Journal of Basic and Environmental Sciences

ISSN
Online:2356-6388
Print:2536-9202

Research Paper Open Access

Groundwater Potential Assessment Using Analytic Hierarchy Process (AHP), Remote Sensing, and GIS: A Case Study from the Zaafarana Region, Western Coast of the Gulf of Suez, Egypt

Ahmed M. Ketkat[1], Ahmed M. El Shenawy[2], Fardous M. Zarif[2], Wafaa E. Afify[1], Hesham M. El Kaliouby[3], Nehad M. Mansour[1]

[1] *Geology Department, Faculty of Science, Benha University, Egypt.*
[2] *Geophysical Exploration Department, Water Resources and Land Division, Desert Research Center, Egypt.*
[3] *Geophysical Sciences Department, National Research Center, Egypt.*
Corresponding author: Ahmed M. Ketkat E-mail address: ***ahmed.katkat@fsc.bu.edu.eg***

Abstract:

This study investigates the groundwater potential in the Zaafarana region through an integrated approach combining morphometric analysis, Analytic Hierarchy Process (AHP) modeling, remote sensing, and GIS techniques. A comprehensive morphometric analysis was conducted on the drainage basins, and seven key parameters (drainage density, basin relief, relief ratio, stream frequency, elongation ratio, length of overland flow, and ruggedness number) were selected for integration into an AHP model. Seven thematic layers (geology, slope, drainage density, LULC, lineament density, soil, and precipitation) derived from remote sensing and GIS data were also incorporated into the AHP model. Due to the lack of existing well data for direct validation, sensitivity analysis was performed by adjusting the weights of all seven parameters of the AHP Model of Thematic Maps by ±5% and ±10% to assess the model's robustness. The results revealed significant variations in morphometric characteristics across the drainage basins, influencing groundwater recharge and flow. The AHP model identified areas with high, moderate, and low groundwater potential, providing valuable insights for targeted exploration and management efforts. Sensitivity analysis demonstrated the model's robustness, with minor changes in criterion weights limiting the overall groundwater potential zones. This integrated approach effectively assessed groundwater potential in a data-scarce arid region, offering a valuable, sustainable water resource management tool in the Zaafarana region and similar environments.

Keywords: Groundwater potential, Zaafarana, Remote sensing, Geographic Information Systems (GIS), Morphometric analysis, Analytical Hierarchy Process (AHP), Hyper-arid regions, Water resource management.

1. Introduction:

Groundwater is essential in arid and semi-arid regions, where surface water is limited and unpredictable, creating challenges for domestic, agricultural, and industrial water needs. Sustainable groundwater management is critical for long-term water security and environmental protection, especially in areas facing population growth and climate change. (Abdessamed et al., 2023; Ali and Mater, 2023; El Ayady et al., 2023; Negm and Elkhouly, 2021; Pinder and Celia, 2006; Todd, D. K., Mays, 2005)

The Zaafarana region in Egypt illustrates these challenges due to its arid climate, scarce rainfall, and limited surface water resources. The complex hydrogeological conditions and lack of data hinder effective groundwater exploration and management (Abdel-Shafy and Kamel, 2016; Aggour, 1990; Ezzeldin, 2010; Wannous et al., 2021).

This study employs remote sensing, Geographic Information Systems (GIS), the Analytic Hierarchy Process (AHP), and morphometric analysis to address these issues. Remote sensing and GIS facilitate the integration of spatial datasets related to hydrogeological factors affecting groundwater. AHP allows for systematic evaluation of these factors for groundwater potential mapping (Ahmadi et al., 2021; Alshehri et al., 2024; Baghel et al., 2023; Elewa et al., 2024; Sikakwe et al., 2024), while morphometric analysis offers insights into hydrological processes influencing groundwater recharge (Bogale, 2021; Chowdhury, 2024; El-Fakharany and Mansour, 2021).

Despite the effectiveness of these techniques in other arid regions, the absence of well data in Zaafarana limits the direct validation of groundwater models. To address this, sensitivity analysis will assess model robustness and the impact of input uncertainties.

The study aims to delineate high groundwater potential zones and evaluate the AHP model's robustness. By demonstrating this integrated methodology's effectiveness in identifying areas for groundwater exploration in data-scarce arid regions, the research seeks to support informed decision-making and sustainable water resource management in Zaafarana

2. Study Area

2.1. Location and Geography

The study area is situated in the northeastern part of Wadi Araba, within the Zaafarana region of Egypt's Eastern Desert (Figure 1), along the western coast of the Gulf of Suez (29.1833° N - 29.3667° N, 32.4° E - 32.6333° E). This location places it within the Gulf of Suez rift system and the Wadi Araba drainage basin. These prominent geological features influence the region's geomorphology and groundwater resources, making the Zaafarana region a compelling location for studying groundwater potential.

2.2. Climate

Zaafarana experiences a hyper-arid desert climate, with characteristically hot summers and mild winters. Temperatures frequently exceed 35°C during the summer, while winter days see milder temperatures ranging from 18°C to 25°C. Rainfall is a scarce event, with the area receiving less than 30 mm annually, mainly during brief winter storms (Aggour, 1990; Ezzeldin, 2010; Ian et al., 2020). These storms can lead to flash floods in the landscape's normally dry riverbeds (wadis). The region is also known for strong northwesterly winds, making it a prime location for wind energy production. High evaporation rates, typical of desert environments, further exacerbate the scarcity of surface water.

2.3. Geological, Structural and Hydrogeological Settings

The Zaafarana area, part of the Gulf of Suez rift basin, exhibits a diverse geological profile with formations ranging from Carboniferous to Quaternary in age (Figure 2) (Aggour, 1990; CONOCO, 1987; Elewa, 2007; Ezzeldin, 2010; Moustafa and Khalil, 1995; Nassim, 1990; Peijs et al., 2012). Eocene formations, primarily limestone, dominate the central and western portions, indicating a shallow marine depositional environment. Eastward, a band of Upper Cretaceous formations, including limestone, chalk, and marl, suggests a similar environment with localized deeper areas. The Lower Cretaceous Malha Formation, a fluvial sandstone, underlies these marine deposits. A small exposure of the Carboniferous Abu Darag Formation, composed of sandstone, shale, and limestone, is present in the northeast. Quaternary alluvial fans and wadi deposits blanket the easternmost zone and overlap Eocene formations in the west.

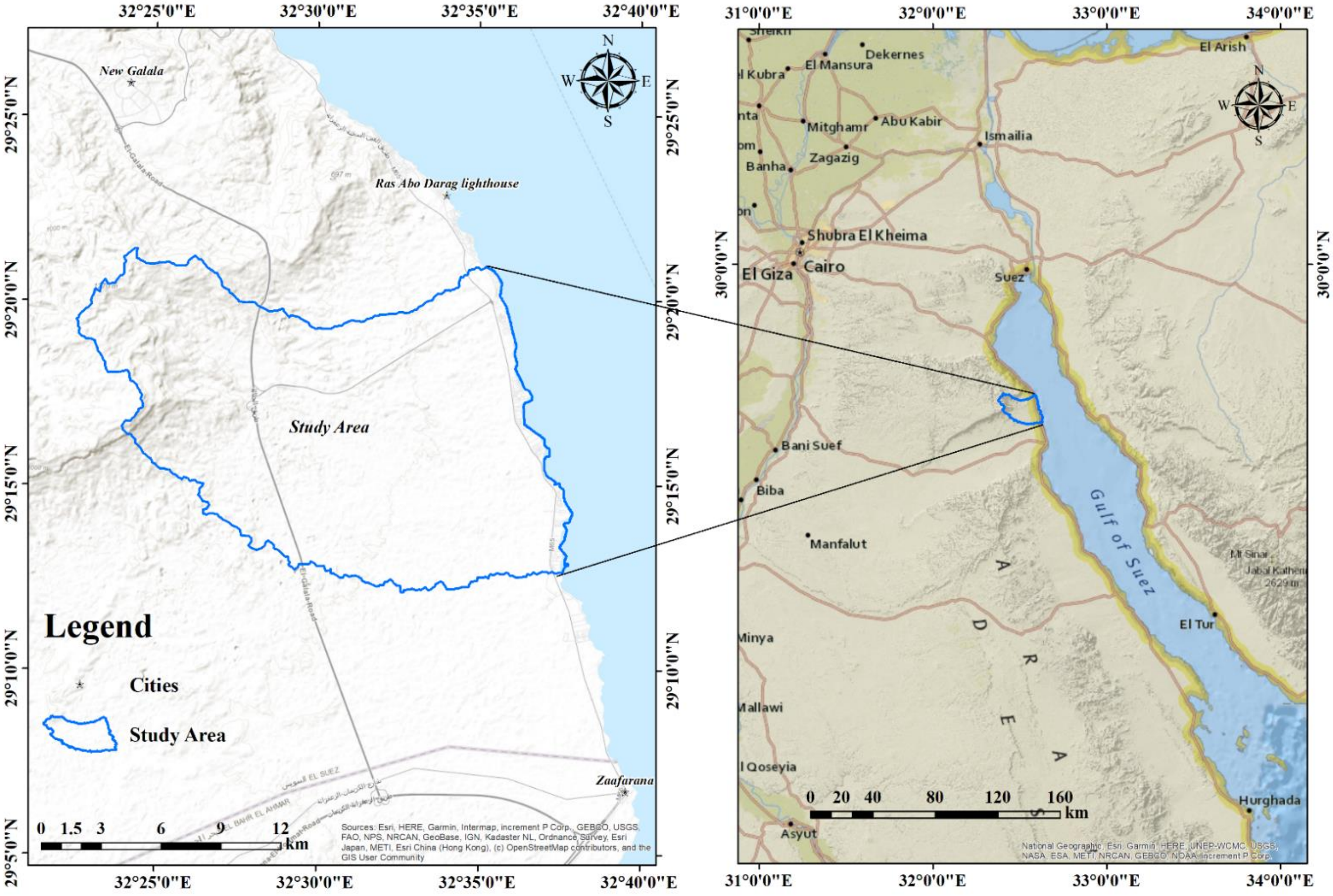

Figure (1): Location of the study area in Zaafarana

Structurally, Zaafarana is defined by the Gulf of Suez rift system, characterized by extensional tectonics and a network of predominantly ENE-WNW and NNW-SSE trending normal faults. This faulting has created a series of horsts and grabens, significantly influencing landscape and subsurface geology. Notably, the faulting has enhanced secondary porosity and permeability in limestone formations, leading to fractured aquifers with increased groundwater storage potential. This complex interplay of tectonic activity, sea-level changes, and depositional environments has shaped the geological framework of the Zaafarana area.

Hydrogeologically, Zaafarana features a complex system with aquifers ranging from shallow Quaternary deposits to deeper bedrock formations (Aggour, 1990; Elewa, 2007; Ezzeldin, 2010). Groundwater flow is generally directed towards the Gulf of Suez, influenced by topography and the fault network. The shallow Quaternary aquifer, composed of alluvial and coastal sediments, is highly susceptible to fluctuations and vulnerable to depletion and contamination due to its limited thickness and reliance on Sporadic rainfall. Analysis of four water points indicates shallow depths to the water table. Still, salinity levels range from 3580 to 30082 ppm, likely due to seawater intrusion and high evaporation rates (Ezzeldin, 2010).

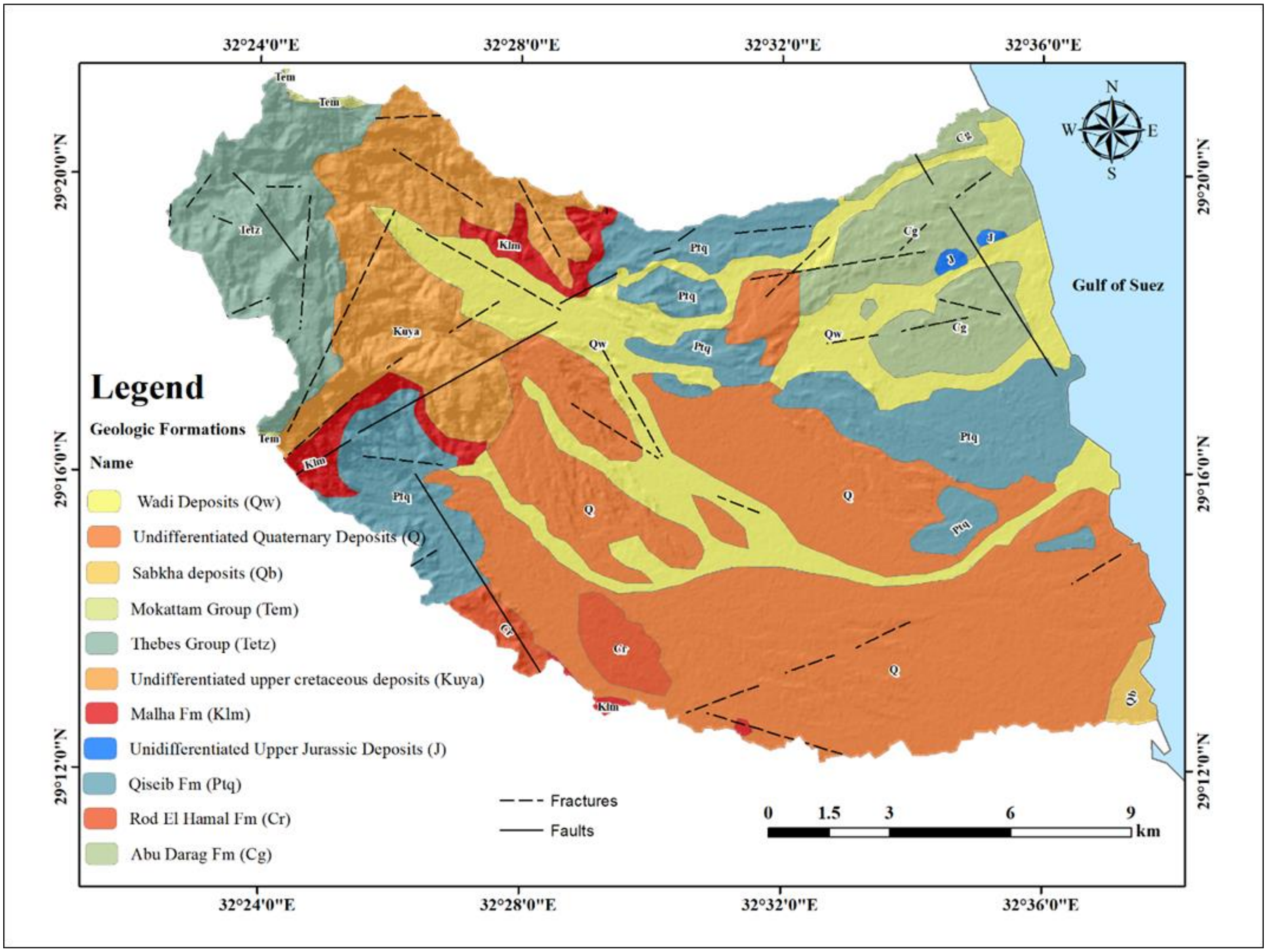

__Figure (2): Geologic Map of the study area__ (CONOCO, 1987)

Deeper bedrock aquifers offer alternative groundwater resources, including the Upper Cretaceous, Lower Cretaceous, and Carboniferous. The Upper Cretaceous aquifer, a fractured limestone and marl formation, exhibits variability in salinity

(1377 ppm to 11801 ppm) and depth to water (0 to 14 meters) (Ezzeldin, 2010). The Lower Cretaceous sandstone aquifer also shows varying salinity (187 ppm to 1410 ppm) and depth to water (0 to 125.7 meters) (Ezzeldin, 2010). Limited data on carboniferous aquifers suggest they may have lower salinity than shallower aquifers. These deeper aquifers are crucial for the region's water supply, but careful management is needed to ensure sustainability and address potential salinity issues.

3. Materials and Methods

This study integrated remote sensing, GIS, morphometric analysis, and the Analytic Hierarchy Process (AHP) to delineate groundwater potential zones in the Zaafarana region of Egypt's Eastern Desert. The integration of these methods is illustrated in the flowchart presented in Figure (3).

3.1. Data Acquisition and Preprocessing

High-resolution Landsat 8 OLI/TIRS (30m) and Sentinel-2 MSI (10m) imagery were acquired from the USGS Earth Explorer platform (https://earthexplorer.usgs.gov/) and the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/), respectively. A 30m resolution Digital Elevation Model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) data, also available on the USGS Earth Explorer platform. Conventional data sources were also utilized, including geological maps (1:500,000 scale) from the Egyptian General Authority for Petroleum and the Egyptian Geological Survey (EGS). Soil data were obtained from the Harmonized World Soil Database (HWSD) (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). Precipitation data were acquired from the Climatic Research Unit Time-Series dataset (https://crudata.uea.ac.uk/cru/data/hrg/).

Satellite imagery preprocessing involved atmospheric correction (FLAASH for Landsat 8 in ArcGIS 10.8; Sen2Cor for Sentinel-2 in SNAP), radiometric calibration, and geometric correction using ground control points and second-order polynomial transformation for precise image registration. DEM preprocessing in ArcGIS 10.8 included filling depressions, determining flow direction, calculating flow accumulation, and delineating stream order based on the Strahler method.

3.2. Morphometric Analysis

A detailed morphometric analysis was performed using the preprocessed DEM to quantitatively assess the drainage basins and their impact on groundwater recharge and flow. The parameters, categorized into linear, areal, and relief aspects, are presented in **Table 1**.

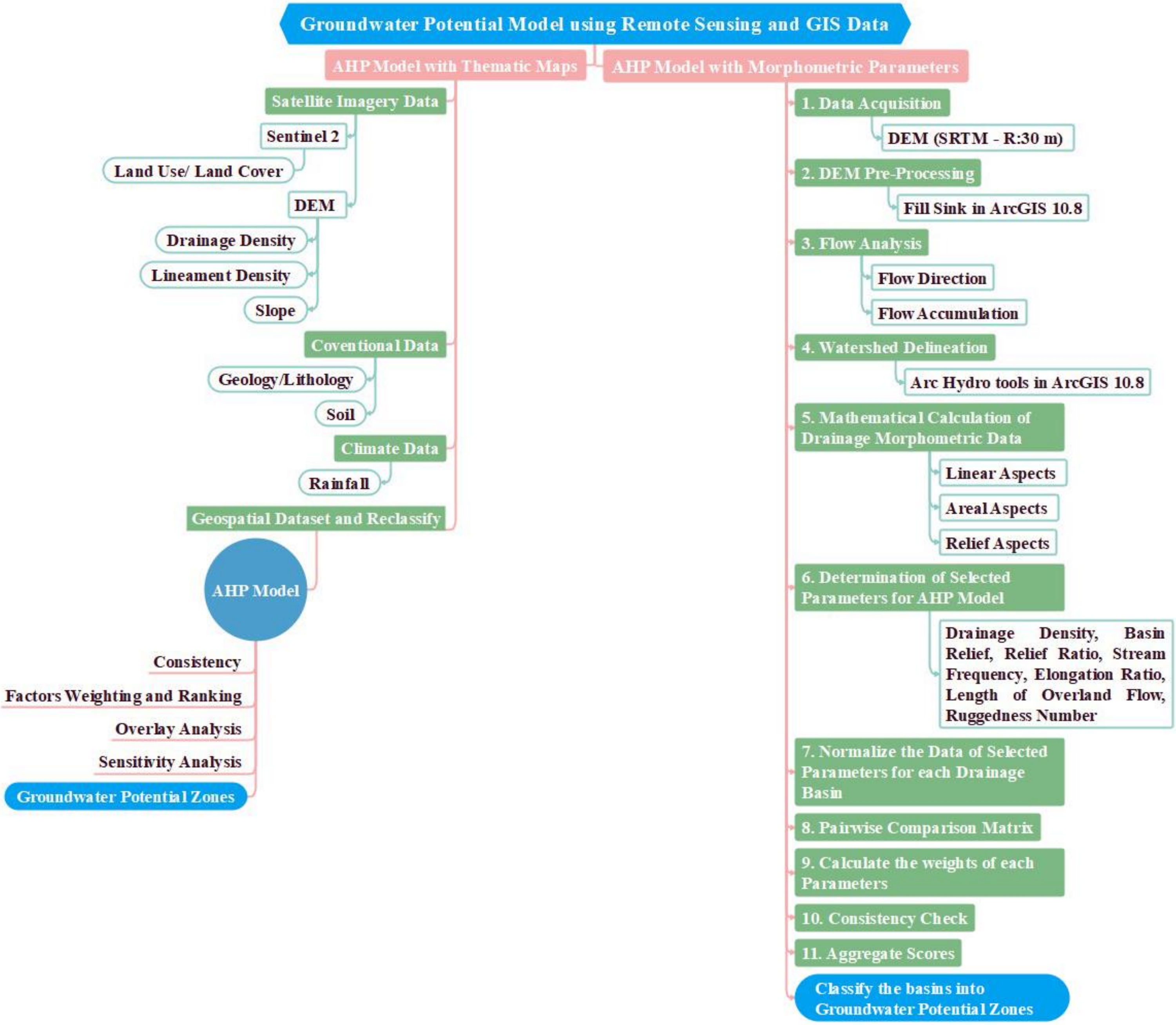

Figure (3): Flowchart illustrating the integrated approach used in the study.

Table (1): Methodology adopted for the computation of Morphometric Parameters

	Morphometric Parameters	Formula/ Definition	References
Linear Aspects	Stream Order (U)	Hierarchical order	(Strahler, 1964)
	Stream Length (LU)	Length of the stream	(Horton, 1945)
	Mean Stream Length (Lsm)	**$Lsm=(Lu/Nu)$** Where: Lu=Mean stream length of a given order (km), Nu=Number of stream segments.	(Horton, 1945)
	Stream Length Ratio (RL)	**$RL= (Lu / Lu\text{-}1)$** Where: Lu= Total stream length of order (u), Lu-1=The total stream length of its next lower order.	(Horton, 1945)
	Bifurcation Ratio (Rb)	**$Rb = (Nu / Nu+1)$** Where Nu=Number of stream segments present in the given order Nu+1= Number of segments of the next higher order	(Schumm, 1956)
Aerial Aspects	Drainage Density (Dd)	**$Dd=(L/A)$** Where: L=Total length of the stream, A= basin area.	(Horton, 1945)
	Stream Frequency (Fs)	**$Fs=(N/A)$** Where: N=Total number of streams, A=Area of basin	(Horton, 1945)
	Texture Ratio (Rt)	**$T=(Nu/P)$** Where: Nu=Total number of streams, P=Perimeter of basin.	(Horton, 1945)
	Form Factor (Rf)	**$Rf=A/(Lb)^2$** Where: A=Area of basin, Lb=Basin length	(Horton, 1945)
	Circulatory Ratio (Rc)	**$Rc= (4\pi A/P^2)$** Where: A= Area of basin, π=3.14, P= Perimeter of basin	(Strahler, 1964)
	Elongation Ration (Re)	**$Re=2\sqrt{(A/\pi)}/ Lb$** Where A=Area of basin, π=3.14, Lb=Basin length	(Schumm, 1956)
	Length of Overland Flow (Lg)	**$Lg=1/2Dd$** Where: Dd Drainage density	(Horton, 1945)
	Constant Channel Maintenance (C)	**$C=1/Dd$** Where: Dd= Drainage density	(Horton, 1945)
Relief Aspects	Basin Relief (Bh)	The vertical distance between the lowest and highest points of the basin.	(Schumm, 1956)
	Relief Ratio (Rh)	**$Rh = (Bh / Lb)$** Where: Bh=Basin relief, Lb=Basin length	(Schumm, 1956)
	Ruggedness Number (Rn)	**$Rn=(Bh\times Dd)$** Where: Bh= Basin relief, Dd=Drainage density	(Schumm, 1956)

These calculations were performed using ArcGIS 10.8 Spatial Analyst tools, Arc Hydro Tools, and Terrain Analysis Using Digital Elevation Models.

3.3. Thematic Layer Generation

Seven thematic layers, representing factors influencing groundwater potential, were generated and illustrated in Figure (4):

1. Geology: A geological map was prepared by interpreting Landsat 8 imagery and incorporating existing geological maps Figure (4. A). This layer provides information on the types of rocks and their distribution, which is crucial for understanding aquifer properties and groundwater occurrence.
2. Slope: Calculated from the DEM Figure (4. B). Slope influences surface runoff and infiltration rates, affecting groundwater recharge.
3. Drainage Density: Calculated using ArcGIS 10.8 Figure (4. C). Drainage density reflects the efficiency of the drainage network in collecting runoff, influencing groundwater recharge potential.
4. Land Use/Land Cover (LULC): LULC data for the study was obtained from the ArcGIS Living Atlas platform, based on ESA Sentinel-2 imagery at a 10-meter resolution Figure (4. D). The dataset for the year 2023 was produced using a deep-learning AI land classification model (https://livingatlas.arcgis.com/landcoverexplorer). LULC influences surface characteristics such as vegetation cover and built-up areas, which affect infiltration rates and groundwater recharge potential.
5. Lineament Density: Lineaments were extracted from Sentinel-2 imagery using PCI Geomatica software, and lineament density was calculated in Figure (4. E). Lineaments often represent underlying geological structures like faults and fractures, which can act as conduits for groundwater flow.
6. Soil: Obtained from the Harmonized World Soil Database (HWSD) Figure (4. F). Soil properties significantly influence infiltration rates and groundwater recharge.
7. Precipitation: Acquired from the Climatic Research Unit Time-Series dataset Figure (4. G). Precipitation is the primary source of groundwater

recharge, and its spatial variation influences the amount of water available for infiltration.

3.4. Analytic Hierarchy Process (AHP) Modeling

The Analytical Hierarchy Process (AHP), a multi-criteria decision-making technique pioneered by Thomas L. Saaty, offers a structured approach to analyzing complex decisions (Saaty, 1980). By deconstructing a problem into a hierarchy of manageable components, AHP facilitates pairwise comparisons and prioritization of factors based on their relative importance. This study leverages AHP to assess groundwater potential, integrating various thematic layers and assigning weights based on their influence on groundwater recharge. Two distinct AHP methodologies are implemented:

- **AHP Model with Morphometric Parameters**

This approach employs quantitative measures of landform shape, known as morphometric parameters, to evaluate groundwater potential (Chowdhury, 2024). Parameters such as drainage density and basin relief are extracted from digital elevation models (DEMs) and normalized to a uniform scale (0 to 1). Subsequently, a pairwise comparison matrix is constructed using Saaty's 1-9 scale to determine the relative significance of each parameter in influencing groundwater recharge.

- **AHP Model with Thematic Maps**

This approach incorporates a broader spectrum of spatial data, utilizing thematic maps encompassing geology, slope, drainage density, lineament density, rainfall, land use/land cover, and soil type (Ahmadi et al., 2021). Each map is assessed based on its impact on groundwater recharge, and weights are assigned accordingly. Pairwise comparison matrices are employed to establish the relative importance of these criteria.

- **AHP Integration and Implementation**

For both approaches, pairwise comparison matrices were constructed based on expert knowledge and a comprehensive literature review to ascertain the relative weights of each criterion in influencing groundwater potential. The AHP model was implemented within the ArcGIS 10.8 software environment. Rigorous consistency checks were performed to ensure the logical coherence of pairwise comparisons. The resultant weights derived from the AHP model were then utilized to calculate the Groundwater Potential Index (GWPI) for each pixel within the study area, generating a groundwater potential map delineating high, moderate, and low potential areas. This comprehensive methodology facilitates a robust and nuanced assessment of groundwater resources.

3.5. Sensitivity Analysis

Sensitivity analysis was conducted by systematically varying the weights of each thematic map by ±5% and ±10% from their initial values (Emara et al., 2024; Javhar et al., 2019; Meng et al., 2024). The resulting changes in the GWPI and the spatial patterns in the groundwater potential map were then analyzed to understand the sensitivity of the model output to variations in the input weights. This provided insights into the relative importance of each criterion and the stability of the model's predictions.

4. Results and Discussion

This section presents the findings of this integrated study, examining the drainage basins' morphometric characteristics, the resulting groundwater potential map derived from the AHP model (incorporating both morphometric parameters and thematic layers), and the model's sensitivity to variations in input parameters. The implications of these findings for groundwater resource management in the Zaafarana region are discussed in detail.

4.1. Morphometric Analysis Results

Morphometric analysis was conducted to characterize drainage basins and assess their potential for groundwater recharging. Key parameters were analyzed and categorized into linear, areal, and relief aspects (Table 2).

4.1.1. Linear Aspects

- **The number of streams (Nu)** represents the total number of stream channels within a basin. Wadi Khurri, with the highest number of streams (Nu = 49), suggests efficient drainage and recharge, while Wadi Malha, with fewer streams (Nu = 25), indicates a less complex network and potentially lower recharge potential.

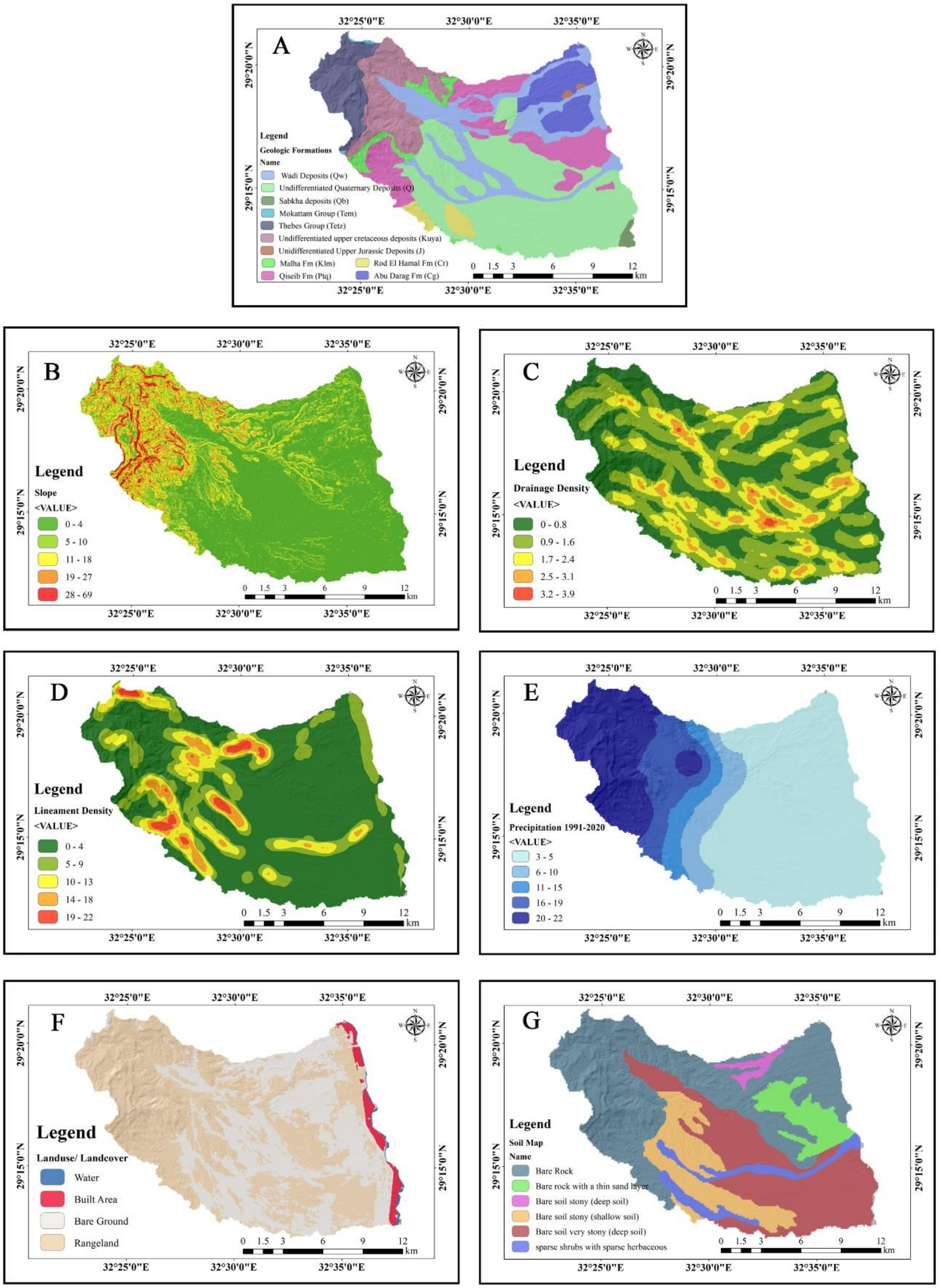

Figure (4): Thematic maps of the Zaafarana area used for groundwater potential modeling: (A) Geological formations map, (B) Slope map, (C) Drainage density map, (D) Lineament density map (E) Precipitation map (1991–2020), (F) Land Use/Land Cover (LULC) map, (G) Soil map.

Table (2): Descriptive statistics of the morphometric parameters for the drainage basins

Basins		Wadi Abu Greifat	Wadi Khurri	Wadi Malha
Basin Geometry	A (km^2)	58.89	84.28	54.73
	P (km)	66.01	59.29	59.85
Linear aspects	Nu	34	49	25
	Lu	51.93	96.06	55.75
	RL	0.27	0.48	0.53
	Lsm	1.04	0.81	0.88
	Rb	6.5	3.43	6.09
Areal aspects	Dd	0.88	1.14	1.02
	Fs	0.58	0.58	0.46
	Rt	0.52	0.83	0.42
	Rf	0.12	0.16	0.12
	Rc	0.17	0.3	0.19
	Re	0.39	0.46	0.38
	Lg	0.57	0.44	0.49
	C	1.13	0.88	0.98
Relief aspects	Bh	1.19	1.21	1.27
	Rh	0.05	0.05	0.06
	Rn	1.05	1.37	1.3

- **Stream length (LU)** measures the total length of all stream channels within a basin. Wadi Khurri's most extensive stream network (LU = 96.06 km) suggests efficient drainage and enhanced recharge. Conversely, Wadi Abu Greifat's shorter total stream length (LU = 51.93 km) indicates a potentially reduced water absorption and recharge capacity.
- **Mean stream length (Lsm)** represents the average length of streams within a specific order. Wadi Abu Greifat, with the highest Lsm (1.04 km), suggests a well-developed drainage network and enhanced recharge potential. Conversely, Wadi Khurri's lower Lsm (0.81 km) may indicate less efficient drainage.
- **Stream Length Ratio (RL)** compares the average length of streams of one order to the next lower order, indicating differences in drainage network structure and its potential influence on runoff and

infiltration. In this case, Malha has the highest RL (0.53), suggesting moderate branching, which may balance runoff and infiltration. Wadi Khurri, with an RL of 0.48, shows slightly less branching, potentially favoring infiltration. Abu Greifat, with the lowest RL (0.27), indicates a simpler network structure with more elongation, which could enhance infiltration potential by allowing water to remain in the basin longer.

- **Bifurcation Ratio (Rb)** compares the number of streams of one order to those of the next higher order, providing insight into drainage network complexity. Abu Greifat has the highest Rb (6.50), indicating the most complex and branched network, which may increase surface runoff and reduce groundwater recharge potential. Wadi Malha has the second-highest Rb (6.09), also suggesting a complex network with similar implications for runoff and recharge. Wadi Khurri, with the lowest Rb (3.43), has a simpler drainage network, which may allow for greater infiltration and potentially higher groundwater recharge compared to the other basins.

4.1.2. Areal Aspects

- **Drainage density (Dd)** is the total length of all streams divided by the basin area. Wadi Khurri's high Dd (1.14 km/km²) suggests a well-developed network and enhanced recharge potential. Wadi Abu Greifat's lower Dd (0.88 km/km²) indicates potentially less efficient drainage and reduced recharge.
- **Stream frequency (Fs)** measures the number of streams per unit area and varies across the basins. Wadi Abu Greifat and Wadi Khurri have the highest Fs (0.58), suggesting better drainage and higher runoff potential, which can enhance groundwater recharge. Wadi Malha has a lower Fs (0.46), potentially indicating less efficient drainage.
- **Drainage texture (Rt)** compares the total length of streams to the basin's perimeter and reveals variations in drainage density and potential water retention. Wadi Khurri exhibits the highest Rt (0.83), indicating a denser drainage network and enhanced water retention, promoting groundwater recharge. Conversely, Wadi Malha shows a lower Rt (0.42),

suggesting a less dense network and potentially reduced water retention.

- **Form factor (Rf)** measures basin shape and varies across basins. It influences runoff and groundwater recharge. Wadi Abu Greifat and Wadi Malha have the lowest Rf (0.12), indicating more elongated shapes with potentially longer runoff times and increased recharge. Conversely, Wadi Khurri has a higher Rf (0.16), suggesting a less elongated shape and potentially reduced recharge.
- **Circularity ratio (Rc)** compares basin area to that of a circle with the same perimeter, varies across the basins, and influences drainage efficiency. Wadi Khurri has the highest Rc (0.30), suggesting a more circular shape and potentially more efficient drainage. Conversely, Wadi Abu Greifat has the lowest Rc (0.17), indicating a less circular shape and potentially less efficient drainage.
- **Elongation ratio (Re)** measures the ratio between the diameter of a circle with the same area as the basin and its maximum length. Wadi Malha exhibits the lowest Re (0.38), suggesting a more elongated shape that can potentially increase groundwater recharge due to longer flow durations. In contrast, Wadi Khurri shows a higher Re (0.46), indicating a less elongated shape with potentially shorter flow durations and reduced recharge potential.
- **Length of overland flow (Lg)** reflects the average distance water travels over land before entering a stream, which varies across the basins. Abu Greifat exhibits the highest Lg (0.57 km), suggesting longer overland flow distances and potentially increased infiltration and groundwater recharge. Conversely, Wadi Khurri shows the lowest Lg (0.44 km), indicating shorter overland flow distances and potentially reduced infiltration.
- **Constant of channel maintenance (C)** indicates terrain resistance to erosion, which varies across the basins. Abu Greifat exhibits the highest C value (1.13), suggesting more resistant terrain, potentially reducing erosion and enhancing groundwater recharge. Conversely, Wadi Khurri shows the lowest C value (0.88), indicating less resistant

terrain and potentially higher erosion rates.

4.1.3. Relief Aspects

- **Basin Relief (Bh)** measures the vertical difference between a basin's highest and lowest points. Wadi Malha has the highest Bh (1.27 km), indicating more incredible potential energy for stream flow and potentially increased recharge. Wadi Abu Greifat has the lowest Bh (1.19 km).
- **Relief Ratio (Rh)** compares basin relief to basin length. Wadi Malha has the highest Rh (0.06), suggesting steeper terrain and potentially higher recharge rates. Wadi Khurri and Abu Greifat have lower Rh (0.05), indicating gentler slopes.
- **Ruggedness Number (Rn)** combines basin relief and drainage density to describe landscape roughness. Wadi Khurri has the highest Rn (1.37), indicating rougher terrain that can influence water flow and infiltration, potentially impacting recharge. Wadi Abu Greifat has the lowest Rn (1.05), suggesting smoother terrain.

4.1.4. Classification of Drainage Basins based on Morphometric Analysis:

Based on the comprehensive analysis of morphometric parameters and their influence on groundwater potential, the three drainage basins can be classified as follows:

Wadi Khurri: This basin exhibits moderate to high groundwater potential characteristics. It has the highest number of streams (Nu = 49) and a relatively high drainage density (Dd = 1.14 km/km^2), suggesting efficient surface drainage. However, the low bifurcation ratio (Rb = 3.43) indicates a simpler, less branched network, which may favor infiltration over rapid runoff. Additionally, the relatively short mean stream length (Lsm = 0.81 km) and moderate texture ratio (Rt = 0.83) imply that while the basin supports some infiltration, its ability to retain water for prolonged absorption may be somewhat limited compared to other basins.

Wadi Malha: This basin displays characteristics suggestive of high groundwater potential. With a low number of streams (Nu = 25) and relatively low drainage density (Dd = 1.11 km/km^2), water may remain in the basin longer, which can favor infiltration. Although the high bifurcation ratio (Rb = 6.09) suggests a complex network that could facilitate runoff in steep areas, it also allows water to spread out across the basin, potentially supporting infiltration in flatter regions. Additionally, the basin's elongated shape (Re = 0.38) and relatively high relief ratio (Rh = 0.06) imply extended flow paths, which could further enhance groundwater recharge opportunities in areas where the slope and soil conditions allow.

Wadi Abu Greifat: This basin exhibits characteristics indicative of high groundwater potential. It has a moderate number of streams and drainage density, balanced to support both drainage and infiltration. The high stream frequency (Fs = 0.58) combined with a relatively long overland flow length (Lg = 0.57 km) suggests efficient drainage with an extended water retention time, which can enhance infiltration. The elongated basin shape (Rf = 0.12) and high constant of channel maintenance (C = 1.13) indicate a favorable area for infiltration per unit stream length, supporting groundwater recharge. Additionally, the high bifurcation ratio (Rb = 6.5) reflects a complex stream network that distributes water throughout the basin, potentially promoting infiltration in permeable areas.

While morphometric analysis provides valuable insights into potential groundwater recharge, a comprehensive evaluation requires consideration of other critical factors, including climate, geology, and human activities, to ensure accuracy and reliability.

4.2. AHP Model Results

The AHP model integrated seven morphometric parameters and seven thematic layers to generate a groundwater potential map for the Zaafarana region. The map delineated four zones as illustrated in Figure (5) and the Areas of Classification of Groundwater Potential Zones in Table (3):

- High Potential: Limited to areas within Wadi Khurri and Wadi Malha, characterized by favorable geological conditions, high drainage density, and significant relief. These areas exhibit features conducive to groundwater recharge and accumulation.
- Moderate Potential: The most dominant zone, covering a significant portion of the study area, including Wadi Abu Greifat. These areas generally possess suitable geological and geomorphological characteristics for groundwater recharge and storage,

although not as optimal as the high-potential zones.

- Low Potential: Predominantly found in the southern and eastern parts of the region, where steeper slopes, less permeable formations, and lower drainage density limit groundwater recharge. These areas may have limited groundwater resources or lower recharge rates.
- Very Low Potential: Restricted to small, isolated areas with the least favorable conditions for groundwater accumulation, such as those with highly impermeable bedrock or very steep slopes.

The AHP model effectively synthesized diverse datasets, providing a spatially explicit assessment of groundwater potential. The dominance of "Moderate Potential" zones (66.82% of the study area) suggests that while the Zaafarana region possesses considerable groundwater resources, careful management is crucial to ensure sustainability. The "High Potential" zones within Wadi Khurri and Wadi Malha represent priority areas for groundwater development but require protection from over-exploitation and contamination.

4.2.1. AHP Modeling with Thematic Maps

In the AHP model incorporating thematic maps, as illustrated in Figure (5), geology emerged as the most influential factor (38%), followed by slope (19%) and drainage density (17%). This underscores the critical role of geological structures and terrain characteristics in controlling groundwater recharge. The presence of permeable rock formations and gentle slopes favors infiltration and groundwater accumulation.

4.2.2. AHP Modeling with Morphometric Parameters

When applying the AHP model specifically to the morphometric parameters, drainage density (30.52%) emerged as the most influential factor in determining groundwater potential, followed by basin relief (16.96%) and stream frequency (16.12%). This highlights the importance of a well-developed drainage network and terrain characteristics in facilitating groundwater recharge. The overall scores derived from this analysis further emphasized the high potential of Wadi Khurri (0.66) and Wadi Malha (0.58), while Wadi Abu Greifat showed moderate to high potential (0.56) Figure (6).

4.3. Sensitivity Analysis and Model Validation

Sensitivity analysis was conducted to evaluate the AHP model's robustness and understand each criterion's influence on the final groundwater potential map. This involved systematically varying the weights of each criterion (±5% and ±10%) and assessing the resulting changes in the spatial distribution of potential zones (Table 4).

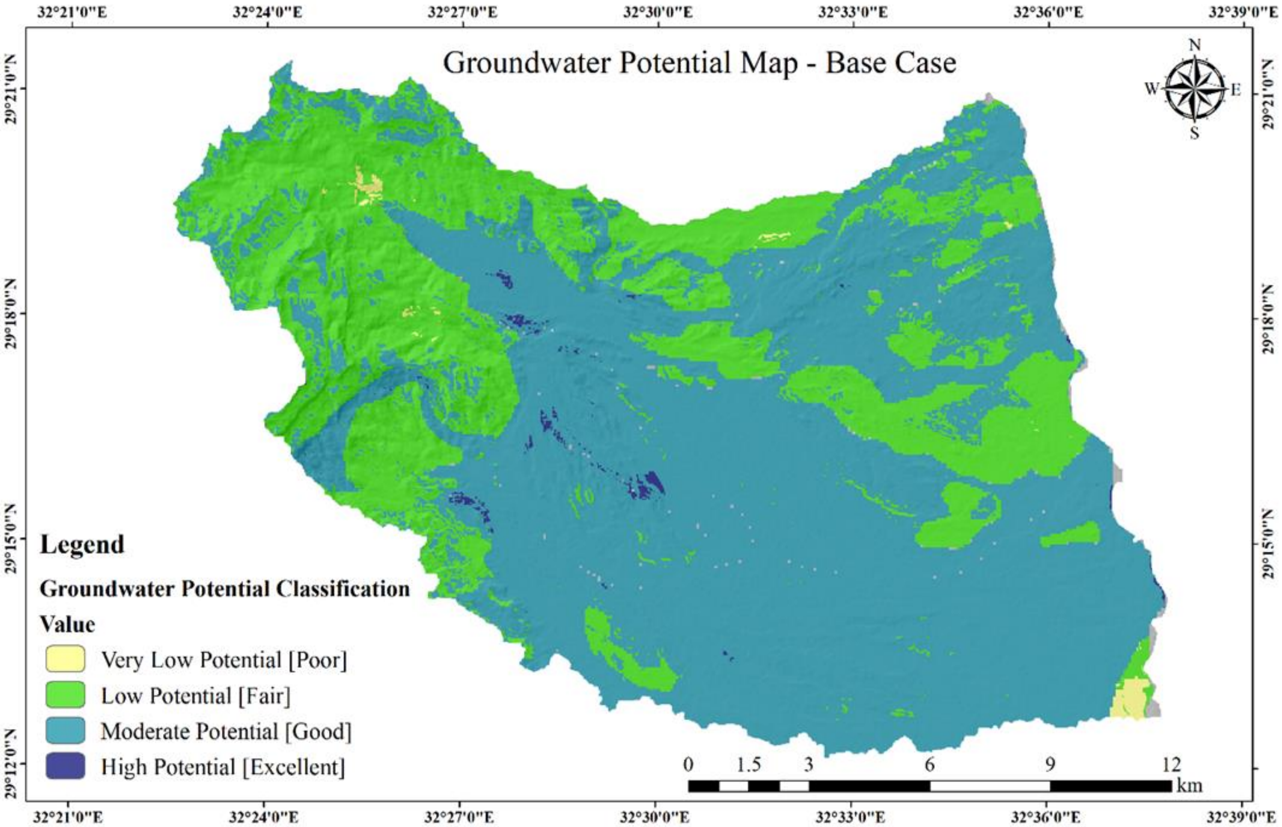

Figure (5): Groundwater potential map of the Zaafarana region generated from the AHP model with Thematic Maps

Table (3): Classification Area of Groundwater Potential Zones

Classes	Area (km^2)	Area (%)
Very Low Potential [Poor]	1.22	0.46
Low Potential [Fair]	85.60	32.32
Moderate Potential [Good]	176.95	66.82
High Potential [Excellent]	1.04	0.39
Sum	264.81	100

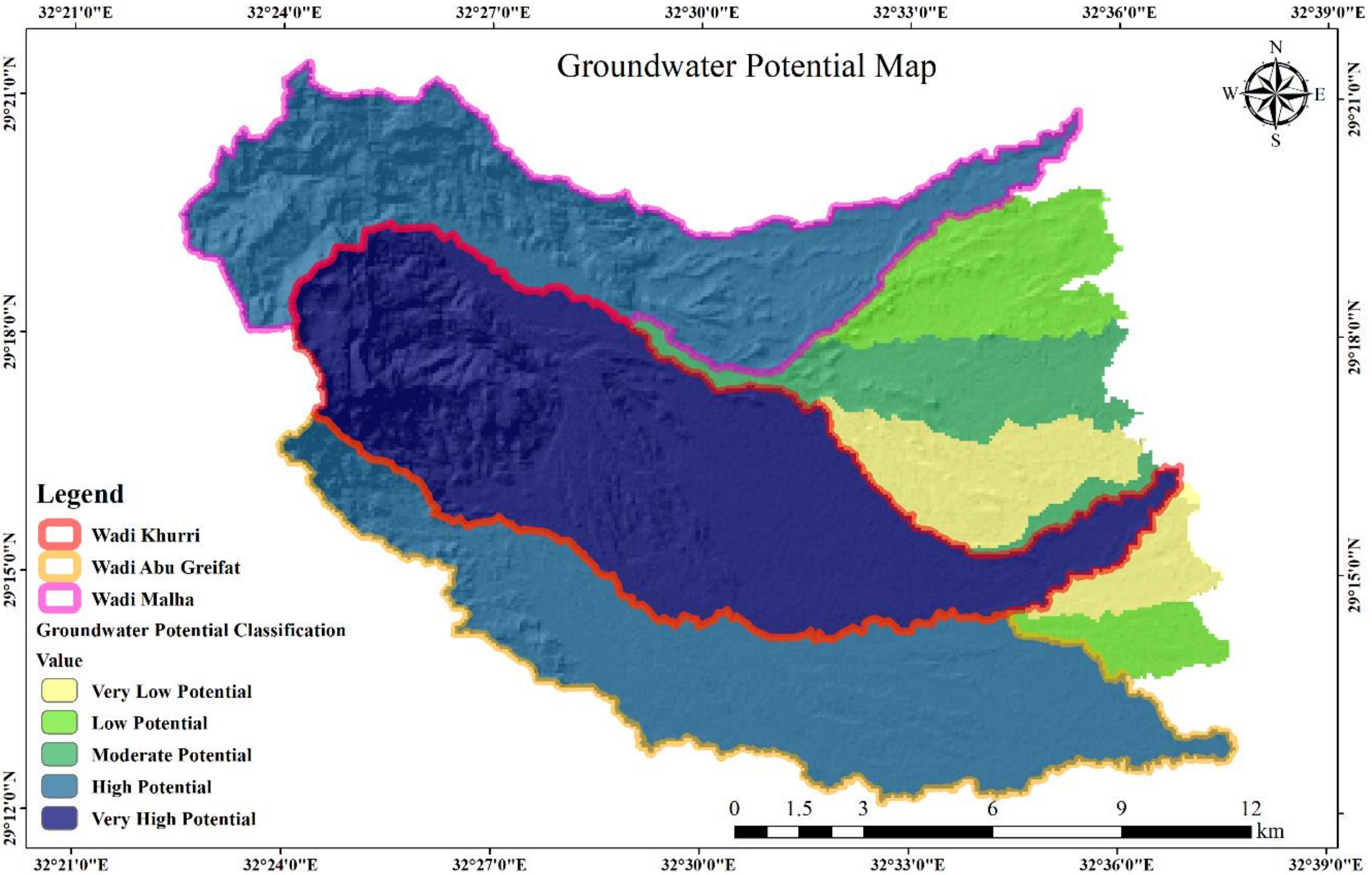

Figure (6): Groundwater Potential Map using selected Morphometric Parameters.

The sensitivity analysis reveals that Geology, Drainage Density, and Precipitation are the most influential parameters in determining groundwater potential zones in the study area. Geology shows a profound impact, with High

Potential zones increasing significantly (+70.46%) when its weight is elevated by 10%, emphasizing the importance of lithological properties in aquifer recharge (Figure 7). Similarly, Drainage Density demonstrates strong correlations, with High Potential zones increasing sharply (+70.78%) at a 5% weight increase, reflecting its role in influencing runoff and infiltration dynamics. Precipitation also emerges as a critical factor, with High Potential zones rising significantly (+74.02%) when its weight decreases, highlighting its direct influence on groundwater recharge. Conversely, parameters such as Slope Figure (8) and Soil exhibit lower sensitivity, where weight changes produce only moderate variations in High Potential zones, indicating a supportive but less dominant role in groundwater recharge processes.

Moderate effects are observed for Lineament Density and Land Use/Land Cover (LULC), which are essential for optimizing the model. Lineament Density enhances subsurface flow and recharge, with High Potential zones increasing (+21.27%) at a 10% weight increase. At the same time, LULC underscores the impact of land management practices, as High Potential zones improve (+38.78%) with reduced weight. Notably, overemphasizing certain parameters, such as Soil, can negatively impact the model, as seen in the 26.59% decline in High Potential zones with a 10% weight increase. These findings highlight the importance of maintaining a balanced parameter weighting in the AHP model to ensure reliable groundwater potential predictions, carefully calibrating dominant parameters such as Geology, Drainage Density, and Precipitation, alongside moderate adjustments in LULC and Lineament Density.

Although direct validation with extensive well data was limited in this study, the consistency between the morphometric analysis, the AHP model results, and the sensitivity analysis provides confidence in the model's reliability. The identification of Wadi Khurri as having the highest groundwater potential across all analyses further supports the validity of the approach. However, it is crucial to acknowledge that the model's accuracy inherently depends on the input data's quality and resolution. Limitations in data accuracy or resolution can affect the precision of the models.

Table (4): Classification Area of Groundwater Potential Zones for each scenario

Scenario	**Area [km^2]**			
	Very Low Potential	Low Potential	Moderate Potential	High Potential
Base Case	1.22	85.60	176.95	1.04
5% Increase in Geology	1.44	86.09	176.16	1.12
5% Decrease in Geology	1.19	84.44	178.18	1.00
10% Increase in Geology	1.39	82.59	179.06	1.77
10% Decrease in Geology	1.21	86.91	175.91	0.78
5% Increase in Slope	1.22	85.01	177.56	1.03
5% Decrease in Slope	1.19	85.81	176.69	1.12
10% Increase in Slope	1.34	84.91	177.80	0.76
10% Decrease in Slope	1.33	86.94	175.45	1.09
5% Increase in Drainage Density	1.38	85.11	176.54	1.78
5% Decrease in Drainage Density	1.23	85.16	177.31	1.12
10% Increase in Drainage Density	1.38	84.65	177.22	1.56
10% Decrease in Drainage Density	1.57	87.44	174.76	1.04
5% Increase in LULC	1.19	85.63	176.98	1.02
5% Decrease in LULC	1.25	85.65	176.46	1.44
10% Increase in LULC	1.01	85.31	177.49	1.00
10% Decrease in LULC	1.25	85.65	176.46	1.44
5% Increase in Lineament Density	1.22	85.60	176.95	1.04
5% Decrease in Lineament Density	1.22	85.60	176.95	1.04
10% Increase in Lineament Density	1.37	87.23	174.94	1.26
10% Decrease in Lineament Density	1.24	83.44	178.80	1.33
5% Increase in Soil	1.22	85.60	176.95	1.04
5% Decrease in Soil	1.22	85.60	176.95	1.04
10% Increase in Soil	1.22	86.59	176.23	0.76
10% Decrease in Soil	1.22	85.60	176.95	1.04
5% Increase in Precipitation	1.22	85.60	176.95	1.04
5% Decrease in Precipitation	1.37	83.46	178.17	1.81
10% Increase in Precipitation	1.22	85.60	176.95	1.04
10% Decrease in Precipitation	1.37	83.46	178.17	1.81

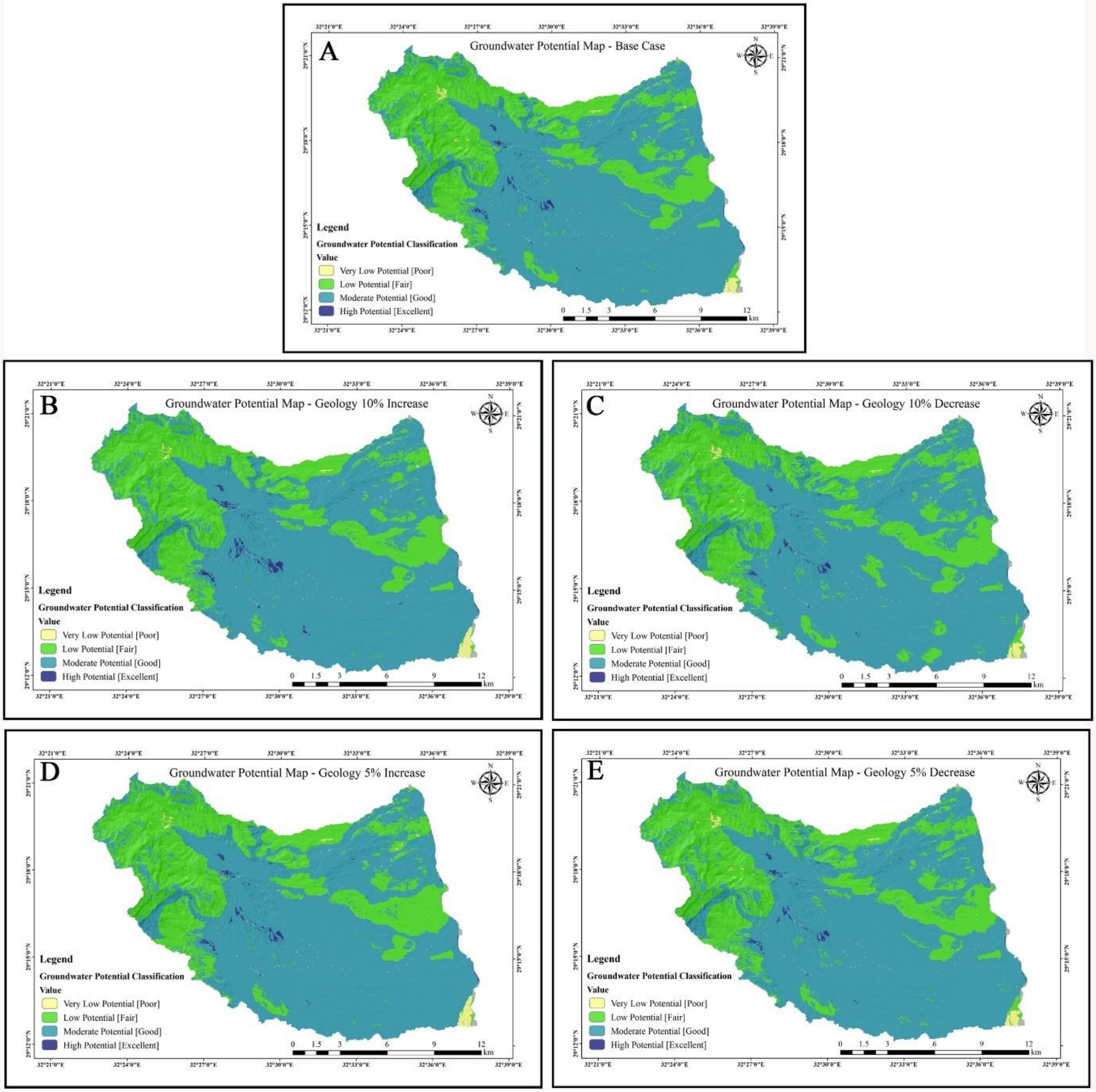

Figure (7): Comparison of Groundwater Potential Classification Base Case vs. Geology Sensitivity Scenarios

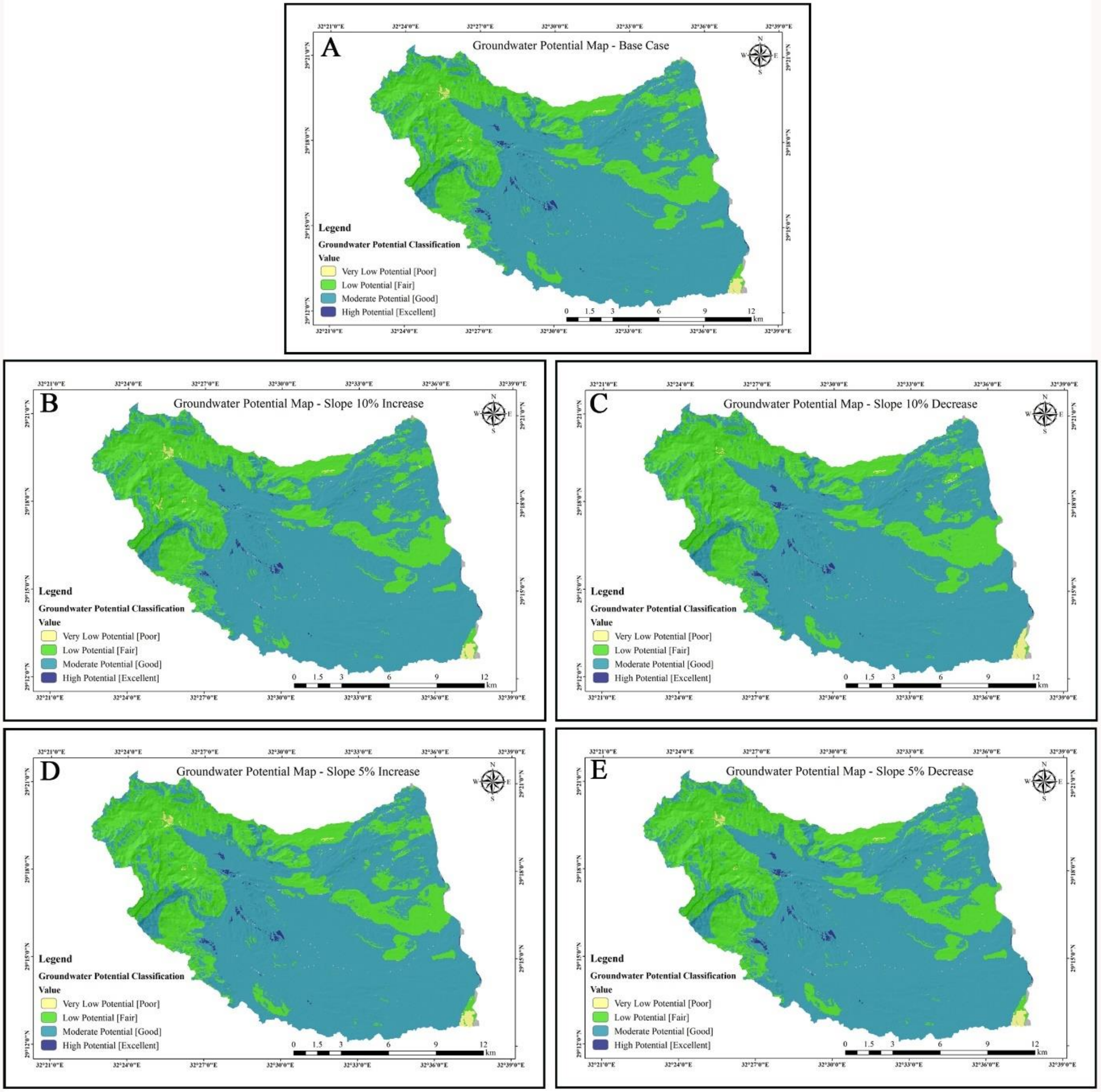

Figure (8): Comparison of Groundwater Potential Classification Base Case vs. Slope Sensitivity Scenarios

5. Conclusion

This study assessed groundwater potential in Zaafarana using a comprehensive approach that integrated morphometric analysis, AHP modeling with morphometric parameters, and AHP modeling with thematic maps.

Morphometric analysis revealed variations in potential across different basins. Wadi Khurri, despite high stream number and drainage density, exhibited moderate to high potential due to a high bifurcation ratio, suggesting a potential for rapid runoff. Wadi Malha displayed high potential characteristics attributed to a low bifurcation ratio and an elongated shape that favors infiltration. Wadi Abu Greifat also showed high potential, with high stream frequency and long overland flow length contributing to increased infiltration.

AHP modeling with morphometric parameters corroborated these findings, with Wadi Khurri receiving the highest score (0.66), followed by Wadi Malha (0.58) and Wadi Abu Greifat (0.56). AHP modeling incorporating thematic maps revealed that 66.82% of the area has moderate potential, with geology emerging as a dominant factor (38%), followed by slope (19%) and drainage density (17%). This underscores the role of geological structures and terrain characteristics in facilitating groundwater recharge.

The sensitivity analysis of the AHP model with thematic maps highlighted the significant influence of geology, drainage density, and precipitation on groundwater potential classification. Adjusting the weights of these factors caused notable changes in the spatial distribution of potential zones, particularly with substantial increases in High Potential zones linked to geology and drainage density. In contrast, the model showed lower sensitivity to changes in factors like slope, land use/land cover (LULC), and lineament density, indicating their relatively moderate to minimal impact on the overall assessment.

These findings have important implications for groundwater management in Zaafarana. High-potential zones, like those in Wadi Khurri and Wadi Malha, should be prioritized for development, but with careful monitoring and regulation to prevent over-extraction. Moderate potential zones should focus on enhancing recharge through techniques like rainwater harvesting and artificial recharge structures. Low potential zones should be designated as protected areas with restrictions on extraction and measures to prevent contamination.

This study demonstrates the value of integrating diverse methods to provide a robust framework for evaluating groundwater potential and guiding sustainable management practices. Future research should incorporate more detailed hydrogeological data and ground-truthing efforts to enhance these findings, including geophysical surveys and test drilling in identified high-potential zones. This will help validate the model's predictions and inform targeted groundwater development strategies

6. Reference

Abdel-Shafy HI, Kamel AH. Groundwater in Egypt issue: Resources, location, amount, contamination, protection, renewal, future overview. Egypt J Chem 2016;59:321–62. https://doi.org/10.21608/ejchem.2016.1085.

Abdessamed D, Jodar-Abellan A, Ghoneim SSM, Almaliki A, Hussein EE, Pardo MÁ. Groundwater quality assessment for sustainable human consumption in arid areas based on GIS and water quality index in the watershed of Ain Sefra (SW of Algeria). Environ Earth Sci 2023;82:1–19. https://doi.org/10.1007/s12665-023-11183-9.

Aggour TAO. Response of Geomorphological and Geological Features on Groundwater in Wadi Araba, Eastern Desert, Egypt. Ain Shams, 1990.

Ahmadi H, Kaya OA, Babadagi E, Savas T, Pekkan E. GIS-Based Groundwater Potentiality Mapping Using AHP and. Environ Sci Proc 2021;2021:1–15.

Ali S, Mater A. Groundwater in Arid and Semi-Arid Areas Monitoring, Assessment, Modelling, and Management. 2023. https://doi.org/https://doi.org/10.1007/978-3-031-43348-1.

Alshehri F, Abd El-Hamid HT, Mohamed A. Mapping coastal groundwater potential zones using remote sensing based AHP model in Al Qunfudhah region along Red Sea, Saudi Arabia. Heliyon 2024;10:e28186. https://doi.org/10.1016/j.heliyon.2024.e28186.

Baghel S, Tripathi MP, Khalkho D, Al-Ansari N, Kumar A, Elbeltagi A. Delineation of suitable sites for groundwater recharge based on groundwater potential with RS, GIS, and AHP approach for Mand catchment of Mahanadi Basin. Sci Rep 2023;13:1–22. https://doi.org/10.1038/s41598-023-36897-5.

Bogale A. Morphometric analysis of a drainage basin using geographical information system in Gilgel Abay watershed, Lake Tana Basin, upper Blue Nile Basin, Ethiopia. Appl Water Sci 2021;11:1–7. https://doi.org/10.1007/s13201-021-01447-9.

Chowdhury MS. Morphometric analysis of Halda River basin, Bangladesh, using GIS and remote sensing techniques. Heliyon 2024;10:e29085. https://doi.org/10.1016/j.heliyon.2024.e29085.

CONOCO. Geological map of Egypt 1:500,000. NH 36 SW, Beni Suef 1987.

El Ayady H, Mickus KL, Boutaleb S, El Morjani ZEA, Ikirri M, Echogdali FZ, et al. Investigation of groundwater potential using geomatics and geophysical methods: Case study of the Anzi sub-basin, western Anti-Atlas, Morocco. Adv Sp Res 2023;72:3960–81. https://doi.org/10.1016/j.asr.2023.08.044.

El-Fakharany MA, Mansour NM. Morphometric analysis and flash floods hazards assessment for Wadi Al Aawag drainage Basins, southwest Sinai, Egypt. Environ Earth Sci 2021;80:1–17. https://doi.org/10.1007/s12665-021-09457-1.

Elewa HH. Groundwater in the Eastern Desert with Reference to Application of Remote Sensing and GIS 2007:1–38.

Elewa HH, Nosair AM, Ibrahim A, Zelenakova M, Pietrucha-Urbanik K, Habib HM, et al. Use of remote sensing, spatial and geophysical modeling, and real recharging capabilities to identify suitable areas for groundwater exploitation in dry coastal areas. J Environ Manage 2024;363:121243. https://doi.org/10.1016/j.jenvman.2024.121243.

Emara SR, Armanuos AM, Shalby A. Appraisal seawater intrusion vulnerability for the Moghra coastal aquifer, Egypt–application of the GALDIT index, sensitivity analysis, and hydro-chemical indicators. Groundw Sustain Dev 2024;25:101166. https://doi.org/10.1016/j.gsd.2024.101166.

Ezzeldin HA. HYDROGEOCHEMICAL STUDIES ON THE AREA BETWEEN EL-AIN EL-SUKHNA AND WADI ARABA , GULF OF SUEZ , EGYPT. 2010.

Horton RE. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bull Geol Soc Am 1945;5:275–370.

Ian H, Osborn TJ, Phil J, Lis D. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset 2020:1–

18. https://doi.org/10.1038/s41597-020-0453-3.

Javhar A, Chen X, Bao A, Jamshed A, Yunus M, Jovid A, et al. Comparison of multi-resolution optical Landsat-8, Sentinel-2 and radar Sentinel-1 data for automatic lineament extraction: A case study of Alichur area, SE Pamir. Remote Sens 2019;11:1–29. https://doi.org/10.3390/rs11070778.

Meng F, Khan MI, Ali S, Naqvi A, Sarwar A, Islam F, et al. Identification and mapping of groundwater recharge zones using multi influencing factor and analytical hierarchy process. Sci Rep 2024:1–17. https://doi.org/10.1038/s41598-024-70324-7.

Moustafa AR, Khalil MH. Superposed Deformation in the Northern Suez Rift, Egypt: Relevance To Hydrocarbons Exploration. J Pet Geol 1995;18:245–66. https://doi.org/10.1111/j.1747-5457.1995.tb00905.x.

Nassim A. Geological and hydrogeological studies on Wadi Araba Area, north Eastern Desert, Egypt. Menoufia University, 1990.

Negm A, Elkhouly A. Groundwater in Egypt’s Deserts. 2021.

Peijs JAMM, Bevan TG, Piombino JT. The Gulf of Suez rift basin. Elsevier B.V.; 2012. https://doi.org/10.1016/B978-0-444-56356-9.00007-9.

Pinder GF, Celia MA. Subsurface Hydrology. 2006. https://doi.org/10.1002/0470044209.

Saaty TL. Decision making with the Analytic Hierarchy Process. Sci Iran 1980;9:215–29. https://doi.org/10.1504/ijssci.2008.017590.

Schumm SA. Evaluation of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Bull Geol Soc Am 1956;67:597–646.

Sikakwe GU, Onwusulu AU, Ojo SA, Agunanna HI. Geoinformatics and Analytic Hierarchy Process (AHP) in modelling groundwater potential in Obudu Plateau, Southeastern Nigeria Bamenda Massif. Appl Geomatics 2024. https://doi.org/10.1007/s12518-024-00565-8.

Strahler AN. Quantitative Geomorphology of Drainage Basins and Channel Networks. In: Chow VT, editor. Handb. Appl. Hydrol., New York: McGraw Hill; 1964, p. 439–76.

Todd, D. K., Mays LW. Groundwater Hydrology. 3rd ed. John Wiley & Sons.; 2005.

Wannous M, Theilen-Willige B, Troeger U, Falk M, Siebert C, Bauer F. Hydrochemistry and environmental isotopes of spring water and their relation to structure and lithology identified with remote sensing methods in

Wadi Araba, Egypt. Hydrogeol J 2021;29:2245–66. https://doi.org/10.1007/s10040-021-02343-x.