200 mm, with approximately 85% occurring during the monsoon period. This temporal concentration of rainfall, combined with high evaporation rates during summer months, creates significant challenges for water resources management. Historical rainfall data (1950-2017) indicates high inter-annual variability with coefficient of variation ranging from 25-35% across the district. Drought conditions occur frequently, with severe droughts recorded in 1972, 1987, 2002, 2009, and 2015-2016. These climatic conditions necessitate effective water conservation and storage strategies to ensure year-round water security.

3. GEOHYDROLOGICAL SETUP

Sagar district lies within the Bundelkhand Massif, representing one of India's oldest crustal blocks with rocks dating to approximately 3.5 billion years. The geological succession includes following group of rocks:

i. Archaean Rocks (>2.5 billion years).
- Bundelkhand Gneissic Complex: Predominantly tonalitic to granodioritic gneisses with migmatitic bands.
- Granite intrusions: Coarse-grained biotite and hornblende granites.
- Basic rocks: Amphibolites, basic dykes, and metamorphosed basic intrusions.

ii. Proterozoic Rocks (2.5-1.0 billion years):
- Bijawar Group: Metamorphosed sedimentary sequences including quartzites, phyllites, and schists.
- Gwalior Group: Sandstones, shales, and conglomerates with limited aerial extent.

iii. Quaternary Deposits:
- Alluvial deposits along river valleys.
- Lateritic formations on upland areas.
- Colluvial and residual soil cover.

The Geological formations of Sagar district are characterized by multiple phases of deformation creating complex folding and faulting patterns, prominent lineament systems trending NE-SW, NW-SE, and E-W directions, shear zones and fracture systems controlling groundwater flow, weathering profiles varying from shallow (<5m) to deep (>30m) depending on rock type and structural controls.

Table-1: Geological Succession in Sagar District

Age	Formation	Rock Type	Thickness (M)	Hydrogeological Significance
Quaternary	Alluvium	Clay, Silt, Sand	05-25	Good Aquifer in Valleys
	Laterite	Lateritic Soil	02-10	Poor to Moderate Aquifer
Proterozoic	Gwalior Group	Sandstone, Shale	50-200	Moderate Aquifer Potential
	Bijawar Group	Quartzite, Phyllite, Schist	100-500	Poor to Moderate Aquifer
Archean	Younger Granite	Biotite Granite	200-1000+	Fractured Rock Aquifer
	Basic Rocks	Amphibolite, Basic Dykes	10-100	Poor Aquifer
	Bundelkhand Gneiss	Gneiss, Migmatite	1000+	Main Fractured Aquifer

Groundwater in Sagar district occurs in two distinct hydrogeological units:

1) Weathered Zone Aquifer: These are unconfined to semi-confined aquifers characterised by thickness: ranging 2-25 meters (average 8-12 meters), Porosity: 8-15%, Permeability: 0.5-5.0 m/day with good water quality, localized contamination.
2) Fractured Bedrock Aquifer: Characterised by depth extending from150 to 200 meters below ground level, Fracture density: highly variable (0.1-2.5 fractures per meter), Transmissivity: 10-150 m^2/day, Storage: limited, primarily in fracture networks, Water quality: variable, often with higher mineral content.

The interconnection between these aquifer units varies spatially, with better hydraulic connectivity in areas of intense weathering and fracturing. Groundwater flow is predominantly controlled by topography in the weathered zone and by structural features in the bedrock aquifer.

4. LAND USE AND WATER DEMAND

The land use of Sagar district is dominated by agriculture. Agricultural land covers 75.2% (771,000 hectares) of the total land. The Second largest land use unit is Forest cover, occupying 12.8% (131,200 hectares) of the land followed by Urban and built-up area: 3.5% (35,880 hectares), Water bodies: 2.1% (21,530 hectares) and Wasteland: 6.4% (65,610 hectares).

Table-2: Water Demand Assessment by Sector (2017)

Sector	Demand (MCM)	Percentage	Per Unit Details
Domestic	46.2	12.80%	55 lpcd (rural), 135 lpcd (urban)
Rural	37.9	10.50%	Population: 1.89 million
Urban	8.3	2.30%	Population: 0.28 million
Agricultural	285.7	79.30%	450-600 mm per crop season
Kharif crops	165.4	45.90%	Area: 95,000 ha
Rabi crops	120.3	33.40%	Area: 70,000 ha
Industrial	28.5	7.90%	Various industries
Large industries	22.1	6.10%	Cement, steel, paper
Small industries	6.4	1.80%	Agro-processing, textiles
Total Demand	360.4	100.00%	-

The total water demand of the district is about 361 million cubic meters per year, out of which the major component is domestic water demand. Per capita domestic water demand in urban area is 135 lpcd and rural area is 55 lpcd. The domestic consumption of water by rural population is 1.89 million cubic meters per year (87% of total) whereas, urban population uses 0.28 million cubic meters per year (13% of total). The total domestic demand of the district is 46.2 million cubic meters per year.

The total agricultural water demand of the district is 285.7 million cubic meters per year. The Irrigated area is about 165,000 hectares (21% of cultivated area). The major crops are: wheat, soybean, gram and mustard. The irrigation requirement is 450-600 mm per crop season for district's crop lands.

The Industrial Water Demand is about 28.5 million cubic meters per year as of now, which may further grow with increase in industrial units. The major industries are: cement, steel, paper and textiles, apart from these, small-scale industries like: agro-processing units and handloom works are also developing in the district.

5. MATERIALS AND METHODS

This study utilized data from multiple sources to comprehensively assess water resources management in Sagar district. The primary sources are published reports and data available online for public use in the portals of different agencies like:Central Ground Water Board (CGWB) monitoring well data (1995-2017), State Water Resources Department records, district administration reports, groundwater survey reports by Madhya Pradesh Water Resources Department etc. The demographic study and general conclusions are based on secondary sources like: published research papers, technical reports, census data and statistical abstracts and meteorological data from India Meteorological Department. The spatial information is based on GIS analysis of satellite imageries and topographic maps published by SOI.

6. ANALYSIS AND INTERPRETATION

The analysis and interpretation of data available across the sources and the time span is done to assess the development and management of water resources of the study area. The most important is groundwater level analysis, which includes: statistical analysis of long-term water level trends, seasonal and annual fluctuation patterns, spatial mapping of water level changes using GIS and calculation of local groundwater depletion rates. The water balance assessment is done through estimation of natural ground water recharge, analysing pumping test data, calculation of net groundwater availability and analysing stage of groundwater development at the aquifer levels. This study also includes aquifer characterization through estimation of transmissivity by analysing pumping test data, specific capacity analysis from well completion reports, fracture density mapping using lineament analysis and weathering profile assessment from drilling logs.

The quality of ground water is another major factor particularly in hard rock terrains. Thus, the water quality assessment of sub surface water resources as well as surface water bodies is also presented in present study. This includes physicochemical parameters of water quality assessment and its suitability for drinking and irrigation. Mapping of water quality variations across the district and identification of contamination sources and pathways is also an important aspect of this study.

The management of water resources is born by scarcity and comparatively new approach towards providing adequate water to society as well as ensuring sustainability of resources for future. This study includes strategy evaluation, assessment of existing water management interventions, cost-benefit analysis of different management approaches, community participation evaluation in water management programs and success rate analysis of artificial recharge structures built across the district.

Despite many efforts and success stories made by different agencies in the pursuit of sustainable water resources development and management, there are certain limitations too, like: limited access to detailed hydrogeological data from private wells, variability in data quality and consistency across different sources and limited information available on traditional water management practices.

7. RESULTS AND DISCUSSION

The availability of ground water largely depends on recharge potential of the aquifers. The amount of average natural recharge of ground water in Sagar district was estimated using multiple approaches given below:

1) Rainfall Infiltration Method: Based on long-term rainfall data (1990-2017) and infiltration coefficients for different geological formations estimated average annual rainfall is 1,050 mm, infiltration coefficient ranges 8-12% for hard rock areas, estimated annual recharge ranges 84-126 mm and total natural recharge is estimated 861-1,291 million cubic meters per year.
2) Water Level Fluctuation Method: The analysis of seasonal water level fluctuation in monitoring wells shows: average seasonal rise: 2.5-4.2 meters, specific yield: 0.02-0.05 (hard rock areas), estimated recharge: 95-115 mm per year, total natural recharge: 975-1,179 million cubic meters per year.
3) Comprehensive Assessment: Based on Central Ground Water Board methodology the estimated net annual groundwater recharge is 1,045 million cubic meters out of which, natural recharge is 920 million cubic meters (88%), recharge from irrigation return flow is 85 million cubic meters (8%) and recharge from other sources is 40 million cubic meters (4%).

Table-3: Groundwater Resource Assessment (2017)

Component	Volume (MCM/year)	Percentage
Natural Recharge	920.5	88.00%
Rainfall infiltration	865.2	82.80%
Stream/tank seepage	55.3	5.20%
Artificial Recharge	85.4	8.20%
Irrigation return flow	62.8	6.00%
Tank/pond recharge	22.6	2.20%
Other Sources	39.6	3.80%
Total Annual Recharge	1,045.50	100.00%
Provision for Domestic/Industrial	52.2	5.00%
Provision for Ecology	52.3	5.00%
Net Available for Development	940.5	90.00%
Current Draft	360.4	38.30%
Balance Available	580.1	61.70%

The availability of ground water is estimated by above assessment of average annual recharge and assessed against annual ground water demand. Which is about 360.4 million cubic meters for year 2017. Out of which domestic use was 46.2 million cubic meters (12.8%), agricultural use was 285.7 million cubic meters (79.3%) and industrial use was 28.5 million cubic meters (7.9%). As per CGWB report of 2017 the net available groundwater is 940.5 million cubic meters (90% of recharge) and demand is 360.4 million cubic meters. This shows the current stage of development to be 38.3% and stands "Safe" as per CGWB classification. The seven blocks of the district namely - Sagar, Khurai, Banda, Deori, Malthone, Shahgarh and Kesli are classified "Safe", two blocks-Rehli and Garhakota are marked "Semi-critical" and only Rahatgarh stands "Critical" as per CGWB report.

Table-4: Block-wise Hydrogeological Characteristics

Block	Area (km^2)	Geology	Water Level Trend (m/year)	Development Stage	Category
Sagar	1,245	Granite-Gneiss	-0.18	35%	Safe
Khurai	1,156	Granite-Gneiss	-0.22	32%	Safe
Rehli	987	Granite-Schist	-0.31	58%	Semi-Critical
Banda	894	Gneiss-Granite	-0.08	28%	Safe
Deori	1,078	Granite-Gneiss	-0.19	41%	Safe
Malthone	756	Gneiss-Quartzite	-0.14	38%	Safe
Shahgarh	1,189	Granite-Gneiss	-0.25	44%	Safe
Garhakota	1,023	Granite-Schist	-0.28	55%	Semi-Critical
Rahatgarh	1,134	Granite-Gneiss	-0.42	72%	Critical
Kesli	790	Gneiss-Granite	-0.16	35%	Safe

The spatial distribution of water quality is mapped across the district and marked 3 quality zones. The central and southern parts of the district, areas with shallow weathered aquifers and locations with good recharge conditions are the "Good Quality Zones". The northern and eastern parts, areas with deeper groundwater levels and regions with intensive agricultural activities fall under "Moderate Quality Zones". Whereas "Poor Quality Zones" encompasses the localized areas with geological controls (fluoride), industrial areas with other potential contaminations and over-exploited zones with increased mineralization.

Present status of water resources development and management of the district shows the changes brought through different schemes of the agencies of Central Govt. as well as State government. The Rajiv Gandhi Mission for Watershed Development (since 2003) covered 485 villages across 8 block and improved groundwater recharge in 60% of treated watersheds. Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) created 2,850 farm ponds, 420 check dams and 1,250 recharge structures through women's self-help groups. Mukhyamantri Jal Swavlamban Abhiyan (2016-2017) has covered all 10 blocks of the district and built 1,850 structures in first phase for water conservation and groundwater recharge.

Table-5: Artificial Recharge Structures Performance Assessment

Structure Type		Number Built	Total Cost (₹ Crores)	Success Rate (%)	Average Impact (m)	Cost Effectiveness (₹/m^3)
Percolation Tanks		185	18.5	70%	0.8-1.2	0.85
Check Dams	Concrete	420	25.2	65%	0.5-0.9	1.15
	Gabion	280	8.4	58%	0.4-0.7	0.95

	Earthen	650	6.5	45%	0.3-0.6	0.65
Recharge Wells		125	3.1	55%	0.6-1.0	1.25
Recharge Shafts		380	5.7	48%	0.4-0.8	1.05
Farm Ponds		2,850	14.3	75%	0.2-0.5	0.35
Traditional Tank Renovation		485	19.4	82%	1.0-1.8	0.55

Apart from new management practices, there are various traditional water management systems in the district about 850 historical/traditional tanks have been identified. There are 485 functional tanks (57% functionality) in the district with storage capacity: 45-50 million cubic meters. There are 125 functional traditional step wells with storage capacity: 2-3 million cubic meters. Various farm-based water harvesting systems are there like- Nala bunding: 8,500 structures across agricultural areas, Field bunding: Practiced in 65% of agricultural land, Crop diversification: Shift towards drought-resistant varieties. These are the examples of traditional knowledge integration with modern techniques.

The Artificial Recharge Interventions are found to be helpful in mitigating water scarcity issues up to a certain extent. For example, 185 percolation tanks constructed with average storage capacity of 15,000-25,000 cubic meters, and 70% showing positive impact on groundwater levels. Similarly, 420 Concrete check dams, 280 Gabion check dams and 650 Earthen check dams constructed and 65% functioning effectively. About 125 Recharge wells and 380 Recharge shafts are built near existing wells and tube wells, 55% showing measurable impact on ground water as a result. Injection wells are also promising but limited data is available for comprehensive assessment of actual impact.

8. CONCLUSIONS

The analysis of water resources management in Sagar district reveals a mixed picture of successes and challenges. The most effective interventions have been those that combine technical solutions with strong community participation and appropriate site selection based on hydrogeological understanding. The most successful interventions are as under:

1) Integrated Watershed Management: The Rajiv Gandhi Mission for Watershed Development demonstrated the highest success rates when implemented with comprehensive planning and community participation. The integration of surface water harvesting, soil conservation, and groundwater recharge created synergistic benefits that enhanced overall water security.
2) Community-Based Management: Villages with active water user associations showed significantly better outcomes in terms of resource sustainability and conflict resolution. The traditional governance systems, when integrated with modern management approaches, provided effective frameworks for collective action.
3) Strategic Artificial Recharge: Percolation tanks and check dams located in appropriate hydrogeological settings (areas with good fracture connectivity and adequate recharge zones) showed consistent positive impacts on groundwater levels. The success rate was highest when structures were designed based on detailed geological surveys rather than generic approaches.

The study clearly demonstrates that successful water resources management in hard rock terrains requires detailed understanding of local hydrogeological conditions. Generic approaches without site-specific assessment often leads to poor outcomes and waste of resources. Key factors for success include: Detailed geological and structural mapping, Understanding of fracture networks and connectivity, Assessment of weathering profiles and aquifer characteristics, Integration of geophysical surveys for site selection.

The most sustainable solutions emerged from the integration of traditional water management systems with modern technologies and scientific understanding. Traditional systems provided proven community management frameworks, while modern approaches offered technical improvements and scaling opportunities.

The transition from crisis-driven interventions to sustainable water management requires long-term commitment, adequate investment, and continuous learning and adaptation. The Sagar district case study provides a foundation for such transformation and offers valuable lessons for water managers, policymakers, and communities working to achieve water security in hard rock terrains.

The ultimate success of water resources management in hard rock terrains depends on recognizing that technical solutions alone are insufficient. Sustainable outcomes require integration of geological understanding, appropriate technology, strong institutions, community participation, and supportive policy frameworks. The Sagar district experience demonstrates that such integration is not only possible but essential for achieving long-term water security in these challenging hydrogeological environments.

REFERENCES

[1] Central Ground Water Board (2017). District Groundwater Information Booklet - Sagar District, Madhya Pradesh. Ministry of Water Resources, Government of India.

[2] Government of Madhya Pradesh (2016). State Water Policy and Implementation Strategy. Water Resources Department, Bhopal.

[3] Geological Survey of India (2015). Geology and Mineral Resources of Madhya Pradesh. GSI Publications, Kolkata.

[4] India Meteorological Department (2017). Rainfall Statistics of Madhya Pradesh (1950-2017). Pune.

[5] Directorate of Economics and Statistics (2017). Agricultural Statistics at a Glance - Madhya Pradesh. Government of Madhya Pradesh.

[6] Central Water Commission (2015). Water and Related Statistics. Ministry of Water Resources, Government of India.

[7] Rajiv Gandhi Watershed Mission (2017). Impact Assessment Report - Sagar District. Government of Madhya Pradesh.

[8] Mukhyamantri Jal Swavlamban Abhiyan (2017). Progress Report and Impact Assessment. Government of Rajasthan (adapted methodologies).

[9] Census of India (2011). District Census Handbook - Sagar. Registrar General and Census Commissioner, India.

[10] National Sample Survey Office (2015). Household Consumption of Various Goods and Services in India. Ministry of Statistics and Programme Implementation.