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Unravelling Artificial Groundwater Recharge Sites Using AHP and GIS Techniques in Kareepra Panchayath, Ithikkara River Basin, Kerala, India

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Abstract

The study focuses on identifying optimal sites for artificial groundwater recharge in Kareepra Grama Panchayath, located in the northwest part of the Ithikkara River Basin, Kerala, India. Employing a combination of Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS), alongside Participatory Rural Appraisal (PRA) and Participatory Rural Mapping (PRM) methods, the study aims to address groundwater recharge needs. The research integrates various thematic layers-slope, relative relief, drainage density, land use, sand percentage, available space, geology, geomorphology, and lineament density-into a multi-criteria decision analysis. Results indicate that areas categorized as moderately stable and highly stable are most suitable for recharge activities. Validation with water yield data confirmed the accuracy of the site selection. The study also provides site-specific recommendations for different artificial recharge structures, including infiltration pits, percolation ponds, injection wells, and pond-cum-injection wells.

Keywords: Artificial Groundwater Recharge, Analytic Hierarchy Process (AHP), Geographic Information Systems (GIS), Kareepra Panchayath, Participatory Rural Appraisal (PRA), Groundwater Management

Introduction

Groundwater plays a vital role in sustaining ecosystems and supporting socio-economic development, particularly in regions like India, where it is a primary source of freshwater. With an estimated annual consumption of 230 cubic kilometres, India is among the largest consumers of groundwater globally (Fienen *et al.*, 2016). The natural recharge of groundwater resources is significantly influenced by climatic and geological factors, which, when combined with unsustainable extraction practices, have led to issues such as drought, declining river and well water levels, and changes in land cover (Levintal *et al.*, 2023). Despite these challenges, current groundwater management practices often overlook the contributions of local stakeholders, focusing predominantly on expert-driven approaches.

The inclusion of stakeholders in groundwater management is essential for developing comprehensive strategies that address both ecological and social dimensions. Enhanced recharge facilities can mitigate the depletion of groundwater resources, making it imperative to integrate scientific methodologies with local knowledge (Rahaman *et al.,* 2019). Decision support tools, including GIS-based analyses and scenario planning, have proven effective in optimizing water resource management by reducing uncertainty, increasing transparency, and incorporating stakeholder perspectives (Bekessy and Selinske, 2017).

The Kareepra Grama Panchayath within the Ithikkara River Basin in Kerala, India, presents a case where sustainable groundwater management is urgently needed. Monitoring of 111 observation wells over a year revealed that this region experiences significant seasonal fluctuations in the water table, with the deepest levels recorded in Kareepra. This study aims to identify suitable sites for artificial recharge within the panchayath using a hybrid approach that combines participatory mapping and GIS-based Analytic Hierarchy Process (AHP) techniques. By involving local stakeholders in the decision-making process, the research seeks to develop a sustainable, community-driven approach to groundwater management that can be replicated in similar contexts.

Artificial recharge has emerged as a crucial strategy for replenishing depleted groundwater reserves. Identifying suitable sites for recharge is critical to the success of these programs, ensuring that interventions lead to meaningful improvements in groundwater levels (Gururani *et al.,* 2023). This study contributes to the body of knowledge on groundwater management by offering a validated methodology for site selection, grounded in both scientific analysis and community participation.

Study Area

The study area, Kareepra Grama Panchayath is situated in the northwestern part of the Ithikkara River Basin, spanning the Kollam

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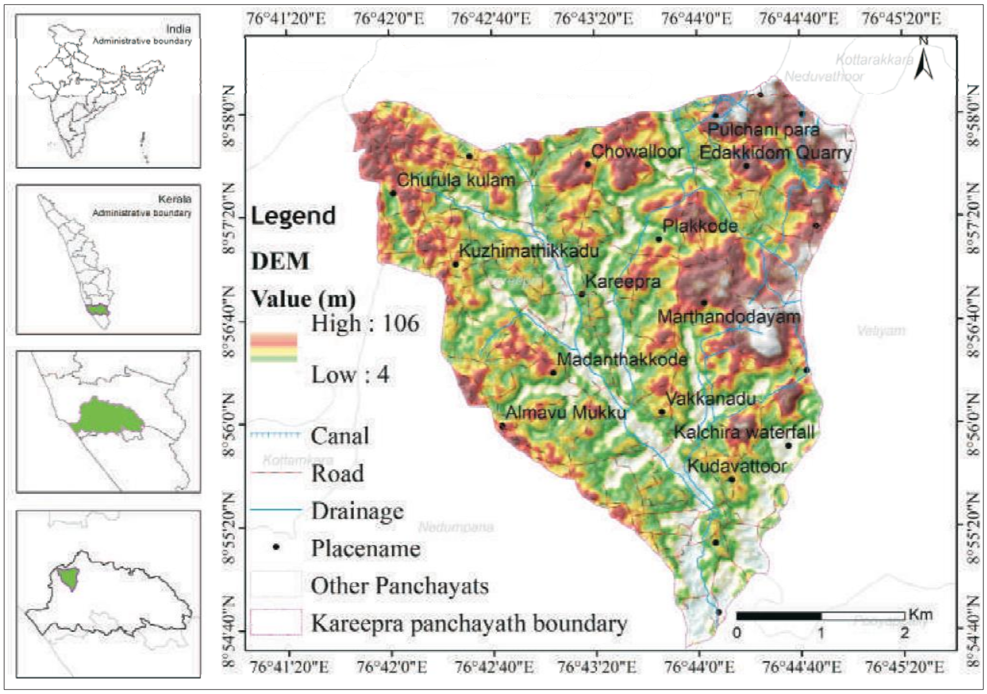

Fig.1. Location map of the Study area (Kareepra Panchayat)

and Thiruvananthapuram districts in Kerala State, India (Fig. 1). The Ithikkara River Basin is stratigraphically diverse, comprising a Precambrian crystalline basement that includes formations such as garnet-biotite gneisses, Khondalite, and Charnockite, along with Neogene formations and Quaternary sediments (Padmalal *et al.*, 2011). Kareepra Grama Panchayath lies between the longitudes 76°43'22.093"E and 76°43'52.185" E, and latitudes 8°54'27.141" N and 8°58'17.731" N. The region is characterized by crystalline geological features and a varied landscape that includes settlements, agricultural crops, diverse vegetation cover, scrubland, and water bodies. The Pallimon River, a tributary of the Ithikkara River (Preeja *et al.*, 2011), flows through the panchayath, contributing to its hydrogeological significance.

The area experiences a tropical climate, influenced by both the southwest and northeast monsoons. In 2023, the region recorded an average monthly rainfall of 189 mm (IMD, 2023). The average monthly temperature in the area ranges from 30°C to 36.5°C. The land use pattern is broadly categorized into settlements, agricultural land, vegetation, scrubland, and water bodies, reflecting the diverse environmental and ecological characteristics of the region.

Materials and Methods

Identifying suitable sites is a critical objective in artificial groundwater recharge programs (Gururani *et al.*, 2023). The Analytic Hierarchy Process (AHP) method and GIS have been widely employed by several authors for delineating suitable sites for artificial groundwater recharge (Allafta, 2020; Saranya and Saravanan, 2020; Souissi, 2018; Kumar *et al.*, 2020).

In this study, depth-to-water level data collected in the field were pre-processed and interpolated using Inverse Distance Weighted (IDW) techniques within the 3D Analyst extension of ArcGIS. Water level measurements taken during the pre- and post-monsoon seasons were utilized to estimate the volume of available space for recharge. Additionally, 12 soil samples, each weighing approximately 1 kg, were collected, and the sand and silt percentages were determined using wet sieving. Assessing terrain stability is essential before constructing artificial recharge structures. This study conducted a slope stability analysis by integrating four key factors: ground slope, relative relief, drainage density, and land use. Various stability zones were delineated by assigning weights and ranks to these thematic layers, informed by both a literature review and stakeholder feedback obtained during PRA (Participatory Rural Appraisal) and PRM (Participatory Resource Mapping) exercises - Action research (Ajayakumar, 2024). The Ranking and weightages (Table 1) was normalized using the AHP technique (Table 2) to produce a meaningful slope stability map, ensuring an accurate representation of terrain stability across the study area (Umar *et al.*, 2014, Chatterjee *et al.*, 2023). The final slope stability map categorized the terrain into highly unstable, moderately unstable, moderately stable, and highly stable zones. The delineation of suitable sites for groundwater recharge was achieved using thematic layers, including geology, geomorphology, lineament density, slope, sand percentage, drainage density, and available space for recharge (Dinesh *et al.*, 2007; Preeja *et al.*, 2011; Arulbalaji *et al.*, 2019; Achu *et al.*, 2020; Appukuttan and Reghunath, 2022, Chatterjee, *et al.*, 2023, Sherin *et al.*, 2023). Slope and relative relief were derived from Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data at 1-arc second resolution. Drainage density was calculated over 1 square kilometre grids, and these values were interpolated using the IDW method in ArcGIS. Relative relief was also processed over 1 square kilometre grids. Land use patterns were classified using Google Earth imagery and verified through field checks.

The weights and ranks assigned to each thematic layer (Table 1, 3) and class were normalized using theAHPmethod (Saaty, 2008). In the AHP approach, scores were based on expertise and insights obtained during the PRA exercises (Table 4). The derived suitable sites were overlaid onto the critical slope map to ensure the stability of these zones. Validation of the derived suitable sites was performed using water yield data. Given the site-specific nature of artificial recharge structures, ideal sites for various structures-such as infiltration pits, percolation ponds, injection wells, and pond-cum-injectionwells-were delineatedby applyingadditional criteria.

Results

Thematic Attributes

Slope (S)

Slope is a critical factor influencing mass movements and groundwater recharge. Steeply sloping areas are prone to aggravated slope failures, particularly when there is accumulation of subsurface water. Conversely, gentler slopes promote increased infiltration and groundwater recharge. Therefore, slope angle is a crucial parameter in identifying groundwater potential zones. Slope is a vital controlling factor for groundwater recharge in complex terrains. Slope characteristics control the velocity of surface flow and as a consequence infiltration rate and groundwater recharge (Fontana and Marchi, 2003; Detty and McGuire, 2010). Rapid runoff on steep slopes reduces the potential for groundwater recharge due to the fact that precipitation drains too fast for effective subsurface infiltration (Yeh *et al.*, 2009). In the study area, slope angles, derived from a Digital Elevation Model (DEM), range from 0 to 27° degrees (Fig.2).

Relative Relief (RR)

Relative relief, which represents the height difference in a unit area, was calculated using DEM data. Thus, in this study, relative relief from the ASTER DEM was derived and processed to create the spatial variation at a grid resolution of 1 × 1 km (Appukuttan and Reghunath, 2022; Ajayakumar, 2024). In the study area, relative relief values range from 11 to 78 meters and are categorized into five classes (Fig.3).

Drainage Density (DD)

Drainage density is the ratio of the total length of streams to the contributing area. It typically shows an inverse relationship with rainfall infiltration: higher drainage density often indicates well-developed channels and increased runoff, while lower density suggests less connected channels and enhanced infiltration. Drainage density connects surface water discharge and underground water movement. The movement of groundwater relies on the characteristics of underneath rocks and soil that affect how water passes through them. A drainage density analysis can reveal groundwater recharge details because it shows the trend of surface water movement across the landscape (Chowdhury *et al.*, 2010). Through ASTER DEM and remote sensing data defined the system of surface water drainage. The drainage density in the study area ranges from 0.053 to 3.3 km/km² and is classified into four categories (Fig.4). The drainage density was processed from SOI toposheets of 1:50,000 scale.

Land Use (LU)

Land use and land cover patterns affect soil moisture,

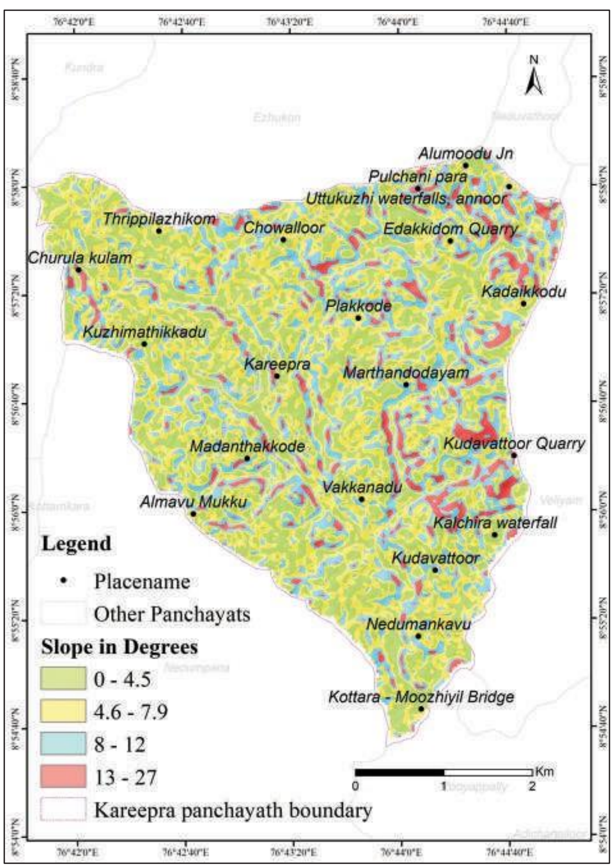

Fig.2. Slope map of the study area (Kareepra Panchayat)

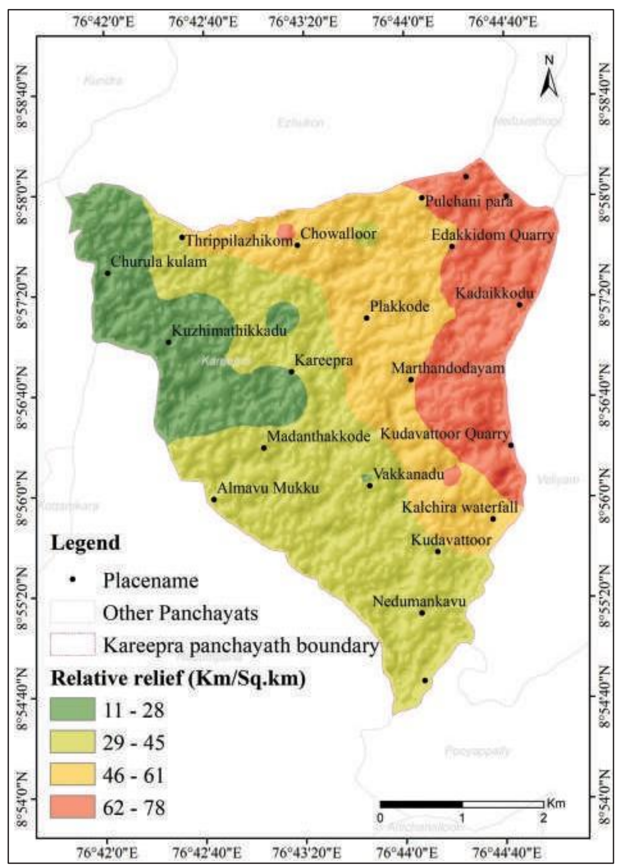

Fig.3. Relative relief map of the study area (Kareepra Panchayat)

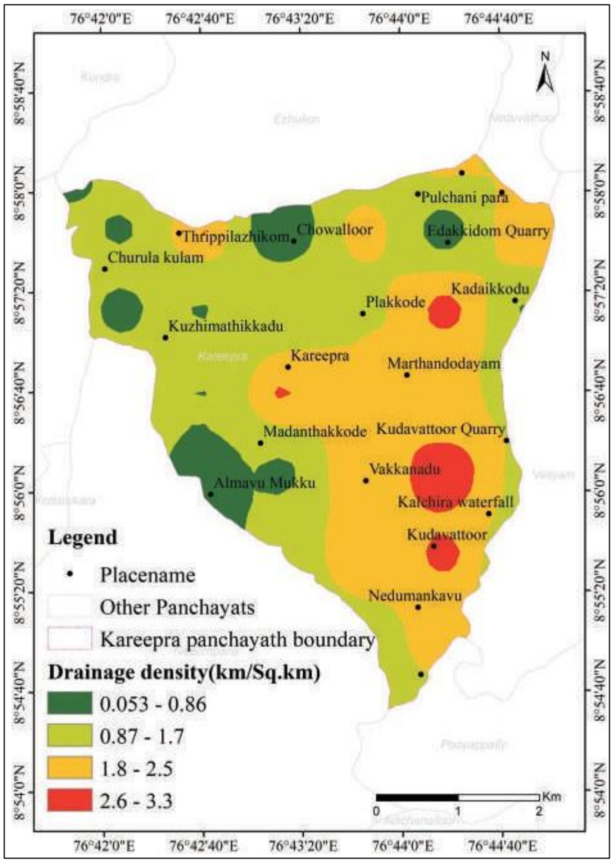

Fig.4. Drainage density map of the study area (Kareepra Panchayat)

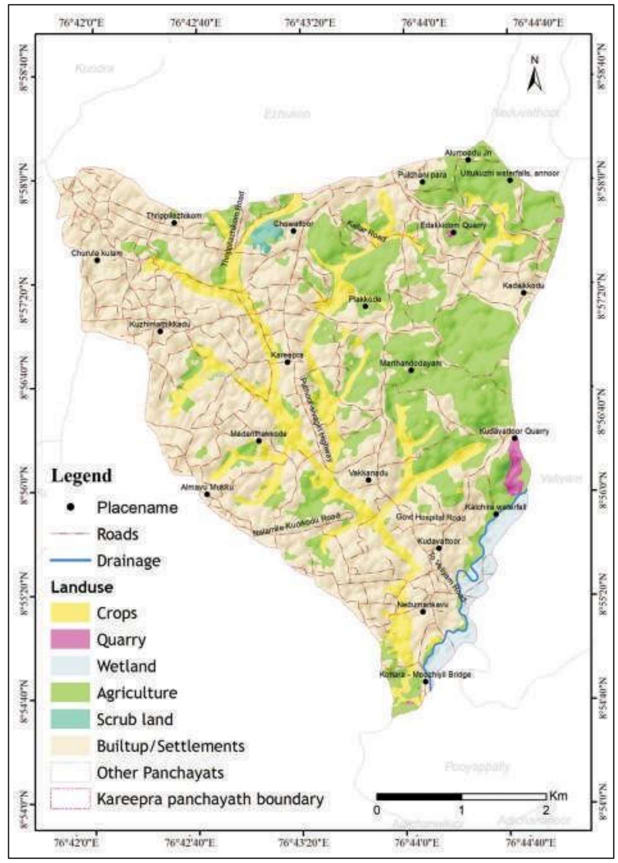

Fig.5. Land use map of the study area (Kareepra Panchayat)

infiltration, and runoff. LULC has a large impact on the hydrological response of a landscape by affecting groundwater recharge rates. LULC changes alter the infiltration, runoff, and evapotranspiration processes and thereby change the recharge dynamics (Collin and Melloul, 2001; Lerner and Harris, 2009; Martin *et al.*, 2017). The study area encompasses built-up areas, agricultural lands, crop lands, wetlands, and water bodies, each influencing these processes (Fig.5). Land use was processed by using Google Earth imagery and verified through field checks.

Sand Percentage (SP)

Groundwater recharge is significantly affected by sand percentage (Das, 2017; Raicy and Elango, 2020). Soils with a higher sand content exhibit greater permeability, facilitating infiltration, while increased clay and silt content restricts water movement, thereby reducing infiltration capacity. The sand percentage, ranging from 42% to 85%, significantly impacts soil permeability and water infiltration rates. Higher sand content generally results in better drainageand increased infiltration (Fig.6a).

Available Space (AS)

The ability of the unsaturated space between groundwater table and land surface to hold water decides if an area is suitable for recharge but studies show this property varies (Central Groundwater Board, 2000; Yeh *et al.*, 2009; Achu *et al.*, 2020). The upper 3 meters of unsaturated soil are always left out from recharging plans because they could cause problems like

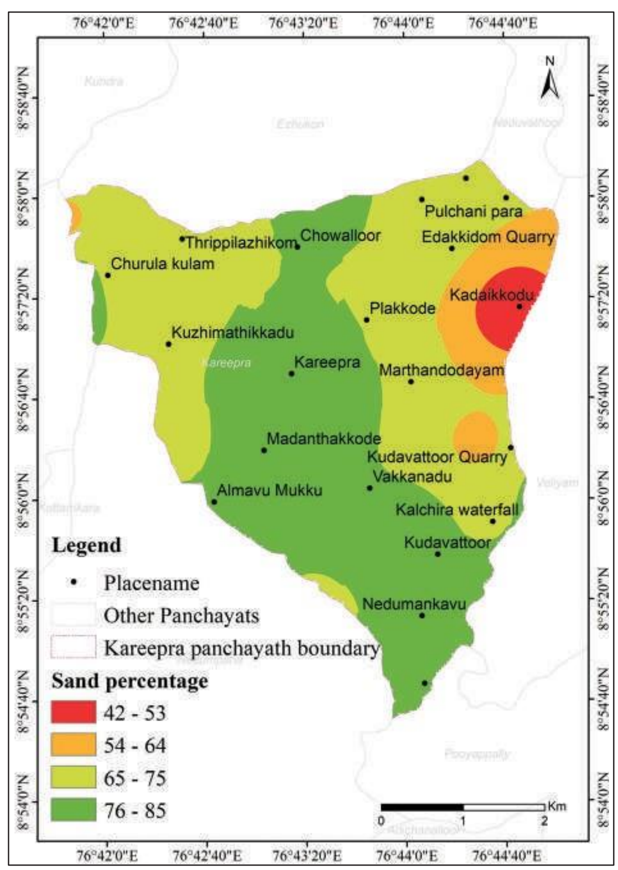

Fig.6a. Sand percentage map of the study area (Kareepra Panchayat)

waterlogged land and salt build-up in the soil. Central Groundwater Board (2000) defined how to determine vadose zone thickness based on groundwater levels - up to 3 meters below ground surface. The space available within the unsaturated zone, which represents the potential for groundwater recharge. Which was calculated by subtracting 3 meters from the mean yearly depth to the water table collected from field survey. This space, equivalent to the unsaturated zone, is crucial for storing recharged water and avoiding swampy conditions. In the study area, available space for recharge, which ranges from 3.5 to 13 meters (Fig.6b).

Geology (GE)

Geological features determine how groundwater moves between the subsurface and surface water zones. The natural way, groundwater moves depends on which rocks hold and release water around us (Biswas *et al.*, 2012). The Ithikkara River Basin lies inside the Kerala Khondalite Belt which ranks as the foremost granite facies supracrustal formation across South India (Ajayakumar and Reghunath, 2025; Nair *et al.*, 2017). The basin contains three identifiable rock zones which run from east to west: Ancient Crystalline Area, a Thin Paleogene Sandstone Area, and Young Deposits in the Western Part (Thomas and Prasannakumar, 2015; Ajayakumar and Reghunath, 2014). The geological process of lateralization runs through all the formations across the basin except within the eastern area. Lateritic area serves as phreatic aquifer and recharged mainly during monsoon period (Aju *et al.*, 2019). In most of the basin area laterite stores groundwater supplies while other subsurface exist in the eastern part. Rock layer and geological formations shape groundwater movement throughout the region (Preeja *et al.*, 2011).

The geology of the study area includes Biotite gneiss, Garnet biotite sillimanite gneiss, Pyroxene granulite, and Sandstone. Each rock type has different water storage properties, with Sandstone and Biotite gneiss offering higher porosity and permeability (Fig. 6c). The Geology data was obtained from the Bhukosh website of GSI.

Geomorphology (GM)

Geomorphology is a vital attribute for the groundwater potential zonation as it gives evidences about the distribution of various landforms and its preference for groundwater presence, movement, *etc.* (Thapa *et al.*, 2017; Rajaveni *et al.*, 2017). The groundwater recharge potential might vary with geomorphological units will be different for their infiltration capacity (Krishnamurthy Srinivas, 1995). Groundwater potential and availability, depends the hydrogeomorphology of the area. Geomorphologic features promote the possibility about groundwater presence, flow and development (Machiwal *et al.*, 2011) The study area features various geomorphological forms, including Lateritic Plateaus, Residual Mounds, and Valley Fills. Valley fills, in particular, are significant for groundwater recharge as they act as natural storage zones (Fig. 7). The geomorphology layer was obtained from IUCGIST, University of Kerala.

Lineament Density (LD)

Lineament density refers to the concentration of linear

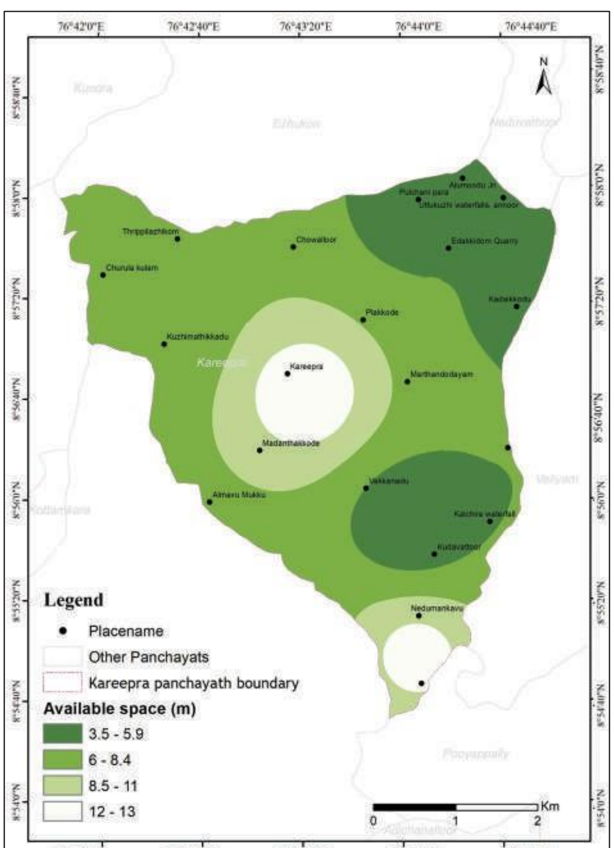

Fig.6b. Available space map of the study area (Kareepra Panchayat)

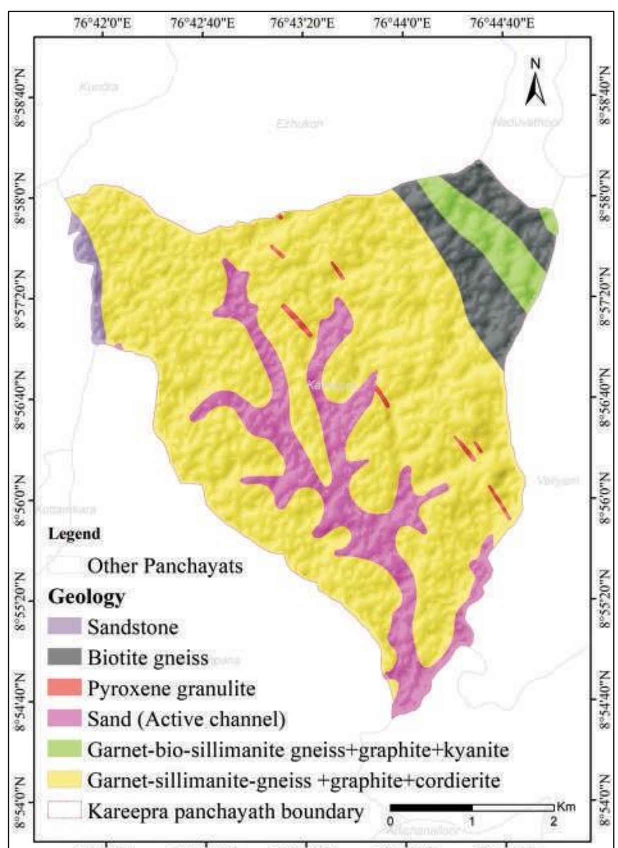

Fig.6c. Geology map of the study area (Kareepra Panchayat)

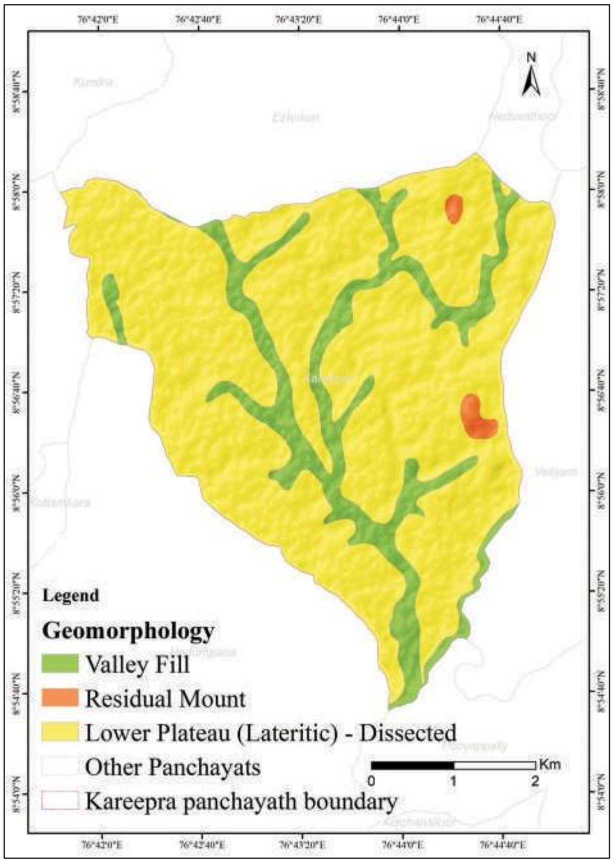

Fig.7. Geomorphology map of the study area (Kareepra Panchayat)

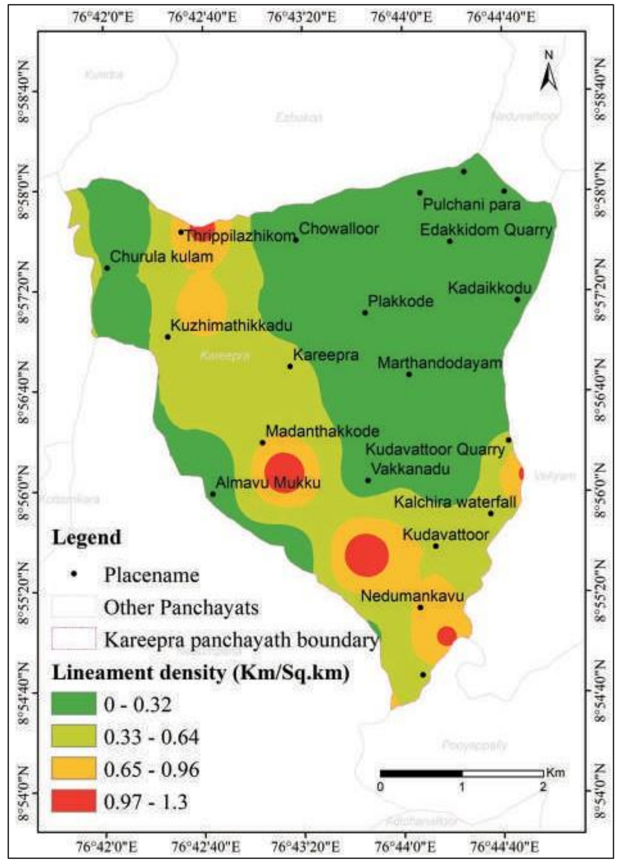

Fig.8. Lineament density map of the study area (Kareepra Panchayat)

geological features such as faults and fractures that play a crucial role in groundwater potential (Sedhuraman *et al.*, 2014). Higher lineament density can facilitate groundwater recharge through increased subsurface fractures. Geologically significant linear and curvilinear landforms such as faults and fractures are structurally and tectonically controlled. In hard rock terrains, lineaments represent zones of permeability, suggestively affecting groundwater recharge. Previous Studies suggest positive correlation between lineaments and groundwater occurrence in crystalline terrains (Assatse *et al.*, 2016; Varade *et al.*, 2018). Underground water flows toward lineaments in solid rock aquifers that help these aquifers accept water. Structural breaks in rocks like fractures help groundwater recharge. Previous studies have shown that when there is higher lineament density, one expects higher well yields (Hung *et al.*, 2005, Assatse *et al.*, 2016). ArcGIS software was used to create the density pattern representation. The Lineament density was processed from SRTM DEM using gridded method (Appukuttan and Reghunath, 2022). The lineament density in the study area ranges from 0 to 1.6 km/km² and is categorized into five classes (Fig.8).

Analytical Hierarchy Process (AHP)
Based on Multi-Criteria Analysis

AHP is a widely used decision-making tool for spatial data management and multi-criteria decision analysis (Tiwari *et al.*, 2022,; Ajayakumar and Reghunath, 2025). AHP employs a pairwise comparison matrix, where weights are assigned to each parameter based on their relative significance. The consistency index (CI) and consistency ratio (CR) were calculated using the following equations, where "λ" is the principal eigenvalue and "n" is the number of parameters:

$$C1 = \frac{\lambda max - n}{n - 1} \quad (1)$$

$$CR = \frac{C21}{R1} \quad (2)$$

The formulation of Slope Stability (Equation 3) and Artificial Recharge (Equation 4) used the following equations:

$$\text{Slope Stability} = LU_r LU_w + RR_r RR_w + DD_r DD_w + S_r S_w \quad (3)$$

$$\text{Artificial Recharge} = GE_r GE_w + GM_r GM_w + LD_r LD_w + SL_r SL_w + SP_r SP_w + DD_r DD_w + AS_r AS_w \quad (4)$$

Where 'r' and 'w' represent the rank and weight of each layer. The CR values were 0.26 (Table 2) for slope stability and 0.3 (Table 4) for artificial recharge site analysis indicating consistency within acceptable limits.

Slope Stability Analysis

The slope stability map was prepared by using AHP technique. This method ensures that each class incorporates an equal number of features, providing an accurate representation of terrain stability (Umar *et al.*, 2014). Numerous researchers have employed the AHP method to enhance the weighting and assessment of individual thematic layers within the methodology, as demonstrated in several studies (Arul balaji *et al.*, 2019; Ghosh, 2021; Ourarhi *et*

Table 1: Weights and ranks assigned for the parameters used for Slope stability

Sl. No.		Parameter	Class	Rank	Weightage
1	Slope Stability	Slope (in degree)	0 - 4.5	4	40
			4.6 - 7.9	3	
			8 - 12	2	
			13 - 27	1	
2		Relative Relief (m/km^2)	11 - 28	4	25
			29-45	3	
			46-61	2	
			62-78	1	
3		Drainage Density (km/km^2)	0.053 - 0.86	1	20
			0.87 - 1.7	2	
			1.8 - 2.5	3	
			2.6 - 3.3	4	
4		Land use	Agriculture	3	15
			Built - Up / Settlements	1	
			Crops	3	
			Scrub Land	2	
			Quarry/Waste Land	1	
			Wet Lands	4	

Table 2: Normalised pairwise comparison matrix for Slope stability

Parameters	SL	LULC	DD	RR
SL	1	3	6	9
LULC	0.33	1	4	6
DD	0.17	0.25	1	2
RR	0.11	0.17	0.5	1

Consistency Ratio CR = 0.26%

Table 3: Weights and ranks assigned for the parameters used for Artificial Recharge

Sl. No.		Parameter	Class	Rank	Weight-age
1	Suitable Sites for Artificial Recharge	Drainage density (km/km^2)	0 - 1.38	4	8
			1.38 - 2.77	3	
			2.77 - 4.16	2	
			4.16 - 5.55	1	
2		Slope (Degrees)	0 - 6	4	9
			6 - 11	3	
			11 - 16	2	
			16 - 22	1	
3		Geomor-phology	Lower plateau (lateritic)-dissected	3	16
			Residual mount	1	
			Valley fill	4	
4		Geology	Biotite gneiss	2	22
			Garnet bio sillimanite gneiss	1	
			Garnet sillimanite gneiss	1	
			Pyroxene granulite	1	
			Sand	4	
			Sandstone	3	
5		Lineament density	0-0.32	1	20
			0.33-0.64	2	
			0.65-0.96	3	
			0.97-1.3	4	
6		Sand Percentage	43-53	1	15
			54-64	2	
			65-75	3	
			76-85	4	
7		Available Space(m)	3.5-5.9	1	10
			6-8.4	2	
			8.5-11	3	
			12-13	4	

Table 4: Normalised pairwise comparison matrix for Suitable sites for Artificial Recharge

	DD	SL	GE	GM	LD	SP	AS
DD	1	0.5	0.12	0.17	0.2	0.25	1
SL	2	1	0.33	0.5	1	2	3
GE	8	3	1	2	2	4	5
GM	6	2	0.5	1	1	2	3
LD	5	1	0.5	1	1	3	2
SP	4	0.5	0.25	0.5	0.33	1	2
AS	1	0.33	0.2	0.33	0.5	0.5	1

Consistency Ratio CR = 0.3%

al., 2023). AHP based structured approach facilitates a more straightforward and systematic assessment of decision factors. (Devanantham, 2020). The Slope stability map was categorized into highly unstable, moderately unstable, moderately stable, and highly stable zones. Moderately stable and highly stable areas were recommendedfor artificial recharge (Fig.9).

Site Specific Methods for Artificial Recharging

Artificial recharge sites were determined by evaluating seven parameters: Drainage Density, Slope, Geology, Geomorphology, Lineament Density, Sand Percentage, and available space (Dinesh *et al.*, 2007; Preeja *et al.*, 2011; Arulbalaji *et al.*, 2019; Achu *et al.*, 2020, Appukuttan and Reghunath, 2022). The suggested sites for artificial recharging were overlaid over the slope stability zones, separating unstable areas and extracting stable areas for further analysis. Various methods for artificial groundwater recharging are

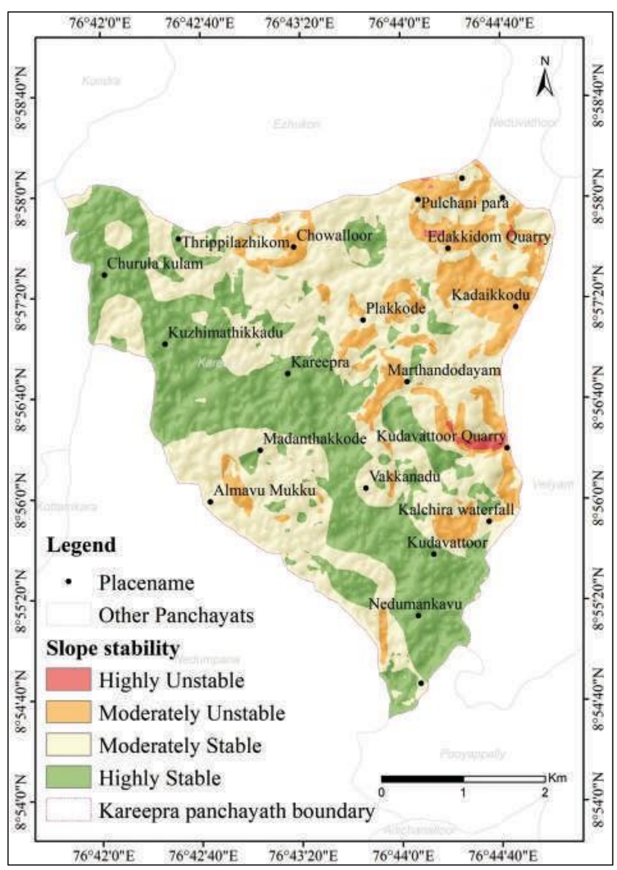

Fig.9. Slope stability map of the study area (Kareepra Panchayat)

site specific. Hence, the areas falling under the high and very high suitability classes cannot be used for all types of artificial recharging methods. Hence, an attempt is made here to find out suitable sites (Fig.10) and for different types of recharging structures in the high priority zones. The artificial recharging interventions considered here are rain water infiltration pits, percolation pond/trench, injection well and percolation pond-cum-injection well. The selection of an appropriate scientific strategy is crucial for optimizing the performance of artificial recharge structures, as their effectiveness is highly site-specific (Central Groundwater Board, 2007; Chowdhury *et al.*, 2010). Comprehensive scientific investigations are necessary to evaluate the suitability of an area for implementing artificial recharge structures (Russo *et al.*, 2014; Raicy and Elango, 2017; Abijith *et al.*, 2020; Central Groundwater Board, 2007; Souissi *et al.*, 2018).

Suitable Areas for Rain Water Infiltration Pits

The areas characterized with higher soil infiltration values (higher than the mean soil infiltration value of the entire study area) in the priority areas are suitable for digging rain water infiltration pits. GIS has been widely applied in delineating suitable locations for artificial recharge structures across various regions (Balachandar *et al.*, 2010; Bahram *et al.*, 2012; Ahmadi *et al.*, 2017). Rainwater infiltration pits were identified as the most effective recharge structures in areas with a higher sand fraction compared to the mean sand fraction (Central Groundwater Board, 2007). This condition is applied in the priority zones to find out the prospective zones for digging rain water infiltration pits (Fig. 11).

Suitable Areas for Percolation Pond / Trench

Percolation ponds were deemed suitable in regions characterized by low drainage density, slopes between 0–5%, and ample space for recharge, as these structures facilitate aquifer replenishment by collecting surface runoff from surrounding areas (Pedrero *et al.*, 2011; Arya *et al.*, 2020) also emphasized the importance of available recharge space as a key criterion for selecting percolation pond sites. The derived suitable zones for percolation pond/trench by applying the above-mentioned conditions are shown in the Fig.12.

Suitable Areas for Injection Wells

The underground lineaments are the conduits for groundwater flow and they also act as storage houses for groundwater. Hence the priority areas were overlapped over the lineament density map to delineate the suitable areas for construction of injection wells (Fig.13). Injection wells, which directly introduce water into aquifers, were found to be most suitable for shallow formations where the overlying aquifer exhibits low permeability (Gale *et al.*, 2002). These structures are particularly effective in regions with high lineament density (Achu *et al.*, 2020). Additionally, a combination of percolation ponds and injection wells can be implemented in areas suitable for both structures.

Suitable Areas for Pond-cum-Injection well

The conditions followed in delineating suitable sites for

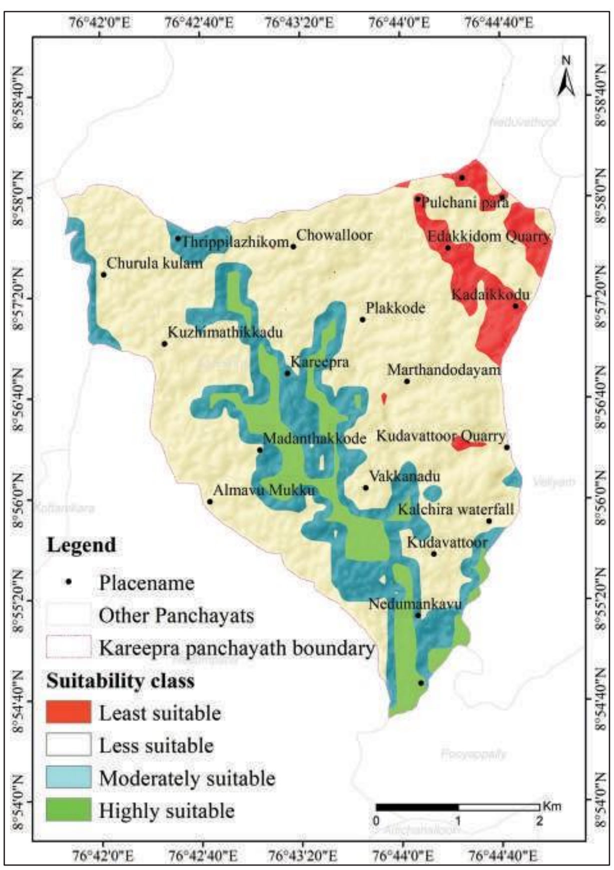

Fig.10. Suitable sites for artificial recharge in study area based on site-specific hydrogeological criteria

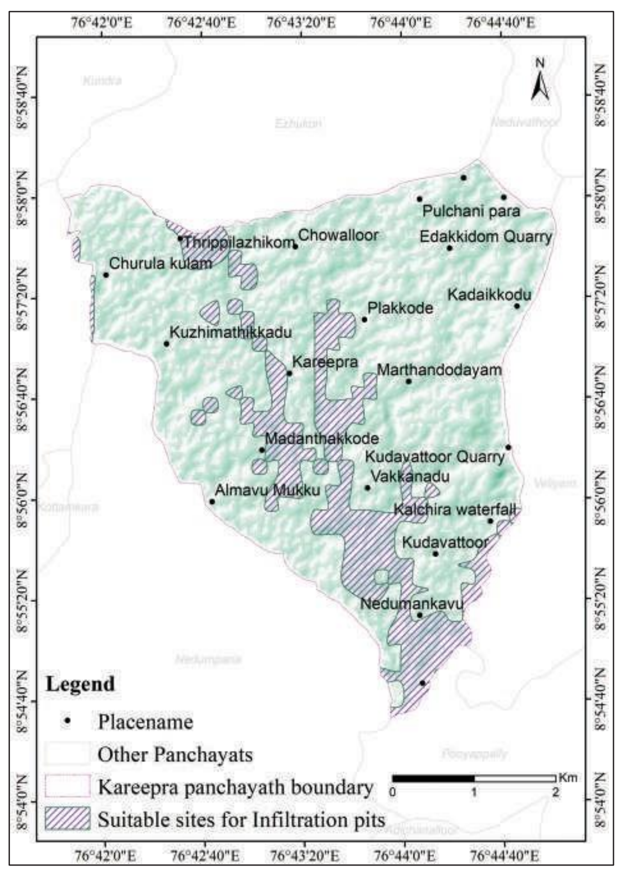

Fig.11. Suitable sites for infiltration pits in study area based on soil infiltration capacity in priority zones

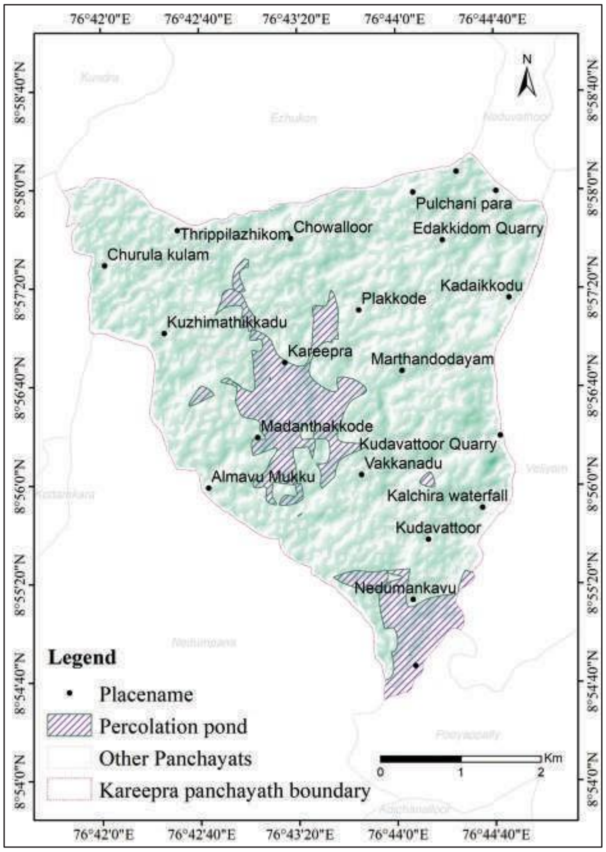

Fig.12. Suitable sites for percolation ponds in study area identified based on drainage density and available space for recharge

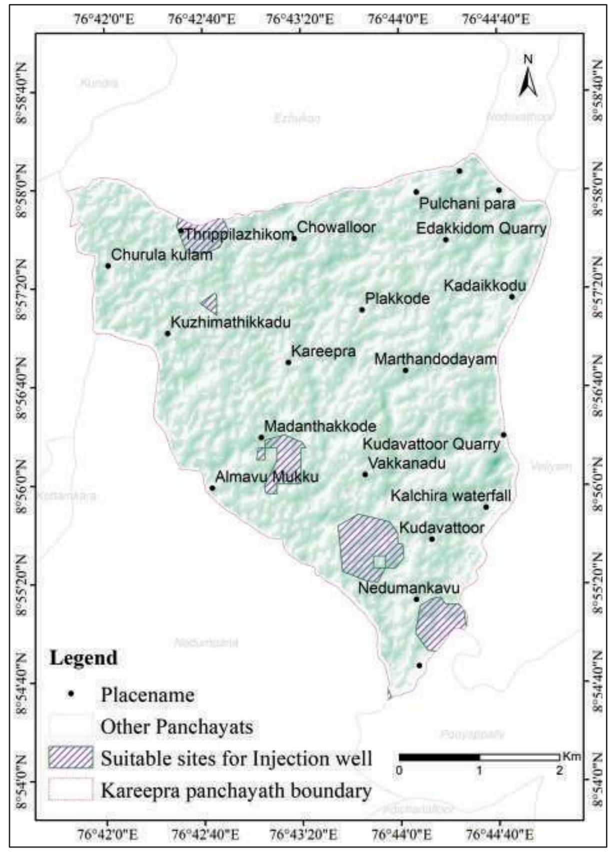

Fig.14. Suitable sites for pond-cum-injection well identified in study area based on drainage density, available space, and lineament density

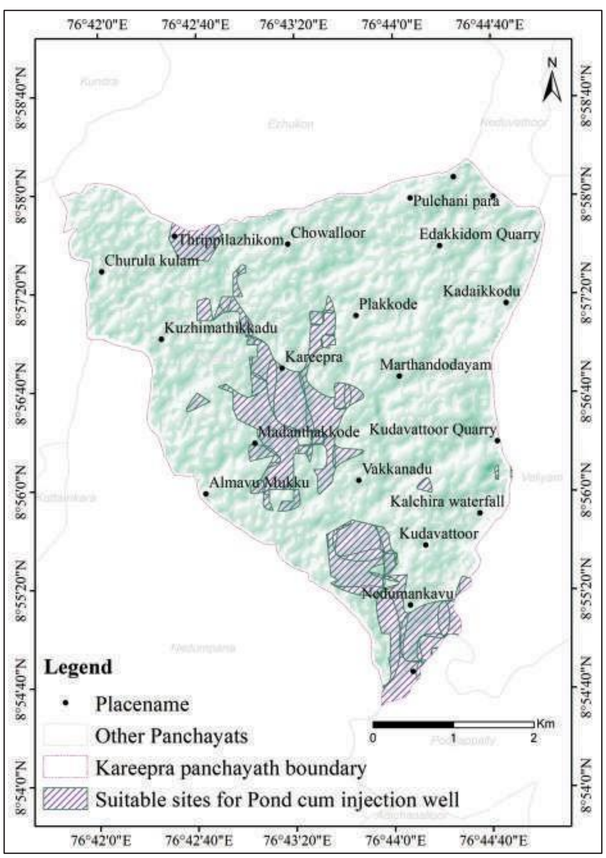

Fig.13. Suitable sites for injection wells identified in study area based on lineament density

ponds and injections wells were applied together over the priority zones. The areas satisfying the set conditions, such as, higher drainage density, higher available thickness for recharging and higher lineament density (Achu *et al.*, 2020). were selected as suitable sites for pond-cum-injection well (Fig.14).

Validation

In this study, the site selection process for artificial recharge structures in Kareepra panchayath was conducted using an integrated geospatial approach in a GIS platform. The suitability of identified recharge sites was validated (Fig.15) against water yield data (Table 5), achieving an AUC of 0.778, indicating acceptable model accuracy (Bui *et al.*, 2016; Achu *et al.*, 2020).

Discussion

The analysis establishes a specific strategy for artificial underground water recharge site identification across the kareepra panchayath of Ithikkara river basin through geological and hydrological and geomorphological parameter assessment. Artificial recharge has ideal conditions in moderately stable and highly stable geographic zones according to the slope stability analysis results. The classification system differentiates between regions with stability problems and regions that offer protective conditions for successful recharge interventions (Achu *et al.*, 2020). Suitable recharge zones located in stable ground help protect the long-term operational success of groundwater restoration projects.

The research work has produced a significant result by

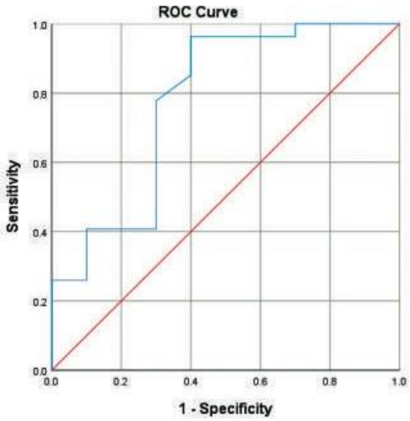

Fig.15. ROC curve for the validation of suitability of identified recharge sites, demonstrating an AUC value of 0.778 indicating acceptable model accuracy

allowing individual artificial recharge structure choices dependent on site-specific hydrogeological conditions. For effective rainwater penetration through the soil infiltration pits prove most appropriate when located in regions with high infiltration capabilities. The Percolation ponds and trenches provide suitable artificial recharge structures for regions with high drainage density and enough space for water retention that supports sustainable groundwater levels throughout both monsoon and post-monsoon timeframes (Raicy and Elango, 2017). The suitable location for injection wells exists in regions where underground fractures help transport water because of high lineament density. Pond-cum-injection wells create artificial recharge possibilities by combining areas with high drainage density with high lineament density and sufficient open space (Central Groundwater Board, 2007; Chowdhury *et al.*, 2010). The custom-made methodology makes sure artificial recharge operations match local hydrogeological conditions while achieving optimal results.

Water yield data enables the validation procedure which confirms the soundness of the selection method for proper sites. The model demonstrated an acceptable accuracy level for suitable recharge zone identification through its AUC value of 0.778 (Bui *et al.*, 2016, Achu *et al*., 2020). Multiple hydrological parameters demonstrate proven effectiveness when used for selecting recharge sites based on this validation test. The promising results need complementary field verifications together with extended monitoring to improve both the model accuracy and recharge site outline precision.

These results create substantial effects on how to manage sustainable groundwater resources within the part of Ithikkara river basin. The implementation of recharge structures in priority zones will improve water availability in groundwater which will help reduce water scarcity. The research establishes the necessity of implementing flexible water management approaches because of changing environmental conditions and land utilization patterns. This method provides tools for water resource managers and policy-makers to make wise decisions regarding methods of groundwater recharge. Future investigations must analyse the variety of long-term effects that recharge structures create while studying new groundwater restoration methods for different climate settings.

Table 5: Validation of the suitability of identified recharge sites

Sl. No.	X	Y	Discharge (lps)	Recharge Suitability	Validation
1	76.7325	8.91107	0.5169	Moderately Suitable	Partially agree
2	76.7344	8.91148	0.8964	Less Suitable	Agree
3	76.7312	8.91817	1.0283	Less Suitable	Agree
4	76.7364	8.91787	1.0571	Less Suitable	Agree
5	76.7147	8.93039	1.0733	Less Suitable	Agree
6	76.722	8.92775	1.0973	Least suitable	Partially agree
7	76.7288	8.92637	1.1508	Less Suitable	Agree
8	76.7378	8.92638	1.2573	Moderately Suitable	Agree
9	76.7433	8.92943	1.3335	Less Suitable	Partially agree
10	76.7129	8.93556	1.4127	Less Suitable	Partially agree
11	76.7197	8.93541	1.4165	Highly Suitable	Partially agree
12	76.7288	8.93541	1.4586	Highly Suitable	Partially agree
13	76.7379	8.93541	1.4954	Less Suitable	Partially agree
14	76.7443	8.93517	1.4958	Less Suitable	Partially agree
15	76.7058	8.94259	1.5471	Highly Suitable	Partially agree
16	76.7106	8.94451	1.5491	Moderately Suitable	Agree
17	76.7197	8.94451	1.5494	Least suitable	Disagree
18	76.7288	8.94451	1.6015	Least suitable	Disagree
19	76.7379	8.94451	1.6200	Less Suitable	Partially agree
20	76.7436	8.94427	1.6234	Less Suitable	Partially agree
21	76.7025	8.95397	1.6721	Less Suitable	Partially agree
22	76.7106	8.95361	1.7160	Less Suitable	Partially agree
23	76.7197	8.95361	1.7399	Moderately Suitable	Agree
24	76.7288	8.95361	1.7408	Moderately Suitable	Partially agree
25	76.7379	8.95361	1.7480	Moderately Suitable	Partially agree
26	76.7449	8.95437	1.7697	Moderately Suitable	Partially agree
27	76.6966	8.96487	1.7711	Moderately Suitable	Partially agree
28	76.7015	8.96266	1.7834	Less Suitable	Disagree
29	76.7106	8.96044	1.7991	Highly Suitable	Agree
30	76.7199	8.96146	1.8195	Less Suitable	Disagree
31	76.7289	8.96248	1.8430	Moderately Suitable	Partially agree
32	76.7379	8.96271	1.8688	Least suitable	Disagree
33	76.746	8.96232	1.8719	Less Suitable	Disagree
34	76.7003	8.96761	1.8818	Moderately Suitable	Partially agree
35	76.7327	8.96756	1.9571	Least suitable	Disagree
36	76.7388	8.96837	1.9865	Least suitable	Disagree
37	76.7432	8.96822	2.3160	Less Suitable	Disagree

Conclusions

This study identifies suitable sites for artificial groundwater recharge in the Kareepra Panchayath of Ithikkara River Basin using GIS, AHP techniques, and participatory methods. Thematic layers, including geology, geomorphology, lineament density, slope, sand percentage, drainage density, and available space were integral in delineating suitable sites for groundwater recharge. Highly unstable and moderately unstable areas, particularly in the eastern part, which has significant agricultural activities, were excluded from consideration while delineating suitable zones for artificial recharge. The suitability analysis classified 3.6% of the area as highly suitable, 15.4% as moderately suitable, 51.4% as less suitable, and 29.4% as least suitable. Recommended recharge structures include rainwater infiltration pits (86.5 sq. km), percolation ponds (18.1 sq. km), injection wells (2.9 sq. km), and combined pond-cum-injection wells (27 sq. km). Validation with water yield data confirmed the model's reliability (AUC = 0.778), demonstrating the effectiveness of a multi-criteria decision-making approach. The study provides a systematic framework for groundwater management, aiding policymakers in sustainable water resource planning. Future research should integrate additional factors like land use changes and climate variability while incorporating field-based validation for improved precision.

Authors' Contributions

AA: Investigation, Formal Analysis, Methodology, Writing - original draft. Visualization, Editing, Software. ***MSN:***

Conceptualization, Supervision**.** **RR:** Supervision, Writing-Reviewing and Editing. **DDSG:** Reviewing and editing.

Conflict of Interest

The authors declare no conflict of interest

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