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Remote Sensing and GIS-Based Assessment of Water Harvesting Structures for Groundwater Recharge: A Comprehensive Review

Surya Prakash[1], Manjeet Singh[2], Kalpana Jain[3], Poonam[4]

Abstract
Groundwater is the primary source of freshwater for domestic, agricultural, and industrial activities in many regions of the world. However, rapid urbanization, intensive groundwater extraction, changing land-use patterns, and climate variability have significantly reduced groundwater availability, particularly in semi-arid and arid regions. Water harvesting structures (WHS), including check dams, percolation tanks, farm ponds, anicuts, and recharge wells, have emerged as effective interventions for enhancing groundwater recharge by increasing infiltration and reducing surface runoff. Assessing the effectiveness of these structures is essential for sustainable watershed management and informed decision-making. Conventional field-based approaches for evaluating groundwater recharge are often time-consuming, expensive, and spatially limited. In contrast, the integration of Remote Sensing (RS) and Geographic Information Systems (GIS) provides a cost-effective, efficient, and spatially comprehensive framework for monitoring, mapping, and assessing groundwater recharge processes over large areas.

This review synthesizes recent advances in the application of RS and GIS for evaluating the impact of water harvesting structures on groundwater recharge. The strengths and limitations of existing methodologies are discussed, with particular emphasis on data availability, spatial resolution, temporal variability, and field validation. Finally, the review identifies current research gaps and highlights future opportunities for integrating geospatial technologies with hydrological models and cloud-based geospatial platforms to improve groundwater recharge assessment and support sustainable water resources management.

Keywords: Groundwater Recharge; Water Harvesting Structures; Remote Sensing; Geographic Information System (GIS); Watershed Management; Geospatial Analysis; Artificial Recharge; Sustainable Water Resources.

1. Introduction

Groundwater is one of the most critical freshwater resources, supporting domestic water supply, agricultural irrigation, industrial activities, and ecosystem sustainability worldwide. Approximately half of the global population relies on groundwater for drinking water, while nearly 40% of the world's irrigated agriculture depends on groundwater resources [1], [2]. In many developing countries, particularly India, groundwater has become the primary source of irrigation due to its reliability and accessibility. However, increasing groundwater abstraction, rapid urbanization, expanding agricultural activities, and changing climatic conditions have led to a significant decline in groundwater levels in many regions. The imbalance between groundwater extraction and natural recharge has resulted in falling water tables, deteriorating groundwater quality, reduced well yields, and increasing vulnerability to droughts.

India is among the largest users of groundwater globally, accounting for a substantial proportion of the world's groundwater withdrawal [6]. The growing demand for food production, population expansion, and industrial development has accelerated groundwater exploitation beyond sustainable limits in many watersheds. Semi-arid and arid regions are particularly vulnerable because of their erratic rainfall, high evapotranspiration rates, and limited natural recharge potential. Consequently, sustainable groundwater management has become a national priority, requiring effective strategies to enhance groundwater recharge while ensuring efficient utilization of available water resources.

Water harvesting structures (WHS) have emerged as one of the most effective approaches for augmenting groundwater recharge and improving watershed hydrology. These structures intercept surface runoff, reduce flow velocity, increase infiltration, and promote percolation into underlying aquifers. Common water harvesting structures include check dams, percolation tanks, farm ponds, recharge wells, recharge shafts, anicuts, contour bunds, and nala bunds [11], [12], [14]. Besides enhancing groundwater recharge, these structures contribute to soil moisture conservation, flood mitigation, sediment control, improved agricultural productivity, and ecosystem restoration. Numerous watershed development programs implemented across India have demonstrated the significant role of water harvesting structures in improving groundwater availability and strengthening water security at both local and regional scales.

Assessing the effectiveness of water harvesting structures is essential for evaluating their contribution to groundwater recharge and for optimizing future watershed management strategies. Traditionally, groundwater recharge assessment has relied on field investigations, groundwater level monitoring, pumping tests, hydrogeological surveys, and water balance analyses [1], [10]. Although these methods provide valuable information, they are often labour-intensive, expensive, time-consuming, and limited in spatial coverage. Moreover, field-based investigations may not adequately capture the spatial variability of watershed characteristics or provide continuous monitoring over large geographic areas.

Advances in geospatial technologies, particularly Remote Sensing (RS) and Geographic Information Systems (GIS), have transformed groundwater resource assessment by enabling efficient spatial and temporal analysis of watershed characteristics. Remote sensing provides repetitive, synoptic, and cost-effective observations of the Earth's surface through satellite imagery, allowing continuous monitoring of land use and land cover (LULC), vegetation dynamics, surface water bodies, soil moisture conditions, and topographic features. The increasing availability of freely accessible satellite datasets, including Landsat, Sentinel, IRS, and Digital Elevation Models (DEMs), has substantially improved the capability to investigate hydrological processes influencing groundwater recharge [3], [8].

Geographic Information Systems complement remote sensing by integrating spatial datasets from multiple sources into a unified analytical framework. GIS facilitates watershed delineation, drainage network extraction, slope and aspect analysis, lineament mapping, drainage density estimation, soil and geological characterization, and spatial overlay analysis. Through multi-criteria decision analysis (MCDA), weighted overlay techniques, and spatial modeling, GIS enables the identification of groundwater recharge potential zones and supports the evaluation of suitable locations for water harvesting structures [20], [21]. The integration of RS and GIS has therefore become a widely adopted approach for watershed planning and groundwater resource management because it combines spatial accuracy, analytical flexibility, and cost-effectiveness.

During the past two decades, numerous researchers have applied integrated RS–GIS techniques to evaluate groundwater recharge, delineate recharge potential zones, and assess the hydrological impacts of water harvesting structures under varying climatic and geological conditions [3], [7], [8]. These studies have utilized diverse datasets, analytical methods, and validation approaches, resulting in valuable but fragmented knowledge. While several review articles have discussed groundwater potential mapping or watershed management independently, relatively few have specifically focused on the application of RS and GIS for assessing the effectiveness of water harvesting structures in enhancing groundwater recharge. Furthermore, rapid advancements in satellite technology, higher spatial-resolution imagery, cloud-based geospatial platforms, and improved GIS-based analytical techniques have created opportunities for more accurate and comprehensive groundwater recharge assessment, warranting an updated synthesis of recent developments.

Therefore, this review aims to provide a comprehensive overview of the application of Remote Sensing and GIS in assessing the impact of water harvesting structures on groundwater recharge. The review summarizes commonly used geospatial datasets, analytical techniques, and assessment methodologies reported in the literature. It further compares findings from previous studies, discusses the strengths and limitations of existing approaches, identifies current research gaps, and highlights future research directions for improving groundwater recharge assessment through integrated geospatial technologies. The outcomes of this review are expected to support researchers, watershed managers, and policymakers in developing scientifically informed strategies for sustainable groundwater management and effective watershed planning.

2. Water Harvesting Structures and Groundwater Recharge

2.1 Water Harvesting Structures

Water harvesting structures (WHS) are engineered interventions designed to capture, store, and utilize surface runoff for enhancing water availability and promoting groundwater recharge. These structures play a significant role in watershed management by reducing runoff velocity, increasing infiltration, minimizing soil erosion, and improving aquifer replenishment. In semi-arid and arid regions, where rainfall is highly variable and groundwater resources are under increasing stress, WHS have become an essential component of sustainable water resource management.

The selection of a suitable water harvesting structure depends on several watershed characteristics, including rainfall intensity, topography, soil texture, geological conditions, drainage patterns, land use, and groundwater depth. Different types of structures are adopted according to local hydrogeological conditions and the intended purpose of water conservation. Check dams are among the most commonly used structures for intercepting seasonal streamflow, reducing runoff velocity, and allowing water to infiltrate into underlying aquifers [11]. Percolation tanks temporarily store runoff and facilitate gradual infiltration through permeable soils, making them particularly effective in hard-rock terrains. Farm ponds primarily serve irrigation and supplemental water storage purposes while also contributing to localized groundwater recharge through seepage. Recharge wells and recharge shafts are designed to convey surface water directly into deeper aquifers, especially in urban areas where natural infiltration is restricted by impervious surfaces. Other commonly adopted structures include contour bunds, nala bunds, gabion structures, and anicuts, each contributing to runoff regulation and groundwater replenishment under specific physiographic conditions [12], [14], [17].

Several watershed development programs have demonstrated that properly designed and maintained water harvesting structures improve groundwater availability, increase well yields, extend irrigation periods, and enhance agricultural productivity. Their effectiveness, however, varies depending on climatic conditions, aquifer properties, structure design, maintenance practices, and watershed characteristics.

2.2 Groundwater Recharge Mechanism

Groundwater recharge refers to the movement of water from the land surface into the subsurface until it reaches the saturated zone of an aquifer [10]. Recharge occurs naturally through rainfall infiltration, river seepage, and soil percolation, while artificial recharge is enhanced through engineered structures such as check dams, percolation tanks, recharge wells, and infiltration basins.

Water harvesting structures modify the natural hydrological cycle by intercepting surface runoff and increasing the residence time of water within the watershed. Instead of allowing rainfall runoff to leave the catchment rapidly, these structures retain water for longer durations, thereby increasing infiltration into the soil profile. As infiltrated water moves downward through unsaturated soil layers, it eventually reaches the groundwater table and contributes to aquifer replenishment. Simultaneously, reduced runoff velocity decreases soil erosion and sediment transport, preserving infiltration capacity and improving watershed health.

The efficiency of groundwater recharge through water harvesting structures depends on several interconnected factors. Rainfall characteristics, including intensity, duration, and seasonal distribution, largely determine the volume of runoff available for recharge. Soil texture and permeability influence infiltration rates, with coarse-textured soils generally allowing greater percolation than clay-rich soils. Geological formations and fracture networks govern groundwater movement and storage, particularly in hard-rock aquifers where lineaments significantly enhance recharge potential. Land use and land cover also affect infiltration, as urbanized areas with impervious surfaces reduce groundwater recharge compared with agricultural lands and forested regions. Topographic slope influences runoff velocity, where gentle slopes generally provide favorable conditions for infiltration compared with steep terrains.

Understanding these controlling factors is essential for identifying suitable locations for water harvesting structures and evaluating their long-term contribution to groundwater recharge.

2.3 Factors Influencing Groundwater Recharge

Groundwater recharge is governed by the interaction of climatic, geological, hydrological, and anthropogenic factors. Numerous studies have identified the following parameters as the most influential variables in recharge assessment [4], [5], [9]:

- **Rainfall:** The primary source of groundwater recharge, controlling runoff generation and infiltration potential.
- **Slope:** Gentle slopes promote infiltration, whereas steep slopes accelerate runoff.

- **Soil Characteristics:** Soil texture, structure, and permeability determine infiltration rates.
- **Geology:** Rock type, weathering, and fracture systems influence groundwater storage and movement.
- **Lineament Density:** Fractures and faults often act as preferential pathways for groundwater recharge.
- **Drainage Density:** Low drainage density generally indicates higher infiltration potential, whereas dense drainage networks are associated with rapid runoff.
- **Land Use/Land Cover (LULC):** Vegetation cover, agricultural practices, and urban development significantly affect infiltration processes.
- **Geomorphology:** Landforms such as valleys, pediments, floodplains, and alluvial deposits exhibit varying recharge characteristics.

Because these parameters exhibit considerable spatial variability across watersheds, their combined assessment requires geospatial techniques capable of integrating multiple thematic layers. Remote Sensing provides updated spatial information on land cover, vegetation, water bodies, and terrain characteristics, while GIS enables the integration and analysis of these datasets for groundwater recharge assessment. Consequently, the combined use of RS and GIS has become the preferred approach for evaluating groundwater recharge potential and assessing the effectiveness of water harvesting structures.

2.4 Need for Geospatial Assessment

Conventional methods for evaluating groundwater recharge largely rely on field observations and hydrogeological investigations, which often require extensive time, financial resources, and skilled personnel. Moreover, field measurements are generally limited to discrete locations and may not adequately represent the spatial heterogeneity of watershed characteristics.

Remote Sensing and GIS overcome these limitations by providing spatially continuous, repetitive, and multi-temporal datasets that facilitate watershed-scale analysis. Satellite imagery enables monitoring of land use dynamics, vegetation changes, water bodies, and terrain conditions, whereas GIS integrates multiple thematic layers for spatial analysis and decision-making. The combination of these technologies allows researchers to identify groundwater recharge zones, evaluate the hydrological performance of water harvesting structures, prioritize suitable intervention sites, and support sustainable watershed management through scientifically informed planning.

Table 1. Types of Water Harvesting Structures and Their Recharge Characteristics

Water Harvesting Structure	Primary Purpose	Suitable Terrain	Recharge Potential
Check Dam	Reduce runoff and enhance infiltration	Seasonal streams	High
Percolation Tank	Surface water storage and recharge	Hard-rock regions	High
Farm Pond	Irrigation storage	Agricultural land	Moderate
Recharge Well	Direct aquifer recharge	Urban and rural areas	Very High

Water Harvesting Structure	Primary Purpose	Suitable Terrain	Recharge Potential
Recharge Shaft	Deep aquifer recharge	Highly impermeable soils	High
Anicut	Water storage across streams	Small rivers	High
Contour Bund	Soil and water conservation	Sloping agricultural lands	Moderate

3. Applications of Remote Sensing and GIS in Groundwater Recharge Assessment

The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has revolutionized groundwater recharge assessment by providing efficient, cost-effective, and spatially explicit tools for watershed analysis. Unlike conventional field-based investigations, geospatial technologies enable continuous monitoring of large geographic areas while simultaneously integrating multiple hydrological, geological, and environmental datasets. The availability of freely accessible satellite imagery, high-resolution digital elevation models (DEMs), and advanced GIS analytical techniques has significantly improved the identification of groundwater recharge zones and the evaluation of water harvesting structures.

Most groundwater recharge studies employ an integrated RS–GIS framework that combines satellite-derived thematic layers with spatial analysis techniques to evaluate the suitability of recharge locations and assess the effectiveness of existing water harvesting structures. The methodology generally involves satellite image acquisition, image preprocessing, extraction of thematic layers, GIS-based spatial analysis, and validation using field observations or groundwater level data.

3.1 Remote Sensing Data for Groundwater Recharge Assessment

Remote sensing provides repetitive and synoptic observations of Earth's surface that are essential for monitoring watershed characteristics influencing groundwater recharge. Optical satellite imagery is widely used for mapping land use and land cover (LULC), vegetation distribution, surface water bodies, and seasonal land surface changes. Digital Elevation Models (DEMs) provide topographic information required for watershed delineation, drainage network extraction, slope analysis, and runoff modelling.

Among the available satellite datasets, Landsat and Sentinel missions are the most widely used because of their free availability, adequate spatial resolution, and long-term data archives. Landsat imagery has been extensively applied for LULC classification and change detection over the past four decades, whereas Sentinel-2 provides higher spatial resolution (10–20 m) suitable for detailed watershed analysis. Sentinel-1 Synthetic Aperture Radar (SAR) data are increasingly used because they can acquire images under cloud cover and provide valuable information on surface moisture and flood inundation [8]. In addition, Indian Remote Sensing (IRS) satellites, Cartosat DEMs, ASTER DEMs, and SRTM DEMs have been widely employed for terrain characterization and watershed mapping.

The choice of satellite dataset depends on the objectives of the study, watershed size, spatial resolution requirements, and temporal availability of imagery. The increasing accessibility of multi-temporal satellite datasets has greatly enhanced the capability to monitor hydrological changes associated with water harvesting interventions.

3.2 Thematic Layers Derived from Remote Sensing and GIS

Groundwater recharge assessment requires the integration of multiple thematic layers that collectively describe watershed characteristics. These thematic layers are generated from satellite imagery, digital elevation models, geological maps, and ancillary datasets before being integrated within a GIS environment.

Land Use/Land Cover (LULC) is one of the most important layers because vegetation, agricultural practices, urban development, and barren lands directly influence infiltration and runoff generation. Dense vegetation generally promotes infiltration by improving soil structure, whereas urbanized areas reduce recharge due to impervious surfaces.

Slope maps derived from DEMs describe terrain steepness and significantly influence runoff velocity. Gentle slopes facilitate infiltration and groundwater recharge, while steep slopes increase runoff and reduce infiltration opportunities.

Drainage density represents the total length of stream channels per unit watershed area and reflects runoff characteristics. Watersheds with lower drainage density generally exhibit greater infiltration potential than highly dissected landscapes.

Lineament density, representing fractures and faults within geological formations, is another critical parameter. In hard-rock terrains, lineaments provide preferential pathways for groundwater movement and substantially enhance recharge potential. Consequently, lineament mapping has become an integral component of groundwater recharge studies [4], [9].

Soil texture and geological formations determine infiltration capacity and groundwater storage characteristics. Permeable soils and weathered rock formations generally support higher recharge rates compared with clay-rich soils and compact bedrock. Geomorphological units, including floodplains, pediments, valleys, and alluvial deposits, are also frequently incorporated because they exhibit varying groundwater storage capacities.The integration of these thematic layers enables comprehensive spatial evaluation of groundwater recharge potential across a watershed.

3.3 GIS-Based Spatial Analysis Techniques

Geographic Information Systems provide a versatile platform for integrating, analysing, and visualizing spatial datasets obtained from remote sensing and field investigations. Various GIS-based analytical techniques have been adopted for groundwater recharge assessment depending on data availability and research objectives.

Overlay analysis is the most widely applied approach, where multiple thematic layers are combined to generate groundwater recharge potential maps. Weighted Overlay Analysis (WOA) assigns relative importance to each thematic layer based on hydrogeological significance, allowing the identification of suitable recharge zones [21], [22].

Multi-Criteria Decision Analysis (MCDA) has become increasingly popular because groundwater recharge is influenced by numerous interacting parameters. Among MCDA techniques, the Analytical Hierarchy Process (AHP) is the most frequently employed method for assigning weights to thematic layers based on expert judgment and pairwise comparisons [20]. Several recent studies have also adopted Fuzzy AHP and hybrid decision-making models to reduce subjectivity and improve spatial prediction accuracy [23], [24].

Buffer analysis is commonly used to evaluate the influence of rivers, reservoirs, and existing water harvesting structures on surrounding groundwater recharge conditions. Interpolation techniques, such as Inverse Distance Weighting (IDW) and Kriging, are frequently applied to generate continuous groundwater level surfaces from observation well data, facilitating before-and-after comparisons of groundwater conditions [5].

The integration of GIS with spatial modelling significantly improves the accuracy of groundwater recharge assessment by enabling simultaneous consideration of multiple environmental variables.

3.4 Integrated RS–GIS Workflow for Recharge Assessment

Most published studies follow a common methodological framework for evaluating groundwater recharge using integrated RS and GIS techniques. Initially, satellite imagery and ancillary spatial datasets are collected and pre-processed to remove geometric and radiometric distortions. Subsequently, thematic layers such as land use, slope, drainage density, lineament density, soil, geology, and geomorphology are prepared within the GIS environment.

Each thematic layer is classified into recharge suitability categories according to hydrogeological characteristics. Appropriate weights are then assigned using methods such as AHP or weighted overlay analysis. The weighted thematic layers are integrated through spatial overlay operations to generate groundwater recharge potential maps, which are finally validated using groundwater level observations, well yield data, recharge measurements, or field investigations.

This integrated workflow provides a systematic and reproducible approach for identifying potential groundwater recharge zones and evaluating the effectiveness of water harvesting structures. Compared with conventional assessment methods, RS–GIS techniques offer higher spatial coverage, lower operational costs, faster analysis, and improved decision support for watershed planning and groundwater management.

Table 2. Common Remote Sensing Datasets and GIS Layers Used in Groundwater Recharge Assessment

Dataset / Layer	Typical Source	Application
Landsat (30 m)	USGS	Land Use/Land Cover
Sentinel-2 (10 m)	ESA	Vegetation and LULC Mapping
Sentinel-1 SAR	ESA	Surface moisture and flood mapping
SRTM DEM	NASA	Slope, drainage, watershed delineation

Dataset / Layer	Typical Source	Application
ASTER DEM	NASA	Terrain analysis
Cartosat DEM	ISRO	High-resolution topography
Soil Maps	NBSS&LUP / FAO	Soil texture and infiltration
Geological Maps	GSI	Rock type and aquifer characteristics
Lineament Maps	RS interpretation	Fracture analysis
Groundwater Level Data	CGWB / State agencies	Validation

Workflow of RS–GIS-Based Groundwater Recharge Assessment:

Satellite Data
↓
Image Pre-processing
↓
Preparation of Thematic Layers
(LULC, DEM, Slope, Soil,
Geology, Drainage,
Lineament, Geomorphology)
↓
GIS Spatial Analysis
(AHP / Weighted Overlay / MCDA)
↓
Groundwater Recharge Potential Map
↓
Validation using Groundwater Level,
Field Survey and Existing WHS

4. Review of Previous Studies

The application of Remote Sensing (RS) and Geographic Information Systems (GIS) for groundwater recharge assessment has expanded considerably over the past two decades. Advances in freely available satellite imagery, improved digital elevation models, and sophisticated GIS-based spatial analysis techniques have enabled researchers to evaluate groundwater recharge potential and assess the effectiveness of water harvesting structures across a wide range of climatic and geological conditions. The reviewed literature indicates that most studies can be broadly categorized into four major themes: (i) groundwater recharge potential mapping, (ii) assessment of water harvesting structures, (iii) integrated RS–GIS approaches for watershed management, and (iv) studies conducted in Indian watersheds.

4.1 Groundwater Recharge Potential Mapping

Groundwater recharge potential mapping represents one of the most widely investigated applications of RS and GIS. Most studies integrate multiple thematic layers, including land use/land cover (LULC), slope, geology, geomorphology, soil texture, drainage density, rainfall, and lineament density, to identify areas favorable for groundwater recharge.

Earlier studies primarily relied on weighted overlay analysis in which thematic layers were assigned subjective weights based on expert knowledge. Although these methods provided useful preliminary assessments, they often lacked systematic procedures for weight assignment and uncertainty evaluation. To address these limitations, more recent investigations have increasingly adopted Multi-Criteria Decision Analysis (MCDA), particularly the Analytical Hierarchy Process (AHP), which provides a structured framework for assigning relative importance to recharge-controlling factors.

Several comparative studies have reported that the integration of AHP with GIS produces more reliable groundwater recharge potential maps [5], [24] than conventional overlay methods because it reduces subjectivity and allows consistent prioritization of thematic layers. However, the quality of the final recharge map remains highly dependent on the accuracy of the input datasets, spatial resolution of satellite imagery, and availability of field observations for validation.

Recent studies have also demonstrated that high-resolution satellite datasets such as Sentinel-2 and Cartosat DEMs improve the delineation of recharge zones [4], especially in heterogeneous watersheds where topographic variations strongly influence infiltration processes. Nevertheless, inconsistencies in thematic layer selection and weighting schemes across different studies continue to limit the comparability of reported results.

4.2 Assessment of Water Harvesting Structures

A growing body of research has focused on evaluating the hydrological impacts of water harvesting structures using integrated geospatial approaches. These studies assess the effectiveness of check dams, percolation tanks, farm ponds, recharge wells, and other recharge interventions by comparing groundwater conditions before and after construction.

Most investigations employ groundwater level monitoring, land use analysis, and satellite-derived indicators to evaluate recharge enhancement. In many watersheds, check dams have been associated with measurable increases in groundwater levels, improved well yields, and enhanced agricultural productivity [7], [9]. Percolation tanks have similarly demonstrated significant recharge benefits in hard-rock regions due to prolonged water storage and increased infiltration opportunities [9].

Several researchers have integrated temporal satellite imagery with groundwater monitoring data to evaluate seasonal and long-term changes associated with water harvesting structures. Multi-temporal analyses have revealed that recharge effectiveness depends not only on the design of the structures but also on rainfall variability, geological formations, soil permeability, and maintenance practices. Structures located in highly fractured geological formations generally exhibit greater recharge efficiency than those constructed in low-permeability terrains.

Despite these positive findings, the literature indicates that many studies evaluate only short-term groundwater responses. Long-term monitoring capable of capturing climatic variability and cumulative recharge effects remains relatively limited. Furthermore, the absence of standardized performance indicators makes comparison among different studies challenging.

4.3 Integrated Remote Sensing and GIS Approaches

The integration of Remote Sensing and GIS has become the standard methodology for groundwater recharge assessment because it combines spatial data acquisition with advanced analytical capabilities. Rather than relying on a single parameter, integrated approaches simultaneously evaluate multiple recharge-controlling variables within a unified spatial framework.

Most published studies follow a similar workflow involving satellite image acquisition, preparation of thematic layers, GIS-based spatial analysis, weighted overlay or AHP modelling, and validation using groundwater observations. The widespread availability of Landsat, Sentinel, and SRTM datasets has significantly improved the accessibility of this methodology [3], [7], [8], particularly for watershed-scale applications.

Several studies have further integrated hydrological models with RS–GIS techniques to improve recharge estimation. These integrated frameworks combine surface hydrology, terrain analysis, and groundwater information, providing a more comprehensive understanding of watershed processes than geospatial analysis alone. Although such approaches generally improve prediction accuracy, they require extensive input data and calibration, which may not be available in data-scarce regions.

Recent research has also explored cloud-based geospatial platforms, such as Google Earth Engine, for processing multi-temporal satellite imagery. These platforms substantially reduce data-processing time and facilitate large-scale watershed analysis [19]. However, their application in groundwater recharge assessment remains relatively limited, indicating an important direction for future research.

4.4 Studies in Indian Watersheds

India has witnessed extensive application of RS and GIS for groundwater recharge assessment because of increasing groundwater stress and the widespread implementation of watershed development programmes. Research has been conducted across diverse hydrogeological environments, including the hard-rock terrains of Rajasthan, Maharashtra, Karnataka, Telangana, Madhya Pradesh, and Gujarat [6], [9].

Many Indian studies have demonstrated that integrating satellite-derived datasets with GIS-based spatial analysis effectively identifies groundwater recharge zones and supports the planning of water harvesting structures. Check dams and percolation tanks have consistently been reported as effective interventions for improving groundwater levels in semi-arid regions [16]. Several watershed-scale investigations have also observed improvements in irrigation reliability, cropping intensity, and groundwater availability following the construction of recharge structures.

Despite substantial progress, the reviewed literature reveals several recurring limitations. First, most studies focus primarily on groundwater recharge potential mapping rather than quantitatively assessing the long-term performance of individual water harvesting structures. Second, field validation is often limited because of inadequate groundwater monitoring networks. Third, considerable variability exists in the thematic layers, weighting methods, and validation procedures adopted by different researchers, making cross-comparison difficult. Finally, relatively few investigations integrate geospatial techniques with hydrological modelling to quantify actual recharge volumes.

Overall, the literature demonstrates that Remote Sensing and GIS provide an effective framework for groundwater recharge assessment and watershed planning. However, greater methodological standardization, long-term monitoring, and integration with hydrogeological models are required to improve the reliability and practical applicability of future studies.

Table 3. Representative Studies on RS–GIS-Based Groundwater Recharge Assessment

Author(s)	Study Area	Methodology	Main Findings
Study 1	India	RS + GIS + Weighted Overlay	Delineated groundwater recharge zones
Study 2	Rajasthan	AHP + GIS	Identified suitable locations for recharge structures
Study 3	Maharashtra	Landsat + GIS	Evaluated impact of check dams on groundwater levels
Study 4	Karnataka	Sentinel-2 + GIS	Improved recharge zone mapping accuracy
Study 5	Gujarat	MCDA + GIS	Prioritized watershed interventions
Study 6	Telangana	RS–GIS Integration	Assessed recharge potential in semi-arid watershed
Study 7	Tamil Nadu	DEM + GIS	Evaluated influence of terrain on recharge
Study 8	Madhya Pradesh	Multi-temporal RS	Monitored groundwater changes after water harvesting

5. Challenges and Future Perspectives

The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has significantly advanced groundwater recharge assessment and the evaluation of water harvesting structures. Despite considerable progress, several technical and methodological challenges continue to limit the reliability and applicability of geospatial approaches.

One of the major challenges is the availability and quality of spatial data. Although freely accessible satellite datasets such as Landsat and Sentinel have greatly expanded opportunities for watershed analysis, their spatial and temporal resolutions may not be sufficient to capture small-scale water harvesting structures or localized recharge processes [4], [8]. Cloud cover during the monsoon season further restricts the use of optical satellite imagery, resulting in incomplete temporal observations. While Synthetic Aperture Radar (SAR) data provide an alternative under cloudy conditions, their application in groundwater recharge studies remains relatively limited.

Another significant limitation is the uncertainty associated with thematic layer preparation and weighting procedures. Most GIS-based groundwater recharge studies employ Weighted Overlay Analysis or the Analytical Hierarchy Process (AHP), where thematic layer weights are assigned using expert judgment [20], [5]. Although these methods are simple and widely accepted, the resulting recharge maps may vary depending on the selection of input parameters and assigned weights. The absence of standardized criteria for weighting groundwater recharge factors makes comparison among different studies difficult and introduces uncertainty into spatial predictions.

Field validation also remains a critical challenge. Many published studies validate groundwater recharge maps using limited groundwater level observations or well inventory data [6]. Because groundwater systems exhibit strong spatial and temporal variability, short-term monitoring often fails to represent actual recharge conditions. Long-term monitoring of groundwater levels, infiltration rates, and aquifer responses is essential for improving the credibility of geospatial assessment methods.

The complexity of groundwater recharge processes presents another important challenge. Recharge is controlled by multiple interacting factors, including rainfall variability, soil characteristics, geological formations, land use dynamics, evapotranspiration, and aquifer properties. Most existing RS–GIS approaches represent these factors using static thematic layers, whereas many hydrological processes are highly dynamic. Consequently, recharge potential maps often represent relative suitability rather than actual groundwater recharge volumes.

Future research should therefore focus on developing integrated assessment frameworks that combine Remote Sensing, GIS, field observations, and hydrological models. The coupling of geospatial techniques with physically based groundwater models can improve recharge estimation and provide more realistic simulations of watershed hydrology. Advances in cloud-based geospatial platforms, particularly Google Earth Engine, offer new opportunities for processing multi-temporal satellite imagery over large watersheds with improved computational efficiency [19]. Similarly, increasing availability of high-resolution satellite imagery and radar datasets can enhance the detection and monitoring of small water harvesting structures.

Machine learning and artificial intelligence also represent promising directions for future groundwater recharge assessment. Algorithms such as Random Forest, Support Vector Machine, Artificial Neural Networks, and Extreme Gradient Boosting have demonstrated improved predictive capability for groundwater potential mapping when compared with conventional statistical approaches [25], [26]. Integrating these data-driven techniques with GIS-based spatial analysis may enhance the accuracy and robustness of groundwater recharge assessments.

Finally, future investigations should emphasize long-term monitoring of water harvesting structures under different climatic and hydrogeological conditions. Standardized methodologies for thematic layer preparation, weighting, validation, and performance evaluation are needed to improve comparability among studies. Such integrated and standardized approaches will contribute to more reliable groundwater recharge assessment and provide stronger scientific support for sustainable watershed management and groundwater conservation.

6. Conclusions

Groundwater depletion has emerged as one of the most pressing challenges for sustainable water resources management, particularly in semi-arid and arid regions where groundwater serves as the primary source of water for agriculture, domestic use, and industrial activities. Water harvesting structures have proven to be effective interventions for enhancing groundwater recharge by reducing surface runoff, increasing infiltration, and improving aquifer replenishment. Their successful implementation, however, depends on appropriate site selection, watershed characteristics, hydrogeological conditions, and continuous performance evaluation.

This review highlights the growing importance of integrating Remote Sensing (RS) and Geographic Information Systems (GIS) for assessing groundwater recharge and evaluating the effectiveness of water harvesting structures. The reviewed studies demonstrate that freely available satellite datasets, including Landsat, Sentinel, and Digital Elevation Models (DEMs), combined with GIS-based spatial analysis techniques, provide an efficient and cost-effective framework for watershed-scale investigations. The integration of thematic layers such as land use/land cover, slope, geology, drainage density, soil, geomorphology, and lineament density enables the identification of groundwater recharge potential zones and supports informed decision-making for watershed planning.

The literature further indicates that GIS-based Multi-Criteria Decision Analysis (MCDA), particularly the Analytical Hierarchy Process (AHP), has become the most widely adopted approach for groundwater recharge mapping [20], [21]. Although these methods have significantly improved spatial analysis, the reliability of groundwater recharge assessment continues to depend on the quality of input datasets, weighting procedures, and field validation. Considerable variation in methodology among published studies limits direct comparison of results and emphasizes the need for standardized assessment frameworks.

Despite substantial progress in the application of geospatial technologies, several research gaps remain. Long-term monitoring of groundwater responses following the construction of water harvesting structures is relatively limited, and many studies focus primarily on recharge potential mapping rather than quantifying actual groundwater recharge. Furthermore, the integration of RS–GIS techniques with hydrological models, climate variability analysis, and advanced data-driven approaches remains insufficient in many watershed studies.

Overall, this review demonstrates that the combined application of Remote Sensing and GIS provides a robust and practical approach for groundwater recharge assessment and watershed management. Future research should focus on integrating high-resolution satellite observations, cloud-based geospatial platforms, hydrological modelling, and field-based monitoring to improve the accuracy and reliability of groundwater recharge estimation. The adoption of standardized methodologies and multidisciplinary approaches will not only enhance scientific understanding of groundwater recharge processes but also support policymakers and watershed managers in developing sustainable strategies for groundwater conservation under changing environmental and climatic conditions.

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