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Delineation Of Groundwater Potential Zones Using Remote Sensing And GIS Techniques And Identifying Suitable Locations For MAR Structures In The Coastal Aquifers Of Cuddalore District

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Abstract

Groundwater resources of coastal regions in developing countries are mostly affected due to the combination of natural disasters as well as poor storm water management. By identifying the suitable places for the construction of Managed Aquifer Recharge (MAR) structures will improve the groundwater potential in an area and also sustain the groundwater resources. The present study was carried out in northern coastal part of Tamil Nadu, India. The objectives of this study are to delineate the groundwater potential zones (GWPZ) and to identify the optimal locations for the construction of MAR structures. Geomorphology, geology, slope, lineament density, drainage density, rainfall, regional groundwater level and land use of the study area were selected as the key factors for this study. The selected factors are processed with combination of Analytic Hierarchy Process (AHP), Multi-Criteria Decision Making (MCDM) technique and Boolean logical approach to delineate GWPZ and to identify the optimum locations for the construction of MAR structures. The processed results specifies that 2.0% (51 km^2) from total study area falls under Excellent; 32% (938 km^2) are good; 4.0% (115 km^2) are above average; 59% (1759 km^2) are fair and 3% (92 km^2) has poor groundwater potential. Eventually, the Boolean logical method was attempted and identified the suitable areas for constructing MAR structures such as check dams, percolation ponds, flood and furrows and ditch and furrows. Based on the regional hydrological setup, feasible locations for construction of check dams were proposed, which will augment the groundwater resources of the study area. These check dams will be beneficial for the surrounding regions by improving the groundwater recharge through cropping the surface runoff during the monsoon as well as flood periods.

Introduction

Groundwater depletion is a major concern in recent times due to rapid urbanization and industrialization in both rural and urban regions across the world. In addition to the rapid extraction of groundwater for agricultural, domestic and industrial purposes, several other factors such as climate change, geogenic or anthropogenic contaminations and improper surface water management will result into groundwater depletion which leads to sea water intrusion in coastal areas. The coastal regions (with 40% of the world population) less than 60 km from the shore are highly vulnerable when compared to the inland regions due to the instant impact caused by sea water intrusions (Jayasekera et al 2011). Among various vulnerable factors in coastal regions, improper management of water is like a double-edged sword which cuts/reduces the groundwater storage by lack of recharge structures and reduce existing groundwater level by over extraction. Manoj et al (2019) reported the importance of optimal groundwater management for maintaining the regional water resources especially in sensitive urbanized regions.

Over decades the groundwater exploration was carried out after the detailed geophysical and geological investigations followed by drilling of wells. These direct methods are considered as time-consuming and extravagant techniques. However, in recent decades due to rapid development in geo-spatial techniques reduces such setbacks and provides effective

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exploration and sustainable management strategy especially for the conservation of groundwater resources. Application of remote sensing data through the Geographic Information Systems (GIS) creates it as an inexpensive technique with help of existing open-access data portal for public use (Anbarasu et al 2020). Jha et al (2010) and Misi et al (2018) reported that the key advantages of remote sensing and GIS are the spectral, spatial and temporal availability of the data and the ability to produce quick and reliable results.

Number of studies was carried out across the world using the GIS and remote sensing techniques for exploration of groundwater potential zones (GWPZ) of an area. Most commonly the data accessibility and availability determine the selection of suitable thematic layers of an area which varies with individual researcher as well as the parameters that influencing the regional groundwater (Selvam et al 2015). The wide and common features that determine the potential groundwater zones are Rainfall, geology, geomorphology, drainage, lineament, fault, lithology, land use/land cover, soil, and slope of the region. These features overlayed one another using AHP-MCDM techniques in the GIS computer code and determine the most suitable, ideal, optimum GWPZ (Machiwal and Singh, 2015; Ponnusamy et al 2022). The integrated AHP-MCDM approach is an ideal technique for delineation of GWPZ with systematic assigning of weightages followed by weighted overlay analysis.

The present study was carried out in coastal regions of Cuddalore, Kallakurichi and Villupuram districts of Tamil Nadu state, India, with an objective to delineate the groundwater potential zones and to identify the optimal locations for construction of MAR structures to enhance the groundwater resources. The study area experiences frequent flood and drought due to excess rainfall and improper water management practices respectively which made this study as an important and essential, now. Further, the novelty of the study is the use of integrated multicriteria decision problems with the validation of field driven data sets for identification of suitable and optimal sites for construction of recharge structures in the region. It is anticipated that the outcome of this study will provide an insight into the water management practices in the coastal areas.

Description of the study area

The study area comprises of four river basins namely Gadilam, Lower Pennaiyar, Paravanar and Uppanar which lies in the Cuddalore, Kallakurchi and Villupuram districts of Tamil Nadu and Union territory of Pondicherry (Fig. 1). All these rivers in the study area are

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non-perennial rivers and are drained towards East and confluence with the Bay of Bengal. The average annual rainfall in the Cuddalore, Kallakurichi and Villupuram districts are 1902 mm to 1384 mm respectively (Indian Meteorological Department, 2004–2006). These coastal districts receive major rainfall from northeast monsoon (October – December) followed by southwest monsoon (June – September) and meagre rainfall during non-monsoon periods (January – May). In general, the rainfall in this region is heavy during low-pressure depressions and cyclones during the northeast monsoon period (CGWB 2009).Henceforth, the study area experiencing multiple threat from various disasters that includes cyclone, storm, flood and tsunami in which the worst damage was recorded in this region during Indian Ocean tsunami (2004), Nisha cyclone (2008), Gaja Cyclone (2018), and intense rainfall induced flood (2015).Climate of the study area is hot tropical and the temperature ranging from 25°C (December) to 31°C (April).

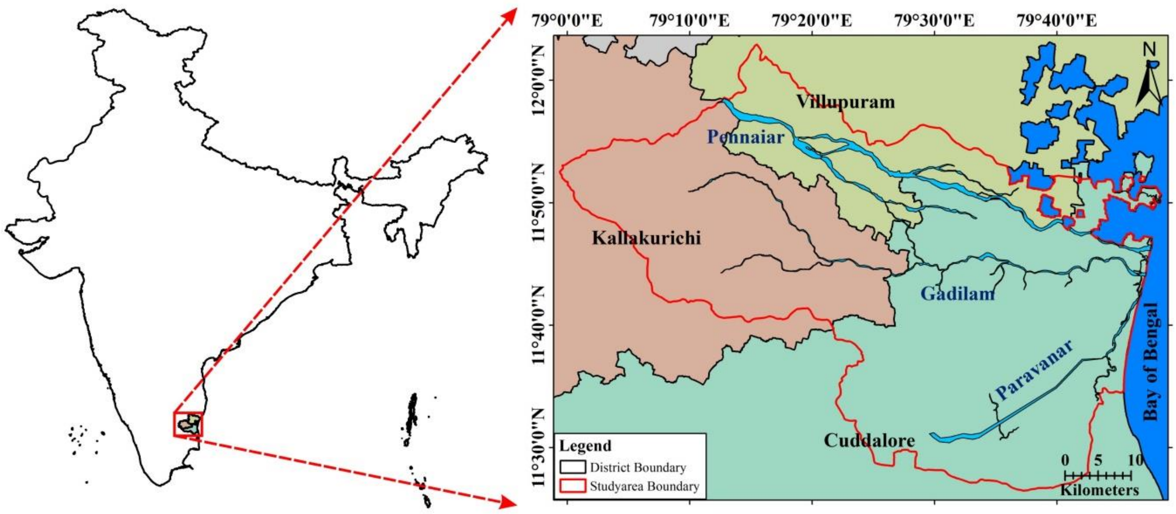

Figure 1. Location of the study area along with the major rivers

Groundwater is the major fresh water resources in the study region which are extracted from unconsolidated Quaternary porous formations in the Eastern side and the fissured and fractured formations of Archaean hard rocks in the western side of the study area. Along the east coast stretch of India, the groundwater extracted for the combined use of domestic and industrial purposes is higher in Cuddalore district (340 Mm^3) whereas for irrigation the maximum is recorded in Villupuram district of Tamil Nadu (1392 Mm^3) (Manivannan et al 2022). Over extraction of groundwater in the coastal region may leads to sea water intrusion.

Methodology

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Remote sensing data along with the regional/site specific data plays a crucial role in surface water and groundwater resource management and planning. In this study, the groundwater potential zones are identified and validated through remote sensing data and conventional data measured in the field respectively. Remote sensing studies utilises multiple combinations of satellite data and other collateral dataset used to understand the characteristic of the regions based on the observation of thematic information (Panahi et al 2017; Anand et al 2021; Ibrahim et al 2021). In this study, the thematic layers such as geomorphology, geology, rainfall, lineament density, land use/ landcover, soil type, slope and drainage density were used for demarcation of GWPZ. These data were obtained after various public organizations and online platforms were analysed in the GIS software (ArcGIS 10.5). The geomorphology, geology, soil types and rainfall data (for about 20 rain gauge stations) for the study area was obtained from Water Resources Department (WRD), Government of Tamil Nadu was used in this study.

The Inverse Distance Weighted (IDW) interpolation technique was used to determine the rainfall distribution in the study area. The land use/landcover map of the study area was prepared using Linear Imaging Self-Scanning Sensor – IV (LISS-IV) the satellite imageries with 5.8m resolution. The drainage density and lineament density maps were prepared from the Shuttle Radar Topography Mission (SRTM) – Digital Elevation Model (DEM) satellite imageries. These thematic layers were geocoded with Projected Coordinate System (PCS) – of Universal Transverse Mercator (UTM) 44°North. All the thematic layers were integrated using ArcGIS to perform various multi-criteria analysis such as AHP and Boolean logical method. AHP technique was performed using raster format of these layers under overlay analysis tool. The weighted overlay analysis process was carried out by assigning the ranks to each parameter of the individual layers (for eight thematic layers) and the influencing factor to each thematic layers (Table S1 and S2, supplementary material) based on the importance in delineating the groundwater potential zones. The larger values were assigned to the factor which have more impact, whereas the lesser value was assigned to the factors which have least impact in groundwater potential zones (Table S1, supplementary material). Further the weight to the features of each thematic layers were assigned on a scale of (9 – 1) based on the relative importance and significance (Table S1, supplementary material). The influencing factor and the weight allotted (Table S1, supplementary material) to each factor and features are computed under weighted overlay analysis in ArcGIS software. In addition to the AHP, the Boolean

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logical approach was infused to identify and optimise suitable MAR structures within the study area. Drainage, lineaments, land use/cover of the area was used to identify the feasible locations to construct MAR. These layers were computed under Boolean logical overlay analysis method and the optimal locations for MAR were derived.

Weightage calculation

The weight assigned to the features of various thematic layers were normalized with AHP technique. The consistency of the weight was verified with consistency ratio using the formula (Satty and Vargas 1987) given below (Eq – 1). The consistency ratio (CR) was calculated based on the consistency index (CI) and random consistency index (RCI). The random consistency index used in the calculation for various criteria is prescribed in Table S2. Each thematic layer was interlinked with the other to derive pair wise comparison matrix normalized weight and consistency ratio (Table S3). The obtained normalized weight is consistent according to the consistent ratio of 0.087 and which was found acceptable as per (Satty and Vargas 1987).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RCI}} \qquad \text{(Eq – 1)}$$

Results and discussion

Drainage and Lineament

Lower Pennair, Gadilam and Paravanar are the major rivers that flows across the study area from west to east and drains in Bay of Bengal. The drainage map of the study area was derived by digitizing the Survey of India toposheets on a 1:50,000 scale (Fig. 2a). An open area between the Gadilam and Paravanar river basin constitute the largest lignite mine (undertaken by Neyveli Lignite Corporation Limited) in the world. Presence of multiple rivers and its tributaries in the gently sloping area resulting in to the presence of numerous surface waterbodies like lakes, ponds and tanks. In general, lower the drainage density resulting into lower surface runoff and higher the infiltration rate i.e., poor drainage zones are identified as most favourable condition for the presence of GWPZ (Al-Saady et al 2016). Hence, Drainage density is considered as the major factor in delineating the GWPZ since it represents the inverse function with hydraulic conductivity. Due to the dense drainage present in this region resulting into higher surface runoff and lower infiltration rate. But, conversely the presence of numerous surface water bodies resulting into the increased groundwater recharge in this region.

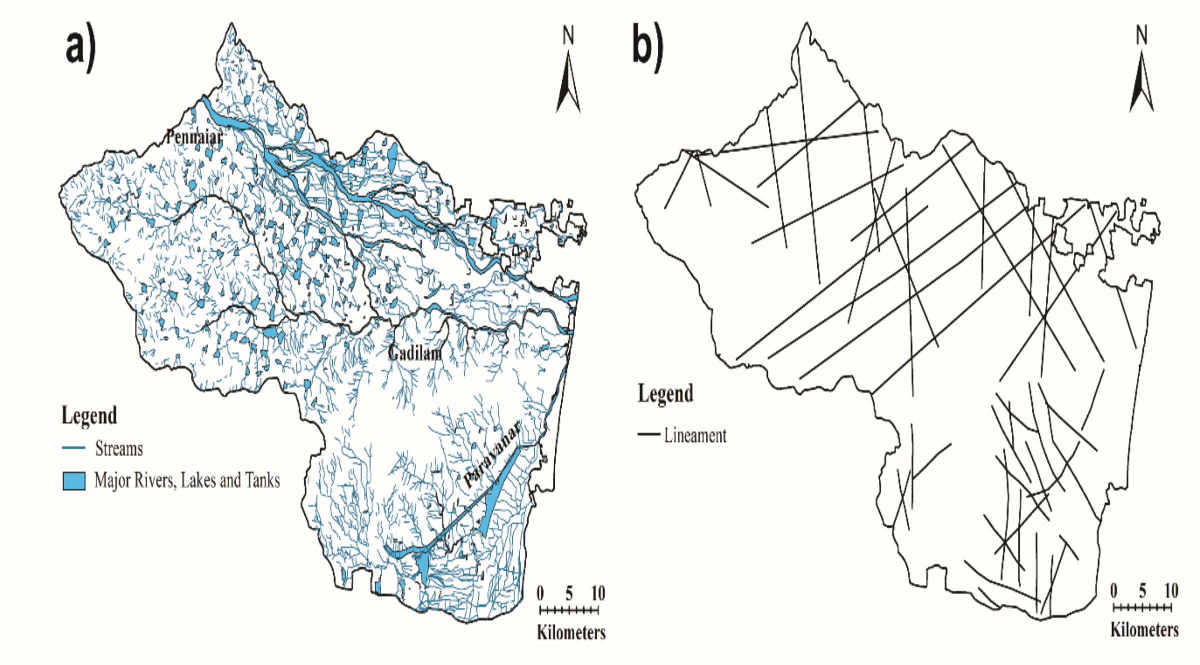

Figure 2. Spatial map of the study area representing a) Drainage and b) Lineament

Lineaments are the structurally controlled linear or curvilinear features developed due the stress and strain caused during the tectonic activity. These lineaments provide major evidence on surface features and express the corresponding subsurface structural features that are responsible for recharging the surface/runoff water as groundwater storage. In other words, the faulted and fractured regions that governs the porosity and permeability of a formation are identified through lineaments. Lineament density of an area indirectly represent the GWPZ, since it denotes the permeable zone. Further, the region with high lineament density indicating good GWPZ and vice versa (Hussein et al 2017). The lineament of this study region is extracted from the satellite imageries (SRTM-DEM & LANDSAT 8) and the trend is primarily found along N-S, E-W, SW-NE and NW-SE directions (Fig.2b). Unlike drainage density, higher the lineament density will be resulting into increased groundwater potential.

Geology and Geomorphology

Geology of the study area in lower Pennair, Gadilam and Paravanarsub-basins are shown in figure 3a. Geologically the western part of the study area is composed of hard rock

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formations viz., granite and hornblende biotite gneiss. Whereas, the central and the eastern part of the study area composed of sedimentary formations that includes sandstone, limestone, alluvium and other coastal deposits. Among these sedimentary deposits, the sandstone formation with regional name called "Cuddalore Sandstone" gains its attention due to the presence of lignite deposits in the Neyveli township. The lignite deposits occur in the Cuddalore formation at a depth ranging from 45 to 120 m from the ground surface (Jayaprakash et al 2012). In general, each formations/unit depicts its physical characteristics and for this study it was prepared based on the existing surface geology map obtained from Geological Survey of India (GSI). The geology map was digitised and the resulting thematic layer represent the heterogeneous formations of the study site which is evident by varying inherent properties of hydrogeologic elements of this region. Considering the multiple formations of this region, its properties were utilised for the evaluation of groundwater potential zone of this region.

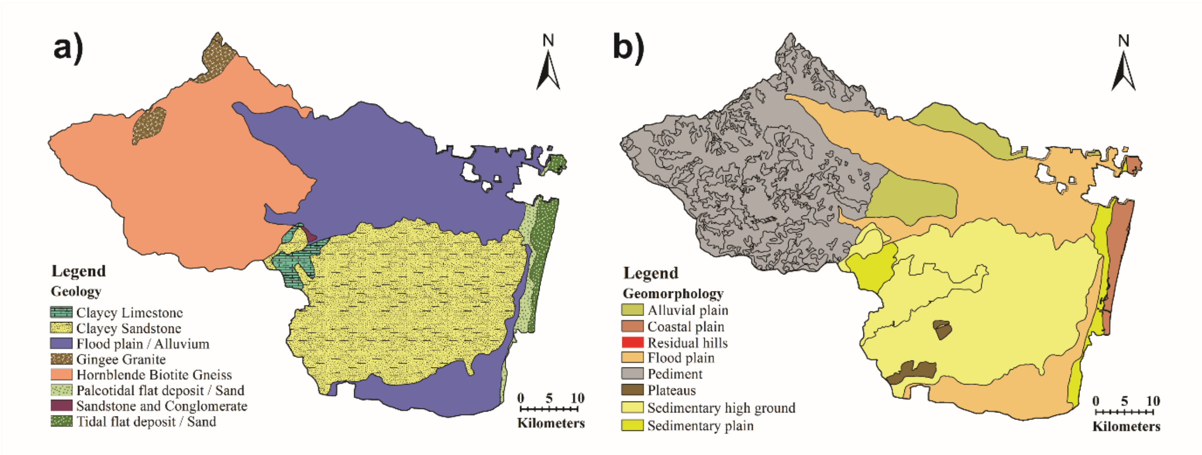

Figure 3. Spatial map of the study area representing a) Geology and b) Geomorphology

Geomorphology is one of the crucial parameters in delineating the GWPZ since it controls the movement of groundwater in the subsurface formations. The geomorphic features of this study area comprise of alluvial, coastal, flood and sedimentary plains, residual hills, pediments and plateaus (Fig.3b). The central and eastern part of the study area are dominant with plains of fluvial and coastal origins whereas the western part of the study area is dominant with pediments derived from the granites and gneissic rocks. The presence of fluvial and coastal plains of the eastern part of this region induces an increased infiltration rate when compared to the pediments present in the western part of the study area. Since the study area is more prone to inland floods and saline water intrusions, the implementation of artificial

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recharge structures over the pediments and plains of this region will be an optimal solution to address the vulnerability of this region.

Soil and Land use/land cover

Soil is one of the determining factors used for delineating the GWPZ since its characteristics influence the groundwater recharge. Soil in the study area reveals by five classes that includes alfisols, entisols, inceptisols, vertisols and reserve forest. The spatial variation soil type of this study area is shown in figure 4a. Among these soil types entisols and inceptisols has more infiltration capacities; therefore, it is considered as the most suitable soil type for groundwater potential. But the dominant soil type of this region is alfisols which has moderate groundwater influence followed by vertisols and reserve forest type.

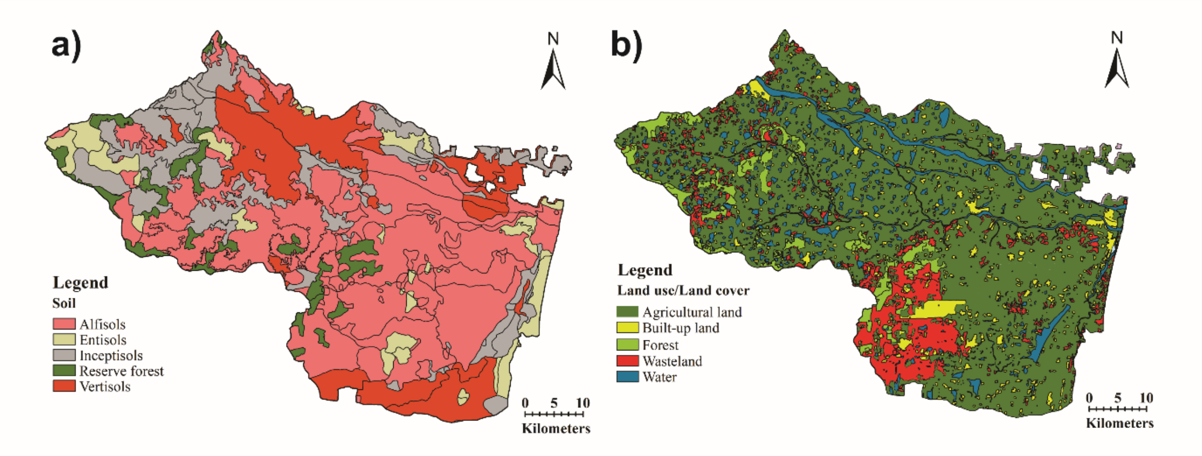

Figure 4. Spatial map of the study area representing a) Soil and b) Land use/land cover

Land use/land cover defines surface characteristics of the terrain and its utilisation in various activities. Based on the land use/land cover map, the hydrological flux such as infiltration, surface runoff and evapotranspiration which are associated with the groundwater occurrence and its distribution can be inferred (Owuor et al 2016). From the land use/land cover map, it is inferred that the study area is dominated with agriculture land followed by waste land, built up and forest area (Fig. 4b). Since the study area is dominated with agriculture activities, the water used for cultivation will act as major recharging factors in this region followed by the forest regions. On the other hand, the minimum recharge zone will be anticipated in the built-up regions due to the presence of concrete settlements and impervious tar roads.

Topography and Slope

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Topography of the study area was prepared using SRTM-DEM data where the elevation of this region ranges from 125m (msl) to 0m (msl) (Fig. 5a). The regional slope of the region is towards the SE direction with lowest elevation of 0 m (msl) along coastal region in eastern part of the study area. Slope is an important factor which indirectly representing the surface runoff and the corresponding infiltration rate. Higher degree of slope will increase the rate of runoff and decrease the rate of infiltration resulting into feeble groundwater recharge potential. The slope of the study area is shown in figure 5b representing flat to lower degree of slope. It indicates that the major part of the study area might have good groundwater potential because of the flat/gentle sloping terrain. The maximum degree of slope is observed in the southern part of the study area where Neyveli lignite mines are located. Because of the large-scale open cast mining the southern part of the region was highlighted with the maximum degree of slope which is about 22° whereas most of the study area are remarked with 0° to 2° slope in eastern part of the study area since its presence are nearer to the coastal region (degree of slope will similar to mean sea level).

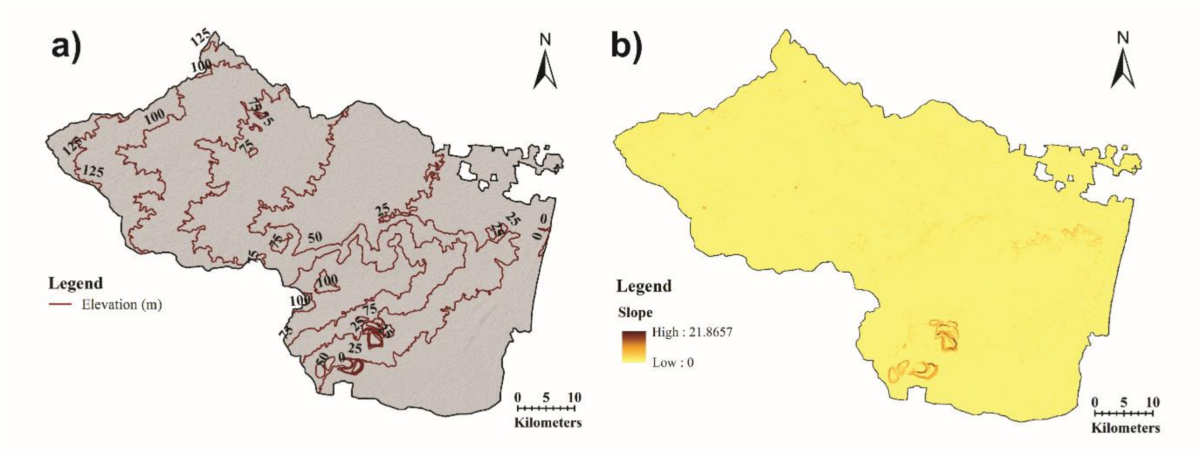

Figure 5. Spatial map of the study area representing a) Topography and b) Slope

Rainfall

Rainfall of a region is the major source of groundwater recharge and depends on multiple factors in which the crucial controlling factors are land use/land cover. Daily rainfall data of 20 rain gauge stations in and around the study area from2011 to 2020 were collected from Public Works Department (PWD), Tamil Nadu. The spatial annual average rainfall map was prepared based on the10-year data (Fig.6a). The spatial variation of the study area is expressed through isohyetal lines, i.e., the annual average rainfall in the study region is at the maximum near the coastal region and gradually reduced towards landward. Based on the

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annual average rainfall, the study area is classified into five zones with rainfall range: (1) 820 mm – 1000 mm (2) 1000 mm – 1100 mm (3) 1100 mm – 1200 mm (4) 1200 mm – 1300 mm (5) 1300 mm – 1520 mm. The maximum weightage is assigned for high rainfall region and vice versa.

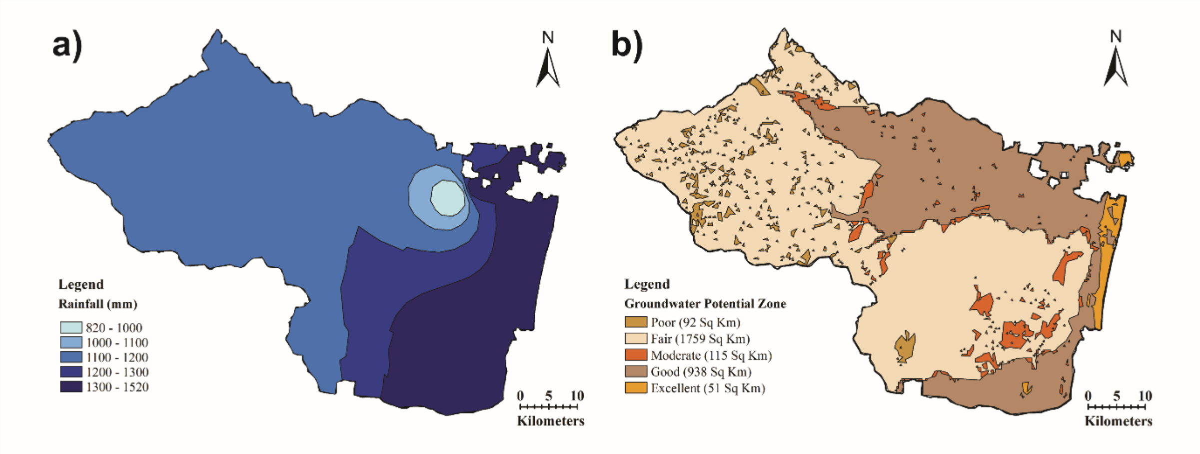

Figure 6. Spatial map of the study area representing a) average annual rainfall (2011-2020) and b) groundwater potential zone

Delineation of groundwater potential zone

Integration of various thematic maps that includes the drainage, lineament, geology, geomorphology, soil, land use/land cover, slope will be resulting into generation of groundwater potential map (Fig.6b). The GWPZ of the study area was prepared by merging the thematic layers through multi influencing weighted overlay analysis and as a result various zonal classification were determined. In this region, the GWPZ were divided into five classes, viz., excellent, good, moderate, fair and poor. Based on the GWPZ map (Fig.6b), it is inferred that the NE, East and SE regions of the study area having excellent and good groundwater potential. Collectively, it is about 989 km^2 of the study area are classified as excellent to good GWPZ due to presence of alluvium and tidal-sand deposits which has high infiltration rate compared to the rest of the study area. About 115 km^2 of study area falls under the moderate GWPZ and are scattered throughout the study area. Mostly the scattered nature of GWPZ was generated when the particular demarcated zone is highly influenced by multiple factors. Further, the major part of the study area, especially the central and NW part are classified as fair GWPZ which covers an area of about 1759 km^2. Intensive agriculture favours groundwater potential whereas the presence of hard rocks with poor infiltration rate reduces the groundwater

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potential resulting a fair GWPZ in major part of this region. Finally, about 92 km^2 of the study area are classified as poor GWPZ which dominantly scattered in the NW part of the study area.

Validation of GWPZ

GWPZ for any area can be identified with help of multiple influencing factors through Geographic Information System. Since the multiple influencing factors are indirect representation utilised for the demarcation of groundwater potential zone, it is essential to ensure the output (GWPZ) through validation. Hence the regional groundwater levels measured in the study area are utilized for this study as validation factor in order to ensure the generated GWPZ. For this purpose, groundwater monitoring well data for the districts of Cuddalore, Kallakurichi and Villupuram districts of Tamil Nadu were obtained from PWD. The general criteria for selecting the wells for validation are: presence of well within the study area boundary and existence of month wise data at least for 7 years and the fall of wells within the delineated GWPZ classes. Based on the criteria, about 7 wells were chosen for the validation of the results. The GWPZ classes such as excellent, good, moderate, fair and poor was compared with the measured groundwater level data to validate the GWPZ map (Fig.7). The groundwater level fluctuation in poor GWPZ ranged from 1 to 24.4 m with an average value of8.4 m, in fair GWPZ from 1to8 m with an average value of 4.05 m, and in good GWPZ from 1.6 to 5.3 m with an average value of 3.3 m. The monitoring wells that fall within the excellent and moderate classes GWPZ are scarce and hence such validation was not incorporated. Finally, the obtained results indicate that groundwater level fluctuation was very shallow in the good GWPZ than in the fair and poor GWPZ in the study region. Thus, the demarcated GWPZ map is validated with the measured groundwater level data from the study area.

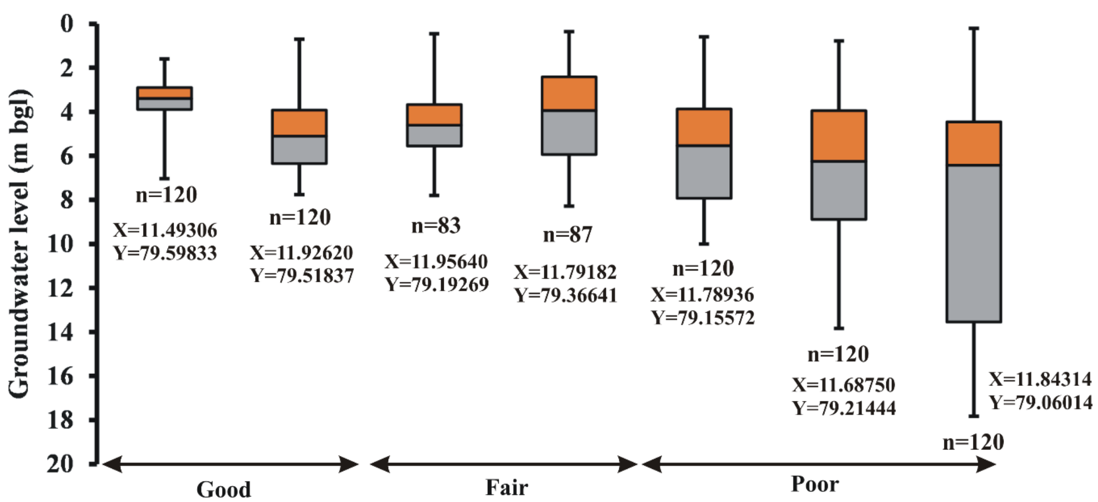

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Figure 7. Groundwater level fluctuation in different GWPZ

Identification of suitable managed aquifer recharge structures

Cross-section

The cross-section of the study area was prepared using the lithologs obtained from the WRD, Tamil Nadu. About 21 litholog data were carefully chosen in such a way that it would represent the subsurface along the major rivers and also parallel to the coastline. Based on the obtained lithologs about four cross-sections were prepared as follows: Cross-section 1 - covering the length of about 24 km along Pennaiar; Cross-section 2 - covering the length of about 18 km along Gadilam; Cross-section 3 - covering the length of about 23 km along Paravanar and Cross-section 4 - covering the length of about 14 km parallel to the shore line from the distance of about 8 km. From the figure 8, it is observed that the sub-surface formations of the study area are dominated with the sand followed by clay, sandstone, clayey sand and sandy clay. Few patches of limestone, laterite and lignite were observed in the study area. Since the subsurface is dominated with the sand formation especially along the Pennaiar and Gadilam rivers, it can be utilised as a potential site for groundwater recharge. Hence the implementation of artificial recharge structures such as check dam, percolation tank etc within the study area will cultivate the excess runoff during floods and enhance the groundwater recharge in the study region.

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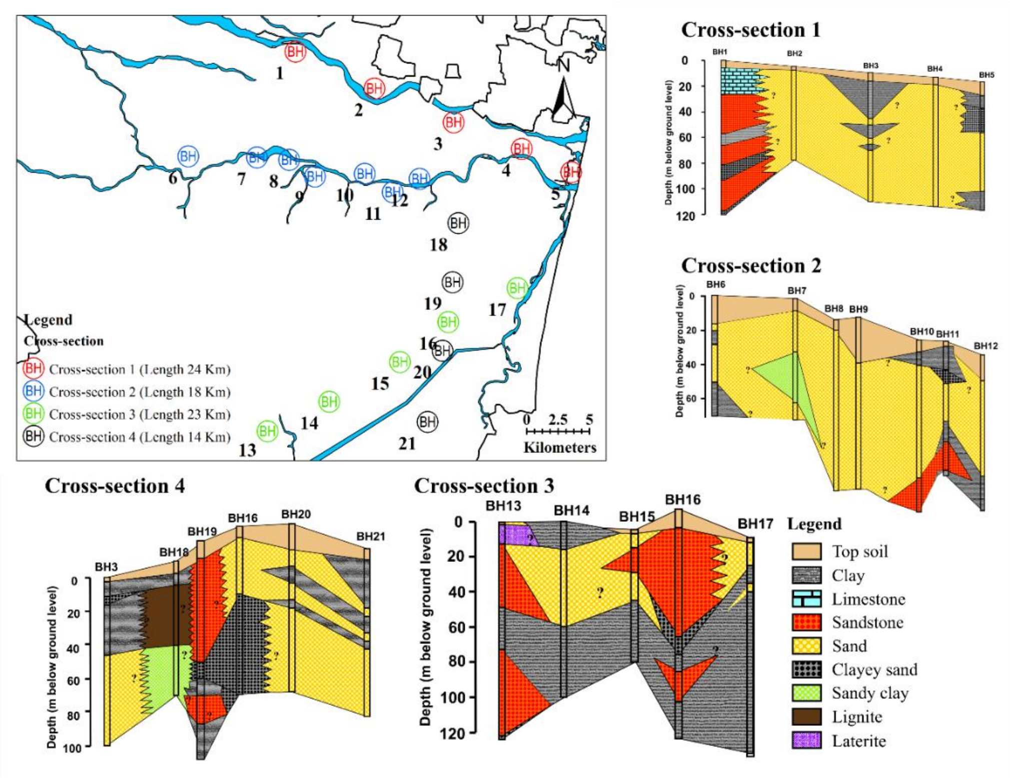

Figure 8. Cross-section along and across the major rivers present in the study area

Optimisation of managed aquifer recharge structures

The selection of suitable sites for groundwater recharge is one of major concern that has been identified for the study area through Boolean logical method. Recharge structures like check dam, percolation ponds, ditch and furrows, flood and furrows are considered as the suitable recharge structures for the study site based on the criteria in table S4 as reported by Anand et al (2021). In addition to the slope and drainage of the study area, the land use and land cover pattern and field observations are also significantly contributing for the site selection of recharge structures. Suitable locations identified for the construction of various MAR structures are shown in figure S1 (supplementary material). Though the suitable sites were selected for the construction of various structures, it is also essential to optimise such sites and type of structures based on its efficiency and regional hydrogeological setup. Considering the fact, the study area with the presence of multiple major rivers and frequent flood events, the study was curbed to suggest suitable sites for construction of additional check dams towards the cropping of excess runoff water in the river channels. Sundaramoorthy et al (2022) reported that the construction of check dams at the confluence point of rivers in the study region prevents the inward of seawater during high tide periods thus improves the water quality of the region.

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In addition to that, from the CGWB (2015) report and the historical data it is clearly evident that the high priority was given to check dams since the surplus quantum of surface water discharged during monsoon in the basin. Further, as agriculture is the major activity in this region, the construction of check dam will improve the double / triple crop system in this region.

Demarcation of suitable sites for construction of check dams were achieved with the help of existing map (Figure S1, supplementary material) prepared through Boolean logical method along with the additional criteria such as stream network (2^{nd} and 3^{rd}order), lineaments and land use and land cover pattern. The suitable site for construction of check dams based on multiple criteria (figure 9a) were overlaid with the GWPZ and integrated with the subsurface sections. Based on the integration of multiple layers along with the existing lithological layers, the optimal locations identified for the construction of check dams are shown in figure 9b. About 10 locations were identified and proposed for the construction of check dams in which 4 locations falls in the surroundings of Pennair and 6 locations falls in the surroundings of Gadilam basin. Based on the GWPZ, out of ten locations five locations are situated over the "Good potential zones" and rest of the five locations are situated over "Fair groundwater potential zone". Since the subsurface formations in the proposed check dams are dominated with sand deposits, the replenishment of aquifer will take place significantly at shorter time interval. Further, the construction of proposed check dam especially in the southern banks of Gadilam river (classified as Fair GWPZ) will be helpful to enhance the regional groundwater potential in this region that sufficiently address the water scarcity during summer especially for domestic and irrigational purposes.

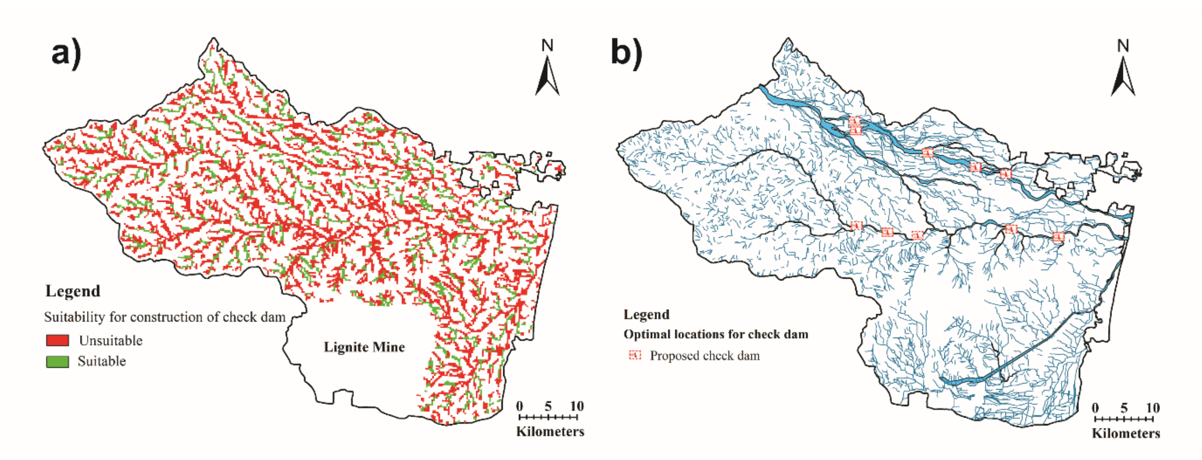

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Figure 9. a) Suitable zone for construction of check dam b) Optimal sites proposed for construction of check dam

Conclusion

The MAR technique is the most promising solution or addressing groundwater depletion especially in coastal regions. The coastal part of northern Tamil Nadu had been affected by frequent cyclonic and flood events over the years and conversely been reported as groundwater deficit region in recent years. Hence, the present study was carried out by delineating the GWPZ for understanding the present scenario of groundwater in this region and identifying the optimal sites for construction of MAR structures to make sustainable groundwater area. Satellite images derived remote sensing data along with conventional data were utilised for the preparation of the thematic layers followed by assigning appropriate weightage through the AHP and MCDM technique. The major findings of the study are

- The increase in drainage density of this region resulting into increase in surface runoff, conversely, the increase in lineament density of this region favours the groundwater recharge.
- Alfisol and Vertisols are dominant soil types of this region and the groundwater potential in this region are naturally high to moderate.
- Agricultural activities cover a major part of the study area that significantly act as a major source of groundwater recharge as irrigation return flow.
- Eventually, the GWPZ of the study area are classified into fives zones viz Excellent (51 km^2), Good (938km^2), Moderate (115km^2), Fair (1759km^2) and Poor (92km^2).
- Major part of the study area falls under 'Good' and 'Fair' GWPZ which collectively covers 32% and 59% of the total study area respectively.
- The GWPZ of the region falls under 'Good' category are pertaining to lower reaches of Pennair, Gadilam and Paravanar whereas rest of the region are dominated with 'Fair' category along with sparse of 'Moderate' and 'Poor' category.
- The study area classified under 'Excellent' category are restricted along the coastal zone due to the presence of recent sand deposit with high permeable formations.
- Based on Boolean logical technique, the suitable regions of MAR structures are identified and the optimal site for construction check dams were recommended.

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