

A Conceptual Framework for Aquifer Delineation and Managed Aquifer Recharge in Deccan Trap Basaltic Terrain of Drought-Prone Area

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Abstract:

Drought-prone regions underlain by Deccan Trap basalt face persistent challenges in groundwater availability due to highly heterogeneous aquifer properties, limited natural recharge, variable fracture networks, and increasing groundwater demand. This study proposes a conceptual framework for aquifer delineation and Managed Aquifer Recharge (MAR) in basaltic terrain by integrating geological, hydrogeological, geophysical, topographical, and remote sensing information. The framework conceptualises aquifer systems through the identification of weathered zones, fractured basalt, vesicular horizons, joints, lineaments, and geological contacts that influence groundwater occurrence and movement. Spatial datasets are integrated within a Geographic Information System to delineate groundwater potential zones and identify suitable locations for MAR interventions. The proposed framework further links aquifer characteristics with recharge structures such as check dams, recharge shafts, percolation tanks, recharge trenches, and injection-based systems according to local hydrogeological conditions. Groundwater-level monitoring, aquifer response assessment, and periodic evaluation are incorporated to support adaptive recharge management. The framework provides a systematic basis for moving from aquifer characterization to site-specific recharge planning and monitoring. It can support sustainable groundwater management in drought-prone Deccan Trap landscapes by improving understanding of aquifer connectivity, recharge potential, and groundwater storage dynamics. The framework is particularly relevant for water-stressed regions where conventional groundwater development alone cannot ensure long-term water security.

Keywords: Deccan Trap basalt; aquifer delineation; managed aquifer recharge; groundwater potential; fractured basalt; hydrogeology; GIS; remote sensing; drought-prone areas; groundwater management.

1. Introduction

Groundwater is a critical component of water security in drought-prone regions, particularly where seasonal rainfall is highly variable and surface-water resources are insufficient to meet domestic and

agricultural requirements. Increasing groundwater abstraction, climatic variability and recurrent droughts have intensified pressure on groundwater systems and created a need for systematic approaches to aquifer characterization and recharge management. Managed Aquifer Recharge (MAR) has emerged as an important groundwater management approach because it enables water available during periods of surplus to be intentionally stored within aquifers for subsequent use or environmental benefits. Recent research also highlights the importance of integrating hydrogeological characteristics, recharge processes and regional water-system interactions when designing MAR interventions.

The problem becomes particularly complex in the Deccan Trap region of India because basaltic aquifers exhibit considerable spatial heterogeneity. Groundwater occurrence is rarely controlled by primary porosity alone. Instead, weathering, joints, fractures, vesicular zones, inter-flow contacts and geological structures substantially influence groundwater storage and movement. Studies of the Deccan Trap province have demonstrated that different basaltic flow units can possess markedly different hydraulic characteristics, resulting in considerable variations in transmissivity, storage and well productivity. Uhl and Joshi's pumping-test investigations in Central India, for example, demonstrated substantial differences in the hydrodynamic behaviour of basaltic aquifers.

The hydrogeological complexity of Deccan basalt also creates challenges for groundwater exploration and aquifer delineation. Electrical-resistivity investigations in Sangli District demonstrated the usefulness of resistivity sounding and profiling for identifying shallow groundwater sources associated with fractured and fissured basalt. More recent hydrogeophysical research has similarly shown that integrating electrical resistivity, induced polarization, anisotropy and borehole information can improve identification of fractured and saturated zones within Deccan basalt. These findings indicate that aquifer delineation in basaltic terrain requires integration of geological, geophysical and hydrogeological evidence rather than reliance on a single indicator.

The role of weathering and structural discontinuities is also evident in groundwater storage. Saha and Agrawal demonstrated that specific yield within a Deccan basalt watershed varies according to geological units, with weathered zones and vesicular basalt exhibiting different groundwater storage characteristics from massive basalt. Similarly, investigations of springs in the Western Ghats have shown that groundwater emergence is associated with lithological variations between basaltic flow units, physiography, recharge areas and hydraulic characteristics of source aquifers. Such evidence emphasises the need to understand aquifer architecture before selecting locations and technologies for groundwater recharge.

Aquifer delineation therefore represents a fundamental step in developing effective MAR strategies for basaltic landscapes. Groundwater potential mapping can combine geological formations, lineament density, drainage characteristics, slope, soil, land use, rainfall and geophysical information to identify areas with greater recharge potential. GIS-based multi-criteria approaches have been applied in semi-arid western India to prioritize MAR sites, demonstrating the usefulness of spatial integration and analytical weighting for identifying suitable recharge zones. However, spatial suitability alone does not guarantee successful recharge. The hydraulic connectivity between recharge structures and target aquifers, aquifer

storage characteristics, groundwater abstraction patterns and post-recharge response must also be considered.

MAR interventions in hard-rock environments require particular attention to local hydrogeological conditions. Research on percolation tanks in South India found that substantial proportions of stored water can infiltrate, but much of the recharged water may subsequently be captured by nearby pumping wells. This demonstrates the importance of assessing groundwater flow and abstraction dynamics when evaluating MAR performance. Research on MAR interventions in India has further argued for distinguishing between the performance of recharge structures and their broader impacts on groundwater resources.

The need for a systematic framework is particularly relevant in drought-prone Deccan Trap areas, where conventional groundwater development can be constrained by heterogeneous aquifer properties and declining groundwater availability. Studies from Maharashtra indicate that weathered and fractured basalt can function as productive aquifer zones, whereas massive basalt may have considerably lower groundwater potential. Groundwater flow modelling in basaltic hard-rock areas of Maharashtra has also demonstrated that groundwater movement is strongly associated with open fractures, fissures, joints and weathered formations. These characteristics make aquifer-specific recharge planning essential rather than adopting uniform recharge structures across an entire watershed.

Against this background, the present conceptual framework proposes an integrated approach for aquifer delineation and Managed Aquifer Recharge in drought-prone Deccan Trap basaltic terrain. The framework links geological and hydrogeological characterization with geophysical investigation, GIS and remote sensing-based spatial analysis, groundwater potential assessment, MAR site selection, recharge-structure selection and post-recharge monitoring. Such integration can provide a structured basis for identifying rechargeable aquifer zones, matching recharge interventions with local hydrogeological conditions and evaluating changes in groundwater storage and levels. The framework is intended to support sustainable groundwater planning in basalt-dominated regions where aquifer heterogeneity and recurrent drought require location-specific recharge interventions.

2. Literature Review

2.1 Hydrogeological characteristics of Deccan Trap basalt

The Deccan Trap province represents one of the largest flood-basalt provinces in the world and occupies a substantial part of western and central India. Its hydrogeological behaviour is fundamentally different from that of porous sedimentary aquifers because groundwater storage and movement are largely controlled by secondary porosity. Weathering, joints, fractures, vesicular horizons, inter-flow zones and geological contacts create discontinuous groundwater-bearing zones within otherwise massive basalt. Deolankar (1980) established that the aquifer potential of Deccan basalts depends strongly on transmissivity and storativity, highlighting the heterogeneous nature of groundwater occurrence in these formations.

Kulkarni et al. (2002) described Deccan basalt groundwater systems as hydrogeologically heterogeneous, with alternating compact and vesicular-amygdaloidal basalt forming different hydraulic units. Their work

indicates that understanding the physical architecture of individual lava flows is necessary for interpreting groundwater movement and storage. Singhal (1997) similarly identified weathered, fractured and vesicular basalt as important aquifer horizons and reported substantial variation in transmissivity between different flow units. These findings are consistent with hydrogeological observations from Maharashtra, where groundwater occurrence is associated mainly with secondary porosity generated through weathering, jointing and fracturing.

Saha and Agrawal (2006) demonstrated that specific yield varies considerably between weathered, massive and vesicular basalt. Their study in the Torla Odha watershed reported higher specific yield in the weathered zone and vesicular basalt compared with massive basalt, demonstrating that aquifer storage is strongly dependent on lithological and structural characteristics. Naik et al. (2002) further demonstrated that groundwater discharge in basaltic terrain is influenced by lithological variations, geomorphology and recharge conditions.

2.2 Aquifer heterogeneity and groundwater occurrence

The heterogeneous nature of basalt creates considerable spatial variation in well productivity. Groundwater may occur under phreatic conditions within shallow weathered and fractured zones and under semi-confined or confined conditions within deeper fractured and vesicular horizons. Field observations from Maharashtra indicate that massive basalt can act as a relatively low-permeability layer, whereas weathered and fractured zones can provide preferential pathways for groundwater flow.

Borehole and aquifer-mapping investigations undertaken in Maharashtra have confirmed this multi-layered character. The National Aquifer Mapping Programme identifies combinations of geological, geophysical, hydrological and chemical information as necessary for characterizing aquifer geometry, hydraulic properties and groundwater quality. Data from Sangli District also demonstrate substantial differences between shallow weathered or fractured basalt and deeper jointed or fractured aquifers in terms of transmissivity, specific yield and well productivity.

The hydrogeological complexity becomes particularly important in drought-prone areas. Bose and Ramakrishna (1978), working in drought-affected Sangli District, demonstrated that electrical-resistivity sounding and profiling could assist in locating shallow groundwater sources within fractured and fissured basalt. Their findings established the importance of geophysical investigation in areas where conventional geological observations alone may not adequately identify productive zones.

2.3 Geophysical approaches for aquifer delineation

Electrical resistivity methods have been widely applied to groundwater exploration in hard-rock environments because variations in resistivity can provide information about weathered zones, fractures and water-saturated formations. Thiagarajan et al. (2018) used electrical resistivity tomography in the Chandrabhaga basin of drought-prone Nagpur District and demonstrated that ERT could delineate groundwater-bearing zones within complex basaltic sequences. Their interpretations were subsequently supported by borehole drilling, strengthening the value of integrated geophysical and hydrogeological investigation.

Gaikwad et al. (2022) applied vertical electrical sounding, resistivity modelling and Dar-Zarrouk parameters to identify groundwater potential zones in a complex geological environment of western Maharashtra. Their results demonstrate that resistivity information can help identify weathered zones,

saturated lineaments and palaeochannels that may represent favourable groundwater locations. Recent work by Khaliq and Singh (2026) further demonstrates the value of combining DC resistivity, induced polarization, resistivity anisotropy and borehole information for identifying fractured and saturated zones within Deccan basalt.

These findings suggest that geophysical methods should not be interpreted independently. Resistivity anomalies can have multiple geological explanations. Consequently, integration with lithological logs, well data, groundwater levels and aquifer tests is necessary for reliable aquifer delineation. The recent hydrogeophysical literature specifically emphasizes geophysical-hydrogeological integration for improving groundwater targeting in basaltic hard-rock settings.

2.4 GIS and remote sensing for groundwater potential assessment

Remote sensing and GIS have become important tools for regional groundwater assessment because they allow multiple surface and subsurface indicators to be integrated spatially. Lithology, geomorphology, slope, drainage density, lineament density, rainfall, soil and land-use characteristics are frequently incorporated into groundwater potential models. Das et al. (2017) applied the Multi-Influence Factor method in Hingoli District, Maharashtra, and demonstrated that integrating geological and geomorphological factors within GIS can identify spatial variations in groundwater potential.

Das and Pardeshi (2018) subsequently integrated eight thematic factors, including lithology, geomorphology, drainage, soil, lineaments, slope, rainfall and land use, to delineate groundwater potential zones in the Pravara basin. Their study illustrates how GIS-based multi-criteria approaches can support groundwater planning in the Deccan Volcanic Province.

Datta et al. (2020) specifically evaluated groundwater-prolific zones in unconfined basaltic aquifers of western India using geospatial modelling and the Multi-Influence Factor approach. Their findings reinforce the importance of integrating geomorphological and structural indicators when evaluating groundwater potential in basaltic terrain. Rajesh et al. (2021) also applied the Analytical Hierarchy Process to groundwater potential assessment in the Godavari basin of Maharashtra, further demonstrating the usefulness of weighted spatial decision-making for regional groundwater assessment.

GIS-based approaches, however, have an important limitation. Surface-based indicators cannot fully represent subsurface fracture connectivity, aquifer thickness or hydraulic properties. Recent research in Maharashtra shows that GIS-based multi-criteria models can produce different recharge-suitability patterns from models that explicitly incorporate subsurface hydrogeological information. Therefore, GIS should be treated as one component of an integrated aquifer-delineation framework rather than as a substitute for field hydrogeology and geophysics.

2.5 Aquifer mapping and groundwater-flow modelling

Aquifer mapping provides a more detailed understanding of groundwater systems by combining geological, geophysical, hydrological, hydraulic and water-quality information. The National Aquifer Mapping Programme in India was developed to generate three-dimensional understanding of aquifer geometry, hydraulic characteristics, groundwater quality and resource availability. Such an approach is particularly relevant to basaltic systems because individual lava flows may behave as separate or partially connected hydraulic units.

Pande et al. (2022) used MODFLOW together with GIS and field observations to model groundwater flow in basaltic hard-rock terrain in Maharashtra. Their work demonstrates the usefulness of numerical modelling for understanding groundwater heads, flow directions and interactions between fractured and less-permeable units. Flow modelling can therefore strengthen the transition from groundwater potential mapping to aquifer management by providing information about hydraulic connectivity and groundwater movement.

Groundwater balance is another important component of aquifer assessment. Saha and Agrawal (2006) showed that specific yield estimation can contribute to groundwater budgeting in Deccan basalt watersheds. Similarly, recent reviews of groundwater recharge estimation emphasise that reliable recharge estimates are fundamental for groundwater management and that method selection must reflect local hydrogeological and climatic conditions.

2.6 Managed Aquifer Recharge

Managed Aquifer Recharge involves intentional enhancement of groundwater recharge for subsequent recovery, storage or environmental benefits. Dillon et al. (2019) reviewed six decades of MAR development and demonstrated its increasing application as a groundwater-management strategy. Zhang et al. (2020) similarly identified MAR as an important approach for improving water security in water-stressed and drought-prone regions, while highlighting technical issues such as clogging, infiltration processes and water-quality protection.

The application of MAR requires a strong connection between recharge structure and aquifer characteristics. Shah (2014), examining groundwater management in Gujarat, argued for integrating hydrogeological and socioeconomic considerations when developing recharge strategies. Dillon and Arshad also emphasize that MAR should be considered within integrated water-resource management rather than as an isolated engineering intervention.

Evidence from hard-rock regions of India demonstrates that recharge structures can increase groundwater availability, but their effectiveness depends strongly on local geological conditions. Massuel et al. (2014) examined small percolation tanks in South India and found that recharge was spatially concentrated around the structures, with groundwater abstraction influencing the persistence of recharge benefits. These findings suggest that the placement of recharge structures should consider both infiltration characteristics and groundwater-flow pathways.

2.7 MAR in basaltic terrain

MAR is particularly relevant to Deccan basalt because drought-prone areas frequently experience seasonal surplus runoff followed by prolonged groundwater stress. Bhusari et al. (2016) developed and implemented an artificial recharge system in Wardha District, Maharashtra, specifically within basaltic terrain. The study reported improvements in groundwater levels and well yields following implementation, demonstrating the potential of appropriately designed recharge systems in water-scarce basaltic environments.

The Central Ground Water Board's recharge guidance also identifies percolation tanks, check dams, recharge shafts, recharge wells and related structures as potential interventions, with selection dependent on geological conditions and infiltration characteristics. In basaltic settings, highly fractured and weathered zones may provide favourable conditions for infiltration, while massive basalt and low-

permeability inter-flow materials may restrict vertical movement. Consequently, recharge structures should be matched to the specific aquifer architecture.

Research from Maharashtra has also demonstrated that artificial recharge zones can be delineated using combinations of geomorphological, geological and hydrogeological factors. Shaikh et al. (2019) assessed artificial recharge zones in the Upper Yerala River basin and emphasized the importance of assigning appropriate weights to factors controlling groundwater occurrence and movement. This supports the integration of spatial suitability assessment with aquifer characterization.

2.8 Recharge effectiveness, water quality and monitoring

The effectiveness of MAR cannot be evaluated solely by measuring the quantity of water introduced into an aquifer. Groundwater-level response, hydraulic connectivity, recharge efficiency, water quality and recovery of stored water are also important. Saha et al. (2022), in their review of artificial recharge initiatives in India, identified site selection, source-water availability, structure design, water quality and post-construction impact assessment as major requirements for successful recharge programmes.

Water quality is particularly important because recharge can alter groundwater chemistry and may introduce contaminants into an aquifer. Zheng et al. (2023) emphasized the need for risk-based approaches to MAR water-quality management and continuous monitoring of potential contaminants. Studies of organic matter and pharmaceutical compounds have also shown that natural attenuation can occur during managed recharge, although the effectiveness of removal depends on hydrogeological and geochemical conditions.

Long-term monitoring is therefore an essential component of MAR evaluation. Van Engelenburg et al. (2020) demonstrated the value of long-term groundwater-level and water-quality observations for assessing the hydraulic and hydrochemical effects of MAR. Similarly, the Central Ground Water Board has developed specific guidelines for assessing the impacts of artificial recharge structures, including monitoring methodologies and post-construction evaluation.

2.9 Research gap

The literature demonstrates considerable progress in the separate application of geological mapping, GIS, geophysical surveys, groundwater monitoring, aquifer modelling and recharge structures. However, the literature also indicates a methodological gap in connecting these components into a single aquifer-specific framework for drought-prone Deccan basalt. Existing GIS studies mainly emphasize groundwater-potential mapping, while geophysical studies focus primarily on groundwater targeting. Recharge studies frequently evaluate individual structures after implementation. The recent field-integrated work of Karan et al. (2026) demonstrates that surface-based GIS models can differ substantially from assessments incorporating subsurface hydrogeological characteristics, particularly in basaltic terrains where fracture connectivity and weathered-zone thickness influence recharge behaviour.

A conceptual framework that systematically connects aquifer delineation → hydrogeological characterization → groundwater potential assessment → MAR site selection → structure selection → recharge implementation → groundwater response monitoring can therefore address this gap. Such integration is consistent with recent developments in aquifer mapping and MAR research, which increasingly emphasize multidisciplinary assessment, field validation and adaptive management.

3. Methodology

This study adopts a Systematic Literature Review (SLR) to develop a conceptual framework for aquifer delineation and Managed Aquifer Recharge (MAR) in drought-prone Deccan Trap basaltic terrain. The methodological approach follows the principles of systematic, transparent, reproducible and evidence-based literature synthesis proposed by Tranfield et al. (2003) and subsequently developed in management and interdisciplinary research. The review also draws on the systematic review approach adopted by Saqib (2020), which emphasises explicit search procedures, transparent selection criteria, reproducibility and synthesis of evidence across the reviewed literature. Saqib (2020) used a systematic review to examine a fragmented research domain and developed a conceptual understanding by systematically classifying and synthesising prior studies. The present study adapts these principles to the groundwater and hydrogeological context.

3.1 Research design

The review was designed around four stages: identification, screening, eligibility assessment and thematic synthesis. This structure is consistent with established systematic review procedures, which require researchers to specify how studies are identified, screened and included before synthesising their findings. The review focused on studies addressing Deccan Trap basalt aquifers, groundwater potential assessment, aquifer delineation, geophysical investigation, GIS and remote sensing, groundwater recharge, MAR, recharge structures and groundwater monitoring. The objective was not merely to summarise individual studies but to identify relationships between the different components and use the accumulated evidence to construct an integrated conceptual framework.

3.2 Literature search strategy

A structured literature search was conducted using major scholarly databases, particularly Scopus and Web of Science, supplemented where necessary by Google Scholar and authoritative institutional repositories for government groundwater reports. The principal search terms included combinations of “*Deccan Trap*” AND “*basaltic aquifer*”, “*basalt groundwater*” AND “*aquifer delineation*”, “*groundwater potential*” AND *basalt*, “*managed aquifer recharge*” AND *India*, “*artificial recharge*” AND *Deccan basalt*, “*electrical resistivity*” AND *basalt groundwater*, “*GIS*” AND *groundwater potential*, and “*aquifer mapping*” AND *Maharashtra*. The use of multiple keyword combinations reduces the possibility of overlooking studies because of differences in terminology. Snyder (2019) argues that systematic literature reviews require clearly defined search procedures because fragmented research fields often employ different terminology for closely related concepts.

3.3 Inclusion and exclusion criteria

Studies were included when they met the following criteria: (i) they addressed groundwater, aquifer characterization, recharge or MAR; (ii) they provided empirical, methodological or conceptual evidence relevant to basaltic or hard-rock aquifers; (iii) they were published in peer-reviewed journals, scholarly books or authoritative institutional publications; and (iv) they contributed evidence relevant to aquifer delineation, recharge suitability, recharge implementation or groundwater monitoring. Studies unrelated to groundwater, studies without sufficient methodological information, duplicate publications and sources lacking identifiable bibliographic information were excluded. The use of predefined inclusion and

exclusion criteria enhances transparency and reduces subjective selection of literature, which is a central requirement of rigorous systematic reviewing.

3.4 Screening and selection of studies

The retrieved records were initially screened through their titles and abstracts. Potentially relevant publications were then examined through full-text assessment. Particular attention was given to studies providing field-based evidence from Maharashtra and other parts of the Deccan Volcanic Province, together with relevant international MAR literature. The screening process followed the principle that systematic reviews should provide an auditable pathway from the initial search to the final evidence base. Saqib (2020) similarly emphasised that systematic reviews should be organised around an explicit method that allows the review process to be understood, reproduced and updated.

3.5 Data extraction and thematic analysis

A structured extraction matrix was used to organise information from the selected studies. The extracted information included author and year, geographical setting, geological context, aquifer type, research objective, methodological approach, data sources, delineation technique, recharge technique, major findings and identified limitations. The evidence was subsequently subjected to thematic synthesis. Five principal themes emerged: (1) hydrogeological characteristics of Deccan basalt, (2) aquifer delineation and geophysical investigation, (3) GIS and remote sensing-based groundwater potential assessment, (4) MAR site and structure selection, and (5) groundwater monitoring and evaluation. This approach follows the logic of systematic synthesis in which findings from individual studies are brought together to identify broader patterns and research gaps rather than treating each publication independently. Snyder (2019) identifies synthesis as a central function of literature review methodology because it enables fragmented evidence to be integrated into a coherent research contribution.

3.6 Conceptual framework development

The final stage involved integrating the themes identified from the systematic review into a conceptual framework. The framework connects geological and hydrogeological characterization → geophysical investigation → GIS and remote sensing analysis → aquifer delineation → groundwater potential assessment → MAR site selection → recharge-structure selection → implementation → groundwater-level and water-quality monitoring → adaptive aquifer management. The framework therefore moves beyond conventional groundwater-potential mapping by explicitly connecting aquifer characterization with subsequent recharge intervention and evaluation. This synthesis approach is consistent with Tranfield et al. (2003), who argue that systematic reviews in management research should generate evidence-informed knowledge rather than simply provide descriptive summaries of previous studies.

4. Conceptual Framework

The proposed conceptual framework integrates aquifer characterization, spatial delineation, groundwater potential assessment, Managed Aquifer Recharge (MAR), and adaptive groundwater management for drought-prone Deccan Trap basaltic terrain. The framework is based on the premise that effective groundwater management requires an understanding of the heterogeneous geological and hydrogeological characteristics of basaltic aquifers before recharge interventions are implemented.

4.1 Data acquisition and preparation

The first stage involves collecting geological, hydrogeological, geophysical, topographical, climatic and land-use data. Geological maps, satellite imagery, Digital Elevation Models, rainfall records, drainage networks, well inventories, groundwater levels, lithological logs and groundwater-quality data provide the basic information required for aquifer assessment. Geophysical data, particularly Electrical Resistivity Tomography and Vertical Electrical Sounding, are incorporated to identify weathered, fractured and saturated zones. Integration of multiple datasets is particularly important in Deccan basalt because groundwater occurrence is controlled largely by secondary porosity rather than primary pore spaces (Deolankar, 1980; Kulkarni et al., 2002).

4.2 Hydrogeological characterization

The second stage focuses on identifying the principal hydrogeological characteristics of the basaltic aquifer system. Particular attention is given to weathered zones, vesicular and amygdaloidal horizons, fractures, joints, lineaments, inter-flow contacts and massive basalt units. These characteristics determine groundwater storage, movement and hydraulic connectivity. Specific yield, transmissivity, hydraulic conductivity, groundwater levels and well yields are incorporated where available. Previous investigations demonstrate substantial spatial variability in specific yield and hydraulic properties within Deccan basalt, confirming the need for aquifer-specific characterization (Saha & Agrawal, 2006; Uhl & Joshi, 1986).

4.3 Aquifer delineation and mapping

The third stage involves delineating the spatial and vertical extent of groundwater-bearing formations. GIS and remote sensing are used to prepare thematic layers representing geology, geomorphology, lineament density, drainage density, slope, land use and land cover. Geophysical interpretation is subsequently used to identify the depth and continuity of weathered and fractured zones. The integration of surface and subsurface information reduces the limitations associated with using GIS-based groundwater potential mapping alone. Geophysical investigations have demonstrated their usefulness for identifying groundwater-bearing fractures and fissured zones in Deccan basalt (Bose & Ramakrishna, 1978; Thiagarajan et al., 2018).

4.4 Groundwater potential assessment

The fourth stage evaluates groundwater potential by integrating the identified hydrogeological and spatial factors. A weighted overlay or Analytical Hierarchy Process (AHP) can be used to assign relative importance to geology, geomorphology, lineament density, drainage density, slope, rainfall, land use, soil and geophysical indicators. The resulting groundwater-potential map can classify the study area into very high, high, moderate, low and very low potential zones. Previous GIS-based studies in Maharashtra have demonstrated the applicability of multi-criteria techniques for groundwater-potential assessment in semi-arid and basaltic environments (Das et al., 2017; Das & Pardeshi, 2018; Datta et al., 2020).

4.5 MAR site suitability assessment

The fifth stage translates groundwater-potential information into MAR suitability assessment. Areas with favourable aquifer characteristics are evaluated against additional criteria such as aquifer storage capacity, fracture connectivity, depth to groundwater, infiltration capacity, surface-runoff availability, land

availability, proximity to demand centres and groundwater quality. This distinction is important because an area with high groundwater potential is not automatically an appropriate location for artificial recharge. MAR requires adequate storage space and hydraulic connectivity between the recharge source and target aquifer (Dillon et al., 2019; Zhang et al., 2020).

4.6 Selection of appropriate MAR techniques

The sixth stage involves matching the selected sites with appropriate recharge structures. Depending on local hydrogeological conditions, possible interventions include percolation tanks, check dams, recharge trenches, recharge shafts, recharge wells, subsurface dykes and recharge through suitable abandoned wells. Structure selection is based on aquifer depth, permeability, fracture characteristics, surface runoff, soil conditions and available recharge water. Research from hard-rock areas of India indicates that recharge effectiveness varies considerably according to local geological conditions and the hydraulic relationship between recharge structures and groundwater abstraction (Massuel et al., 2014).

4.7 MAR implementation

The seventh stage involves detailed field investigation and implementation of the selected recharge intervention. This includes site-specific geophysical surveys, infiltration testing, aquifer testing, recharge-structure design and assessment of source-water quality. Institutional and community participation should also be incorporated because groundwater extraction and recharge occur within interconnected social and hydrological systems. The implementation stage should therefore include construction, operation, maintenance and integration with broader watershed-management activities.

4.8 Monitoring and evaluation

The eighth stage evaluates MAR performance through continuous monitoring of groundwater levels, groundwater quality, recharge response, well yields and storage changes. Pre-MAR and post-MAR groundwater conditions are compared to determine whether recharge has improved groundwater availability. Water-quality parameters should also be monitored because recharge can modify groundwater chemistry and potentially introduce contaminants into aquifer systems (Zheng et al., 2023). Monitoring therefore provides empirical evidence for determining whether the selected recharge intervention is achieving its intended outcomes.

4.9 Adaptive aquifer management

The final stage establishes a feedback mechanism between monitoring results and future groundwater-management decisions. Monitoring data can be used to refine aquifer boundaries, update groundwater-potential maps, modify MAR structures and revise recharge strategies. The framework therefore follows an adaptive management cycle rather than treating MAR as a one-time engineering intervention. This approach is consistent with the broader MAR literature, which emphasises monitoring, evaluation and integration of recharge with sustainable groundwater management (Dillon et al., 2019; Saha et al., 2022). The framework establishes a direct relationship between aquifer characteristics and recharge decisions. Its principal contribution is the integration of geological, geophysical, GIS-based and hydrogeological evidence with MAR planning and post-recharge monitoring. This provides a systematic basis for

identifying suitable recharge locations and selecting interventions appropriate to the heterogeneous aquifer conditions of drought-prone Deccan Trap basaltic terrain.

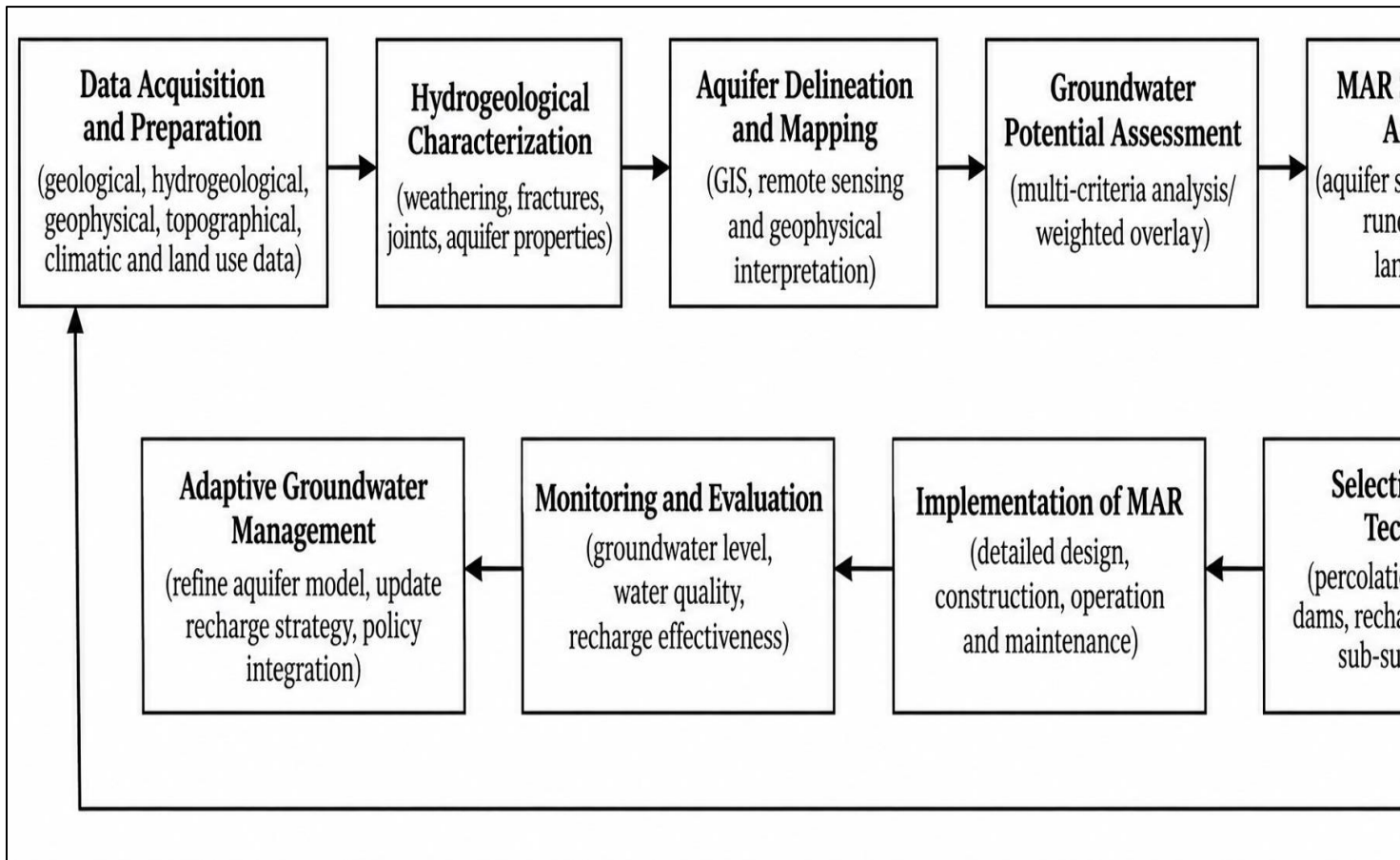


Figure 1: Conceptual Framework

Source: Authors Own Work

5. Discussion

The proposed conceptual framework demonstrates that effective aquifer delineation and Managed Aquifer Recharge (MAR) in drought-prone Deccan Trap terrain require integration of geological, hydrogeological, geophysical and spatial information. Previous research consistently indicates that Deccan basalt aquifers are highly heterogeneous, with groundwater occurrence controlled by weathering, fractures, joints, vesicular horizons and inter-flow contacts. Kulkarni et al. (2002) established that the Deccan basalt groundwater system is hydrogeologically heterogeneous and that sheet joints and vertical joints can act as important groundwater-flow pathways. This finding supports the framework's emphasis on hydrogeological characterization before selecting recharge locations.

The importance of aquifer architecture is further supported by Saha and Agrawal (2006), who found substantial variation in specific yield within different basaltic units. Their study reported higher specific yield in the weathered zone and vesicular basalt, whereas massive basalt exhibited considerably lower values. These findings indicate that recharge planning based only on surface characteristics may overlook important differences in groundwater storage capacity. The proposed framework therefore places aquifer characterization before groundwater-potential assessment and MAR site selection.

The inclusion of geophysical investigation in the proposed framework is also consistent with previous research. Electrical resistivity techniques have been used successfully to identify fractured and weathered zones within basaltic terrain. Bose and Ramakrishna's investigation in Sangli demonstrated the usefulness of resistivity methods for groundwater exploration in the Deccan Trap. Similarly, subsequent hydrogeophysical investigations have demonstrated that resistivity information can help identify subsurface zones potentially associated with groundwater occurrence. These findings support combining geophysical information with geological and groundwater data rather than relying exclusively on surface indicators.

The framework also incorporates GIS and remote sensing because groundwater occurrence varies spatially across basaltic landscapes. Das and Pardeshi (2018) integrated lithology, geomorphology, slope, soil, lineament density, drainage density, land use and rainfall using GIS-based influencing-factor and frequency-ratio approaches to delineate groundwater-potential zones in the Pravara basin of Maharashtra. Their findings support the use of multi-criteria spatial analysis in the proposed framework. However, GIS-based mapping primarily provides spatial indications of groundwater potential and does not independently establish aquifer thickness, fracture connectivity or hydraulic conductivity. Therefore, the proposed framework extends previous GIS approaches by integrating spatial modelling with geophysical and hydrogeological evidence.

The proposed transition from groundwater-potential assessment to MAR suitability assessment represents an important distinction. A zone with high groundwater potential may not necessarily be the most appropriate location for recharge. MAR requires sufficient aquifer storage, suitable infiltration conditions and hydraulic connectivity between the recharge structure and the target aquifer. Massuel et al. (2014), studying small percolation tanks in a hard-rock environment in South India, found that approximately 61% of tank inputs percolated, but the resulting recharge spread only about 200 m from the tank edge. They also found that approximately 80% of the percolated water was subsequently pumped within the first 100 m. These findings demonstrate that recharge effectiveness is strongly influenced by local groundwater-flow and abstraction conditions.

The framework's emphasis on structure-specific MAR selection is therefore supported by previous empirical evidence. Percolation tanks may be effective where surface storage and infiltration conditions are favourable, while recharge shafts or wells may be more appropriate where a shallow low-permeability layer restricts vertical infiltration but deeper fractured aquifers have adequate storage capacity. The selection of recharge technology should consequently be based on aquifer architecture rather than applying a uniform recharge strategy across the entire study area.

Another important implication concerns groundwater monitoring. Previous research indicates that the benefits of artificial recharge cannot be evaluated simply by measuring the volume of water entering a recharge structure. Changes in groundwater levels, groundwater quality, well yields and spatial patterns of groundwater recovery must also be examined. Saha and Agrawal (2006) demonstrated the value of groundwater-level observations for estimating specific yield and understanding seasonal aquifer behaviour in Deccan basalt. The proposed framework therefore incorporates pre-MAR and post-MAR monitoring as an integral component rather than treating monitoring as a separate activity.

The framework also addresses a limitation identified across earlier approaches. Many groundwater-potential studies concentrate on delineating favourable zones, while MAR studies often focus on evaluating particular recharge structures. The proposed framework connects these stages through a sequential decision process. Aquifer characterization informs delineation; delineation informs

groundwater-potential assessment; groundwater potential and aquifer properties inform MAR site selection; site characteristics determine recharge-structure selection; and monitoring results inform adaptive management. This creates a stronger linkage between groundwater assessment and management intervention.

The literature further suggests that groundwater management in basaltic terrain should be considered at an aquifer or watershed scale. Kulkarni et al. (2002) showed that different basaltic units can form distinct groundwater systems with different hydraulic relationships. Similarly, Massuel et al. (2014) demonstrated that the influence of recharge structures can remain spatially concentrated and interact strongly with local groundwater abstraction. Therefore, MAR planning should consider groundwater flow paths, existing wells, abstraction intensity and aquifer connectivity rather than focusing only on the physical location of recharge structures.

The conceptual framework consequently extends previous findings by integrating surface information, subsurface characterization, spatial modelling, recharge intervention and monitoring within one management cycle. The approach is particularly relevant to drought-prone Deccan Trap areas where heterogeneous aquifer properties make generalized groundwater-development strategies less reliable. Previous empirical studies provide strong support for the individual components of the framework, while their integration provides a structured basis for moving from aquifer delineation towards evidence-based MAR planning and adaptive groundwater management.

6. Conclusion

This study proposes an integrated conceptual framework for aquifer delineation and Managed Aquifer Recharge (MAR) in drought-prone Deccan Trap basaltic terrain. The framework recognises the heterogeneous nature of basaltic aquifers, where groundwater occurrence and movement are influenced by weathering, fractures, joints, vesicular horizons and inter-flow contacts. By integrating geological and hydrogeological investigations with geophysical techniques, GIS, remote sensing and groundwater-potential assessment, the framework provides a systematic basis for identifying suitable aquifer zones and MAR locations. It further links site suitability with the selection of appropriate recharge structures and incorporates groundwater-level, water-quality and recharge-effectiveness monitoring. The proposed adaptive approach can support more scientifically informed groundwater management by connecting aquifer characterization with recharge implementation and subsequent evaluation. Its application can contribute to improving groundwater storage, strengthening drought resilience and supporting sustainable water-resource management in Deccan Trap regions. Future empirical validation through field-based aquifer testing, MAR implementation and long-term monitoring would strengthen the applicability of the framework across different basaltic landscapes.

7. Implications

The proposed framework has important theoretical, methodological and practical implications for groundwater management in drought-prone Deccan Trap terrain. Theoretically, it connects aquifer heterogeneity, groundwater potential and MAR within an integrated conceptual model, extending existing approaches that often examine these components separately. Methodologically, it demonstrates the value of combining geological, hydrogeological, geophysical, GIS and remote-sensing information for evidence-based aquifer delineation and recharge planning. Practically, the framework can assist groundwater authorities, watershed managers and local institutions in identifying suitable recharge zones,

selecting site-specific MAR structures and establishing monitoring systems for evaluating recharge performance. The approach can also support more efficient allocation of limited water resources, improved groundwater availability during drought periods and long-term aquifer sustainability. Its application can further provide a basis for developing location-specific groundwater management plans in other hard-rock and basaltic regions with comparable hydrogeological conditions.

8. Limitations and Future Research Directions

8.1 Limitations

The study has several limitations. First, the proposed framework is conceptual and has not yet been validated through field implementation in a specific Deccan Trap watershed. Second, basaltic aquifers exhibit substantial spatial and vertical heterogeneity, which may limit the transferability of a generalized framework across different geological settings. Third, the effectiveness of GIS and remote-sensing-based assessment depends on the availability, resolution and accuracy of geological, climatic, geophysical and groundwater datasets. Fourth, the framework does not provide site-specific estimates of recharge rates, aquifer storage capacity or long-term groundwater response because these parameters require field measurements and aquifer testing. Finally, MAR performance can be influenced by seasonal rainfall variability, groundwater abstraction, source-water quality, clogging and changes in land use, which cannot be fully captured within a conceptual model.

8.2 Future Research Directions

Future research should empirically validate the framework through field-based case studies in selected Deccan Trap watersheds. Integrated Electrical Resistivity Tomography, Vertical Electrical Sounding, borehole logging, pumping tests and groundwater-level monitoring can be used to improve three-dimensional aquifer characterization. Future studies should also employ remote sensing, GIS, machine learning and hydrogeological modelling to improve groundwater-potential and MAR-suitability prediction. Numerical models such as MODFLOW can be used to simulate groundwater-flow patterns and estimate the effects of alternative recharge scenarios. Long-term monitoring should examine groundwater-level recovery, recharge efficiency, water quality and aquifer storage before and after MAR implementation. Comparative studies of check dams, percolation tanks, recharge shafts and recharge wells could further identify which interventions perform under different basaltic aquifer conditions. Future research should also incorporate climate-change scenarios, groundwater abstraction patterns, economic feasibility and community participation to develop adaptive and locally appropriate MAR strategies for long-term groundwater security.

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