Remote Sensing and GIS for Sustainable Aquifer Recharge Management in the Cuddalore Coastal Zone, Tamil Nadu, India

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Abstract
This study identifies optimal sites for managed aquifer recharge (MAR) to mitigate groundwater depletion and seawater intrusion in coastal aquifers of Cuddalore district, Tamil Nadu. Using geospatial techniques, it integrates lithology, soil, geology, geomorphology, LULC and aquifer characteristics with GIS-based multi-criteria decision analysis. The Analytical Hierarchy Process (AHP) ranks influencing factors to delineate groundwater potential zones. Approximately 468 km² is classified as having high recharge potential, recommending recharge shafts, percolation ponds and injection wells to enhance groundwater levels by 3-5 meters annually and mitigate seawater intrusion. Validation with 20 years of hydrological data supports the suitability of these zones, emphasizing their role in sustainable water management.

The study addresses increasing groundwater stress due to rapid urbanization and climate variability, promoting the use of non-traditional water sources and strategically planned MAR structures. The findings highlight MAR's potential to replenish aquifers, to improve water quality and to meet the water demands of coastal regions.

Keywords: Managed aquifer recharge, Groundwater depletion, GIS, Analytical Hierarchy Process, Cuddalore aquifers, lithological mapping, Recharge structures.

Introduction

Groundwater is an essential resource for humanity, yet it has become increasingly stressed in many regions of the subcontinent due to rapid and uneven development. Effective management of groundwater resources is crucial, especially in the face of climate change which has led to over 70% of annual rainfall occurring within one to two days. This results in quick runoff to low-lying areas, further diminishing recharge opportunities. To address this challenge, managed aquifer recharge involves artificially replenishing aquifers with rainwater through various methods such as surface spreading, contour bunds, percolation ponds, check dams, injection wells, infiltration galleries, recharge shafts and recharge pits. It can be an economic, benign, resilient and socially acceptable solution to water problems[9]. Managed Aquifer Recharge (MAR) enhances the natural recharge of groundwater reservoirs by utilizing non-traditional water sources such as excess surface water, stormwater and treated wastewater, thereby promoting long-term water sustainability[2]. Shallow infiltration ponds can enhance groundwater recharge by enabling around 5% of additional rainfall to be utilized, transforming barren lands into eco-hydrologically productive pasturelands[28]. Groundwater recharge is influenced by various factors including climatic conditions, surface-water hydrology, topography, local geology, soil types, vegetation and landuse/land cover. Changes in precipitation, temperature and evapotranspiration can significantly impact these dynamics[15].

The selection of recharge methods varies based on regional soil, lithology, water sources and drainage characteristics. Excess rainfall or runoff, if not effectively utilized or stored in reservoirs, ultimately infiltrates the soil or flows into oceans. Recharge wells and canals are effective in mitigating saltwater intrusion in coastal aquifers, enhancing groundwater quality and increasing rainwater recharge capacity, particularly when recharge canals are positioned near the toe of the saltwater wedge[4, 19]. However, recharge and injection wells require limited land space, present technical challenges in design and necessitate proper water quality management along with the establishment and maintenance of conveyance and pumping systems. Incorporating an artificial recharge facility enhances groundwater storage, mitigates groundwater overdraft and boosts hydropower generation while having minimal effects on environmental flows[18].

In Cuddalore district, recharge techniques like percolation tanks, check dams, recharge shafts and rainwater harvesting have proven practical for managing unconfined coastal aquifers[13]. Percolation ponds can further enhance the quality and quantity of groundwater in saline aquifers by collecting and storing rainwater[21]. To sustainably manage groundwater resources against overexploitation, it is essential to reduce usage through recycling, reuse and wastewater management, or to artificially increase the storage capacity of aquifers.

Remote sensing and GIS technologies are valuable tools for identifying suitable areas for water harvesting and aquifer recharge, particularly in regions with sandy silt loam soils, barren land and fracture-filled formations[3]. By utilizing GIS-based multi-criteria decision analysis, studies have successfully identified suitable zones and locations for artificial recharge structures[6,16,17,23].

Substantial investigations have been conducted in Cuddalore district, Tamil Nadu, India, encompassing studies on hydrogeochemical characteristics of groundwater[6,8], groundwater discharges in coastal zones[7], identification of groundwater pollution sources using the electrical resistivity method[25], hydrogeophysical investigations of subsurface conditions[22]. Remote sensing and GIS technique are cost-effective, robust and efficient methods for identifying groundwater-potential zones[5,14]. This study aims to identify groundwater-potential zones by integrating geo-environmental factors such as geology, geomorphology, drainage, soil and landuse/land cover (LULC), combined with water level data to determine suitable sites for rainwater recharge, ultimately replenishing water quality and levels in the area.

Material and Methods

The study area is located in Cuddalore district, Tamil Nadu, South India. It extends between the latitudes 11°29'00"N to 11°51' N and longitudes 79°29' E to 79°47'50"E covering an area of approximately 926 km^2 (Figure 1). The study area is traversed by ephemeral rivers including the Then Ponnaiyar, Gadilam, Paravanar and Vellar Rivers, which flood during the monsoon season and primarily flow eastward in a sub-parallel drainage pattern. The eastern coastal region near Porto-Novo is characterized by lagoons and backwaters. The Ponnaiyar river, originating from the Nandi hills of Karnataka, is a seasonal river, while the southern part of the district is drained by the Vellar river, which is fed by its three major tributaries: Manimuktha, Gomukhi and Mayura[10]. The area has a hot tropical climate (summer) from March to May, followed by the southwest monsoon, which lasts until September.

The northeast monsoon, occurring from October to December, contributes significantly to the annual rainfall, ranging from 1050 mm to about 1400 mm. The highest recorded temperature is 40.3°C in June while the lowest is 20.4°C in January. The relative humidity recorded in the area ranges from 60% to 83%, with the highest humidity levels observed during the northeast monsoon period. This climate pattern makes the region highly vulnerable to both droughts and floods, directly affecting groundwater recharge and availability[27]. In addition, a predominantly flat terrain interspersed with small hillocks, the sandy coastal plains, river basins and wetlands plays an important role in the hydrological cycle.

Geology: The flood plains of Ponnaiyar, Gadilam, Paravanar, Vellar rivers comprise of various types of soils, fine to coarse grained sands, clay, silt etc. The sand dunes with a thickness of 10 to 15m sand are found from Cuddalore to Proto Nova. The unconsolidated quaternary sediments consist of fluvial and coastal alluvium deposits. Sedimentary formations consist of sand, clay, clayey sand and sandy clay from the Recent to Cretaceous Age. In some parts, Tertiary Uplands found within the stretch like Capper hills comprise of Laterite followed by sand, clay and sandstone in the western parts of the study area as shown in figure 2a.

Two significant faults are revealed in the Cuddalore district: one along with the crystalline – sedimentary contact in the western direction of the site and another parallel to it at a distance of 1.5 km. West of Porto Novo shows the existence of a Graben, a structural trough in the sedimentary tract. The thickness of aquifer ranges from 10m to 40 m followed by top soil or clay.

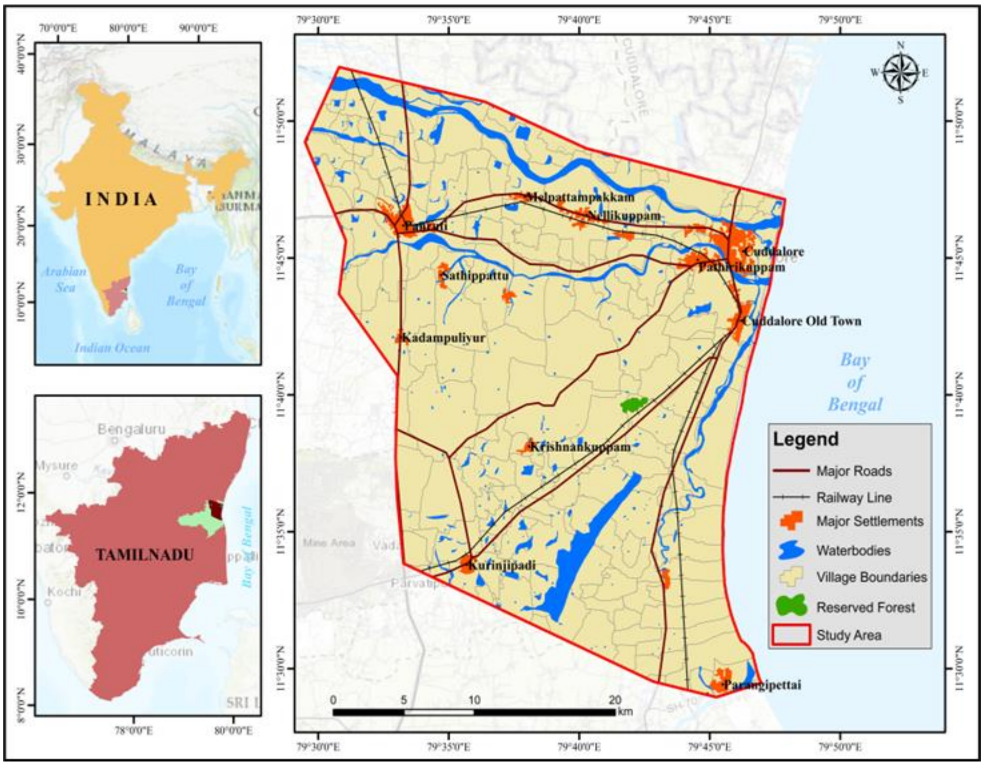

Figure 1: Study area location map

Soil: Soil is another important determining factor influencing the groundwater recharge in an area. The study area is covered by major four types of soils: alfisols, entisols, inceptisols, vertisols but most predominant soil type is alfisols covering more than 70% of area having moderate groundwater recharge capacity. The coastal area was mostly covered by entisols characterized by moderate to good groundwater recharge capacity. The spatial variation soil types of the study area are shown in figure 2b.

Geomorphology: Geomorphologically, the region is characterized by lateritic uplands, pediment pediplain complex, flood plains, deltaic plains and coastal plains, gently sloping toward the east and southeast as presented in figure 3a. Elevations range from 90 meters inland to 1 meter near the coast, where ephemeral rivers flow from west to east, primarily in a sub-parallel pattern to the coastline. Flooding occurs during the monsoon season and seawater intrudes through lagoons in the River Uppanar during high tide, impacting water quality. The central region features sedimentary high grounds composed of Cuddalore sandstone from the tertiary period, with elevations exceeding 80 meters.

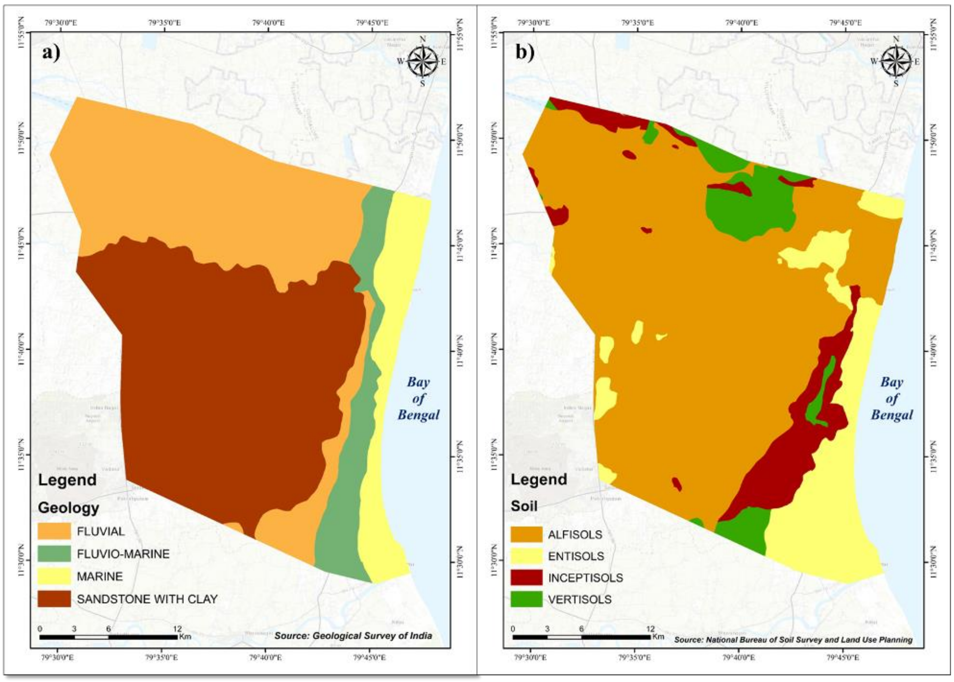

Figure 2: Geology (a) and Soil (b) map of the study area

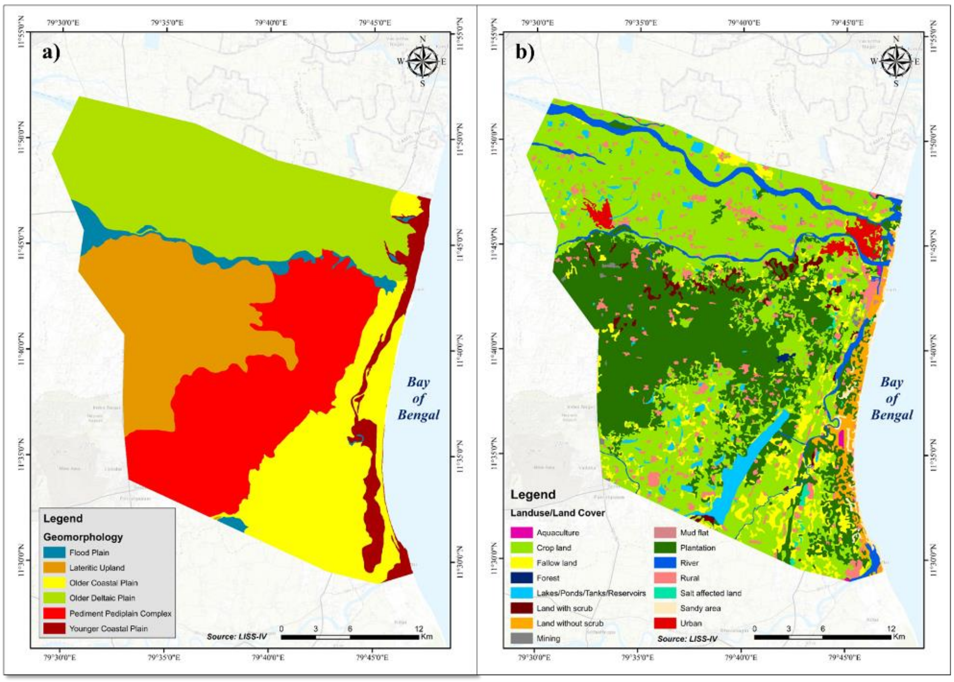

Figure 3: Geomorphology (a) and Landuse/Land Cover (b) map of the study area

The eastern coastal plain, influenced by the Ponnaiyar, Vellar and Coleroon river systems, encompasses the floodplain and includes a marine sedimentary plain. Between the fluvial floodplain and the marine sedimentary plain, fluvial marine deposition is evident, characterized by back waters.

Methodology: To identify suitable locations for rainwater recharge and achieve a rise in groundwater levels, this study incorporated remote sensing techniques, lithological data from bore wells and geophysical data collected in the field. Remote sensing studies utilized various satellite data combinations and collateral datasets to analyse regional characteristics based on thematic information[5]. Thematic layers such as geology, rainfall, lithology, geomorphology, landuse/land cover (LULC), elevation and drainage patterns were employed to demarcate optimal sites for rainwater recharge. Data for this analysis, spanning 20 years (1994-2024), were obtained from public organizations and online platforms including the Water Resources Department (WRD) of Tamil Nadu.

The landuse/land cover map was generated using Linear Imaging Self-Scanning Sensor–IV (LISS-IV) satellite imagery with a resolution of 5.8 meters while drainage density was mapped using Shuttle Radar Topography Mission (SRTM)-Digital Elevation Model (DEM) data. Rainfall distribution across the study area was determined using the Inverse Distance Weighted (IDW) interpolation technique. All thematic layers were geo-referenced using the Universal Transverse Mercator (UTM) 44°N coordinate system and integrated into GIS framework for multi-criteria analyses.

The Analytical Hierarchy Process (AHP) method was employed to rank parameters within the thematic layers (eight in total) and to compute the influence of each factor in delineating groundwater potential zones. Ranks were assigned based on the relative importance of each layer and a weighted overlay analysis was conducted to calculate influencing factors. Higher values were assigned to factors with greater impact, while lower values were given to those with the least impact on groundwater potential zones.

Additionally, the features of each thematic layer were weighted on a scale of 9 to 1, based on their relative importance and significance. The influencing factors and their respective weights were determined through a weighted overlay analysis. The Boolean logical method was used to further refine and optimize suitable MAR structures. Based on lithology, soil type, drainage, slope and LU/LC data, feasible methods for constructing recharge structures and determining optimal locations for MAR were derived.

Results and Discussion

The study identifies suitable locations, including wastelands and areas along rivers, for recharging rainwater and floodwater within the area. Based on the analysis of over 120 lithological locations, 20 years of average rainfall and water level data, as well as landuse patterns, recommends specific sites for improving groundwater levels within the study area. The focus is on recharging the first and second aquifer zones, with depths reaching up to 100 meters. By interpreting the lithological sequences and comparing groundwater level data from shallow wells and tube wells, the study successfully enhanced groundwater recharge in the aquifer zones.

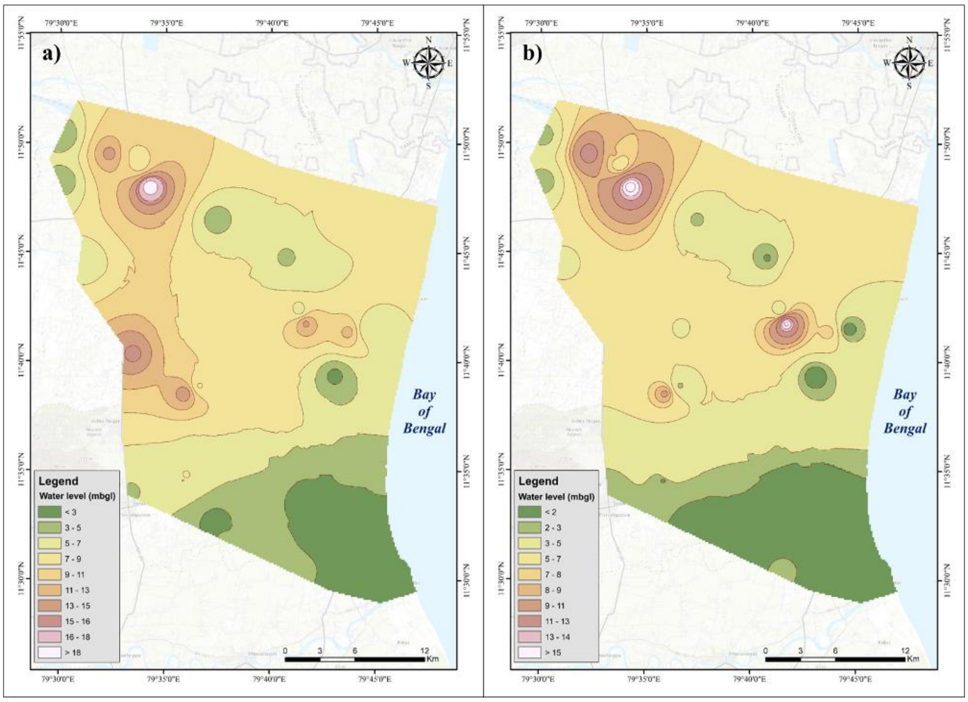

Figure 4: Groundwater level contours of open wells (a) for pre-monsoon and (b) post-monsoon, averaged over 2004-2024

Interpretation of water levels: The water table in the coastal zone remains generally shallow throughout the year. Groundwater occurs within dunes, beach ridges and phreatic aquifers of recent, quaternary and alluvial formations. The depth of the unconfined aquifers ranges from 5 to 40 meters, with deeper zones extending from 60 to 120 meters while the deep confined aquifers range between 150 and 300 meters below ground level. The average groundwater level of open wells in the pre-monsoon period between 2004 and 2024, varies across the region. In the north-western part of the study area, the water levels are notably deeper where water levels are predominantly greater than 18 meters below ground level (mbgl). In contrast, the south region exhibits shallow water levels, especially near the coast, with levels less than 3 mbgl.

The central region shows moderate water levels, generally between 5-9 mbgl (Figure 4a). While in post-monsoon, the groundwater levels improve across most areas, with more regions showing water levels <2 mbgl. Notably, the north-western part areas which had deeper pre-monsoon water levels, continue to show recovery with levels in the range >15 mbgl. There is also significant improvement in the southern areas, where water levels shift from deeper levels (5-9 mbgl) to moderate levels (2-5 mbgl) in the post-monsoon period (Figure 4b). Distinct spatial variations in groundwater levels were observed with shallower levels generally concentrated in the southern parts which correspond to more permeable formations that facilitate quicker recharge.

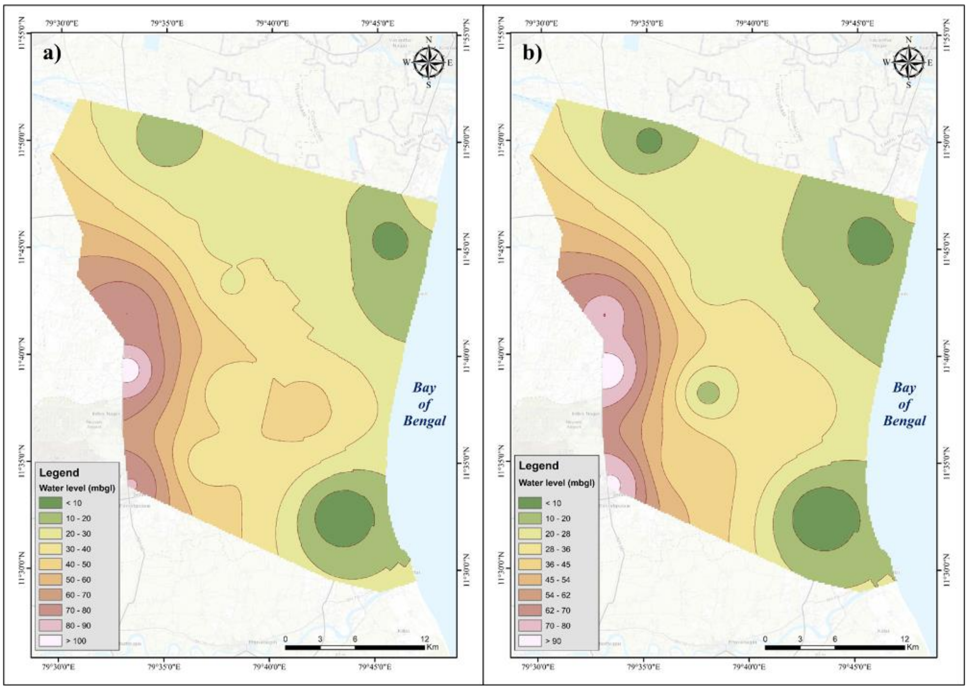

Figure 5: Groundwater level contours of tube wells (a) for pre-monsoon and (b) post-monsoon, averaged over 2004-2024

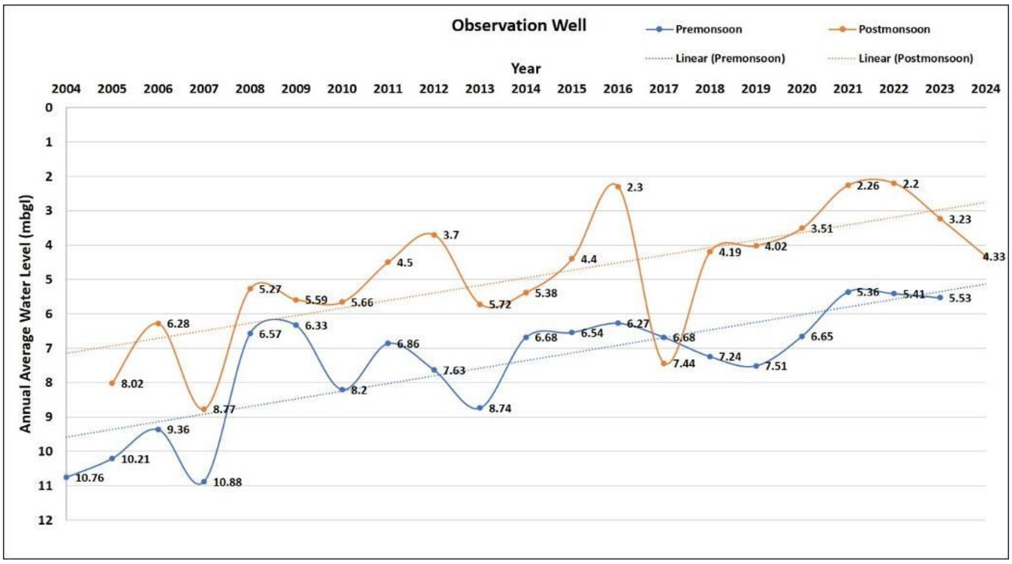

Figure 6: Water level trend of observation wells for pre-monsoon and post-monsoon averaged over 2004-2024

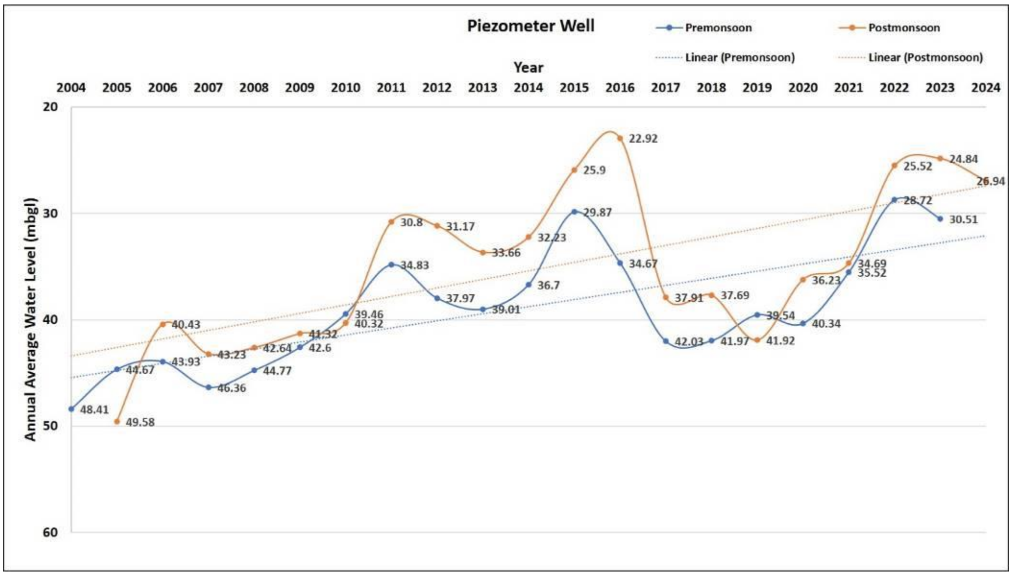

Figure 7: Water level trend of piezometer wells for pre-monsoon and post-monsoon averaged over 2004-2024

The tube well data during pre-monsoon from 2004 to 2024 shows that the deeper aquifers exhibit significant spatial variation in average water levels. In the northern parts, water levels are below 20 mbgl, with some areas reaching 30 mbgl. The western region shows even deeper levels, reaching up to 90 mbgl. The southern regions generally maintain water levels between <10 mbgl (Figure 5a). Similar to open wells, the water levels in the tube wells also show improvement during post-monsoon season, particularly in the northern and western areas. While the northern areas show recovery to around 10-20 mbgl, the western regions still maintain deeper levels between 60-80 mbgl.

Post-monsoon levels are consistently shallower compared to pre-monsoon levels which indicate the significant impact of monsoon rainfall in replenishing both shallow and deep aquifers in the region (Figure 5b). However, even in these deeper regions, a slight recovery is noticeable compared to pre-monsoon levels. This suggests areas where groundwater recharge may be slower or less effective, possibly due to lower recharge rates, higher groundwater abstraction, or the presence of less permeable formations or confined aquifers.

There is a general increasing trend of groundwater level in observation wells where it is getting closer to the surface over the years, indicating increased groundwater availability. The pre-monsoon water level started at 10.76 mbgl in 2004 and reached its lowest point of 5.36 mbgl in 2021. There are fluctuations observed in some years, particularly during 2007 (10.88 mbgl) and 2013 (8.74 mbgl), when the water level deepened temporarily before increasing (Figure 6). Similar trend was observed in the post-monsoon where water level data shows a steady improvement, reaching its shallowest level of 2.2 mbgl in 2022. Fluctuations are evident in years like 2007 (8.77 mbgl) and 2017 (7.44 mbgl) when the water level was deeper than usual, likely due to reduced precipitation[20] (Figure 6). In general, groundwater levels exhibit seasonal fluctuations with overall increasing trend between 2004 and 2024 while post monsoon levels generally are shallower due to recharge during the monsoon. Likewise, water levels in piezometer wells fluctuate from 2004 to 2024, with a general trend of improvement in groundwater availability during both the monsoons. However, there are some years with higher water levels below the ground, suggesting lower water availability. The pre-monsoon levels generally decrease from 2004 (48.41 mbgl) to 2023 (30.51 mbgl), suggesting an increasing trend in groundwater availability. A decline to 46.36 mbgl in 2007 and 42.03 mbgl in 2017 indicates reduced water availability in these years compared to others (Figure 7).

The post-monsoon levels show a similar increasing trend in terms of higher water availability. The water levels gradually decrease over the years, from 49.58 mbgl in 2005 to 24.84 mbgl in 2023. The lowest post-monsoon level recorded is 22.92 mbgl in 2016, indicating maximum recharge and availability of water (Figure 7). It is observed that a general decrease in both pre- and post-monsoon water levels, particularly from 2015 onward. The years 2005, 2007, 2017 and 2019 show significant fluctuations, where deepened water levels indicate temporary declines in water availability due to reduced precipitation[20]. These fluctuations could be influenced by factors such as varying rainfall patterns, water extraction rates, or other environmental conditions affecting groundwater recharge and discharge.

Landuse/ Land Cover (LULC): Landuse/ Land Cover (LULC) play a significant role in the recharge of rainwater and floodwater, which is essential for managing unconfined coastal aquifers. LU/LC features directly influence the rate and efficiency of groundwater recharge. Figure 3b represents the spatial distribution of different land cover types in the study area. Agriculture land is the predominant land cover type, occupying a significant portion of the area, with a total of 741 km^2 (80%). It mainly covers the central and western parts of the region, showing the dominance of agricultural activities in this area. Built up land representing urban and developed regions, covers about 81 km^2 (8.8%). These areas are scattered throughout the map but are more concentrated in the northern part of the study area, indicating settlements or urban growth centres.

Forest covers a minimal area of 0.76 km^2 (0.1%) limited within the study area. They appear as small patches, suggesting a relatively low presence of natural forest cover. Wastelands occupy 21 km^2 (2.3%) and are primarily located along fragmented patches scattered throughout, indicating areas with minimal vegetation or productivity. Water bodies including rivers, lakes, or reservoirs, cover 63 km^2 (6.8%) and are mainly observed in the northern and southern parts of the map, signifying natural or man-made water sources. Wetlands cover 19 km^2 (2.1 %) and are located along the eastern coastal boundary. These areas play a critical role in biodiversity and coastal stability[24]. This spatial distribution highlights a region dominated by agricultural land with notable features of built-up areas and water bodies, while forest cover is minimal and wetlands are primarily confined to the coast.

Topography and Slope: Topography of the area plays another influencing factor for rainwater recharge. If degree of slope is high, surface runoff is naturally more and in turn decreases the rate of infiltration and finally reduces the total groundwater recharge. The slope map of the study area is prepared using SRTM-DEM where the elevation of this region ranges from 90 to 0 meters above mean sea level (amsl). The regional slope of the region is towards the southeast direction with lowest elevation of 0 m (MSL) along coastal region in eastern part of the study area. The slope of the study area represents flat to lower degree of slope (Figure 8a). It indicates that the major part of the study area has good potential of groundwater recharge due to the flat/gentle sloping terrain[12]. The maximum degree of slope is observed in the western part of the study area.

Rainfall: Rainfall is the major and crucial source of groundwater recharge in an area and depends on multiple factors in landuse/land cover are the crucial controlling factors. Daily rainfall data of rain gauge stations in and around the study area from 2004 to 2024 were collected from Water Resources Department (WRD), Tamil Nadu. The spatial annual average rainfall map was prepared based on the 20-year data (Figure 8b). The spatial variation of the study area is expressed through rain fall isohyetal lines i.e. the annual average rainfall in the study region is maximum near the coastal region and gradually reduced towards landward. Based on the annual average rainfall, the study area is classified into five zones with rainfall range: 1000-1190 mm, 1190-1260 mm, 1260-1330 mm, 1330-1400 mm and 1400 – 1500 mm.

Delineation of groundwater potential zone: The groundwater potential recharge map was prepared by integrating thematic maps using a multi-influencing weighted overlay analysis. This analysis resulted in the classification of the area into three recharge potential zones: high, moderate and low recharge areas. The groundwater potential zone map reveals that the northeastern, eastern and western regions, covering approximately 468 km² (50%), are classified as highly rechargeable areas for groundwater due to the presence of alluvium and tidal-sand deposits with high infiltration rates[1].

Moderate recharge areas, accounting for about 276 km² (30%), are mainly scattered in the southern part of the study area. Intensive agriculture enhances groundwater potential whereas the presence of hard rocks with low infiltration rates reduces it, leading to a moderate recharge across most of the study region[11,16,26]. Low recharge zones, covering around 182 km² (20%), are dispersed across the study area, particularly in the southern region (Figure 8a).

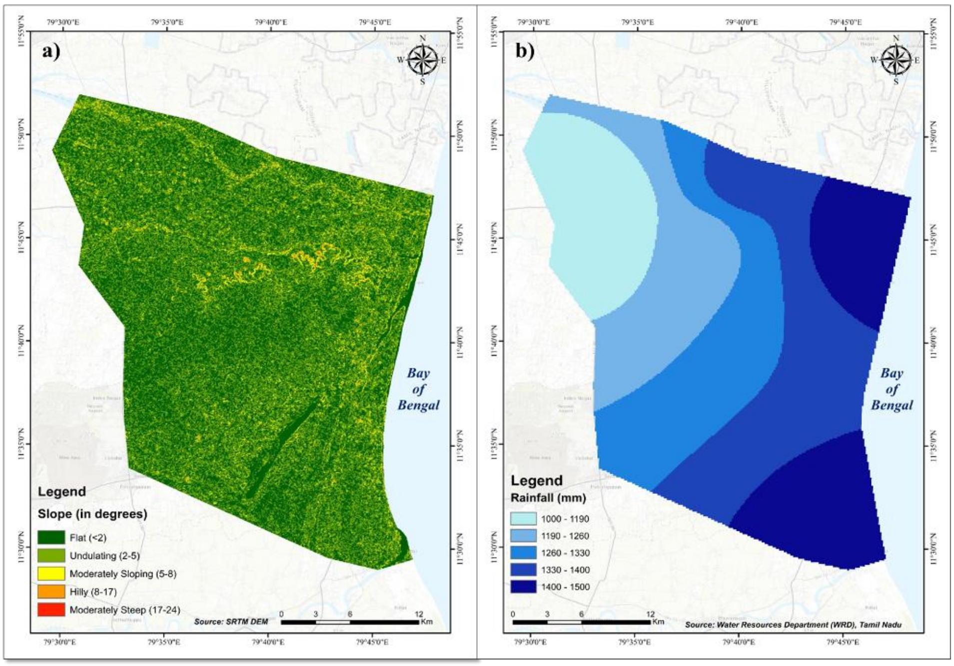

Figure 8: Slope (a) and Annual average rainfall from 2004 - 2024 (b) map

Site suitability analysis: The study identified suitable locations for managed aquifer recharge structures by interpreting lithological cross-sections across 12 profiles in the Cuddalore district (Table 1). Each profile, extending between 23 km and 32 km, reveals critical variations in aquifer thickness, sand deposits and clay layers. Profile 1 (Rampakkam to Gundu Uppalavadi) highlights recharge potential at depths of 19-24 m, influencing water levels up to Visuvanathapuram Dam, with a recharge capacity of 216 MCM/year. Profile 2 (Akkadavalli to Devanampattinam) demonstrates maximum sand thickness near Chavadi village and recommends recharge shafts at depths of 20-30 m, potentially recharging 174 MCM/year. Profile 3 (Akkadavalli to Thiruppaliuyur) suggests recharge structures in government land to address dry aquifers, with a recharge estimate of 69 MCM/year.

Profiles 4 and 5, covering diverse terrains, indicate areas with substantial sand thickness and clay barriers, offering recharge potentials of 99 MCM/year and 360 MCM/year, respectively while also acting as barriers against seawater intrusion. Profiles 6 and 7, spanning Siruvathur to Sembankuppam, highlight regions with significant recharge potential using indirect methods, estimated at 96 MCM/year and 220 MCM/year. Profiles 8 to 12 emphasize diverse recharge potentials ranging from 90 MCM/year to 474 MCM/year, with prominent zones near Poondiyankuppam and coastal areas exhibiting excellent sand and clay formations (Figure 9b). Overall, strategic construction of recharge shafts, injection wells and percolation ponds across these profiles can enhance groundwater levels, can safeguard against seawater intrusion and can mitigate aquifer depletion effectively[21].

Table 1
Lithological cross-sections of the study area

Profile Number	No. of litho-logs interpreted	Buffer Zone	Length of the profile (Km)	Area (Km^2)	Subsurface suitable for Recharge (in Hectares) (60% in total area)	% of volume recharge (in mcm)	Suggested Recharge methods
1	18	3	23	72	21600	216	Direct
2	16	2	28	58	17400	174	Direct and Indirect
3	9	1	27	23	6900	69	Indirect
4	9	2	30	42	4200	160	Direct
5	14	2	32	72	35600	460	Indirect
6	7	2.5	28	65	9600	90	Indirect
7	8	2.5	29	75	29500	300	Indirect
8	9	3	25	79	47400	700	Direct
9	9	3	26	72	21600	216	Direct and Indirect
10	10	3	25	60	22000	220	Indirect
11	6	3.5	24	80	12000	120	Direct
12	5	3.5	26	100	15000	90	Direct and Indirect

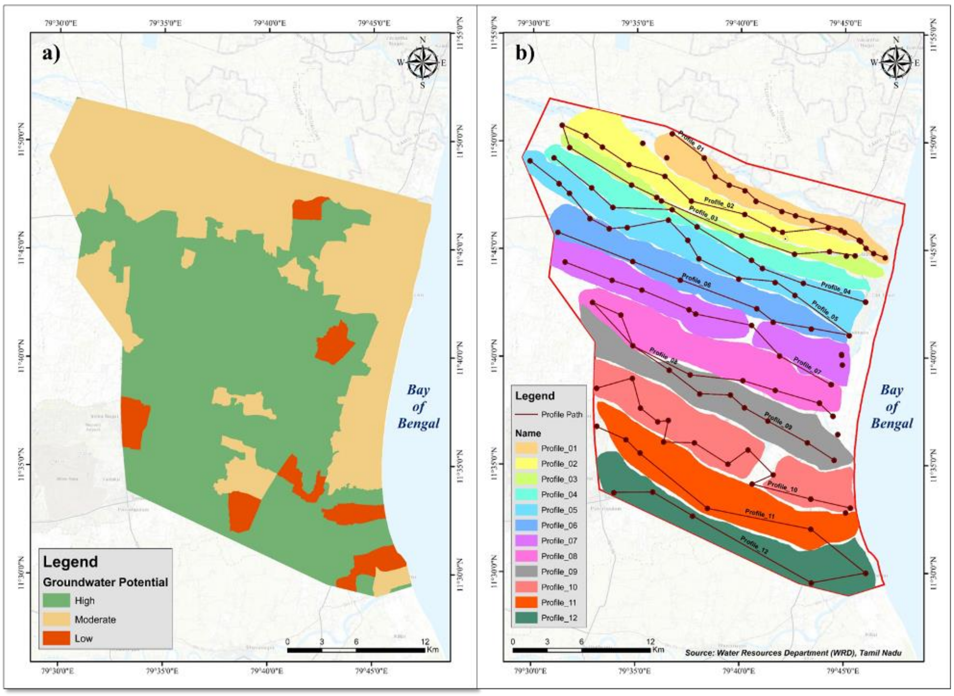

Figure 9: Delineation of groundwater potential zone (a) and Lithology profile (b) map

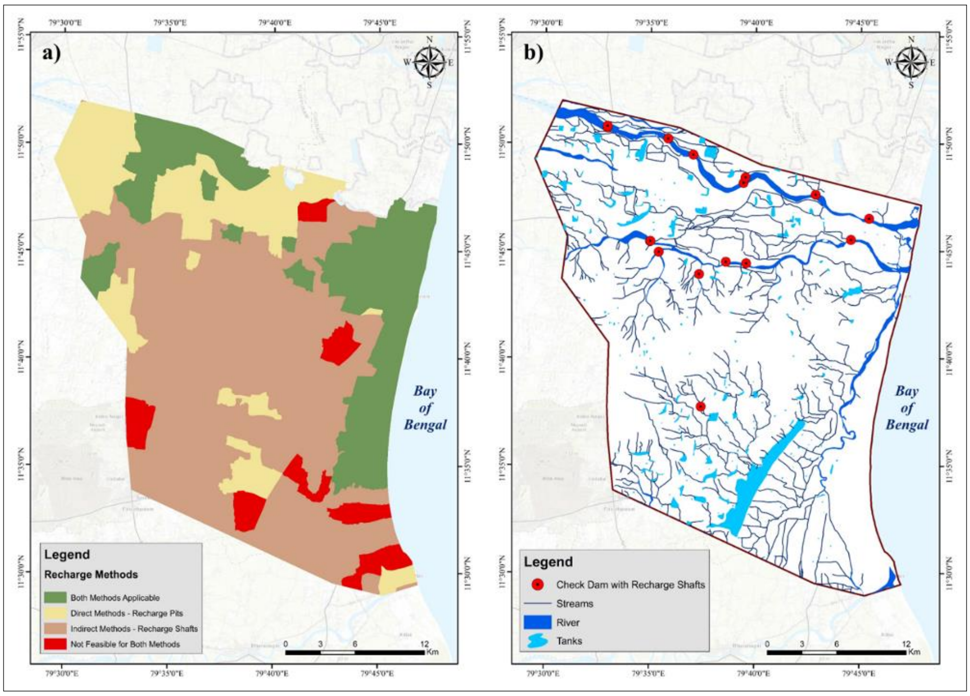

Figure 10: Recharge methods (a) and Existing check dam and recharge structures (b) map

Validations of groundwater recharge areas: The identification of the most suitable locations for groundwater recharge is influenced by multiple factors analysed on Geographic Information System (GIS). Since these factors indirectly represent the potential recharge zones, it is essential to validate the outputs. To ensure the applicability of the suggested recharge methods and to quantify the volume of rainwater or floodwater that can be effectively recharged, lithology and groundwater level data from the Water Resources Department, Tamil Nadu, were utilized (Figure 10a, b).

Based on the lithology, water level and thematic maps prepared for the study area, appropriate recharge methods - whether direct or indirect were recommended. These methods estimate a recharge potential ranging from 2700 MCM/year to 2800 MCM/year. Groundwater monitoring well data for the study area, obtained from the Water Resources Department of Govt. of Tamilnadu, plays the crucial role in validating these findings and ensuring the sustainability of groundwater levels while reducing the risk of further depletion.

Conclusion

This study systematically identified optimal and suitable groundwater recharge zones in the unconfined coastal aquifers of Cuddalore coastal area, using GIS multi-criteria decision analysis and remote sensing techniques. The analysis outlined high, moderate and low recharge zones covering 468 km², 276 km² and 182 km² respectively. High-potential zones were found in areas with favourable lithological and soil properties such as alluvium and tidal-sand deposits while moderate zones were associated with agricultural regions limited by hard rock formations. Low-potential zones, primarily in the southern part of the area faced infiltration challenges due to impermeable strata.

Seasonal variations in groundwater levels, with significant improvements during post-monsoon, were highlighted, particularly in high-potential zones. Lithological profiles revealed recharge volumes ranging from 69 to 700 MCM/year, with a total recharge capacity of 2700–2800 MCM/year validated through field data. Recommended managed aquifer recharge (MAR) structures including percolation tanks, recharge shafts and injection wells at depths of 30–80 meters, align with site-specific conditions to enhance groundwater recharge.

The study advocates prioritizing MAR interventions in high-potential zones to mitigate over-extraction, reduce seawater intrusion and improve agricultural productivity by 10–15%. These findings underscore the critical role of advanced geospatial tools in combating groundwater depletion and ensuring long-term groundwater sustainability in coastal regions.

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