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Delineation of Ground Water Recharge Potential Zones in Lahore District, Punjab, Using Remote Sensing and GIS Techniques

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Abstract : Lahore is the provincial capital of Punjab and the second most populous city in Pakistan. Aquifer recharge rates have been continuously decreasing over a long period of time, which has caused a significant decline in the water table level. Rapid population growth, urban development, and industrialization have all raised the demand for water supplies. Due to significant infrastructural development, a considerable portion of the land is now impervious and rainfall now drains as surface runoff rather than recharging the aquifer level. Average annual rainfall, one of the primary sources used to replenish the Lahore aquifer, is insufficient to prevent the depletion of the water table, and River Ravi stays almost dry except in rainy seasons. Geographic information system (GIS) and remote sensing (RS) techniques are used to find suitable areas for replenishment in the Lahore aquifer system in order to enhance sustainability and prevent decreasing groundwater levels. Distance from the water channel, land use/land cover (LULC), slope, geology, drainage density, rainfall, lineament density, and soil type are the eight layers that have been integrated with the GIS overlay analysis. Thematic maps are generated using both conventional and remote sensing data. These maps are eventually converted to raster data. Very good, good, moderate, poor, and very poor are the five zones that have been delineated. A good to very good suitable part was found to constitute 46.34% of the total study area.

Keywords: Groundwater, GIS, remote sensing, potential aquifer, overlay analysis.

Introduction

The primary elements of a hydrological system are groundwater recharge and accumulation. They are the result of water infiltrating through different layers of rocks and soil after rainfall in the watershed basin. The rate of infiltration fluctuates from area to area and is influenced by precipitation, composition of the rocks and soil, topography, climate, and moisture levels (Adham et al., 2010; Abdullateef et al., 2021). As a result, there will be regional variations in groundwater availability. The supply of usable surface water will often be relatively limited in areas with lower precipitation. For domestic and agricultural purposes, the inhabitants of such places have to rely on groundwater. The groundwater levels in various locations have decreased as a result of the increase in groundwater extraction. However, due to extensive development, the proportion of open areas that may be used for natural recharges has decreased (Chenini et al., 2010). In the regions where different rock layers are present, there are significant fluctuations in groundwater availability. To increase the supply of groundwater, it is required to recharge the depleted groundwater resources by artificial means.

In recent decades, different datasets have been integrated using GIS and RS techniques to identify suitable zones for groundwater recharge. The RS analysis and GIS for aquifer recharge potentiality depict hidden hydrogeologic features and deal with informative factors at the surface such as lithologic composition, drainage, lineaments frequency, and density, and LULC, It offers a more accurate computation and empirical evaluation of the recharge potential. Geospatial technology is a quick and economical technique employed in the demarcation of groundwater recharge potential zones (GRPZ) by combining numerous data from the slope, lineaments, lithology, LULC, etc. These data are used to generate themed maps with GIS software. Throughout the past decade, many researchers, including (Chenini et al., 2010; Adham et al., 2010; Yeh et al., 2014; Samson and Elangovan, 2015; Selvam et al., 2015; Souissi et al., 2018; Abdullateef et al., 2021) have employed RS and GIS to explore aquifers and identify groundwater recharge locations. GIS was used to demarcate the potential zone for groundwater by (Magesh et al., 2012; Agarwal et al., 2013; Kannan et al., 2016; Nasir and Zahid, 2018; Bera et al., 2020) Hydrogeological modeling has been developed by (Solomon and Quiel, 2006; Memon et al., 2020; Vellaikannu et al., 2021)with the use of GIS. A suitable framework for the multidimensional interpretation of various sets of data for evaluation in groundwater resource modeling and management can be provided by integrating GIS and RS. Therefore, utilizing GIS and RS techniques, the current study aims to examine the recharging of water into subsurface media and to generate a map of the district of Lahore's various zones with the potential for recharge.

Lahore is located between 31°15′ and 31°45′ N and 74°01′ and 74°39′ E, (fig. 1) and has a total area of 1842 km^2. It is surrounded by the Kasur district on the south, the Sheikhupura district on the north and west, and the Wagah on the east. North-western Lahore is bordered by the Ravi River. Due to urbanization and people's movement to Lahore, this city's population is continuously expanding dramatically (Mahmood et al., 2013). The city completely depends on groundwater (Kanwal et al., 2015). Rainfall and the Ravi river are the main sources of recharging the groundwater in Lahore (Mahmood et al., 2013; Kanwal et al., 2015).

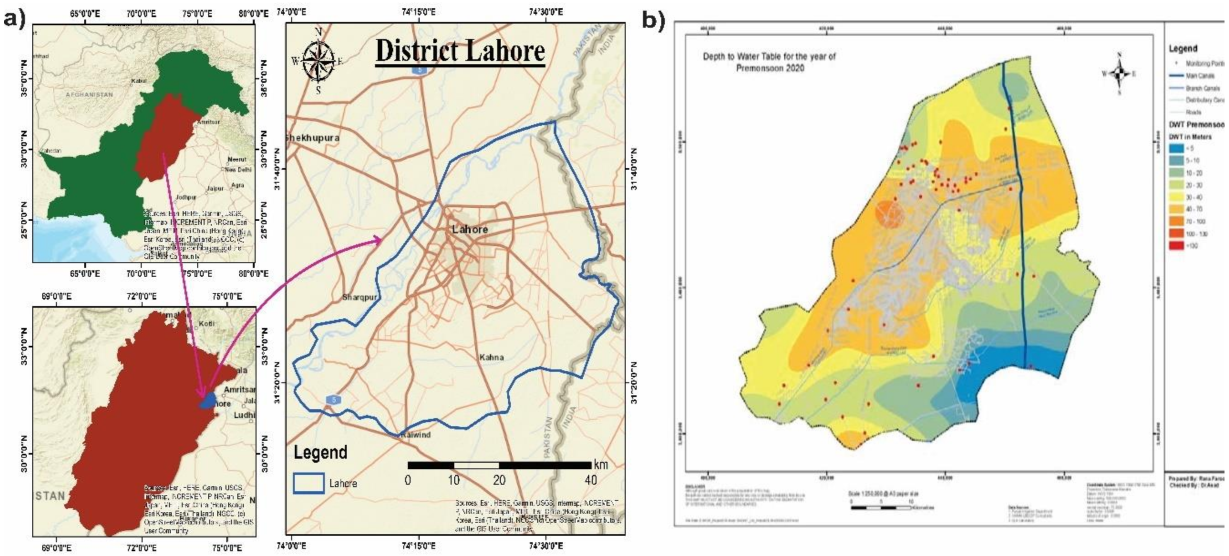

Fig. 1 a) Geographic location of the study area. b) Depth to the water table for the year of pre-monsoon 2020 (Qureshi and Syed, 2014).

Lahore is a subtropical, semi-arid territory with a mean annual precipitation of 575mm, however, this may range between 300-1200mm, accounting for more than 40% of yearly aquifer recharge. The Ravi river's water flow influences a significant proportion of the remaining recharge supply. The main issue is that the region's need and availability for water are out of balance due to the excessive use of groundwater and inequitable distribution of the aquatic environment, making water governance a crucial issue to address (Kanwal et al., 2015). Groundwater overuse should be reduced, which would benefit the area's natural resources and reduce ever rising pumping costs in Lahore.

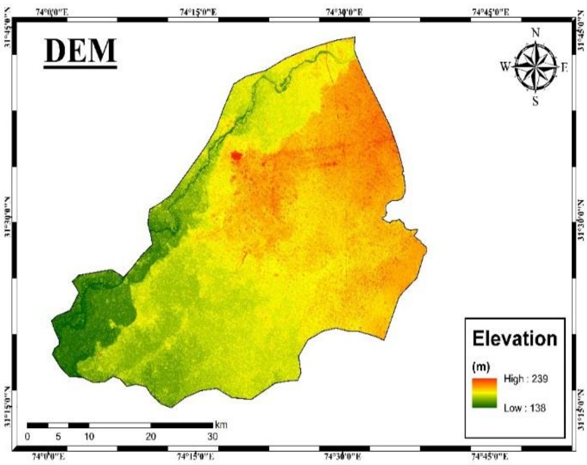

Fig. 2 SRT elevation model of study area.

Materials and Methods

Using the Euclidean distance approach, a digital thematic distance from streams map is created in order to integrate the impact of rivers and streams on GRPZ. Thematic layers such as LULC, rainfall, drainage density, slope, geology, lineament density, and soil type, of the research area are prepared using Pakistan geological, tectonic maps, satellite imagery like SRTM DEMand other collateral data (Fig. 2).

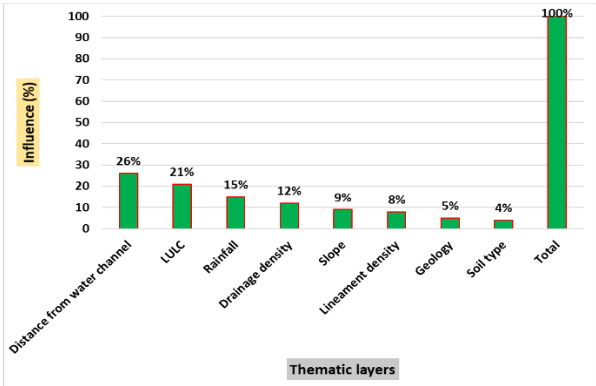

Fig. 3 weights of thematic layers used in this study for groundwater recharge.

The integration of all the thematic layers is done using the multicriteria decision-making (MCDM) analytic hierarchy process (AHP). Based on their ability to retain groundwater, individual thematic layers and the categories that correspond to them are given knowledge base weights, which are computed (Fig. 3). Visually evaluating imagery that has been digitally upgraded makes an effort to utilize the complementary skills of the human mind and the computer. (Abdalla, 2012). The complete methodology flowchart is shown in Figure 4. These parameters impacting groundwater recharge, as well as their respective weight, were assembled from prior research (Edet et al., 1998;

Kumar et al., 2007; Chowdhury et al., 2009; Ravindran and Selvam, 2014; Satheeshkumar et al., 2016; Pinto et al., 2017).

Results and Discussion

Distance from streams

In a watershed, groundwater recharge occurs frequently near stream banks. In order to incorporate the influence of rivers and streams on GRPZ, a digital thematic distance from streams map was prepared using the Euclidean distance method, (fig. 4). For distance to the streams and rivers in the range of 0–500 and 510–1500, there is a high potentiality of groundwater. In contrast, distances in the ranges of 1600–3500, 3600–5000, and more than 5100 have lower groundwater recharge potentiality.

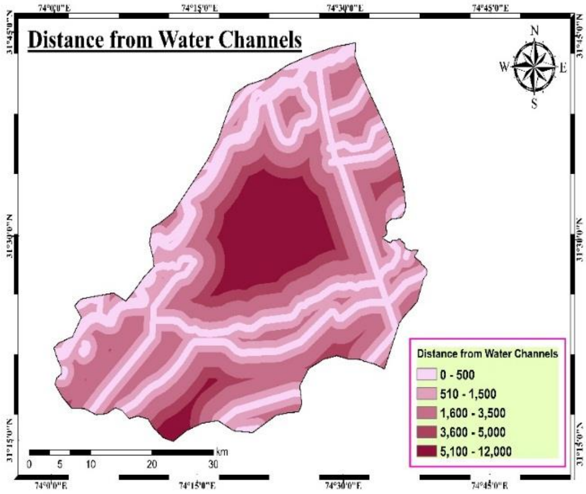

Fig. 4 Map showing distance from water channels.

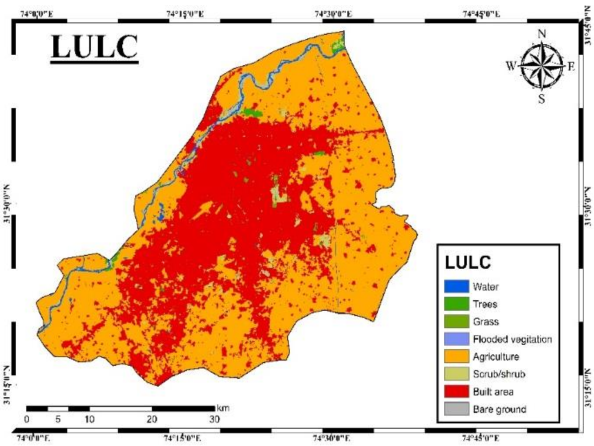

Fig. 5 LULC map of the Lahore district.

LULC

Runoff, groundwater recharge, and evapotranspiration are hydrogeological processes that are directly impacted by a basin's LULC. Diverse land use types have quite different recharge and runoff conditions (Saraf and Chaudhary, 1998; Yeh et al., 2014). LULC map 2020 with a spatial resolution of 10m is obtained on the Esri website. Eight classifications were used to categorize the research region, including waterbodies, trees, grass, flooded vegetation, agricultural land, scrub/shrub, built area, and bare ground (Fig. 5). Land use categorization for weighted overlay analysis was determined based on land-use type, area coverage, and capacities to permeate water, as well as their capabilities to hold water on the surface of the ground. Water bodies and flooded vegetation were given a higher weightage due to their high water holding capability, contrary to the low-weighted barren land and built-up areas.

Rainfall

Rainfall is the primary source of groundwater recharge, determining the quantity of water available to permeate the groundwater system (Obi et al., 2000). The Climatic Research Unit (University of East Anglia) and NCAS datasets are used to create the rainfall map for the period 2011–2020 for this study. After importing the data into a GIS platform, the spatial interpolation method Inverse distance weighted (IDW) is used to create the rainfall map. The average annual rainfall from 2011 to 2020 was calculated using cell statistics, and it was then categorized into five subclasses with values spanning from 580 to 730 mm/year. (Fig. 6). A high groundwater recharge potential is often indicated by a high yearly rainfall distribution (Murthy, 2000; Srivastava and Bhattacharya, 2006). Therefore, during the evaluation of the feasibility of groundwater recharge, the region with a huge amount of yearly rainfall is given a higher weight value than the area with a low amount.

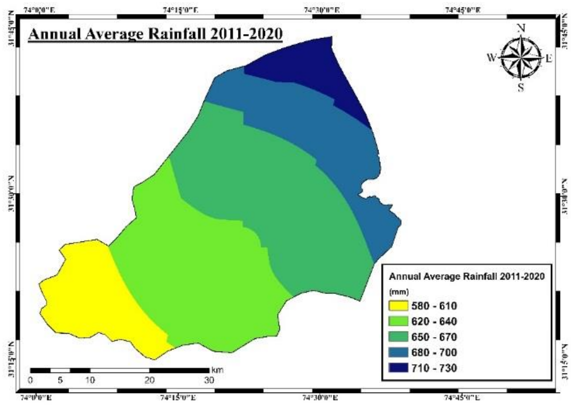

Fig. 6 Map showing annual average rainfall 2011-2020 in the study area.

Drainage Density

The closeness of the water channel placement is referred to as drainage density. It is the quantification of the cumulative length of all orders' stream segments in a given unit of area. An inverse relationship exists between drainage density and permeability. Rainfall penetration decreases when the rock permeability decreases, but this has the opposite effect of making surface runoff more prevalent (Senthilkumar et al., 2019). Implementing the hydrology tool in ArcGIS 10.5, the enhanced DEM is utilized to determine the pattern of water accumulation and surface flow. Five classes of drainage density have been established for the research region. These classifications have been given the following designations: "very good" (0.77 km/km^2), "good" (0.62 km/km^2), "moderate" (0.47 km/km^2) "poor" (0.31 km/km^2), and "very poor" (0.16 km/km^2). In the south and central part of the research region, there is a high drainage density (0.77 km/km^2) (Fig. 7). The drainage density has a relationship with runoff water and permeability, which indirectly influences the availability of groundwater recharge potential zones.

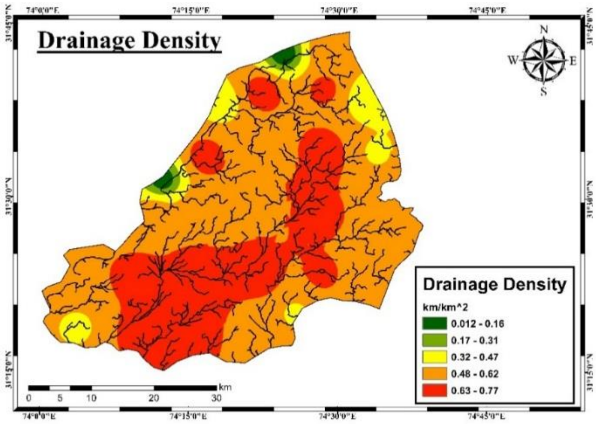

Fig. 7 Drainage density map of the study area.

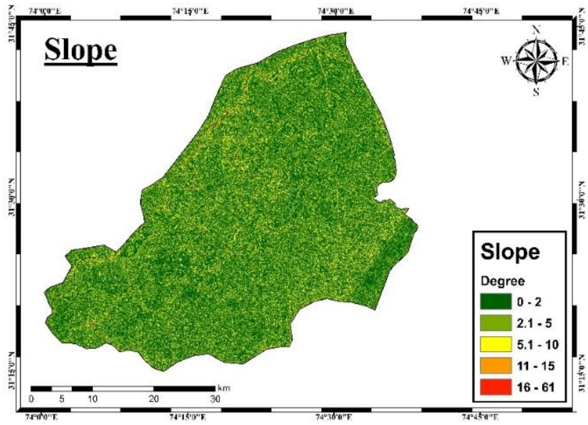

Fig. 8 Map showing the slope (degree) of the Lahore territory.

Slope

Any terrain's slope is crucial in permitting water to infiltrate the underlying system (Sing et al., 2011). In areas with a moderate slope, the runoff will be slow, allowing a longer period for rainfall to infiltrate, while areas with a steep slope will experience significant runoff with a little time for rainwater to permeate the ground. The DEM of 12.5 m spatial resolution was used to generate the slope map of the research area, which was then divided into 5 categories: almost level/no slope (0-2 degrees), gentle slope (2.1-5 degrees), moderate (5.1-10 degree), moderate to severe (10.1-15 degree), and extremely steep (> 15 degrees) (Fig. 8). According to the factors influencing the aquifer recharge, holding, and occurrence, the ranks were given to each slope class.

Lineament Density

In bedrock areas, lineaments are linear or curvilinear features on the earth's surface that indicate the weaker section of the surface and underlying rocks and are regarded as secondary aquifers. Satellite data is used to map these lineaments, which can be associated with bedding planes, lithological contacts, faults, joints, and fractures. In order to convert the morphological patterns into a numerical value, lineaments are taken from the tectonic map of Pakistan prepared by Kazmi and Rana in (1982). Lineaments enhance secondary permeability and secondary porosity and thus are reliable indications of groundwater recharge (Yeh et al., 2014; Souissi et al., 2018). This depicts the total length of lineaments in a given region as follows:

$$Lineament\ density = \sum_{i=1}^{n} \frac{L}{A} \quad (1)$$

where Li represents the total length of all lineaments in kilometers and A denotes the area of the grid in square kilometers. Near lineament junction sites, there is a considerable possibility for groundwater recharge. High lineament density areas have significant potential for groundwater recharging (Haridas et al., 1998). Figure 9. The lineament density map for the study area, which shows that the study area's southern side exhibits a high level of lineament density with a value that ranges from 0.34 to 0.46 km/km^2 (fig. 9).

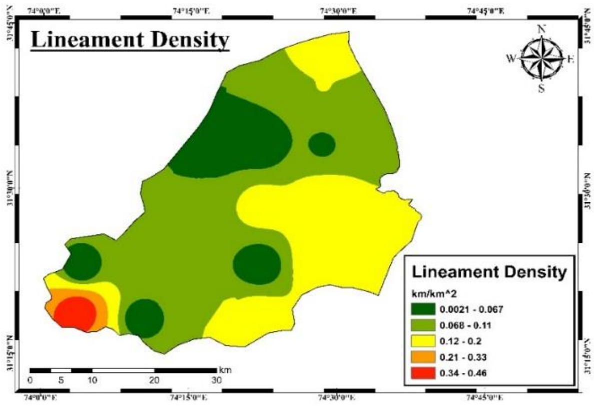

Fig. 9 Lineament density map of the Lahore district.

Geology

The geology of a region is thought to be a crucial factor in controlling groundwater recharge. It is beneficial to comprehend the structural significance, lithology, and various geological features in the research area with regard to their ability to infiltrate water (Senthilkumar et al., 2019). In Geological Survey of Pakistan's 1:1,000,000 scale geological map is used to map the geology of the study area. The relevant data was retrieved, digitized, and categorized correspondingly. Loess deposits of the upper terrace, stream deposits, and stream bed and meander belt deposits are the three main geological units that have been observed in the digitization of geological maps (Fig. 10). Depending on the potential for groundwater recharge and infiltration capacity, different ratings were given to various lithological units. Stream and stream bed and meander belt deposits received a high rating, whereas loess deposits of the upper terrace received a low one.

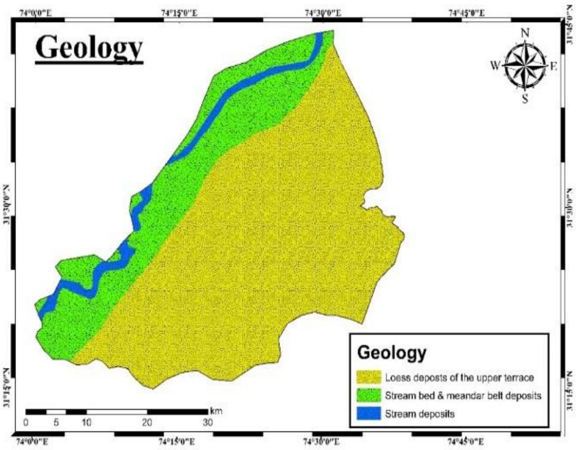

Fig. 10 Geological map of the study area.

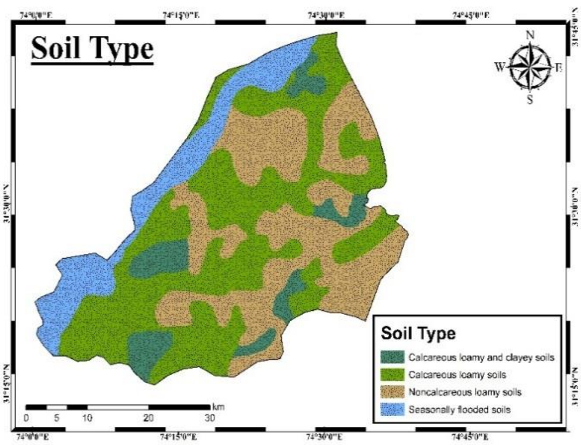

Fig. 11 Soil type map of the study area.

Soil Type

In the unsaturated zone, the mobility of groundwater is significantly influenced by soils. It is determined by the soil's moisture content, penetration rate, grain size distribution, and particular composition (Pratap et al., 2000; Selvam and Sivasubramanian, 2012). A soil map of Punjab (1978) created by the Pakistani Soil Survey was modified, digitalized, and categorized into four soil classes using the GIS platform (Fig. 11). Calcareous loamy soils dominate the majority of the watershed's soils (44.27%), whereas seasonally flooded soils are most prevalent towards the watershed's northwestern boundary (8.88%). Non-calcareous loamy soils cover up the sections of the region in the northern and southern parts (33.35%), while calcareous loamy and clayey type soil (1.69%) also occurs in a very minor patch along the edges of the study area. Calcareous loamy and clayey soils have a low infiltration rate and have less availability for groundwater recharge than seasonally flooded and calcareous loamy soils, which have a high infiltration rate.

AHP /MCDM

A well-known multi-criteria technique called the AHP method has been employed in the GIS-based suitability processes (Saaty 1980; Kumar et al., 2007; Pinto et al., 2017; Abdul lateef et al., 2021). Utilizing MCDM (AHP) approach, a pairwise comparison matrix was performed to assess the significance of two-layer maps in order to demonstrate that one of them has a greater impact on the groundwater recharge than the other. (Table 1). Since the consistency ratio (CR) value was calculated to be 0.012, it was regarded as suitable. Maps of distance from water channels, LULC, geology, drainage density, rainfall, lineament density, slope, and soil type are prepared and given the appropriate normalized weights (Table 2). The relative weight of each criterion and its related classes was taken into account in order to compute the total weightage of both the major criteria and sub-criteria (Table 3). A raster map with a 12.5m × 12.5m pixel size was created by each thematic map. Eventually, a raster map of the potential zone for groundwater recharge was generated by employing the cumulative weight in the GIS environment.

Table 1 Pairwise comparison Matrix table of ten thematic layers chosen for the present study.

Parameter	DWC	LULC	R	DD	S	LD	G	ST
DWC	1	1	2	2	3	4	5	6
LULC	1	1	1	2	2	3	4	5
R	1/2	1	1	1	1	2	3	4
DD	1/2	1/2	1	1	1	2	2	3
S	1/3	1/2	1/2	1	1	1	2	3
LD	1/2	1/3	1/2	1/2	1	1	2	3
G	1/5	1/4	1/3	1/2	1/2	1/2	1	2
ST	1/6	1/5	1/4	1/3	1/3	1/3	1/2	1

Note: DWC= Distance from water channels ; LULC= Land use/land cover; R= Rainfall; DD= Drainage density; S= Slope; LD= Lineament density; G= Geology; ST= Soil type

Table 2 Normalized AHP matrix.

Parameter	DWC	LULC	R	DD	S	LD	G	ST
DWC	0.25	0.21	0.30	0.24	0.28	0.29	0.26	0.22
LULC	0.25	0.21	0.15	0.24	0.18	0.22	0.21	0.19
R	0.13	0.21	0.15	0.12	0.18	0.14	0.15	0.15
DD	0.13	0.10	0.15	0.12	0.09	0.14	0.10	0.11
S	0.08	0.10	0.08	0.12	0.09	0.07	0.10	0.11
LD	0.06	0.07	0.08	0.06	0.09	0.07	0.10	0.11
G	0.05	0.05	0.05	0.06	0.05	0.04	0.05	0.07
ST	0.04	0.04	0.04	0.04	0.03	0.02	0.03	0.04

According to their ability to absorb water, each thematic layer's classes were reclassified and given the appropriate rankings (Table 3). The GRPZ map was generated using a weighted overlay analysis of cumulative weight percentages that were allocated for maps of distance from water channels, LULC, Rainfall, drainage density, geology, slope, lineament density, and soil type (Fig. 12). Higher weight represents a greater possibility for water infiltration, while lower weight indicates a lesser possibility of water infiltration. The groundwater recharge potential map of the study area is classified into five zones based on the weighted overlay analysis: very good, good, moderate, poor, and very poor potential. Good potential zone is the most dominant at 38.47%, followed by the moderate potential zones at 29.19%, the poor and very poor potential zone at 18.79% and 5.68%, respectively, and the very good potential zone at 7.87%. The bar chart depicts the proportional percentage of each zone (fig. 13). GRPZ have very good potential in the area's northern and northeastern parts, while the good potential is seen in the study area's periphery (Fig. 13). Small portions of poor and very poor GRPZ are detected in the study area's central and southern parts.

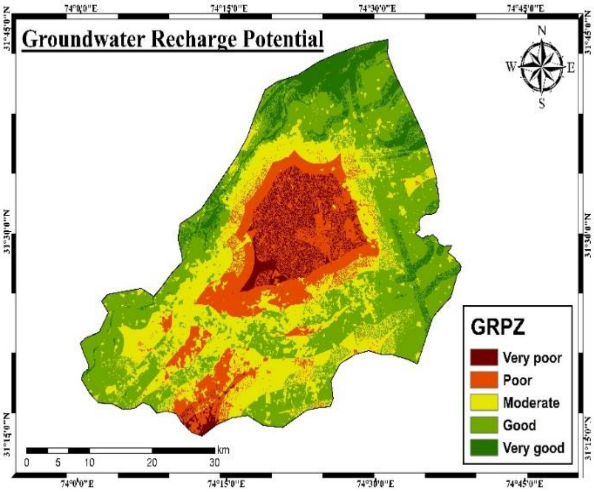

Fig. 12 Map showing the GRPZ of the Lahore district.

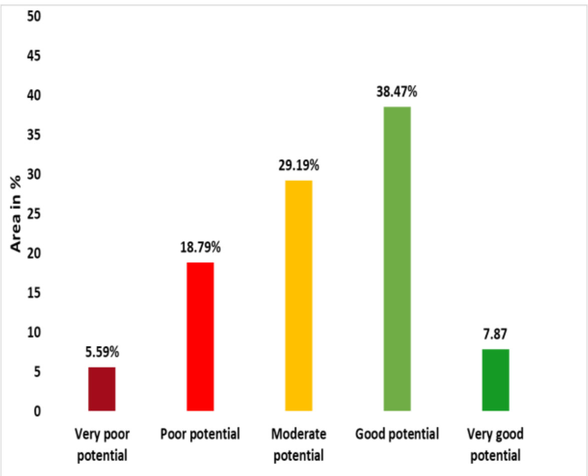

Fig. 13 % potential zones for groundwater recharge of the study area.

Table 3 Thematic layer wise features, weightage, and rankings

Influencing factor	Classes	Weight	Influence (%)	Rank Scale (1-9)	Descriptive Scale
Distance from water channels	0-500	0.26	26	8	High-very high
	510-1500			7	High
	1600-3500			5	Moderate
	3600-5000			3	Low
	5100-12000			1	Very low
LULC	Water	0.21	21	8	High-very high
	Trees			4	Low-moderate
	Grass			5	Moderate
	Flooded vegetation			6	Moderate-High
	Agriculture			6	Moderate-High
	Scrub/shrub			5	Moderate
	Built up			2	Very low-low
	Bare ground			3	Low
Rainfall (mm)	580-610	0.15	15	4	Low-moderate
	620-640			5	Moderate
	650-670			6	Moderate-High
	680-700			7	High
	710-730			8	High-very high
Drainage density (km/km^2)	0.012-0.16	0.12	12	8	High-very high
	0.17-0.31			6	Moderate-High
	0.32-0.47			5	Moderate
	0.48-0.62			4	Low-moderate
	0.63-0.77			3	Low
Slope (Degree)	0-2	0.09	9	9	Very high
	2.1-5			7	High
	5.1-10			6	Moderate-High
	11-15			5	Moderate
	16-61			2	Very low-low
Lineament density (km/km^2)	0.0021-0.067	0.08	8	4	Low-moderate
	0.068-0.11			5	Moderate
	0.12-0.2			6	Moderate-High
	0.21-0.33			7	High
	0.34-0.46			8	High-very high
Geology	Loess deposits of the upper terrace	0.05	5	4	Low-moderate
	Streambed & Meander belt deposits			6	Moderate-High
	Stream deposits			7	High
Soil type	Seasonally flooded soils	0.04	4	7	High
	Calcareous loamy & clayey soils			5	Moderate
	Calcareous loamy soils			3	Low
	Non-calcareous loamy soils			4	Low-moderate

Conclusion

It is concluded that areas with very good groundwater potential account for 7.87% of the entire area (144.89 km^2), good potential areas cover 38.47%, and moderate potential areas constitute 29.19% of the area (537.37 km^2) while, poor and very poor recharge potential areas have 18.79% and 5.68% of the whole area (345.95 km^2) and (104.53 km^2) respectively. The results of this study may be useful for developing groundwater resources in sustainable and efficient manner. Geophysical techniques (of. Vertical electrical sounding and seismic refraction) can be used to validate these results by measuring the groundwater level fluctuation and volume of the aquifer.

References

Abdalla, F. (2012). Mapping of groundwater prospective zones using remote sensing and GIS techniques: a case study from the Central Eastern Desert, Egypt. *Journal of African Earth Sciences*, **70**, 8–17.

Abdullateef, L., Tijani, M.N., Nuru, N.A., John, S., Mustapha, A. (2021). Assessment of groundwater recharge potential in a typical geological transition zone in Bauchi, NE-Nigeria using remote sensing/GIS and MCDA approaches. *Heliyon*, **7**(4).

Adham, M.I., Jahan, C.S., Mazumder, Q.H., Hossain, M.M.A., Haque, A.M. (2010). Study on groundwater recharge potentiality of barind tract, Rajshahi District, Bangladesh using GIS and remote sensing technique. *Journal Geological Society of India*, **75**, 432-438.

Agarwal, E., Rajat, A., Garg, R.D., Garg, P.K. (2013). Delineation of groundwater potential zone: an AHP/ANP approach. *J. Earth Syst. Sci.*, **122** (3), 887–898.

Bera, A., Mukhopadhyay, B. P., Barua, S. (2020). Delineation of groundwater potential zones in Karha river basin, Maharashtra, India, using AHP and geospatial techniques. *Arab. J. Geosci*, **13**, 693.

Chenini, I., Mammou, A. B., May, M.E.l. (2010). Groundwater recharge zone mapping using GIS-based multi-criteria analysis: a case study in Central Tunisia (Maknassy Basin). *Water Resources Management*, **24** (5), 921–939.

Chowdhury, A., Jha, M.K., Chowdary, V.M., Mal, B.C. (2009). Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. *Int. J. Remote Sens.*, **30** (1), 231–250.

Edet, A.E., Okereke, C.S., Teme, S.C., Esu E.O. (1998). Application of remote-sensing data to groundwater exploration: a case study of the Cross River State, southeastern Nigeria. *Hydrogeology Journal*, **6** (3), 394–404.

Haridas, V.R., Aravindan, S.,Girish, G. (1998). Remot e sensing and its applications for groundwater favourable area identification. *Quarterly Journal of GARC*, **6** (6), 18–22.

Kanwal, S., Gabriel, H., Mahmood, K., Ali, S.R., Haidar, A., Tehseen, T. (2015). Lahore's groundwater depletion-a review of the aquifer susceptibility to degradation and its consequences. *Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan*, **20**, 26-38.

Kannan, R., Venkateswaran, S., Prabhu M.V., Satheeskumar, S. (2016). Geomorphological mapping for identification of groundwater potential zones in hard rock areas using geospatial information—a case study of Nagavati Watershed in Dharmapuri District, Tamil Nadu, India. *Indian J Appl Res*, **6** (2), 68–70.

Kumar, P.K.D, Gopinath, G., Seralathan, P. (2007). Application of remote sensing and GIS for the demarcation of groundwater potential zones of a river basin in Kerala, southwest coast of India. *International Journal of Remote Sensing*, **28** (24), 5583–5601.

Mahmood, K., Rana, A.D., Tariq, S., Kanwal, S., Ali, S. R., Ali, A., Tahseen, T. (2013). Groundwater levels susceptibility to degradation in Lahore Metropolitan. *Science International-Lahore*, **25** (1),123-126.

Magesh, N.S., Chandrasekar, N., Soundranayagam, J. P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. *Geoscience Frontiers*, **3** (2), 189-196.

Memon, A., Ansari, K., Soomro, A.G., (2020). Estimation of groundwater potential using GIS modeling in Kohistan region Jamshoro district, Southern Indus basin, Sindh, Pakistan (a case study). *Acta Geophys*, **68**, 155–165.

Murthy, K.S.R. (2000). Groundwater potential in a semi-arid region of Andhra Pradesh: a geographical information system approach. *Int. J. Remote Sens.*, **21** (9),1867–1884.

Nasir, M.J., Khan, S., Zahid, H. (2018). Delineation of groundwater potential zones using GIS and multi influence factor (MIF) techniques: a study of district Swat, Khyber Pakhtunkhwa, Pakistan. *Environ Earth Sci*, **77**, 367.

Obi, R., Chandra, G.P., Mouli, K., Srivastav, S.K., Srinivas, C.V., Maji, A.K. (2000). Evaluation of groundwater potential zones using remote sensing data—a case study of Gaimukh watershed, Bhandara district, Maharashtra. *J. Indian Soc. Remote Sens.*, **28** (1), 3–19.

Pinto, D., Shrestha, S., Babel, M.S., Ninsawat, S. (2017). Delineation of groundwater potential zones in the Comoro watershed, Timor Leste using GIS, remote sensing and analytic hierarchy process (AHP) technique. *Appl. Water Sci.*, **7**, 503–519.

Pratap, K., Ravindran, K.V., Prabakaran, B. (2000). Groundwater prospect zoning using remote sensing and geographical information system: a case study in Dala-Renukoot area, Sonbhadra District Uttar Pradesh. *J. Indian Soc. Remote Sens.*, **28** (4), 249–263.

Qureshi, A.S., Ali, H.S. (2014). Situation analysis of the water resources of Lahore: Establishing a case for water stewardship. 10.13140/2.1.4000.6728.

Ravindran, A., Selvam, S. (2014). Coastal disaster damage and neotectonic subsidence study using 2D ERI technique in Dhanushkodi, Rameshwaram Island, Tamilnadu, India. *MiddleEast J Sci Res*, **19**(8), 1117–1122.

Saaty, T.L. (1980). The analytic hierarchy process: planning, priority setting, resource allocation. New York, NY: McGraw-Hill International Book Company.

Samson, S., Elangovan, K. (2015). Delineation of groundwater recharge potential zones in Namakkal District, Tamilnadu, India using remote sensing and GIS. *J. Indian Soc. Remote Sens.*, **43** (4),769–778.

Satheeshkumar, S., Venkateswaran, S., Kannan, R. (2016). Application of geoinformatics for groundwater prospects zones—a case study for Vaniyar sub basin of Ponnaiyar river in South India. *Indian J. Appl. Res.*, **6** (2),310–313.

Selvam. S., Sivasubramanian, P. (2012). Groundwater potential zone identification using geoelectrical survey: a case study from Medak district, Andhra Pradesh, India. *Int J Geomat Geosci*, **3** (1), 55–62.

Selvam, S., Magesh, N.S., Sabarathinam, C., Sashikkumar, M.C. (2015). A GIS based identification of groundwater recharge potential zones using RS and IF technique: a case study in Ottapidaram taluk, Tuticorin district, Tamil Nadu. *Environ Earth Sci*, **73**, 3785–3799

Saraf, A. K., Choudhary, E. R. (1998). Integrated remote sensing and GIS for ground water exploration and identification of artificial recharge sites. *Int. J. Remote Sens.*, **19** (10), 1825–1841.

Senthilkumar, M., Gnanasundar, D.,Arumugam, R. (2019). Identifying groundwater recharge zones using remote sensing & GIS techniques in Amaravathi aquifer system, Tamil Nadu, South India. *Sustain Environ Res*, **29** (15).

Singh, C. K., Shashtri, S., Singh. A., Mukherjee, S. (2011). Quantitative modeling of groundwater in Satluj river basin of Rupnagar district of Punjab using remote sensing and geographic information system. *Environ. Earth Sci.*, **62** (4), 871–881.

Souissi, D., Msaddek, M.H., Zouhri, L., Chenini, I., May, M.E.I., Dlala, M. (2018). Mapping groundwater recharge potential zones in arid region using GIS and Landsat approaches, southeast Tunisia. *Hydrological Sciences Journal*, **63** (2), 251-268.

Solomon, S., Quiel, F. (2006). Groundwater study using remote sensing and geographic information systems (GIS) in the central highlands of Eritrea. *Hydrogeol. J.*, **14** (10), 1029–1041.

Srivastava, P. K., Bhattacharya, A. K. (2006). Groundwater assessment through an integrated approach using remote sensing, using remote sensing, GIS and resistivity techniques: a case study from a hard rock terrain. *Int J Remote Sens*, **27** (20), 4599–4620.

Vellaikannu, A., Palaniraj, U., Karthikeyan, S. (2021). Identification of groundwater potential zones using geospatial approach in Sivagangai district, South India. *Arab J Geosci*, **14**, 8.

Yeh, H. F., Lin, H.I., Lee, S.T., Chang, M.H., Hsu, K.C., Lee, C.H. (2014). GIS and SBF for estimating groundwater recharge of a mountainous basin in the Wu river watershed, Taiwan. *J Earth Syst Sci*, **123** (3), 503–516.