IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982. Volume 13, Issue 4 Ser. I (July – August 2025), PP 18-24
www.iosrjournals.org

Groundwater Resource Management In Upper Son River Basin, Anuppur District, Central India

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Abstract:
This study presents a comprehensive evaluation of groundwater resources in the Son Basin, with a focused assessment of the Anuppur District in Madhya Pradesh, India. Groundwater serves as a critical lifeline for agriculture, domestic use, and emerging industrial activities. Despite all administrative blocks being classified as "Safe" with low groundwater extraction levels (ranging from 18.85% in Anuppur to 33.00% in Jaithari), the increasing reliance on groundwater, particularly for irrigation, signals potential future stress. The geology of area is characterized by hard rock formations such as sandstone and granite gneiss with coal seams that limits groundwater storage due to low porosity and permeability. Structural complexities, coupled with clayey to loamy soils, further hinder natural recharge, raising concerns over long-term sustainability. Based on NAQUIM findings, two aquifers in Son Basin show significant static reserves, providing short-term resilience. To improve recharge and ensure long-term groundwater sustainability, the study recommends 76 artificial recharge structures— 29 check dams, 36 nala bunds, and 11 percolation ponds—strategically placed using geomorphological and hydrological criteria. Rooftop rainwater harvesting is encouraged in urban and semi-urban areas to recharge shallow aquifers. The study advocates for integrated water resource management that combines GIS-based watershed modeling, machine learning, morphometric analysis, and traditional knowledge with community participation, presenting a sustainable, scalable model for managing hard rock, monsoon-dependent aquifer systems in India.
Keywords: *Groundwater Management, Artificial Recharge, Hard Rock Aquifers, Son Basin, Sustainable Water Resources*

Date of Submission: 21-07-2025 Date of Acceptance: 31-07-2025

I. Introduction

The Son Basin, predominantly located within the Anuppur District of Madhya Pradesh, forms a vital component of Ganga river system. Originating from the Amarkantak hills, Son River flows across geologically and ecologically diverse terrains before merging with the Ganga in Bihar. It is a critical source of freshwater for drinking, irrigation, and industrial use, with its groundwater resources playing a significant role in supporting the socio-economic development of the region (Tiwari and Tiwari, 2022a). Despite its importance, increasing water demand driven by agriculture, population growth, and climate variability has placed the basin's groundwater resources under stress, requiring effective and sustainable resource management strategies. The hard rock aquifers predominant in the region offer limited storage capacity, making them highly vulnerable to over-extraction and quality degradation (Ramesh and Elango, 2012; Batabyal and Chakraborty, 2015).

Groundwater sustains both rural and urban communities in the basin and underpins extensive irrigation systems essential for regional food security (Gupta et al., 2023). However, natural recharge, largely reliant on monsoonal precipitation, remains constrained, raising concerns about long-term sustainability (Hsin-Fu Yeh et al., 2016; Achu et al., 2020). The geological complexity, featuring Gondwana and Vindhyan formations, further complicates aquifer behavior and recharge dynamics (Rai et al., 2017; Tiwari et al., 2025). Advanced tools such as machine learning, GIS, and multiscale spatial modeling have improved the accuracy of groundwater recharge potential and water quality assessment, enabling more effective watershed prioritization (Das and Pal, 2019; Kaline de Mello et al., 2020). These methods have been successfully applied in comparable Indian basins, providing valuable frameworks for application (Jaafarzadeh et al., 2021). The spatial variability in hydrogeology and groundwater chemistry is influenced by lithological heterogeneity, agricultural return flows, and other anthropogenic pressures (Chaurasia et al., 2018; Bhattacharya et al., 2021). Areas with pronounced soil erosion and variable recharge capacities can be identified through morphometric and geospatial analysis, supporting targeted conservation interventions (Jasmin and Mallikarjuna, 2014; Khan and Jhariya, 2017).

Water quality assessment in the region has been conducted using various Water Quality Index (WQI) approaches that synthesize multiple physico-chemical parameters into interpretable formats (Amiri et al., 2014; Bora and Goswami, 2017; Bijalwan et al., 2023). Several studies across India and abroad have employed such indices to evaluate groundwater and surface water quality, highlighting the utility of WQI in understanding pollution loads, health risks, and potable suitability (Chaudhry et al., 2019; Kadam et al., 2019; Gradilla-Hernández et al., 2020; Karunanidhi et al., 2021; Parmar and Samnani, 2023). Hydrogeochemical studies further illuminate the dominance of parameters like TDS, EC, and major ions (e.g., Ca^{2+}, Mg^{2+}, Cl^{-}) in defining water quality, particularly in semi-arid and monsoonal catchments (Batabyal and Chakraborty, 2015). While assessments by national and state agencies generally indicate that groundwater extraction in Madhya Pradesh remains within "safe limits," emerging semi-critical zones in high-irrigation areas underscore the urgency of implementing integrated water resource management (Tiwari and Tiwari, 2022b). These strategies must include artificial recharge, conjunctive use of surface and groundwater, and continuous quality monitoring in the face of changing land use patterns and climatic shifts (Chetia et al., 2011; Mustapha et al., 2013; Khuhawar et al., 2018).

This paper aims to deliver a comprehensive assessment of groundwater resources in the Son Basin, particularly within the Anuppur District, by integrating hydrogeochemical analysis, morphometric evaluation, recharge potential mapping, and WQI modeling. By leveraging established analytical frameworks (Kadam et al., 2019; Menberu et al., 2021) and applying insights from comparable river basins, this study contributes to more informed groundwater governance. It emphasizes sustainability within the unique hydrogeological and socio-economic context of the Son Basin and extends its relevance to similar monsoon-dependent basins globally.

II. Material And Methods

Study Area

The proposed study area encompasses around 1040 square kilometers and length of Son river is about 43 km within this catchment, specifically located in the Anuppur district. It is represented on the Survey of India (SOI) toposheets 63E/12 and 63E/16, mapped at a scale of 1:50,000. Geographically, the study area extends between latitudes 23°00′ N to 23°14′ N and longitudes 81°41′ E to 81°57′ E, and is characterized by an elongated shape oriented in a northeast-southwest (NE–SW) direction.

The geology of the study area is predominantly composed of major sandstone formations interbedded with coal seams, along with occurrences of fine-grained sandstone and granite gneiss, as identified in the Central Ground Water Board (CGWB) reports. These lithological units form part of the regional stratigraphy and significantly influence the area's hydrogeological characteristics, particularly in terms of porosity and groundwater movement. Minor geological units include limited exposures of clay and dolerite, which are sparsely distributed within the study region.

Structurally, the area does not exhibit significant tectonic disturbances, although geomorphic lineaments, aligned predominantly parallel to the local drainage systems, are observed—particularly within the sandstone and pediplain-covered regions. Additionally, joints and fractures of structural origin are notably present in the Kaimur Hill Range, trending in a northeast–southwest (NE–SW) direction, influencing subsurface water movement in the southern portion of the study area.

The soil types across the basin are mainly clayey and loamy, which contribute to moderate to low permeability and influence both surface runoff and groundwater recharge potential. These soil characteristics, in conjunction with the underlying geology, are crucial for understanding the hydrological response of the area. The study area lies within the broader Ganga Basin, and these geological and soil features collectively shape its hydrogeological and environmental behavior.

The table 1 shows the extent of various administrative blocks falling within the defined study area. Jaithari has the highest inclusion, with 83.32% (430.2 sq km of 516.34 sq km) of its area falling within the study boundary. Anuppur follows with 73.34% coverage, making both blocks highly relevant for spatial analysis. Kotma, with only 14.34% of its area included, has limited representation in the study area. (Figure 1)

Table 1: Area of various blocks

S. No.	Block	Total Area (Sq Km)	Falls in Study Area (Sq Km)	Falls in Study Area (Percentage)
1.	Anuppur	671.48	492.49	73.34
2.	Jaithari	516.34	430.2	83.32
3.	Kotma	817.03	117.2	14.34

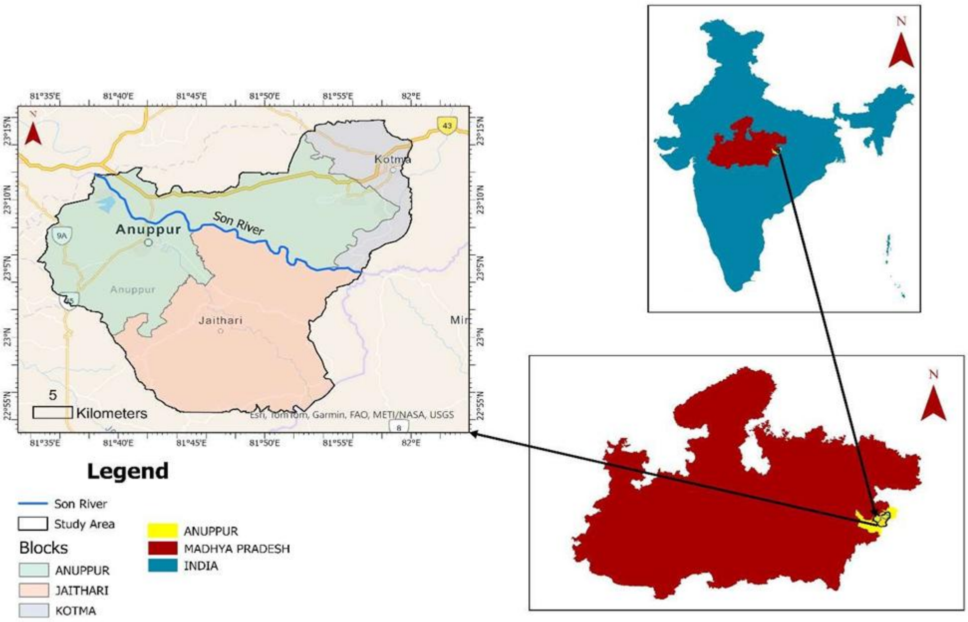

Fig. 1: Location Map

III. Result

Groundwater Resources

The assessment of groundwater resources is essential for framing a sustainable water management strategy for Son River basin in Anuppur district. This analysis draws on data from Central Ground Water Board's 2021–2022 report and the National Aquifer Mapping and Management Program (NAQUIM), reflecting conditions as of March 2020 (Udsaiya, 2022). However, due to varying degrees of spatial overlap with the study area, not all blocks contribute equally to the groundwater resource evaluation. The data, presented as of March 2020, provides a comprehensive overview of both dynamic (replenishable) and static (non-replenishable) groundwater reserves, extraction patterns, and overall hydrogeological health. (Table 2 and 3)

Total Groundwater Potential and Aquifer System

The NAQUIM study estimates a total groundwater resource of 1015.62 million cubic meters (MCM) for the district, distributed across two aquifer systems. The first aquifer holds the entire dynamic (replenishable) resource—255.94 MCM—representing the sustainable limit of annual groundwater withdrawal. Additionally, significant static resources—non-replenishable reserves—are present: 550.65 MCM in the first aquifer and 209.03 MCM in the second, total of 759.68 MCM. Among the blocks, Jaithari holds the highest dynamic resource (118.72 MCM), followed by Anuppur (84.51 MCM) and Kotma (52.71 MCM). This variation reflects both hydrogeological differences and the extent to which each block is included in the mapped study area.

Groundwater Extraction and Usage Patterns

Groundwater usage in Anuppur district is driven predominantly by agriculture, which accounts for 57.41 MCM (about 85.5% of the total 67.13 MCM gross groundwater draft). Domestic and industrial use contributes a modest 9.72 MCM. Jaithari exhibits the highest usage (39.17 MCM), aligned with its substantial agricultural footprint. In contrast, Anuppur (15.93 MCM) and Kotma (12.03 MCM) show lower extraction levels, corresponding with their smaller spatial or agricultural representation in the study area.

Stage of Groundwater Development and Sustainability Categorization

The Stage of Groundwater Extraction—the ratio of gross draft to net annual replenishable groundwater—serves as a key sustainability indicator. All assessed blocks fall within the 'Safe' category:

- Anuppur: 18.85%
- Kotma: 22.84%
- Jaithari: 33.00%

These values confirm that groundwater usage remains well below critical limits across all blocks. The district also maintains a healthy Net Ground Water Availability for future use: 18809.35 Ham (equivalent to 188.09 MCM). This surplus capacity is sufficient to support projected demands, including a domestic water requirement of 10.45 MCM by 2025.

Table 2: Dynamic Ground Water Resources of Anuppur district (as on March 2020)

Assessment Unit Name	Ground Water Extraction for Irrigation Use (Ham)	Ground Water Extraction for Domestic Use (Ham)	Total Extraction (Ham)	Annual GW Allocation for Domestic Use as on 2025 (Ham)	Net Ground Water Availability for future use (Ham)	Stage of Ground Water Extraction (%)	Categorisation
Anuppur	1228.61	364.14	1592.75	390.82	6832.23	18.85	Safe
Jaithari	3450.60	467.65	3918.25	501.91	7920.09	33.00	Safe
Kotma	1062.72	141.44	1204.16	151.80	4057.03	22.84	Safe
Total	5741.93	973.23	6715.16	1044.53	18809.35	74.69	Safe

(CGWB Report, 2021-2022) (*Ham=Hectare-meter)

Table 3: Total Ground Water Resources (Outcome of NAQUIM)

	Anuppur	Jaithari	Kotma	Total
First Aquifer				
Dynamic Resources (MCM)	84.51	118.72	52.71	255.94
Static Resources (MCM)	365.84	39.27	145.54	550.65
Total Resources (MCM)	450.35	157.99	198.25	806.59
Second Aquifer				
Static Resources (MCM)	140.08	25.50	43.45	209.03
Total GW Resources (MCM)	590.43	183.49	241.70	1015.62
Irrigation GW Draft (MCM)	12.29	34.50	10.62	57.41
Domestic + Industries	3.64	4.67	1.41	9.72
Gross Ground Water Draft (MCM)	15.93	39.17	12.03	67.13
Stage of Ground Water Extraction (%)	18.85	32.99	22.83	74.67
Category	Safe	Safe	Safe	Safe

(CGWB Report, 2021-2022) (*MCM = Million Cubic Meters)

Artificial Recharge Structures

Artificial recharge refers to the process of enhancing the natural replenishment of groundwater by storing surplus surface water in underground aquifers. This can be achieved by either spreading or impounding water on the ground to promote infiltration and percolation through the soil, or by directly injecting water into aquifers through recharge wells. The primary objective of artificial recharge is to store excess water during periods of availability so it can be utilized during dry seasons. In India, artificial recharge has become an integral component of watershed development (Jain S.K., 2012). When implemented with sound scientific planning, these techniques can significantly improve groundwater sustainability. Artificial recharge accelerates the movement of surface water into underground formations using engineered methods such as infiltration structures or surface waterbased recharge systems. In areas with hard rock formations, natural porosity and permeability are often inadequate, leading to poor recharge rates. Consequently, groundwater extraction often exceeds natural replenishment, making it insufficient to meet irrigation and domestic water needs (Garg S.K., 1973). To address this imbalance, artificial recharge becomes a necessary intervention.

The rate of groundwater percolation varies with factors such as rainfall patterns, soil and lithological conditions, landforms, temperature, and humidity. As a result, subsurface water availability differs from place to place. Moreover, traditional ponds and tanks in many regions have lost their storage and recharge capacities due to siltation and encroachment for agricultural use. These structures can be restored and converted into effective recharge systems—such as percolation tanks—through desilting and structural rehabilitation, including the addition of suitable waste weirs. In the study area, several village ponds and tanks have been identified that can be modified to enhance groundwater recharge. In locations where aquifers have been significantly depleted due to excessive water use, artificial recharge plays a critical role in restoring groundwater levels and preserving excess surface water for future needs. This study aimed to identify suitable zones for artificial recharge, ensuring that the methods selected align with the site-specific characteristics.

Following extensive field assessment and analysis, a total of 76 recharge structures are proposed. These include:

Table4: Suggested artificial recharge structures in study area

S. No	Type of structures	No. of structures to be constructed
1.	Check Dam	29
2.	Nala Bund	36
3.	Percolation Pond	11

Nala Bunds

Nala bunds are cost-effective structures constructed across drainage lines or small streams in upper catchment areas. Typically made from boulders or rough stone, they are especially suitable for first- and second-order drainages. These structures help reduce surface runoff velocity during the monsoon, allowing more water to infiltrate into the ground. The construction of nala bunds in sloped terrains is particularly effective in slowing down rainwater flow and promoting groundwater recharge. A total of 22 nala bunds are recommended based on the hydrological and topographic characteristics of the region. Their proposed locations are detailed in Table 4 and illustrated in Figure 2.

Check Dams / Stop Dams

Check dams or stop dams are small-scale masonry structures constructed across slopes or drainage lines to intercept surface runoff and retain water, enhancing groundwater recharge through subsurface infiltration. These are especially effective in areas with moderate to favourable terrain conditions. Typically built across third-order or higher-order drainage systems and on gently sloping ground, check dams play a crucial role in controlling excessive runoff during the monsoon season. They are among the most widely used interventions in watershed management and conservation programs. Besides improving groundwater potential, check dams also serve the dual purpose of providing surface water for irrigation, domestic use, and livestock consumption. A total of 38 check dams has been proposed in the study area based on field evaluation and site suitability.

Percolation Ponds

Percolation ponds are reservoir-like structures designed to capture and store surface runoff, allowing it to percolate slowly into the ground. These multifunctional structures not only collect water but also contribute to groundwater recharge and help address irrigation requirements. Positioned downstream in the landscape and typically located along second- or third-order drainages, percolation ponds act as localized recharge zones that absorb rainwater efficiently. These ponds are especially beneficial in enhancing groundwater availability in areas where surface water may otherwise be lost due to rapid runoff. A total of 15 percolation ponds has been recommended for construction, as detailed in Table 4 and illustrated in Figure 2.

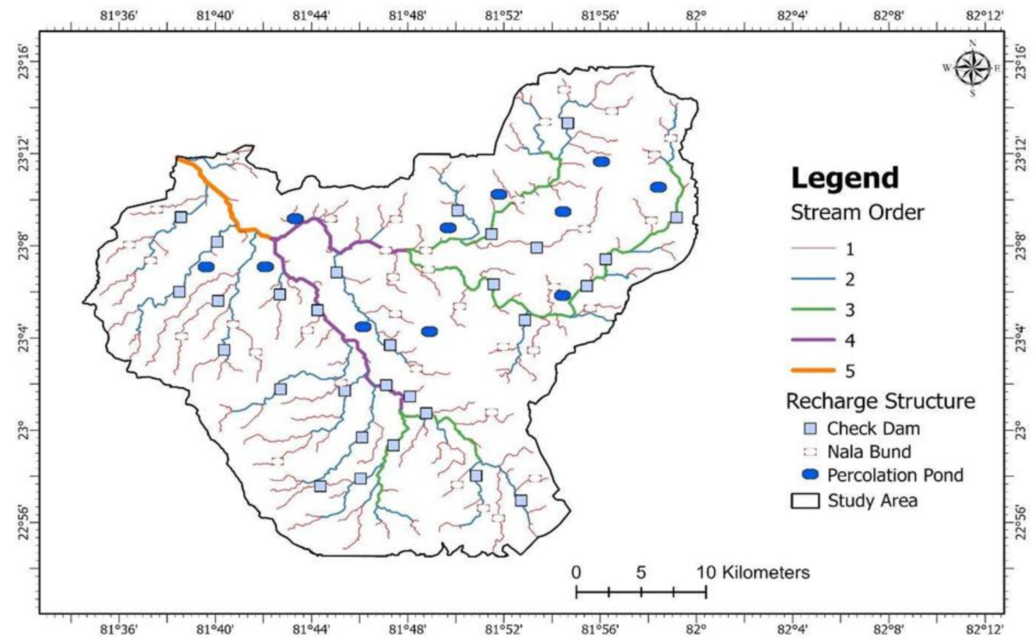

Fig. 2: Suggested artificial recharge structures map of the study area

Rainwater Harvesting Structures

Rainwater harvesting is a technique that captures and stores rainwater from rooftops and other surfaces for future use or direct recharge into the ground. In urban and semi-urban areas, rooftops serve as ideal catchment zones due to their large surface area and planned drainage outlets. A considerable volume of rainwater is often lost through these systems if not harvested. To recharge groundwater in such areas, recharge shafts, trenches, and wells can be constructed. In regions where the topsoil has low permeability or consists of clay, recharge wells with injection pipes are used to bypass the impermeable layer and deliver water directly to deeper aquifers. In areas with unconfined aquifers and sandy soil with high permeability, recharge shafts without injection pipes are effective. The depth and diameter of these structures are determined by local aquifer characteristics and the volume of water intended for recharge. In areas lacking existing infrastructure, rooftop water harvesting offers a practical solution to enhance groundwater storage and reduce water scarcity during dry periods.

IV. Conclusion

The comprehensive evaluation of groundwater resources in the Son Basin, specifically within the Anuppur District of Madhya Pradesh, underscores the region's current hydrogeological stability while highlighting pressing concerns regarding its long-term sustainability. Groundwater plays a pivotal role in sustaining agricultural productivity, domestic needs, and emerging industrial demands in the region. Despite the district being categorized as "Safe" across all administrative blocks—with low stages of groundwater extraction (ranging from 18.85% in Anuppur to 33.00% in Jaithari)—the increasing dependence on groundwater, particularly for irrigation, necessitates proactive resource management.

The geology of study area, comprising hard rock formations like sandstone and granite gneiss with coal seams, limits groundwater storage due to low porosity and permeability. This, along with structural complexity and clayey to loamy soils, hinders recharge and increases vulnerability to overextraction. The groundwater potential, as indicated by the NAQUIM study, reveals significant static reserves across two aquifers, offering resilience against short-term fluctuations. To sustain and enhance groundwater availability, artificial recharge structures have been proposed based on geomorphological suitability and hydrological assessments. A total of 76 structures—including 29 check dams, 36 nala bunds, and 11 percolation ponds—are recommended across the basin. These engineered solutions are designed to increase infiltration, reduce surface runoff, and store monsoonal surplus water, particularly in areas with pronounced slope gradients and drainage density. Additionally, rooftop rainwater harvesting systems are encouraged in urban and semi-urban settings to utilize otherwise lost rainwater and directly recharge shallow aquifers.

Long-term groundwater security in the Son Basin hinges on integrated water resource management that blends traditional knowledge with modern tools like GIS-based watershed modeling, machine learning, and morphometric analysis for precise planning. Although the basin currently maintains a safe groundwater status, growing pressures from agriculture, population, and climate variability demand adaptive, participatory governance. Sustaining groundwater levels requires combining scientific assessments with community-led conservation, efficient water-use practices, and investment in artificial recharge infrastructure. These strategies not only ensure water availability for future needs but also offer a replicable model for managing similar monsoon-dependent, hard rock aquifer systems across India and beyond.

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