Spatial Assessment of Groundwater Potentiality Using GIS-Based Weighted Overlay Analysis: A Case Study of Leylan, Kirkuk, Iraq

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Abstract

Groundwater resources in the Leylan sub-district of Kirkuk, Iraq, face severe stress due to overexploitation, random drilling, and mismanagement, necessitating urgent scientific strategies for sustainable water exploration. This study aims to delineate Groundwater Potential Zones (GWPZs) across the region (743.33 km²) by integrating Geographic Information Systems (GIS) and Remote Sensing (RS) utilizing the Weighted Overlay analysis. Ten diverse geo-environmental and hydrological conditioning factors were evaluated: annual precipitation, lithology, stream frequency, slope, geology, elevation, lineament density, drainage density, soil types, and Land Use/Land Cover (LULC). The thematic layers were standardized and assigned relative weights based on their hydrogeological significance. Spatial integration was executed utilizing the GIS Weighted Overlay tool, governed by the mathematical model of the Groundwater Potential Index ($GWPI = \sum(Wi \times Ri)$

The resulting spatial model successfully categorized the study area into three distinct zones. Strategically, the **High Potential Zone**, which represents the prime target for well localization and Managed Aquifer Recharge (MAR), covers 180.69 km² (24.31% of the total area) and is characterized by highly permeable formations and optimal topographic depressions. The **Moderate Potential Zone**, acting as a vast regional aquifer reserve, encompasses the majority of the territory at 562.01 km² (75.61%). Conversely, the **Low Potential Zone** is highly restricted, occupying only 0.63 km² (0.09%) in isolated pockets. These findings provide a robust, data-driven framework to assist regional decision-makers in optimizing sustainable groundwater management and mitigating further hydrological depletion

• **The Moderate Potential Zone**: This zone covers a nearly whole size of the study area and carries a high proportion: 75.61% of study area of 562.01 km². It's largely the terrain of the territory in most of the region and includes most of the plains, middle and transition areas in the region.

• **The High Potential Zone**: It is a maximal area 180.69 km² and constitutes a large part of the drainage basin (24.31% of all the area in the total drainage basin). It is a long, topographic depressions and is distributed as the focal belts over the area and is composed of points like the ones at the belt, where the centre and southern parts intersect and the terrain features, where the topographic depressions meet

. • **The Low Potential Zone**: Only a small area of 0.63 km² (0.09%) is for which the region is found most effectively, as it is mostly confined in the very small pockets. Keywords: Groundwater Potential

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Zones (GWPZs)'Geographic Information Systems (GIS)'Remote Sensing (RS)'Multi-Criteria Decision Analysis (MCDA)'Managed Aquifer Recharge (MAR)'Spatial Modeling

. **Keywords:** Groundwater Potential Zones, Weighted Overlay Analysis, Lineament Density, Lithological Formations, Hydrological Factors, Managed Aquifer Recharge.

Introduction

Geographic Information Systems (GIS) and Remote Sensing (RS) have become pivotal in assessing groundwater potential in arid and semi-arid regions (12)(5). Advances in these technologies enable the integration of thick spatial data from various sources to significantly improve the prediction accuracy of aquifer locations compared to traditional methods (4)(10). Previous empirical investigations have successfully utilized GIS-based Weighted Overlay analysis to map groundwater potential zones (GWPZs) in various water-stressed environments. For instance, researchers identified parallel trends in mapping GWPZs across Ethiopia using this framework (20), while a similar Weighted Overlay and Multi Influence Factor (MIF) procedure was applied to create a groundwater potential map for the Swat District by integrating multiple thematic layers (15).

Despite the proven efficacy of these methodologies globally, many regions suffering from extreme water stress still lack systematic groundwater exploration (1). In Iraq, and specifically in the Leylan sub-district of Kirkuk Governorate, groundwater remains a critical lifeline but is subjected to severe anthropogenic stress. Currently, groundwater resources in the Leylan area are heavily overexploited and mismanaged. The prevalent practice of random, unregulated well drilling—conducted without a scientific site selection process—has led to significant financial losses, severe water shortages, and the alarming salinization of key groundwater basins.

Therefore, the primary objective of this study is to delineate and map GWPZs in the Leylan sub-district using a GIS-based Weighted Overlay approach. By thoroughly evaluating key environmental indicators, this research aims to develop a reliable scientific framework to guide optimal well placement and ensure the sustainable management of water resources in the region

Material and Methods

2.1. Data Acquisition, Pre-processing, and Field Survey

The assessment of groundwater potentiality relies on the integration of various spatial datasets. Cloud-free multispectral satellite imagery (e.g., Landsat-8 OLI / Sentinel-2), geological maps, and meteorological records (from the Iraqi Meteorological Organization) were acquired for the study area. To address spatial data gaps in precipitation records, the Inverse Distance Weighting (IDW) interpolation method was applied to meteorological data (18). For topographical and hydrological feature extraction, the **ASTER GDEM v3 (30-meter spatial resolution)** was utilized, and the drainage network and slope layers were derived using the standard D8 flow routing algorithm embedded within the GIS Spatial Analyst tools (8).

To ensure spatial consistency and accurate distance measurements (such as lineament and drainage densities), all raw spatial datasets were projected onto a unified, equal-distance coordinate system (WGS

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1984 UTM Zone 38N), which is specific to the Kirkuk region (7). Furthermore, all thematic layers were converted into Raster format and resampled to a uniform spatial resolution of 30 × 30 meters (cell size) to avoid any spatial mismatch during the integration process. Additionally, a comprehensive field survey was conducted in the Leylan sub-district between October 1 and October 6, 2025, to visually verify the prevailing geological outcrops, confirm Land Use/Land Cover (LULC) patterns, and collect coordinates and yield data for 28 existing groundwater wells.

2.2. Thematic Layers Reclassification In this semi-quantitative spatial model, the ten conditioning factors—geology, lithology, slope, elevation, drainage density, stream frequency, lineament density, soil types, LULC, and precipitation—were reclassified into five distinct suitability classes: Very Poor (1), Poor (2), Moderate (3), Good (4), and Excellent (5). The physical criteria for this reclassification were established based on local hydrogeological principles (17). For instance, areas with high lineament density and gentle slopes were assigned the highest rank (14) due to their significant capacity to enhance water infiltration, whereas impermeable lithology or steep slopes were assigned the lowest rank (1) reflecting high surface runoff.

2.3. Lineament Extraction and Density Mapping Lineaments, which represent surface expressions of geological structures such as faults, fractures, and joints, play a vital role in secondary porosity and groundwater movement. In this study, lineaments were mapped using a highly reliable visual-manual digitizing technique based on shaded relief (Hillshade) models derived from the ASTER GDEM v3 (30-meter spatial resolution).

To prevent directional bias caused by a single light source, four separate Hillshade layers were generated within ArcGIS using a fixed solar altitude of 45° and four distinct sun azimuth angles: 45° (Northeast), 135° (Southeast), 225° (Southwest), and 315° (Northwest). This multi-directional lighting enhanced the visibility of linear geological features running in different directions across the terrain.

Instead of using automated extraction software—which frequently misidentifies artificial features like roads, agricultural borders, and irrigation canals as geological lineaments—all structural features were visually identified and manually digitized on-screen at a consistent scale. This manual interpretation ensured that only true geological and geomorphological structures were captured, while all cultural and anthropogenic features were strictly excluded from the dataset. Once the clean lineament vector layer was completed, the Line Density tool in ArcGIS was utilized with a search radius of 1,000 meters to generate the final Lineament Density map (km/km^2).

2.4. Weight Assignment via Analytic Hierarchy Process (AHP)

2.5. Spatial Integration (Weighted Overlay)

The spatial integration was executed utilizing the **Weighted Overlay** tool within the GIS Spatial Analyst extension. The final Groundwater Potential Index (GWPI) for each spatial cell was calculated using the following mathematical model:

$$:GWPI=\sum(Wi\times Ri)$$

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Where: Prior to weight assignment, the selected factors were conceptually assessed to minimize severe multicollinearity effects, ensuring that closely related variables do not disproportionately inflate the final model. Subsequently, relative weights were determined based on the relative influence of each criterion on groundwater recharge. To ensure scientific objectivity rather than personal judgment, the **Analytic Hierarchy Process (AHP)** was employed to derive the normalized weights for the thematic layers, guided by existing hydrogeological literature (16) (**9**) (12)

- **GWPI**: Groundwater Potential
- Index.
- **Wi**: The relative weight assigned to factor i.
- **Ri**: The suitability rating score assigned to the specific class of factor i.

The finalized weights (Wi) and assigned sub-class ratings (Ri) for all parameters are presented in Table 1

No.	Thematic Layer (Criteria)	Assigned Weight (%)
1	Lithology	18%
2	Lineament Density	20%
3	Drainage Density	9%
4	Slope	11%
5	Geology	16%
6	Stream Frequency	7%
7	Precipitation	6%
8	Soil	6%
9	Land Use / Land Cover (LULC)	4%
10	Elevation	3%
		100%

2.6. Model Validation

To validate the reliability of the derived theoretical model, a ground-truthing spatial cross-validation was conducted. The precise coordinates of 28 actual groundwater wells, gathered during the field survey, were superimposed as a point layer onto the final GWPZs map. The actual operational yield of these wells (categorized as Good, Moderate, and Poor) was then spatially compared against the predicted zones to assess the model's predictive accuracy.

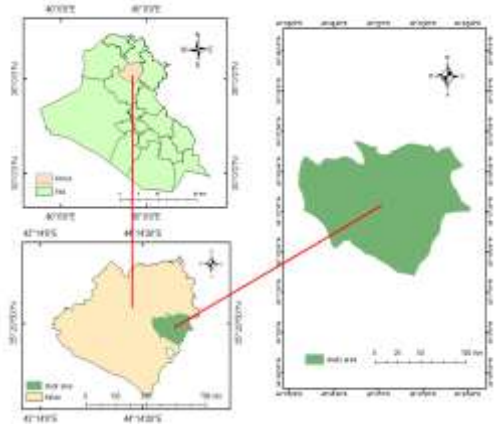


Figure 1: Map of the study area.

Results and Discussion

3.1. Factors Influencing Groundwater Potential Mapping

3.1.1. Rainfall

Figure 2 and Table 2illustrate the spatial distribution of annual precipitation across the Leylan sub-district. Daily and monthly rainfall records were acquired from the Iraqi Meteorological Organization and Seismology (IMOS), utilizing database records from the Kirkuk Meteorological

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Station and the local Leylan agricultural office over a 12-year recent period (2014–2025). This specific timeframe was selected to capture the most contemporary hydro-climatological dynamics and severe drought cycles affecting the region. The computed long-term mean annual precipitation exhibits a spatial distribution ranging from 214 mm in the lower plains to 243 mm in the higher elevated areas.

To maintain strict methodological consistency across the ten thematic layers within the Weighted Overlay framework, this continuous precipitation surface was standardized and reclassified into five distinct suitability classes (Table 2). However, from a practical hydrogeological perspective, the absolute spatial gradient of annual rainfall across the region is relatively narrow (only 29 mm, or approximately 13.5% variation). In semi-arid regions like Kirkuk, actual aquifer recharge is predominantly governed by localized, high-intensity, short-duration storm events (rainfall intensity) that trigger rapid runoff and infiltration, rather than uniform annual averages.

To address this limitation and avoid over-amplifying the role of this narrow annual rainfall gradient, the spatial model does not rely on precipitation as a dynamic local recharge indicator. Instead, localized runoff infiltration pathways are effectively captured by the highly weighted hydrological layers, specifically drainage density and stream frequency. Furthermore, to mitigate potential multicollinearity stemming from the orographic correlation between precipitation and topography, very low relative weights were assigned to both elevation (3%) and precipitation (6%) in the final Groundwater Potential Index (GWPI). This conservative weight assignment ensures that the spatial model is not artificially biased by topographically-controlled climatological factors, yielding a highly realistic representation of regional groundwater potentiality.

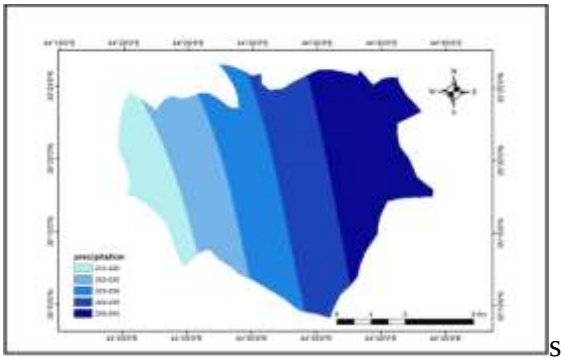

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Figure 2: Mean annual rainfall map of the study area.

Table 2: Categories, spatial extents, and suitability ratings of total annual precipitation within the study area.

Rainfall (mm)	Classification	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
220–214	Very Low	84.90	11.42	Very Low	1
225–220	Low	124.74	16.78	Low	2
230–225	Light / Moderate-Low	155.60	20.93	Moderate	3
235–230	Moderate	178.27	23.98	High	4
243–235	High	199.82	26.88	Very High	5

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3.1.2. lithological

his analysis has shown that the lithological units map covers the study area, highlighting the predominance of three geologic conglomerates conglomerate rocks (Conglomerate), river deposits (Fluvial Sediments), and clastic rocks (Clastics); 40.69%, 39.69%, and 22.62% (the total area; Table 3) across multiple lithological geographical data processing steps.

The areas with conglomeratic rocks and fluvial sediments exhibit the highest potential for groundwater storage and infiltration. within this study area. In contrast, these potentials sharply diminish in clastic rock-characterized zones. The variation emphasizes the significant role of the lithological factor as a cornerstone parameter for groundwater potentiality mapping and aquifer recharge measurements.

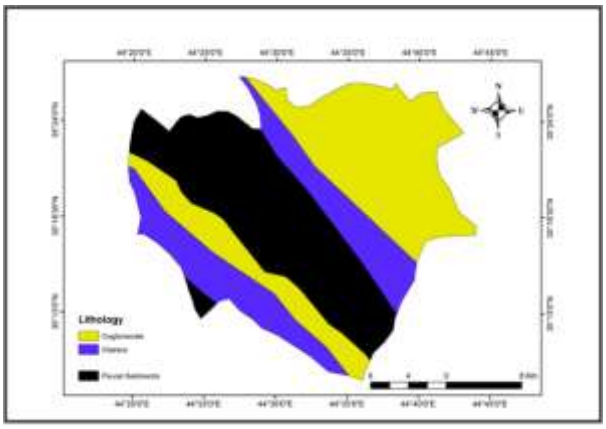


Figure 3: Lithological map of the study area

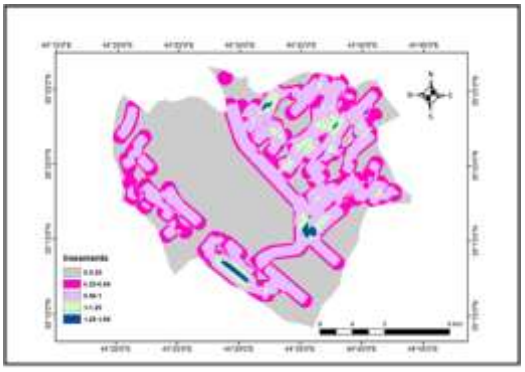
Table 3: Lithological units, spatial distribution, and groundwater suitability ratings in the study area.

Lithology Class	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
Clastic Rocks (Clastics)	168.04	22.62	Moderate to Low	2
River Deposits (Fluvial Sediments)	272.76	36.69	Very High	5
Conglomeratic Rocks (Conglomerate)	302.53	40.69	High	4

3.1.3. Lineament Density

Thus in regions with high lineament density of 1.25–1.55, the correlation can be observed in Figure 4 and Table 4, revealing a high groundwater potential, since fractures and faults are ubiquitous, thereby presenting a significantly enhanced permeability of the rock units, which facilitate the groundwater flow and circulation (2).

Figure 4: Lineament density map of the study area.



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Table 4: Lineament density classes, spatial distribution, and their suitability for groundwater potential.

Range (km/km2)	Classification	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
0.25–0.00	Very Low	355.0	47.76	Very Low	1
0.50–0.25	Low	133.17	17.92	Low	2
1.00–0.50	Moderate	222.4	29.92	Moderate	3
1.25–1.00	High	27.61	3.71	High	4
1.55–1.25	Very High	5.14	0.69	Very Hig	

3.1.4. Stream Frequency

Lower stream frequency areas, e.g. in terms of 0-1 /km^2 as shown in the Figure 5 and Table 5 generally present their surface characteristics in poor hydrological network development. This, in turn, enhances the residence time of surface water, thereby increasing the chance of water infiltration and percolation in the layers underneath that aquifer. On the other hand, high stream frequency (3–5 streams/km²)values signify the high density of the high surface drainage network which increases the velocity of surface runoff which decreases the ground water recharge opportunities drastically. There is thus much lower groundwater potential in these regions.

Figure 5: Stream frequency map of the study area.

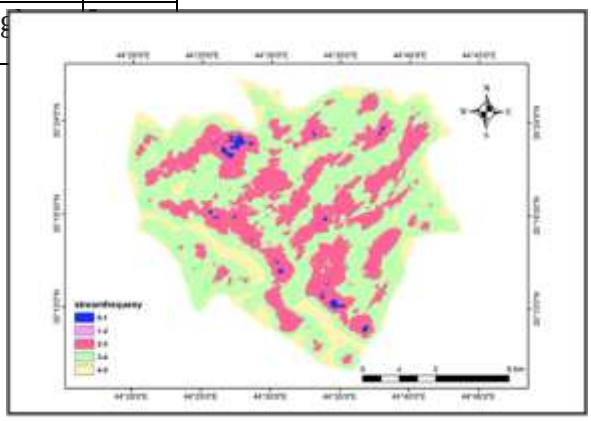


Table 5: Stream frequency classes, spatial distribution, and groundwater suitability ratings in the study area.

Range (streams/km2)	Hydrological Classification	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
1–0	Very Low	5.00	0.70	Very High	5
2–1	Low	0.62	0.06	High	4
3–2	Moderate	232.68	31.30	Moderate	3
4–3	High	410.87	55.27	Low	2
5–4	Very High	94.16	12.67	Very Low	1

3.1.5. Slope

Slope plays an extremely critical role in groundwater recharge as it directly controls the velocity of surface runoff and the duration of water infiltration into the soil. In this study, the slope map was generated from the ASTER GDEM v3 using the Slope tool

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in ArcGIS Spatial Analyst, with the output unit set strictly to **Degrees(^{0})** representing the slope angle.

To evaluate the infiltration capacity, the slope was reclassified into five distinct suitability classes (Table 6):

- **Flat to very gentle slopes (<3^{0}):** Awarded the highest suitability rating (5) because low-velocity runoff in flat terrains provides maximum retention time, allowing significant surface water to infiltrate and recharge the aquifer.
- **Gentle slopes (3□ -6 □)**Classified as Good (4).
- **Moderate slopes (6□-12 □)** Classified as Moderate (3).
- **Steep slopes(12□ - 18□)** Classified as Poor (2).
- **Very steep slopes (>18□):** Assigned the lowest suitability rating (1) because steep topography accelerates surface runoff, triggering high erosive velocity and preventing effective infiltration into the groundwater system.

Figure 6: Slope map of the study area

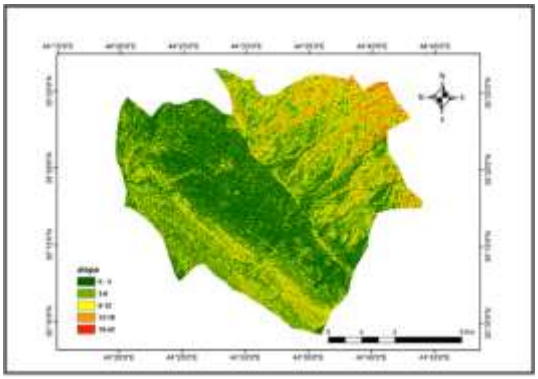


Table 6: Slope classes, spatial distribution, and groundwater suitability ratings in the study area.

Slope Range (Degrees □)	Classification	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
3>	Very Gentle	280.31	37.71	Very High	5
6–3	Gentle	255.96	34.43	High	4
12–6	Moderate	160.36	21.57	Moderate	3
18–12	Steep	36.15	4.86	Low	2
<43	Very Steep	10.51	1.41	Very Low	1

3.1.6. Soils

The surface area of 323.66 km² (43.57%) consists of the Yy10-2/3a soil unit which possesses good overall capacity for water

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recharge. This soil type has a generally lighter texture (sandy to sandy-silt loam) resulting in increased permeability rates and less surface runoff. As a result, deep water can potentially percolate into the system, which would make it highly suitable.

The second layer was the Xk9-2/3a based soil unit with an area of 153.59 km² (26.65%) under the groundwater potential suitability criteria. It is of medium texture (silty-clay loam with some sand), and hence medium permeability. This creates an intermediate state of groundwater recharge in the middle between retaining and draining water.

The study indicates that Xk28-b soil type is the least ideal unit to be set as a part for a land area of 266.08 km² (35.78%) of the mean soil area. Soil classification in this way derives from the fact that clayey or silty-clay textures predominate, increasing surface runoff rates cause a massive loss of permeability but also make recharge opportunities very difficult. Therefore, the soil units in the study area were ranked in descending order according to groundwater potentiality in the study area as indicated as:

- **Yy10-2/3a**: High Suitability
- **Xk9-2/3a**: Moderate Suitability
- **Xk28-b**: Low Suitability

Figure 7: Soil map of the study area.

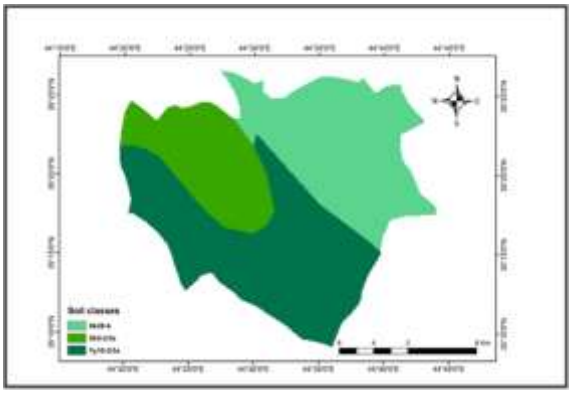


Table 7: Categories, spatial extents, and suitability ratings of soil units within the study area.

Soil Class	Area (km2)	Percentage (%)	Hydrogeological Classification	Rating
Xk28-b	266.08	35.79	Low Suitability	1
Xk9-2/3a	153.59	20.66	Moderate Suitability	3
Yy10-2/3a	323.66	43.54	High Suitability	5

3.1.7. Land Use and Land Cover (LULC)

In this study, the reclassification of the LULC layer reflects the localized hydro-meteorological and anthropogenic conditions of the Leylan sub-district. Water Bodies (0.70 km²) were assigned a High suitability rating (5). Hydrogeologically, these standing water features in Leylan act as focused recharge basins (depression-focused recharge hotspots). The continuous presence of water builds up substantial hydrostatic pressure (hydraulic head), which actively drives water downward into the underlying highly permeable conglomeratic aquifers, overcoming minor clay-silt sedimentation (19)(21).

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Furthermore, both Croplands (191.66 km²) and Pastures/Rangelands (502.98 km²) were assigned a Moderate suitability rating (3). This uniform classification is based on the prevailing land-use dynamics in northern Iraq. Pasturelands in this region are heavily affected by overgrazing and intensive livestock trampling, which severely compacts the upper soil horizons and lowers natural infiltration rates **(3)**. This ecological degradation levels their recharge potential to that of agricultural croplands, where soil tillage benefits are offset by heavy machinery compaction and soil crusting during fallow periods (6). Consequently, both layers exhibit moderate hydraulic conductivity over the annual cycle, justifying their joint classification as Class 3.

..**Figure 8:** Land Use/Land Cover (LULC) map of the study area.

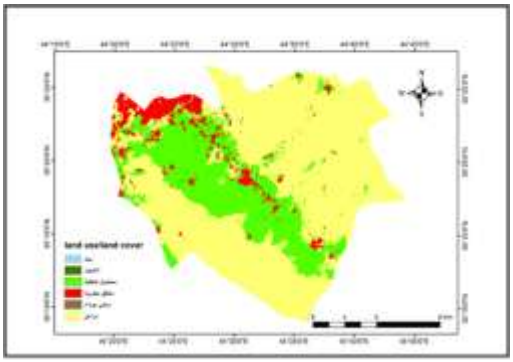


Table 8: LULC classes, spatial distribution, and groundwater suitability ratings in the study area.

LULC Class	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
Water Bodies	0.70	0.10	Very High	5
Trees	0.10	0.01	High	4
Field Crops	191.66	25.78	Moderate	3
Pastures / Rangelands	502.98	67.67	Moderate to High	3
Barren Land	3.59	0.48	Low	2
Urban Areas	44.30	5.96	Very Low	1

3.1.8. Elevation Above Sea Level (Elevation)

The indirect influence of elevation above sea level on groundwater distribution refers to the fact that elevation serves as a geomorphological determinant of surface runoff direction, transport energy, and spatial variations in infiltration rates. As a rule, low-elevation areas act as sinks for surface water to be deposited in a way that will increase groundwater recharge potential. On the other hand, high-elevation terrains are closely related to faster surface runoff velocities and shorter surface water residence time, which leads to a very low likelihood for deep water in subsoil aquifers.

Figure 9 and Table 9 illustrate that low-elevation regions (235-330m) have a relatively favorable water surface pool and infiltration situation that can be useful as a recharge ground water. When the elevation increases gradually, the kinetic energy of surface runoff increases, and the contact time between the water and the surface decreases, resulting in a smaller infiltration rate. In result, rapid runoff dynamics and steeper relative slope in very high elevation

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regions (660--862 m) make them to be highly resistant to groundwater recharge capability

.**Figure 9:** Elevation map of the study area.

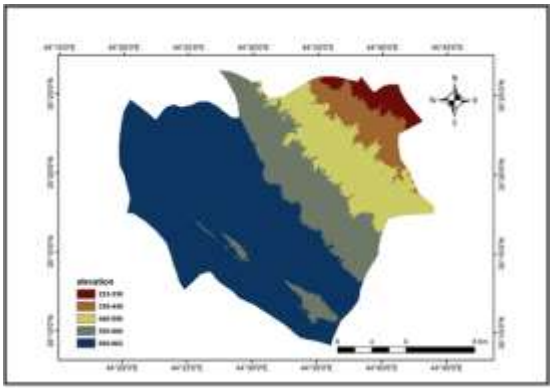


Table 9: Elevation classes, spatial distribution, and groundwater suitability ratings in the study area.

Range (m)	Topographic Classification	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
–235 330	Low Plain / Lowland	23.85	3.21	Very High	5
–330 440	Moderately Undulating	48.53	6.53	High	4
–440 550	Intermediate / Transitional	115.81	15.58	Moderate	3
–550 660	Sub-Mountainous / High	145.28	19.58	Low	2
–660 862	Mountainous / Very High	409.87	55.14	Very Low	1

3.1.9. Geological Formations (Geology)

• **Bai Hassan Formation:** Very appropriate (Rating 5) for groundwater potentiality. This is largely explained by the lithology of it primarily formed from cemented gravels (conglomerates) intercalated with sandstone and silt. These geological elements yield an High secondary porosity and permeability, and render the formation a perfect hydrogeological environment suited to groundwater infiltration, accumulation and economic storage.

• **Injana Formation (and related Fat'ha Formation):** Proximately forming a longitudinal band from the northwest to the southeast, the Injana Formation is moderately to high groundwater suitable. The permeability in these geological sequences can be clearly stratified. Contrary to the neighbouring Fat'ha Formation which is influenced periodically by the enrichment of carbonate rocks or structural fissures which strengthen its permeability, the Injana Formation is made up of successive successions of sandstone, silt and clay. The particular stratigraphic sequence makes it an efficient hydrogeological conduit and a local good reservoir for subsurface groundwater**.**

• **Mukdadiyah Formation**: The Mukdadiyah Formation, which lies alongside the Injana Formation, consists of 168.30 km², representing 22.64% of the total study area in a linear band and is moderately suitable for groundwater purposes. Its lithology is mainly argillaceous (clayey) sandstone and fine-grained sandstone mixed with clay. This mixed lithological entity presents a relatively more severe restriction to the flow of the groundwater when compared to the highly permeable Bai

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Hassan Formation. Therefore, it is of moderate hydrogeological quality with good storage volume but low groundwater flow rate and poor permeability.

- **Pleistocene**-Holocene deposits (Quaternary): Recent surface deposits are located mainly in the western and southwestern region of the sample. They cover 179.17 km² of spatial area. This amounts to 24.10% of total area.

Figure 10: Geological map of the study are

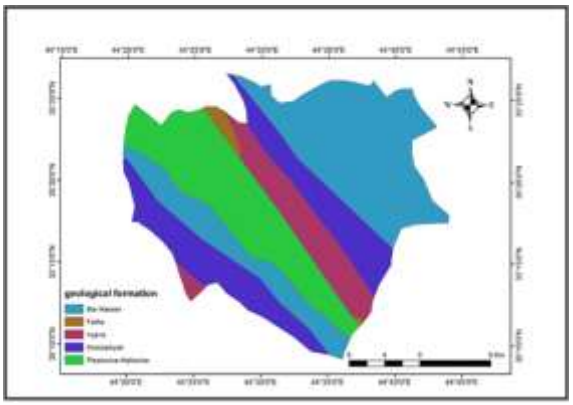


Table 10: Geological formations, spatial distribution, and their groundwater suitability ratings in the study area.

Geological Formation	Area (km2)	Percentage (%)	Groundwater Suitability	Rating
Bai Hassan	302.52	40.69	Very High	5
Fat'ha	8.62	0.11	High	4
Injana	84.72	11.39	Moderate to High	4
Mukdadiyah	168.30	22.64	Moderate	3
Quaternary Deposits	179.17	24.10	Low	1

3.1.10. Drainage Density

Both as shown in Figure 11 and Table 10, low drainage density (0.00–0.25 and 0.25–1.25 km km²) areas have relatively high groundwater recharge capacity. This is largely due to the low development of the surface drainage network, which leads to more surface water infiltration and deep percolation opportunities.

At high drainage density (2.00–3.50 km/km²) values, however, the hydrological surface is highly dissected. This condition induces faster surface runoff and reduced contact time of water and the soil profile, leading to a pronounced decline in groundwater recharge potential.

Figure 11: Drainage density map of the study area.

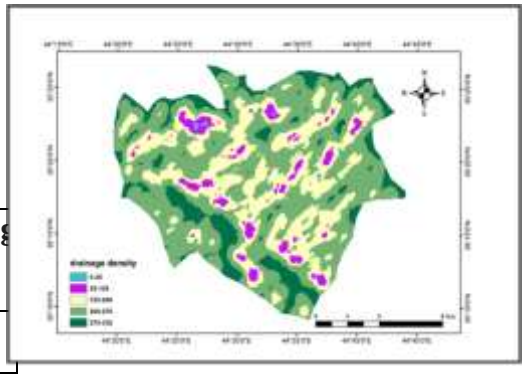


Table 11: Drainage density classes, spatial distribution, and groundwater suitability ratings in the study area.

Range (km/km²)	Classification	Area (km²)	Percentage (%)	Groundwater Suitability	Rating
0.25–0.00	Very Low	1.21	0.16	Very High	5
1.25–0.25	Low	32.74	4.40	High	4
2.00–1.25	Moderate	222.69	29.96	Moderate	3
2.75–2.00	High	389.21	52.36	Low	2
3.50–2.75	Very High	97.48	13.11	Very Low	1

3.2. Groundwater Potential Zone Mapping

Based on hydrogeological significance and directly impacting groundwater recharge, storage, and transmission, the weights of several essential multi-criteria layers for these groundwater potential zones were defined. Moreover, these assignments were corroborated by pre-identified findings of the literature in groundwater potentiality assessment. The Weighted Overlay tool in the **ArcGIS 10.8** environment (Table 11) spatially overlaid these thematic layers.

Table 11: Assigned weights and rates for the thematic layers influencing groundwater potential mapping.

3-3Assessment of Groundwater Potential Zones (GWPZs)

The Groundwater Potential Zone (GWPZ) map serves as a fundamental blueprint for implementing water localization strategies and ensuring sustainable resource management. The spatial delineation of these potential zones represents the definitive outcome of integrating measured hydrological, geomorphological, and geological criteria within the study area, utilizing Geographic Information Systems (GIS) and Remote Sensing (RS) techniques. Table (12) and Figure (12) classify the study area into three primary zones based on their capacity for groundwater recharge and storage:

3-3-1. Moderate Potential Zone

The moderate potential zone is by far the largest (largest area in absolute terms) in the study area, measuring 562.01 km² or 75.61% of total area. Most parts of this land, in plains and transitional zones, are in this zone.

This zone dominates due to some balance of the environmental variables present in these tracts. It is characterized by moderate drainage density and stream frequency and is largely affected by moderately permeable geological structures, including the Mukdadiya Formation.

This configuration provides the territory a consistent and favorable capacity for surface rainwater infiltration and is thus not only a large scale sustainable regional reservoir but also an aquifer reserve. Smart planning in this part of the zone plays a great role in optimising the water distribution.

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At the highest level, a systematic space for production wells needs to be built to avoid the continuous Cone of Depression. Also, the use of advanced irrigation technology is of utmost importance to minimize the consumption value as well as to achieve an eco-hydrological balance with natural recharge rates and discharge (pumping) requirements

.3-3-2. High Potential Zone

Spatial distribution This zone is the second most significant area (approximately 180.69 km²) and accounts for 24.31% of the study area. It is a well-defined line running northwest to southeast and isolated areas of the western and southern peripheries.

This zone is therefore characterized by a high score as of the maximal synergistic correlation between the physical governing variables. Geographically, it is coincident with very permeable gravelly and sandy lithologies, the Bai Hassan Formation.

This is accompanied by a low frequency of streams in some areas which permits inflow of natural (fast) water into, without loss to surface runoff. This zone consequently has relatively abundant and deep aquifers. This 24.31% area is a hydrological hotspot of managed aquifer recharge (MAR) and direct water localisation (4)

.3-3-3. Low Potential Zone

At a spatial scale of little more than 0.63 km², this zone constitutes only 0.09% of the total area. It appears on the map as highly restricted, isolated focal points. The near-total absence of the low potential zone represents a very positive indicator of the overall hydrogeological characteristics of the study area.

This confirms that nearly the entire catchment basin is a highly promising environment, fluctuating exclusively between moderate and high potential capacities for groundwater localization and storage.

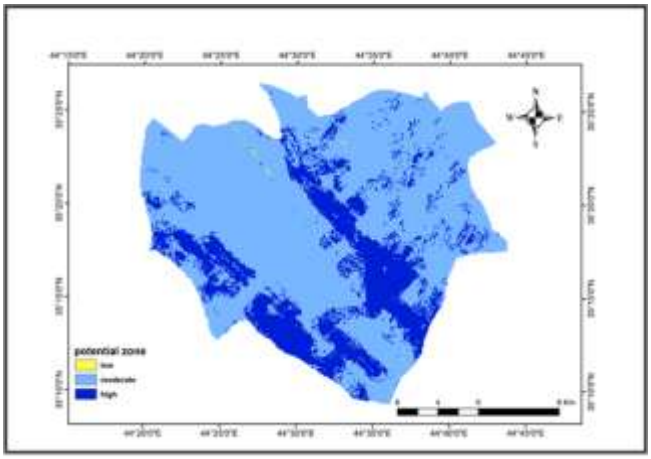


Figure (12): Groundwater Potential Zones (GWPZs) Map of the Study Area.

Table (12): Classification, Spatial Extent, and Percentage Distribution of Groundwater Potential Zones in the Study Area.

Potential Zone Classification	Area (km²)	Percentage (%)	No.
Low	0.63	0.09	**1**
Moderate	562.01	75.61	**2**
High	180.69	24.31	**3**

Conclusions

M**ethodological Efficacy:** This study successfully integrated GIS, Remote Sensing, and Multi-Criteria Decision Analysis (MCDA) to evaluate the groundwater potentiality of the Leylan sub-

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district (743.33 km²) using ten diverse geo-environmental and hydrological indicators.

Favorable Hydrogeological Settings: The spatial analysis revealed that areas characterized by highly permeable geological structures (e.g., Bai Hassan conglomeratic rocks and alluvial deposits), gentle topographic slopes, and high lineament densities exhibit the highest capacities for groundwater storage and recharge.

Groundwater Potential Zones (GWPZs): The study area was effectively delineated into three distinct zones:

- **Moderate Potential (75.61%):** The dominant zone acting as a sustainable regional aquifer, requiring systematic well-spacing and rational water management.
- **High Potential (24.31%):** Serving as critical hydrological "hotspots." These areas are highly suitable for Managed Aquifer Recharge (MAR) interventions, particularly for harvesting surplus flash flood waters.
- **Low Potential (0.09%):** Covering a negligible spatial extent, thereby confirming that the Leylan catchment basin as a whole remains a highly promising environment for groundwater storage.

Future Implications: The developed geospatial maps provide a robust and reliable decision-making framework for regional authorities to implement sustainable groundwater resource management and well-drilling strategies in the coming decade

References

1. Al-Abadi, A. M., Al-Shamma'a, A. M., & Al-Jiburi, H. K. (2016). Prediction of groundwater flowing well zone at An-Najaf Province, central Iraq using evidential belief functions model andGIS.*Environmental Earth Sciences*, 75(4), 1-18.
2. Arulbalaji, P., Padmalal, D.,&Sreelash, K. (2019). GIS and AHP techniques based delineation of groundwater potential zones: a case study from southern Western Ghats, India. Scientific Reports, 9(1), 2082. Https://doi.org/10.1038/s41598-019-38567-x
3. Castellano, M. J., & Valone, T. J. (2007). Livestock, soil compaction and water infiltration rate: evaluating a potential desertification recovery mechanism. *Journal of Arid Environments*, 71(1), 97-108. https://doi.org/10.1016/j.jaridenv.2007.03.014
4. Fetter, C. W. (2018). *Applied Hydrogeology* (4th ed.). Waveland Press.
5. Ghorbani Nejad, S., Falah, F., Daneshfar, M., Haghizadeh, A., & Rahmati, O. (2017). Delineation of groundwater potential zones using remote sensing and GIS-based data driven models. Water, 9(12), 1081. Https://doi.org/10.3390/w9121081
6. Heath, R. C. (1983). *Basic ground-water hydrology* (U.S. Geological Survey Water-Supply Paper 2220). U.S. Geological Survey.

ISSN 2072-3857

7. Jassim, S. Z., & Goff, J. C. (2006). Geology of Iraq. Dolin, Prague
8. Jenson, S. K., & Domingue, J. O. (1988). Extracting topographic structure from digital elevation model data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing, 54(11), 1593-1600.
9. Jhariya, D. C., Kumar, T., Gobinath, M., Diwan, P., & Kishore, N. (2016). Assessment of groundwater potential zone using remote sensing, GIS and multi criteria decision analysis techniques. Journal of the Geological Society of India, 88(4), 481–492. https://doi.org/10.1007/s12594-016-0511-9
10. Khan, R.,&Moharana, P. (2019). Delineation of groundwater potential zones using geospatial techniques and overlay models.
11. Machiwal, D., & Jha, M. K. (2015). Identifying sources of groundwater contamination in a hard-rock aquifer system using multivariate statistical analyses and GIS-based geostatistical modeling techniques. Journal of Hydrology: Regional Studies, 4, 80-110.
12. Machiwal, D., Jha, M. K., Singh, P. K., & Mohan, C. (2011). Assessment of groundwater potential in a semi-arid region of India using GIS-based multi-criteria decision making techniques. Water Resources Management, 25(5), 1359-1386.
13. Mohammed, O. A., & Sayl, K. N. (2021). A GIS-based multicriteria decision for groundwater potential zone in the West Desert of Iraq. IOP Conference Series: Earth and Environmental Science, 856(1), 012049.https://doi.org/10.1088/1755-1315/856/1/012049.
14. Mukherjee, I., & Singh, U. K. (2020). Delineation of groundwater potential zones in a drought-prone semi-arid region of east India using GIS and analytical hierarchical process techniques. Catena, 194, 104681.Https://doi.org/10.1016/j.catena.2020.104681
15. Nasir, M. J., Khan, A., Zahid, H.,&Khan, S. (2018). Delineation of groundwater potential zones using GIS and multi influence factor (MIF) techniques: A study of district Swat, Khyber Pakhtunkhwa, Pakistan.
16. Saaty, T. L. (1980). The Analytic Hierarchy Process. McGraw-Hill, New York.
17. Sener, E., Davraz, A., & Ozcelik, M. (2005). Determination of groundwater potential zones in Senirkent-Yalvac Basin (Isparta, Turkey) using GIS and remote sensing. Hydrogeology Journal, 13(8), 1202-1212.
18. Shepard, D. (1968). A two-dimensional interpolation function for irregularly-spaced points. Proceedings of the 1968 23rd ACM National Conference, 517
19. Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal*, 10(1), 52–67.

ISSN 2072-3857

https://doi.org/10.1007/s10040-001-0170-8

20. Tolche, A. D. (2021). Assessment of groundwater potential zones using GIS and remote sensing techniques. Water Practice&Technology.

21. Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing applied methodologies for assessing groundwater recharge. *Hydrogeology Journal*, 10(1), 1839.https://doi.org/10.1007/s10040-001-0176-2

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