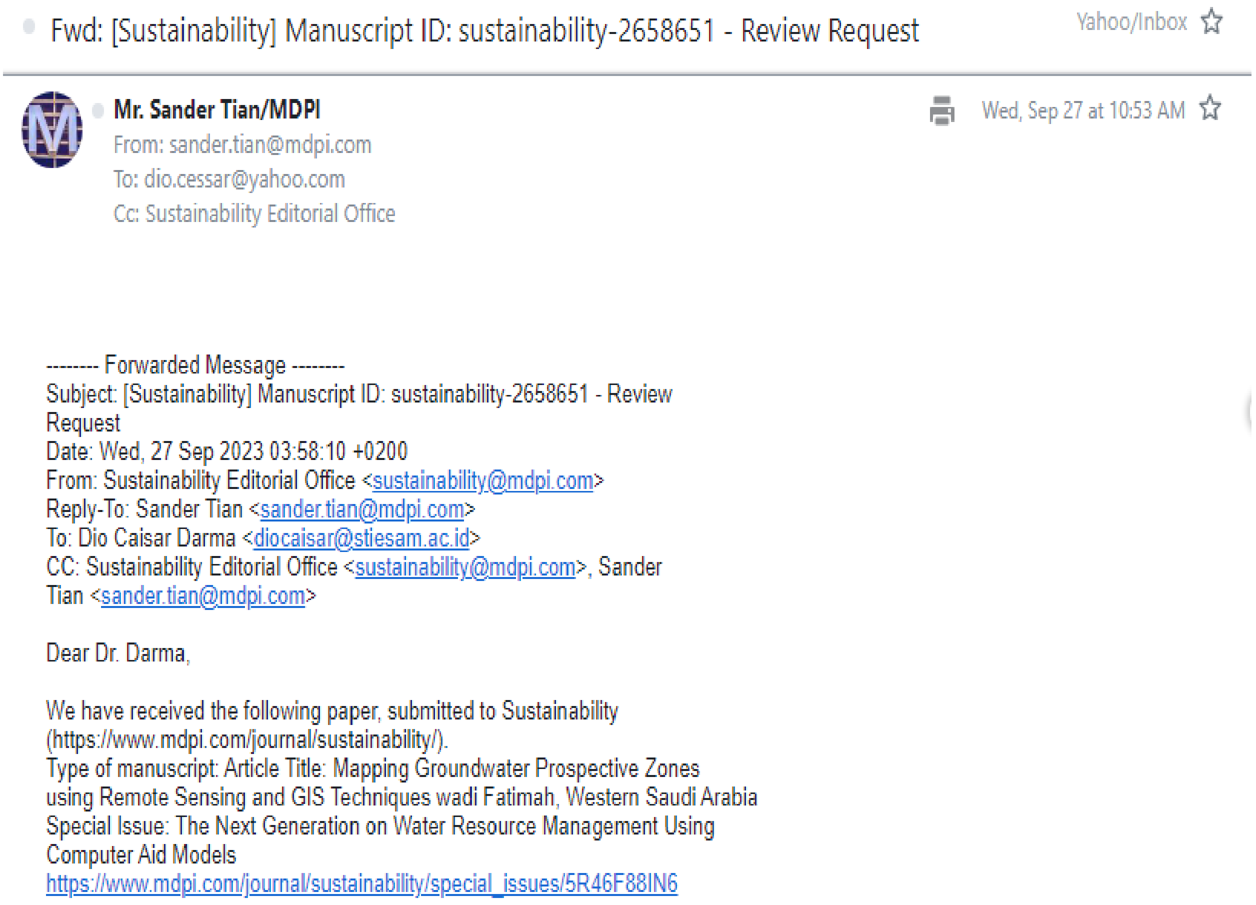

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Wed, Sep 27 at 10:53 AM

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Type of manuscript: Article Title: Mapping Groundwater Prospective Zones using Remote Sensing and GIS Techniques wadi Fatimah, Western Saudi Arabia
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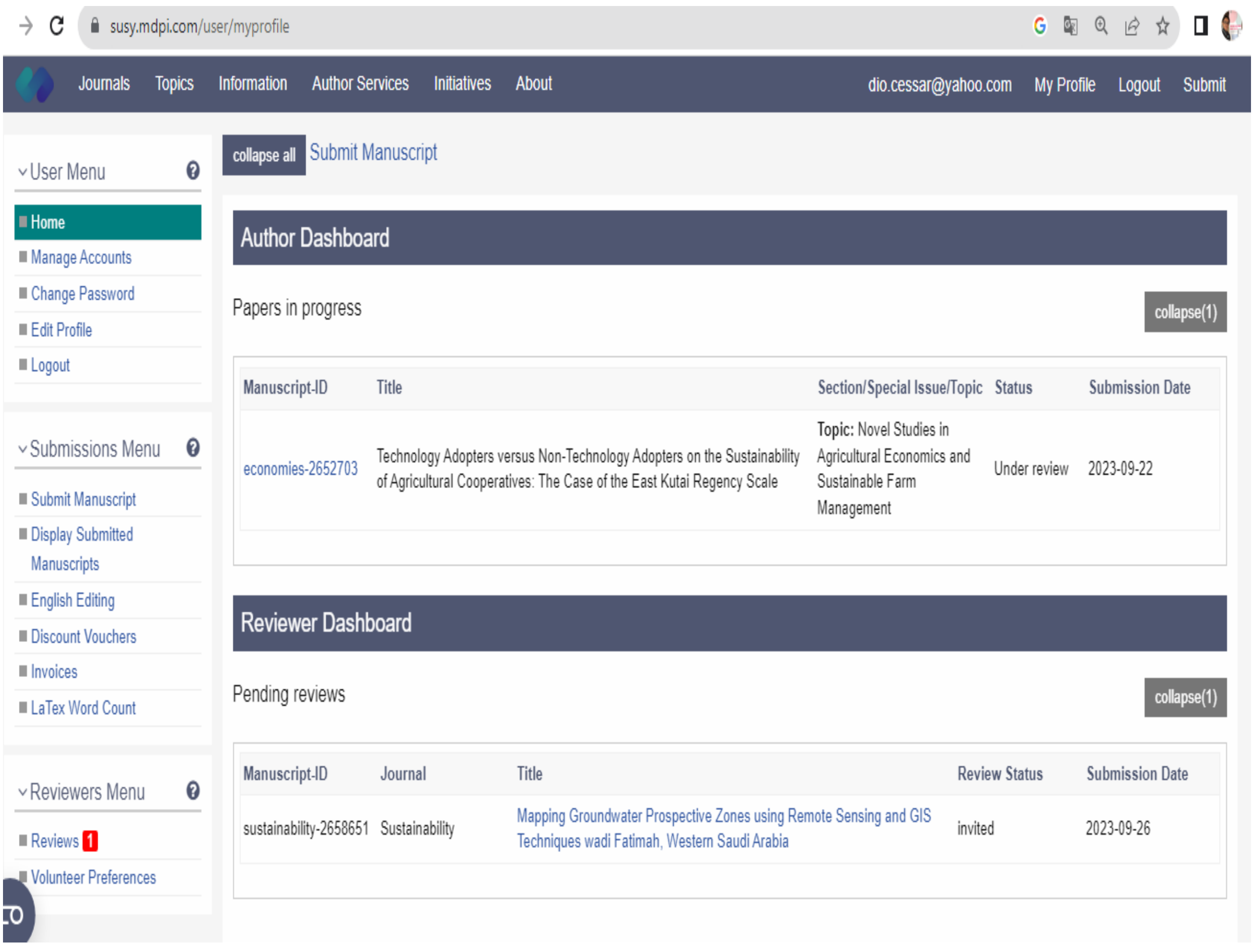
https://www.mdpi.com/journal/sustainability/special_issues/5R46F88IN6



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Manuscript-ID	Title	Section/Special Issue/Topic	Status	Submission Date
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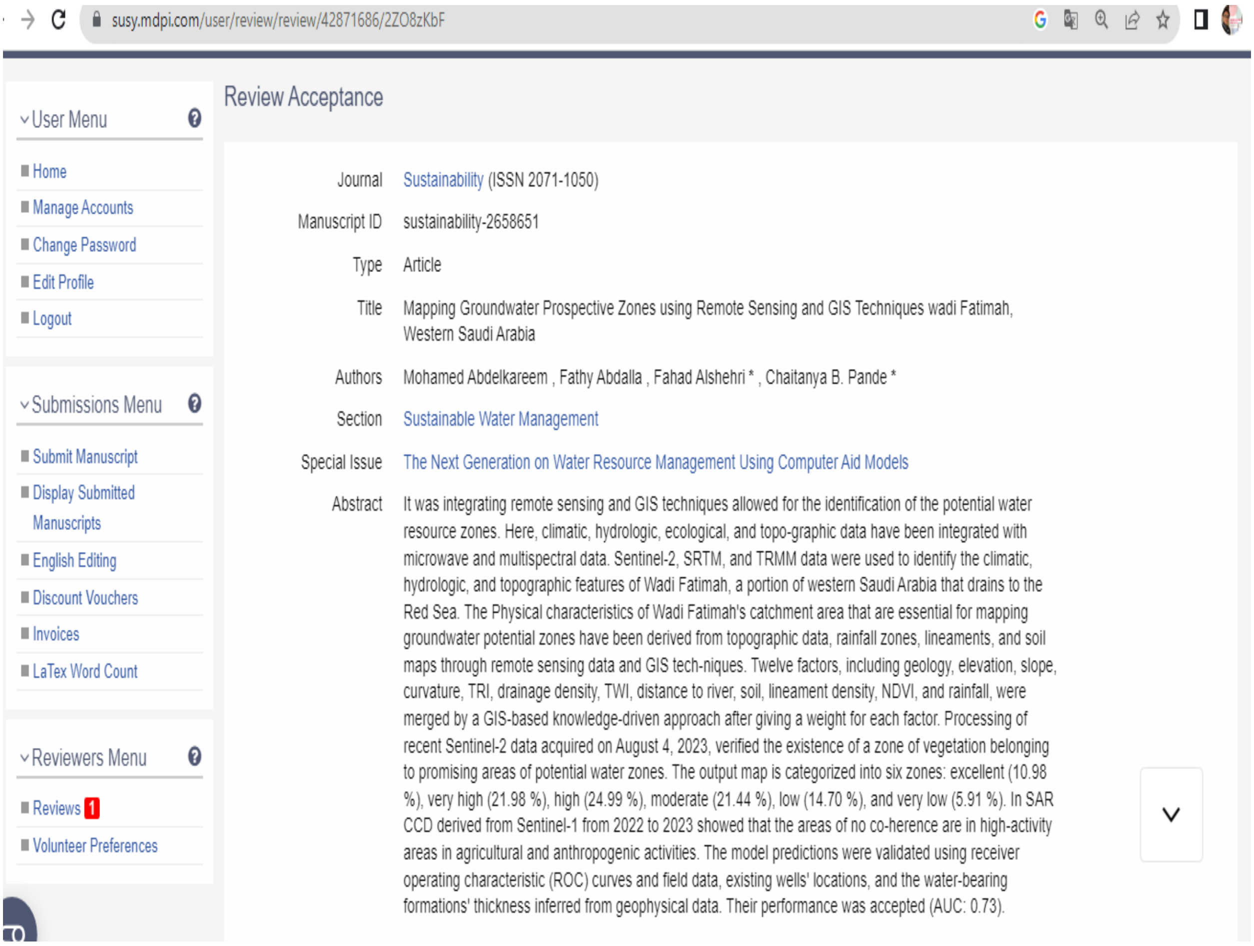
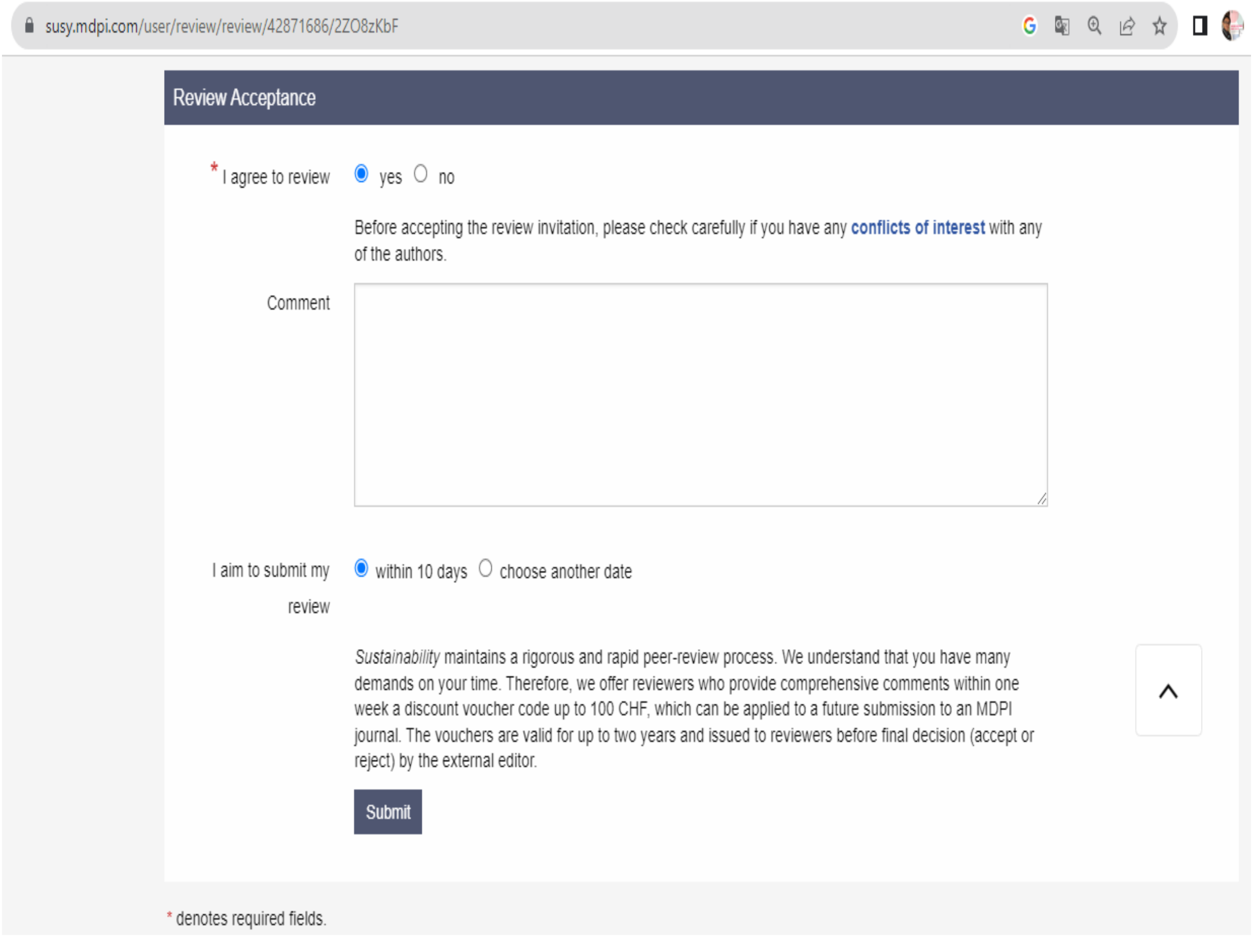
Manuscript-ID	Journal	Title	Review Status	Submission Date
sustainability-2658651	Sustainability	Mapping Groundwater Prospective Zones using Remote Sensing and GIS Techniques wadi Fatimah, Western Saudi Arabia	invited	2023-09-26



Review Acceptance

Journal	Sustainability (ISSN 2071-1050)
Manuscript ID	sustainability-2658651
Type	Article
Title	Mapping Groundwater Prospective Zones using Remote Sensing and GIS Techniques wadi Fatimah, Western Saudi Arabia
Authors	Mohamed Abdelkareem , Fathy Abdalla , Fahad Alshehri * , Chaitanya B. Pande *
Section	Sustainable Water Management
Special Issue	The Next Generation on Water Resource Management Using Computer Aid Models
Abstract	It was integrating remote sensing and GIS techniques allowed for the identification of the potential water resource zones. Here, climatic, hydrologic, ecological, and topo-graphic data have been integrated with microwave and multispectral data. Sentinel-2, SRTM, and TRMM data were used to identify the climatic, hydrologic, and topographic features of Wadi Fatimah, a portion of western Saudi Arabia that drains to the Red Sea. The Physical characteristics of Wadi Fatimah's catchment area that are essential for mapping groundwater potential zones have been derived from topographic data, rainfall zones, lineaments, and soil maps through remote sensing data and GIS tech-niques. Twelve factors, including geology, elevation, slope, curvature, TRI, drainage density, TWI, distance to river, soil, lineament density, NDVI, and rainfall, were merged by a GIS-based knowledge-driven approach after giving a weight for each factor. Processing of recent Sentinel-2 data acquired on August 4, 2023, verified the existence of a zone of vegetation belonging to promising areas of potential water zones. The output map is categorized into six zones: excellent (10.98 %), very high (21.98 %), high (24.99 %), moderate (21.44 %), low (14.70 %), and very low (5.91 %). In SAR CCD derived from Sentinel-1 from 2022 to 2023 showed that the areas of no co-herence are in high-activity areas in agricultural and anthropogenic activities. The model predictions were validated using receiver operating characteristic (ROC) curves and field data, existing wells' locations, and the water-bearing formations' thickness inferred from geophysical data. Their performance was accepted (AUC: 0.73).



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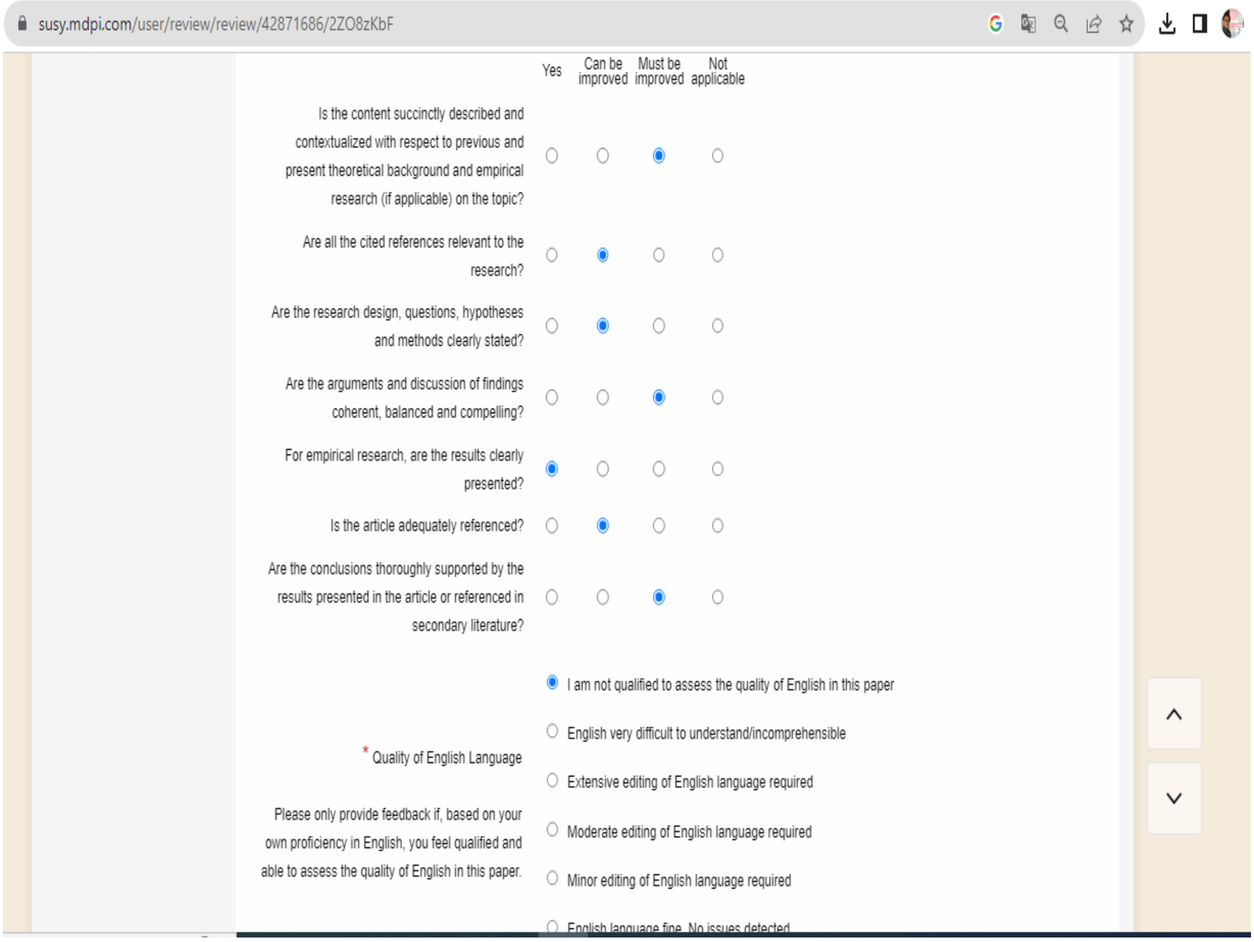

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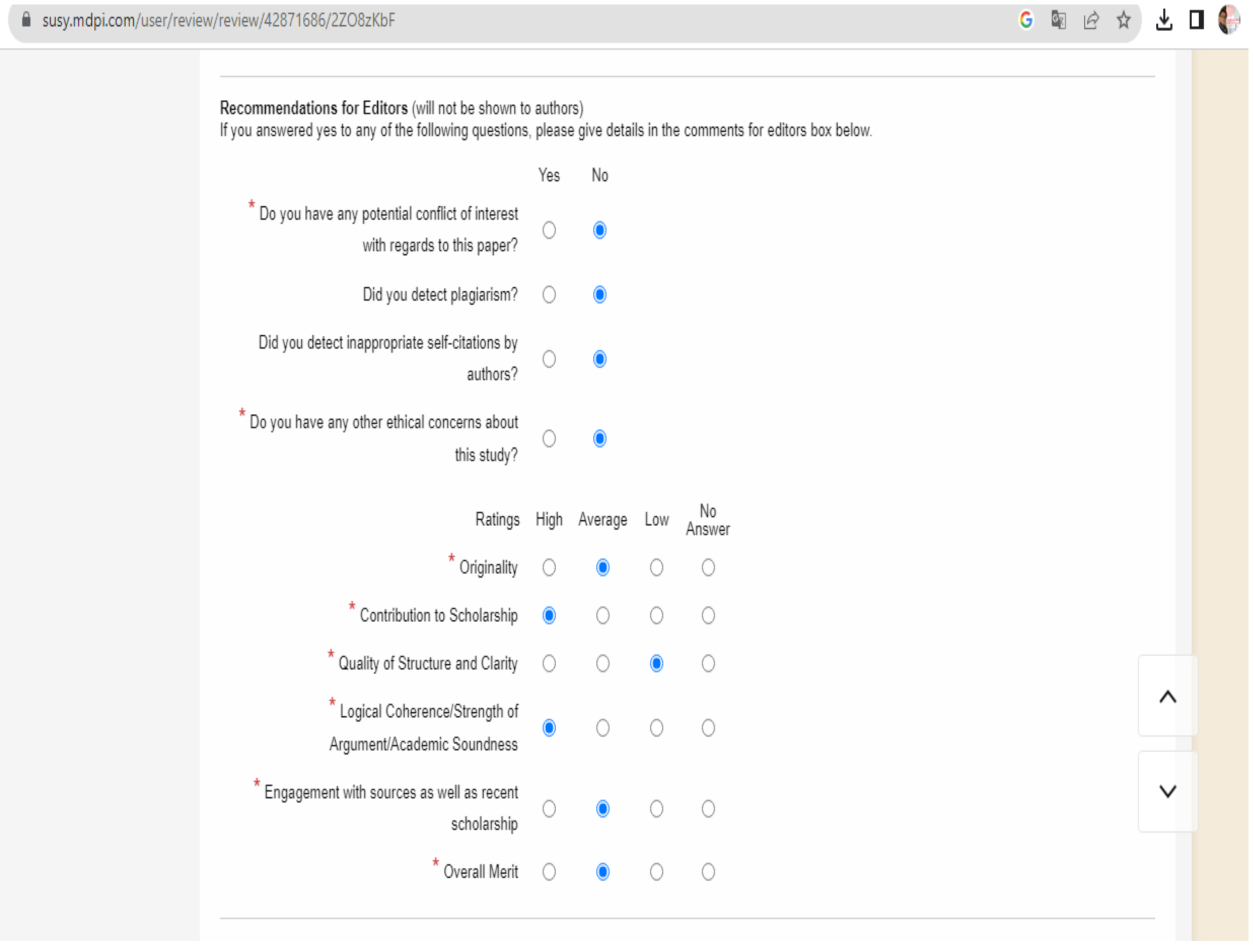

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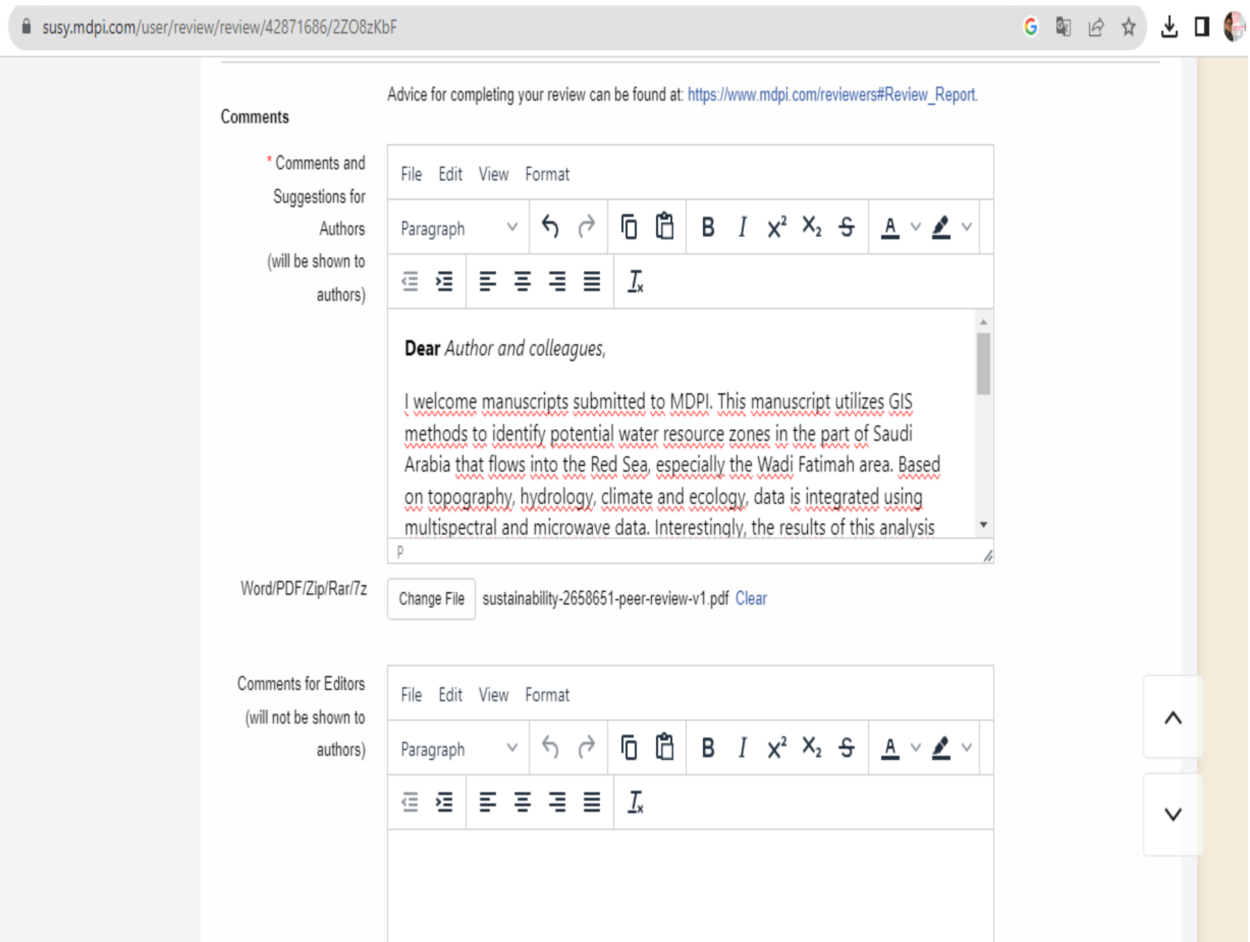

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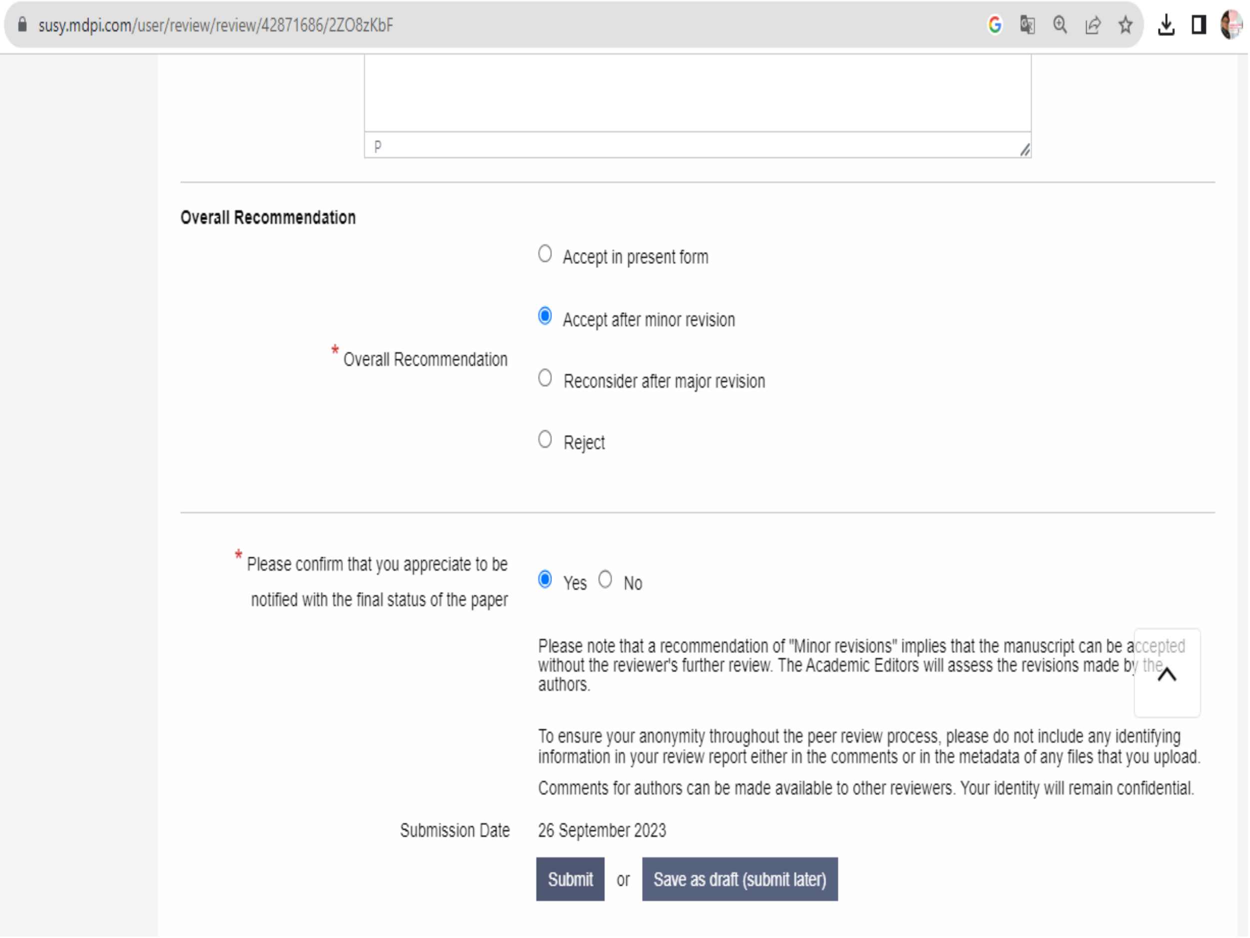

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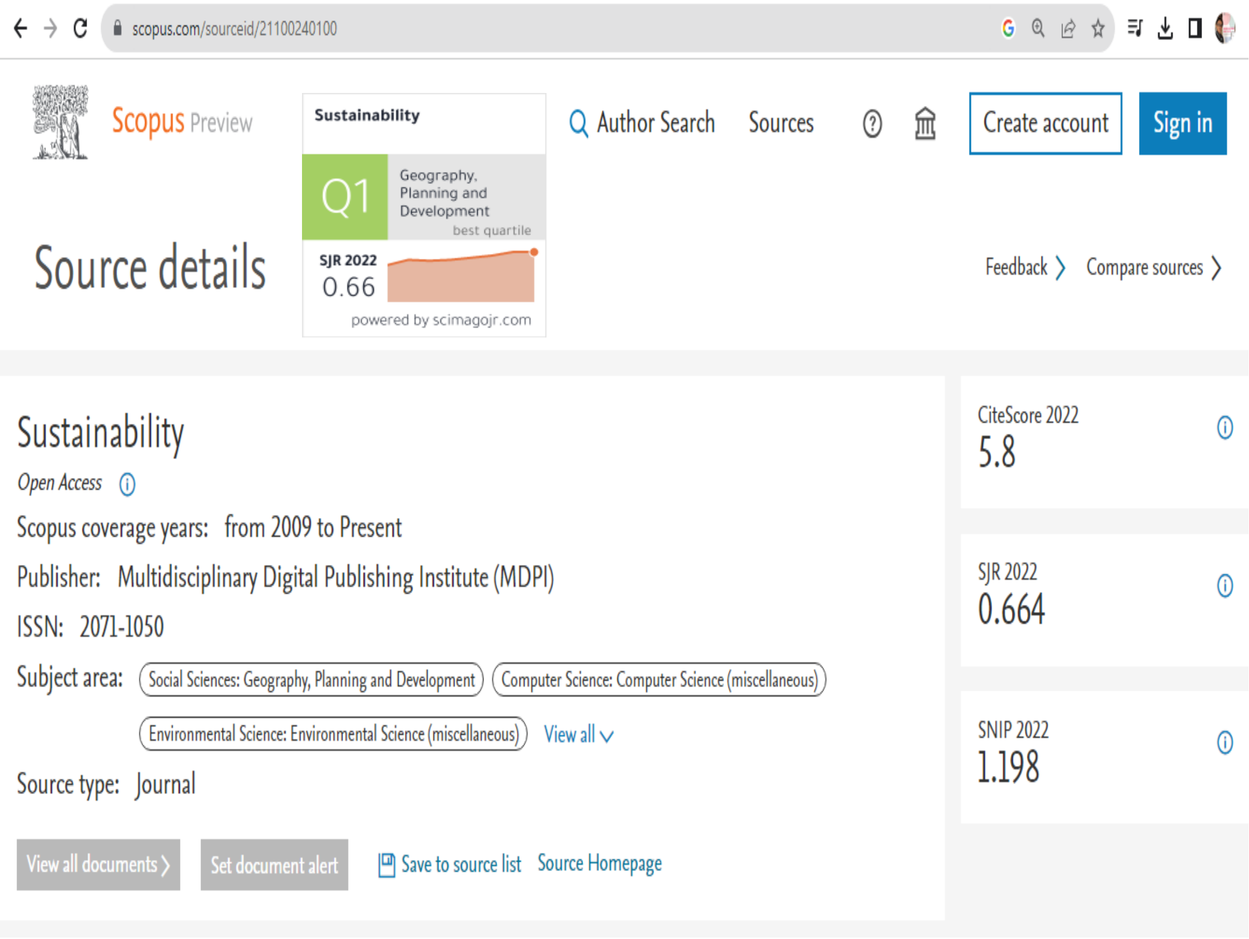

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Publisher: Multidisciplinary Digital Publishing Institute (MDPI)

ISSN: 2071-1050

Subject area: Social Sciences: Geography, Planning and Development; Computer Science: Computer Science (miscellaneous); Environmental Science: Environmental Science (miscellaneous)

Source type: Journal

CiteScore 2022
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Article

Mapping Groundwater Prospective Zones using Remote Sensing and GIS Techniques wadi Fatimah, Western Saudi Arabia

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Abstract: It was integrating remote sensing and GIS techniques allowed for the identification of the potential water resource zones. Here, climatic, hydrologic, ecological, and topographic data have been integrated with microwave and multispectral data. Sentinel-2, SRTM, and TRMM data were used to identify the climatic, hydrologic, and topographic features of Wadi Fatimah, a portion of western Saudi Arabia that drains to the Red Sea. The Physical characteristics of Wadi Fatimah's catchment area that are essential for mapping groundwater potential zones have been derived from topographic data, rainfall zones, lineaments, and soil maps through remote sensing data and GIS techniques. Twelve factors, including geology, elevation, slope, curvature, TRI, drainage density, TWI, distance to river, soil, lineament density, NDVI, and rainfall, were merged by a GIS-based knowledge-driven approach after giving a weight for each factor. Processing of recent Sentinel-2 data acquired on August 4, 2023, verified the existence of a zone of vegetation belonging to promising areas of potential water zones. The output map is categorized into six zones: excellent (10.98 %), very high (21.98 %), high (24.99 %), moderate (21.44 %), low (14.70 %), and very low (5.91 %). In SAR CCD derived from Sentinel-1 from 2022 to 2023 showed that the areas of no coherence are in high-activity areas in agricultural and anthropogenic activities. The model predictions were validated using receiver operating characteristic (ROC) curves and field data, existing wells' locations, and the water-bearing formations' thickness inferred from geophysical data. Their performance was accepted (AUC: 0.73).

Keywords: Water; Remote Sensing; Wadi Fatimah; GIS; Saudi Arabia

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date

1. Introduction

Many regions in the Great Sahara and Arabian Peninsula are currently experiencing water scarcity, largely driven by frequent droughts and expanding agriculture and settling. Such regions suffer from limited rainfall and surface freshwater, representing <1% of the world's freshwater. In comparison, over 30% is preserved in underground aquifer water (Chow et al., 1988), supplying ~ 80% of the world's rural population with a safe water supply. One of the water supplies that can address the issue of water scarcity is groundwater. In arid-semi-arid conditions, groundwater resources are significant natural resources that contribute to potable, industry, and agriculture ~ 50%, 40%, and 20%, respectively (Molden, 2007). Thus, groundwater is vital compared to surface water (Jaafarzadeh et al., 2021). Growing populations and a wide range of social, economic, environmental, and climatic factors are the primary causes of growing demands on freshwater availability. Supplies for water are vital for the growth of urban, agricultural, and industrial activities (Hasanuzzaman et al., 2022). Population growth and food rules are the biggest challenges to reaching sustainable development goals (Connor, 2015). The availability of freshwater resources has become a critical issue due to the high demand for agricultural, domestic, and industrial uses (Hasanuzzaman et al., 2022; Chakraborty et al., 2021; Shit et al., 2019; Chen et al., 2019; Alshehri et al., 2020). Therefore, > 2 billion people worldwide are suffering from freshwater scarcity, and it is expected that by 2050, over one-third of the worldwide population will suffer from water scarcity (WWDR, 2018). Climate change is one of the prominent challenges in the twenty-first century, contributing to drought and water insufficiency problems (WHO, 2015) and surface water supply systems.

The main origin of groundwater is precipitation that penetrates down soil pores into shallow aquifers. Rainwater may mainly act in infiltration and overflow, depending on the intensity of the storm, the type of vegetation present, the temperature, and many other factors, including geology, topography, climatic conditions, soil, land use, land cover, slopes, distances from rivers, and precipitation levels (Abd Manap et al., 2014; Salman et al., 2018; Abdelkareem et al., 2023). The use of remote sensing and GIS to map groundwater resources has grown in popularity (Jha et al., 2007; Sun et al., 2022). Implementing some of these techniques may be beneficial to reveal potential areas of water resources (Li et al., 2023; Abdekareem et al., 2023; Abdekareem & Abdalla, 2022). Several studies have demonstrated the usefulness of using RS and GIS to locate probable groundwater sources (Naghibi et al., 2019; Chen et al., 2019; Chen et al., 2020; Jha et al., 2007; Abdelkareem et al., 2012; Sun et al., 2022; Abdelkareem & El-Baz, 2015). A GIS technique can handle big data spatial data for processing and combination to predict and allow for finding additional water resources (Yariyan et al., 2020). For mapping groundwater potentiality, methodologies based on data and knowledge were used (Machiwal et al., 2010). Multiple fields of knowledge, such as overlay analysis (Zhu & Abdelkareem, 2021), analytical hierarchy process (AHP) (Razandi et al., 2015; Senthilkumar et al., 2019), Boolean logic (Riad et al., 2011), index overlays, and fuzzy methods (Maity et al., 2022; Muthumaniraja et al., 2019).

The main objective of the present study is to model and delineate groundwater prospective zones GPZs in the Wadi Fatimah basin, western Saudi Arabia. This objective is achieved by preparing thematic maps for the most important contributing parameters that indicate groundwater potential, including elevation, slope, curvature, TRI, drainage density, TWI, distance to river, soil, lineament density, NDVI, and rainfall through the GIS module. Field observations and geophysical investigations are applied to test the validity of the resulting GIS module.

2. Study area

Wadi Fatimah is located within the Makkah region (Fig. 1a); it covers a large area of the south and east of Jeddah and extends from NE to SW with an area that exceeds 100 km2. It is located between longitudes 39° 15` and 40° 30` and latitudes 21° 16` and 22° 15` N, as shown in Figure 1. Wadi Fatimah drainage basin, which drains toward the Red Sea, gets its importance from its location in the central-western part of the Kingdom. It is the closest drainage basin to the three major cities: Jeddah, Makkah, and Taif. The Hijaz Escarpment altitude (high Sarawat Mountains) in the east is the primary factor controlling the quantity and pattern of rainfall, where they act as an orographic cooling barrier and hence its duration, intensity, distribution, and return periods are major influences (Subyani & Alhamadi, 2011). The basin is considered significant, with a greater chance of collecting more flood and rainwater than the smaller basins. Rainfall occurs during the spring and summer, where the average annual precipitation varies from >500 mm in the eastern parts near the Hijaz Escarpment to <100 mm in the western part near the Red Sea coast, reflecting the effect of topography. The average evaporation rates exceed 2000 mm/yr. The infiltration rate is low due to the Fatimah group's carbonate and quartz–feldspar epiclastic rocks (Moore & Al-Rehaili, 1989). The recharge areas for surficial groundwater aquifers in Wadi Fatimah lie near Taif province, estimated at 72mm/y (Alyamani & Hussein, 1995; Alshehri et al., 2023).

Geologically, Wadi Fatimah is located within the Makkah Quadrangle; it comprises different rock units with ages ranging from the Precambrian basement complex to the Tertiary sedimentary and lavas and the Quaternary alluvial deposits. These rock units are affected by structural elements such as faulting and dykes in the area. The thickness of the Quaternary fill deposits formed from mudstones, sandstones, and conglomerates in the study area varies from 10 m near the upstream parts to 20 m or more in the downstream parts (Al Sefry et al., 2003; Alshehri & Abdelrahman, 2023). Geomorphologically, Wadi Fatimah and its surrounding shows three main geomorphic units. These units are the high mountainous area (Proterozoic rocks), the hilly area (dissected and weathered rocks), and the pediment plain (Qari, 2009). Wadi Fatimah comprises sub-catchments like Wadi Ashshamiyah, Wadi Alyamaniyah, Wadi Bani Omair, and Wadi Howarah.

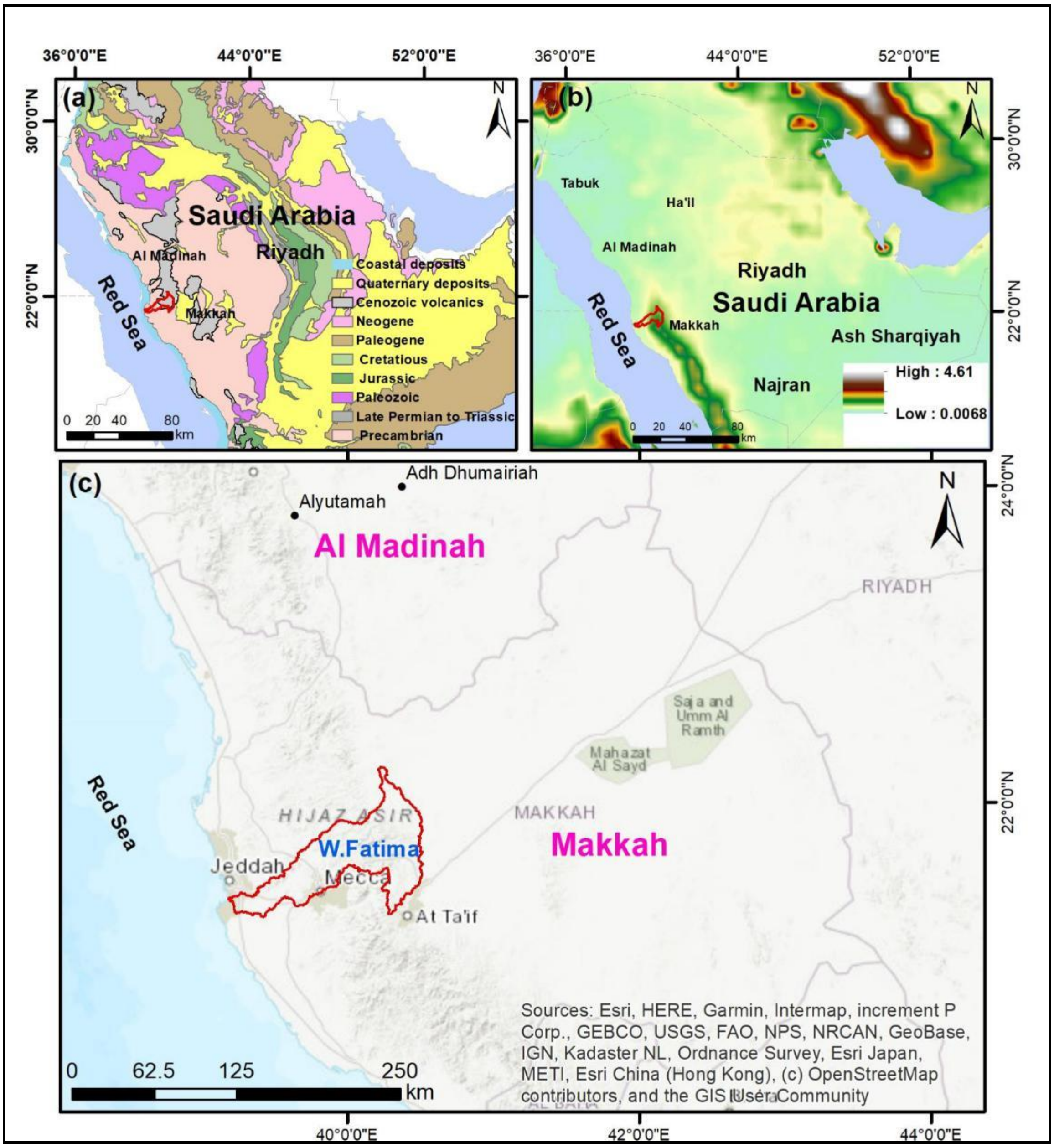


Figure 1. Location map of Wadi Fatimah.

3. Materials and Methods

3.1. Data used and methods:

This study used remote sensing data and GIS techniques to reveal the prospective areas of water resources. Integration of multi-criteria such elevation, slope, curvature, TRI, drainage density, TWI, distance to river, soil, lineament density, NDVI, and rainfall to reveal possible water resource areas using remote sensing data from radar and optical sensors (Fig.2). These eleven thematic GIS maps were merged. Digital elevation models (DEMs) generated from the Shuttle Radar Topography Mission's SRTM (30 m cell size) data. SRTM-30 m resolution NASADEM 1arc second WGS84 data from the SRTM were utilized to characterize the topographical parameters (elevation, slope, curvature, TRI) and hydrologic parameters (e.g., drainage density, TWI, distance to the river). The stream networks were delineated using 8-D approach (O'Callaghan & Mark, 1984) that is very important in generating stream-density maps, TWI, and distances to rivers (Abdelkareem et al., 2023).

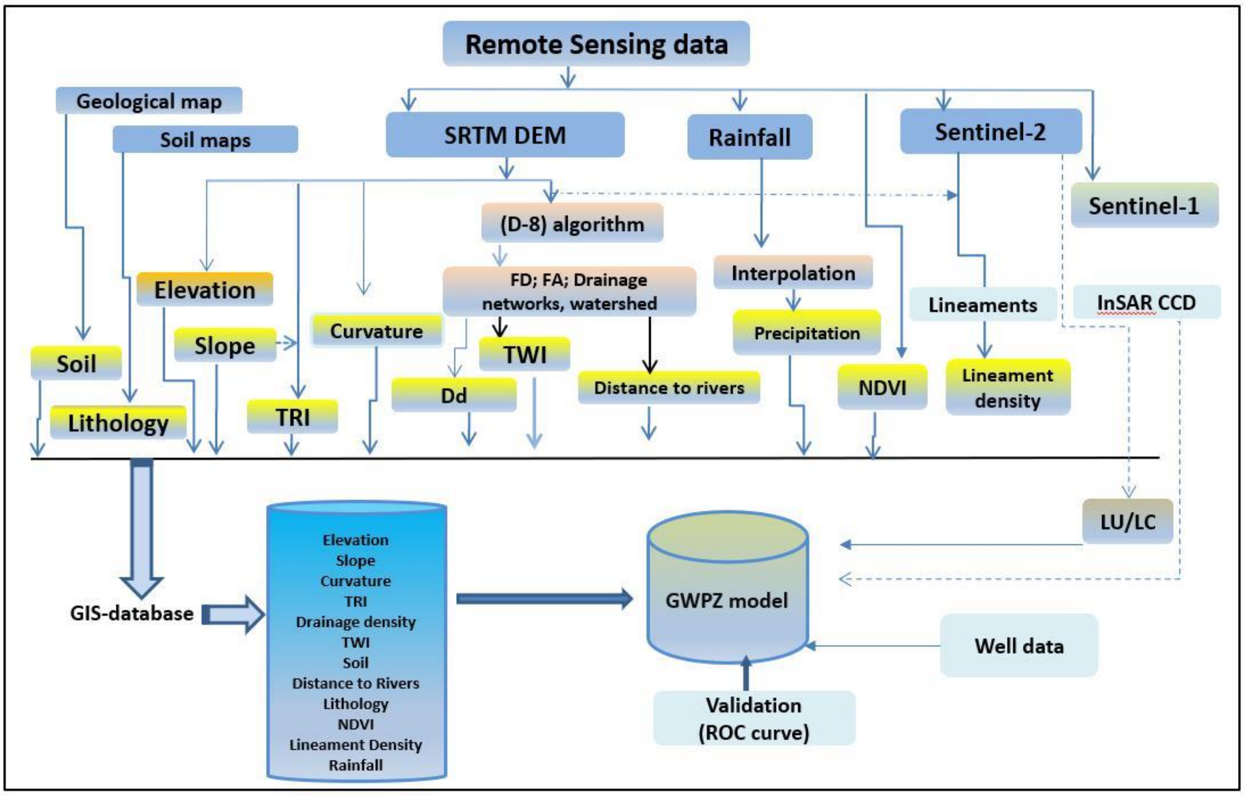


Figure 2. Data and methods utilized in the present study.

The Normalized Difference Vegetation Index (NDVI) composites are generated by computing multiple Advanced Very High-Resolution Radiometer (AVHRR) daily readings to produce a nearly cloud-free image depicting the maximum greenness. The NDVI ratio from bands one and two of the AVHRR composite is combined to form a derived NDVI band composite, in addition to vegetation rainfall data. The data on average rainfall was collected using TRMM satellite observations. Using the kriging interpolating application, the generated rainfall average statistics are spatially scattered and cover the period from January 1, 1998, to November 30, 2015. The information was obtained from this website address: https://giovanni.gsfc.nasa.gov/giovanni/. Two scenes of the Sentinel-2B satellite were acquired on 04/08/2023 and 19/08/2019. The VIS/NIR bands have pixel sizes of 10 m for the blue B2 (490 nm), green B3 (560 nm), red B4 (665 nm), and infrared B8 (842 nm). The SWIR bands (B11: 1610 nm, B12: 2190 nm) have 20 m-wide pixels. These bands of the Sentinel-2 are rendered as zip-compressed files in Sentinel's exclusive SAFE format. By stacking the jpg files for bands B2, B3, B4, and B8 with a spatial resolution of 10 m and B11 and B12 with a resolution of 20 m, a single GeoTIFF file with a consistent pixel size of 10 m is produced. A subset of this data has been handled utilizing SNAP software during preprocessing to decrease processing time and data. Each pixel in a theme layer corresponds to the same location in the used overlay analysis. In order to produce a groundwater prospective zones (GWPZs) map as the output, several components of the input's eleven layers must be integrated. Every layer and subclass has a numerical rank, a crucial point to remember. The user can mathematically combine the layers to give each pixel on the final GWPZ map a new rank. The minimal input cell size (90 m) was integrated with the research area's GWPZs map, which represents the weighted average of the combined data-based maps (multi-criteria) in this model utilizing a weighted overlay technique based on geographic information systems (GIS). For this purpose, the following equation-1 was used.

$$\text{GWPZ} = \sum_{=1} \times \qquad (1)$$

where *Li* is the normalized weight of an evidentiary layer of the I parameter and *Fi* denotes the magnitude of the inter-map (sub-class) features. This makes it possible to combine the eleven theme maps on a pixel basis in accordance with the equation.

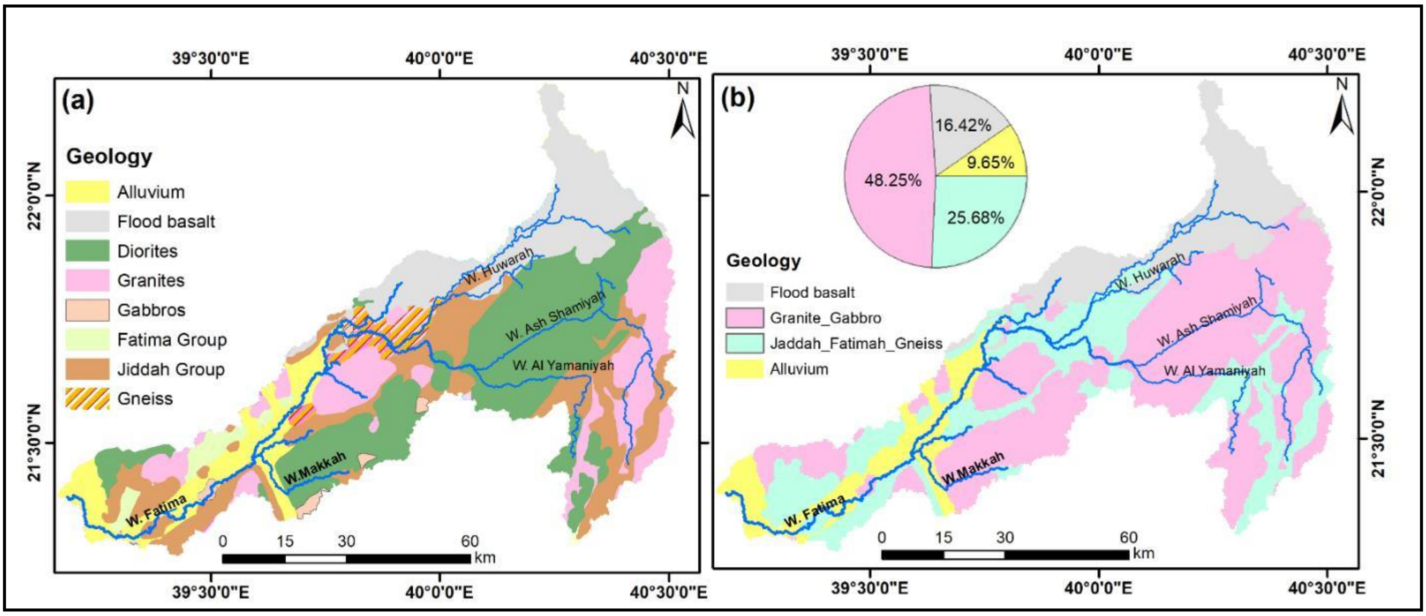
4. Results and Discussion:

4.1. Factors controlling groundwater occurrence and infiltration

In the present research, we integrate different data sets and measures to obtain an in-depth comprehension of Wadi Fatima's optimum areas of groundwater. These factors cover the geologic, climatic, hydrologic, and ecologic features.

4.2. Geology

The characteristics and geometric features of the lithologic units are significant in controlling the occurrence, movement, and accumulation of groundwater. This is due to pore spaces (Benjmel et al., 2020; Abdelkareem et al., 2023). For example, zones with well-sorted clastic deposits would hold water rather than massive bedrock. Based on the geologic map of Saudi Arabian Shieild (1963-1983), Wadi Fatimah is built up of gneiss (ortho- and para), volcaniclastics belonging to basaltic to andesitic rocks (Jiddah Group), metasediments to metavolcanic including marbles (Fatima Group), gabbros, diorites and various sorts of granites from tonalites to alkali granites either gray or pink colors. These rocks are partially covered by flood basalts (Fig. 3a). Several wadis dissected these rocks and filled them with Quaternary deposits, including aeolian sand. Based on the geological map, the geologic map was simplified into four classes: alluvium, Jaddah-Fatima formation, flood basalt, and granites-gabbros that occupied 9.65, 25.68, 16.42, and 48.25% of the entire area, respectively (Fig.3 b).



177

Figure 3. (a) Geologic map of the studied Wadi Fatima; (b) simplified geologic map. 178

4.3. Elevation 179

Elevation affects the direction, surface runoff, and groundwater recharging (Abdalla et al., 2020; Abdelkareem et al., 2023; Yousefi et al., 2020). Groundwater potential is significantly influenced by elevation (Naghibi et al., 2019; Abdelkareem et al., 2023), unlike how it relates to the groundwater resource (Karimi-Rizvandi et al., 2021; Li et al., 2023). Because of the low topography downstream, precipitation cannot concentrate in locations of high height (Abdelkareem & Abdalla, 2022). The elevation chart of the research area (Fig. 4a) is separated into five zones: 0-369, 369.1-756, 756.1-1096, 1097-1440, and 1441-2290m, which cover 30.45, 20.97, 23.01, 16.58, and 9% of the basin, respectively. The topography layer is an important layer that governs the direction of water flow over the land; it also controls the occurrence of groundwater and recharge potential (Maity et al., 2022; Abdalla et al., 2020). 180–190

Table 1. Factors controlling groundwater occurrence and infiltration. 191

Geology	Rank	Normalized weight %	Area %
Alluvium	7	0.389	9.56
Flood basalt	5	0.278	16.42
Jaddah-Fatima Group	4	0.222	25.68
Granites-Gabbros	2	0.111	48.25
		Elevation	
1441– 2290	2	0.067	9
1097– 1440	4	0.133	16.58
756.1 - 1096	7	0.233	23.01
369.1 - 756	8	0.267	20.97
0-369	9	0.300	30.45
		Slope	
0 – 4.347	8	0.320	46.19
4.348– 10.14	7	0.280	22.73
10.15– 17.18	5	0.200	16.29
17.19– 25.67	3	0.120	10.31
25.68– 52.78	2	0.080	4.48

Curvature			
-5 to -0.388	2	0.182	14.01
0	4	0.364	69.48
0.001 to 5.21	5	0.455	16.50
TRI			
0.111– 0.379	6	0.353	17.71
0.379– 0.483	5	0.294	33.73
0.483– 0.590	4	0.235	33.14
0.590– 0.888	2	0.118	15.42
Dd			
0.091– 0.594	2	0.095	11.38
0.594– 0.808	4	0.190	30.19
0.808– 1.006	7	0.333	40
1.007– 1.456	8	0.381	18.43
TWI			
4.25– 7.02	2	0.10	36.20
7.02– 8.72	4	0.20	34.16
8.72 – 10.85	6	0.30	21.34
10.86– 17.83	8	0.40	8.29
Distance to River			
0 – 281.6	8	0.50	47.14
281.7 - 609	6	0.38	34.80
609.1 - 1670	2	0.13	18.06
Rainfall			
0.192 – 0.2677	1	0.071	19.93
0.2678– 0.3652	3	0.214	15.18
0.3653– 0.4527	4	0.286	43.34
0.4528– 0.6209	6	0.429	21.55
NDVI			
400 - 820	2	0.111	23
821 - 1400	3	0.167	34.04
1400 - 1800	5	0.278	19.43
1800 - 9315	8	0.444	23.53
Soil			
Loam3	2	0.133	81.26
Loam2	3	0.200	13.22
Loam1	4	0.267	3.16
Sandy loam	6	0.400	2.36
Lineaments			
0 – 7.95	2	0.074	22.10
7.95– 18.5	4	0.148	26.04
18.76– 29.83	6	0.222	24.30
29.84– 42.33	7	0.259	20.09
42.34– 72.45	8	0.296	7.47

4.4. Slope 192

The occurrence and infiltration capacity of groundwater flow is directly influenced 193 by surface slope, one of the most crucial control parameters (Al Saud, 2018). It may be 194 used as a general factor in the direction of groundwater flow (Gupta & Srivastava, 2010). 195

The slope is a crucial component of watershed governance and the possibility of groundwater zone mapping (Al Saud, 2018). The likelihood of finding groundwater varies greatly depending on the terrain: extremely high, high, moderately high, low, and very low (Elewa & Qaddah, 2012; Zhu & Abdelkareem, 2021). The infiltration is inversely related to the slope (Adiat et al., 2012). When it rains, water runs off steep slopes quickly, not having enough time to percolate beneath the surface and replenish the saturated zone. As a result, locations with steeper slopes produce less recharge due to high surface runoff velocity and vertical percolation (i.e.,), thus affecting water occurrences. The slope angle controls recharge by influencing the amount of land surface infiltration, runoff, drainage, and subsurface drainage (Naghibi et al., 2019). On an elevation map of the study area (Fig. 4b), five zones have been recognized: 0-4.34, 4.34-10.14, 10.15-17.18, 17.19-25.67, and 25.68-52.78, that covering 46.19, 22.73, 16.29, 10.37, and 4.48% of the basin, respectively (Fig. 2b).

4.5. Surface curvature

Water accumulation, the rate of infiltration, and overflow are all influenced by the curvature of the land surface [Benjmel et al., 2020; Yariyan et al., 2020; Abdelkareem et al 2023). The DEM is used to initiate a land surface curvature map, which is classified into three categories: concave, convex, and flat (Figure 4c) each class has a certain capability for holding water and may cause runoff. For instance, flat and areas of curvature, which also have a higher infiltration rate, are better at collecting water than convex surfaces. Flat and concave land surfaces are where water tends to collect and penetrate; hence, places with high levels of curvature (or vice versa) are given high weight values (Mukherjee, and Singh 2020; Abdelkareem et al., 2023; Abd El-Hamid at el. 2023). The output curvature map was divided into three categories: (- 5.60 to - 0.38), (0), and (0.0001 – 5.21); (Fig. 4c).

4.6. Terrain roughness index

The TRI is a geomorphic parameter that is used in revealing groundwater occurrences. The presence of groundwater potentiality corresponds to the TRI values. It was established to assess the landscape's diversity and can be applied to investigating groundwater [Kalantar et al., 2019; Moghaddam et al., 2020; Abdelkareem et al., 2023; Li et al., 2023]. This factor can be determined through the formula -2 below:

$$= \sqrt{({}^{2} \quad - {}^{2})} \tag{2}$$

Based on the accumulation and infiltration of groundwater, the TRI map results have been classified into four zones: 0.11–0.37, 0.37–0.48, 0.48–0.59, and 0.59–0.88 that covering 17.71, 33.73, 33.14, and 15.42, respectively (Fig. 4d).

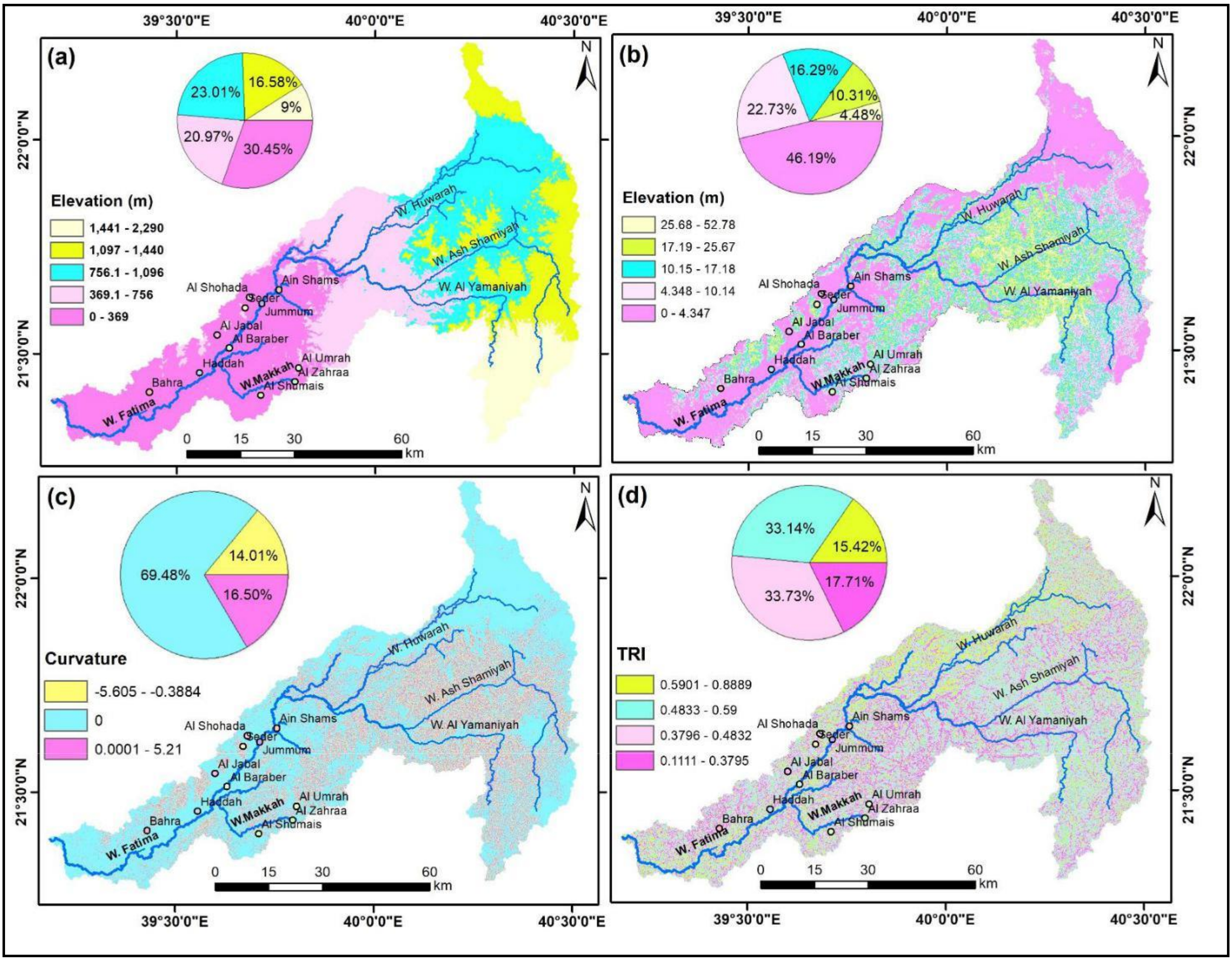


Figure.4 (a) elevation; (b) slope; (c) curvature; (d) TRI

4.7. Drainage density

The present and past climatic and hydrologic conditions, as well as the recharge capacity of shallow alluvial aquifers, mainly depend upon the characteristics and geometry of the stream (Fig. 5a). Drainage density is an important hydrologic factor in mapping prospective areas of water infiltration and accumulation. Drainage density is calculated by dividing the combined length of all the streams and rivers in a drainage basin by its overall area Harini et al. (2018). An area's drainage system is impacted by the type of vegetation, the type of soil, infiltration, slope gradient, and the composition and structure of the bedrock (Abd Manap et al., 2014). An area with less drainage density results in greater infiltration and less surface runoff. Accordingly, groundwater development is appropriate in locations with low drainage density (Magesh et al., 2012). Furthermore, because drainage density is a measurement of surface runoff, it infers groundwater recharge indirectly (Jha et al., 2007). According to Cevik and Topal (2003), higher drainage densities result in less infiltration and faster surface flow. According to Yeh et al. (2009) and Pinto et al. (2015), high drainage density values suggest a low groundwater potential zone since they are conducive to runoff. The drainage density of the studied basin (Fig. 5b) ranges from 0.091 to 1.456, which is classified into four classes: 0.091 – 0.594, 0.594 – 0.808, 0.0808 – 1.006, 1.007 – 1.456, that occupying an area of 11.38, 30.19, 40, and 18.43%, respectively.

4.8. Topographic wetness factor (TWI)

The TWI is a secondary topographic factor that is employed to reveal topographic effects on the location and capacity of runoff and infiltration capability (Rahmati et al., 2018), and thus groundwater occurrences (Li et al., 2023; Abdelkareem et al., 2022, 2023). Such a factor determines the relationship between the earth's surface wetness and slope variation (Pourghasemi, 2014; Alshehri et al., 2023). Moreover, it defines how the water accumulation in a place is influenced by topography. Thus, zones of high slope angle and areas of high altitudes have more runoff, which minimizes their capability for holding water resources. On the other hand, areas of low elevation tend topographical wetness or water accumulation (Abdelkareem et al., 2023; Hasanuzzaman et al., 2022). The TWI map is classified into three categories (Fig. 5c): 4.25 – 7.02, 7.02 – 8.72, 8.72 – 10.85, 10.86 – 17.83, covering 36.20, 34.16, 21.34, 8.29, respectively.

4.9. Distance to River

Water flow in a basin can be aided by recharging the stream bed and the nearby areas to stream flow (Abdelkareem et al., 2023; Sun et al., 2022; Li et al., 2023). In arid, high-elevation, and desert areas, the infiltration comes from drainage systems holding water from precipitation. Such water seeped into groundwater aquifers (Cuthbert et al., 2016). The distances between locations and rivers indicate that groundwater harvesting may be possible (Golkarian et al., 2018). With increasing distance from rivers, recharge of groundwater frequently decreases. In order to lead to stream water loss, bedrock reservoirs in valleys do so (Rahmati et al., 2018). In Arc GIS 10, the spatial analyst tools, we used the Euclidean distance tool to extract the distance to river categories (Jaafarzadeh et al., 2021; Abdelkareem et al., 2023). The resulting map (Fig. 3d) is classified 0 – 281.6, 281.7 – 609, and 609.1 – 1670, occupying 47.14, 34.80, and 18.06, respectively.

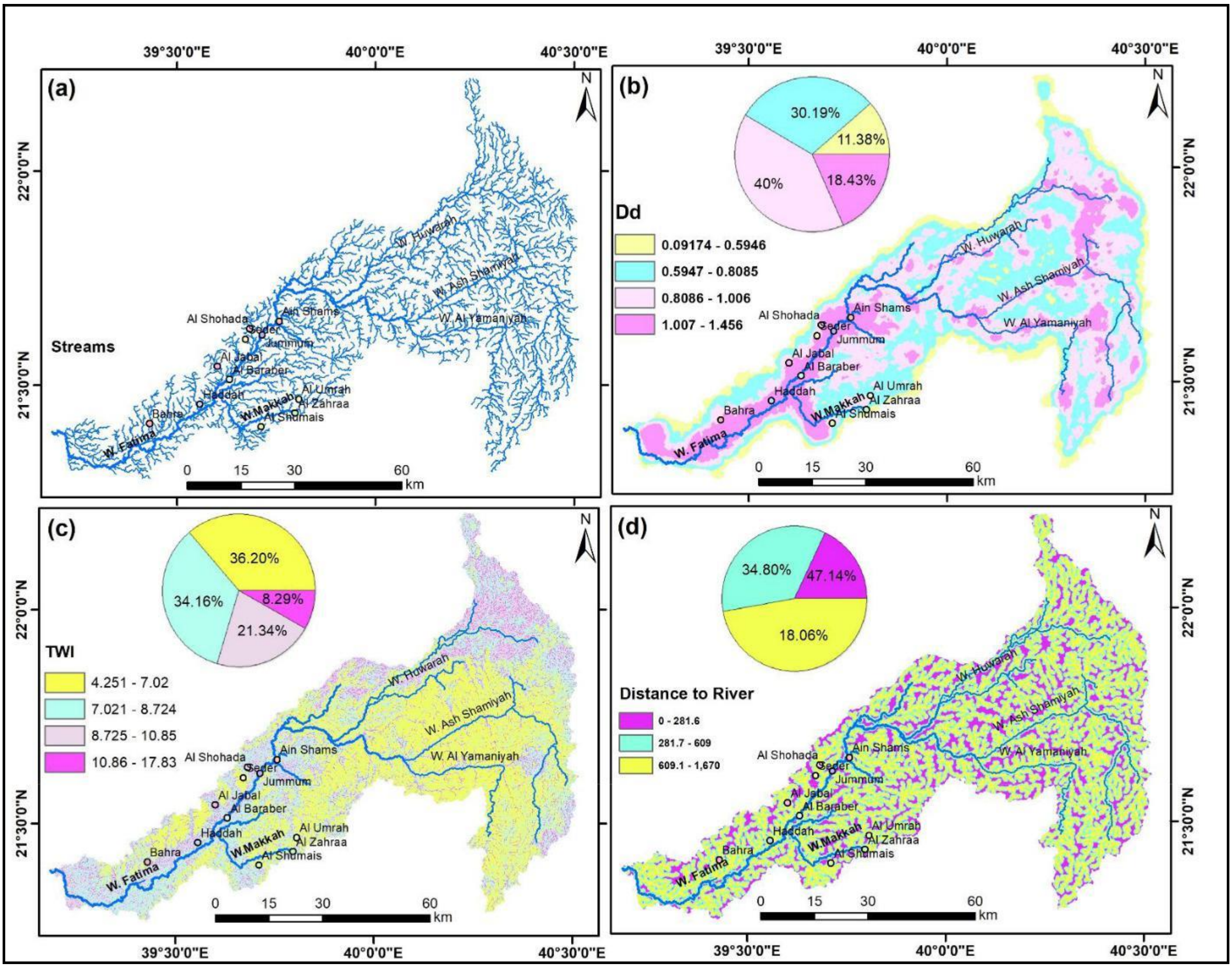


Figure 5. (a) streams; (b) Dd; (c) TWI; (d) Distance to River.

4.10. Vegetation

For groundwater potential zones, the NDVI is a commonly used parameter (Singh et al. 2009, Senthil kumar et al. 2019). The density and coverage of the vegetation were displayed on a map using the Normalized Difference Vegetation Index (NDVI). The NDVI ranges from -1 to 1. The NDVI result map of the study area is classified into 4 categories based on the natural break method; are 210–900, 900–1500, 1500-2500, and 2500-10000, respectively (Fig. 4a), covering areas of 23, 34.04, 19.43, and 23.53 % of the area, respectively (Table 1).

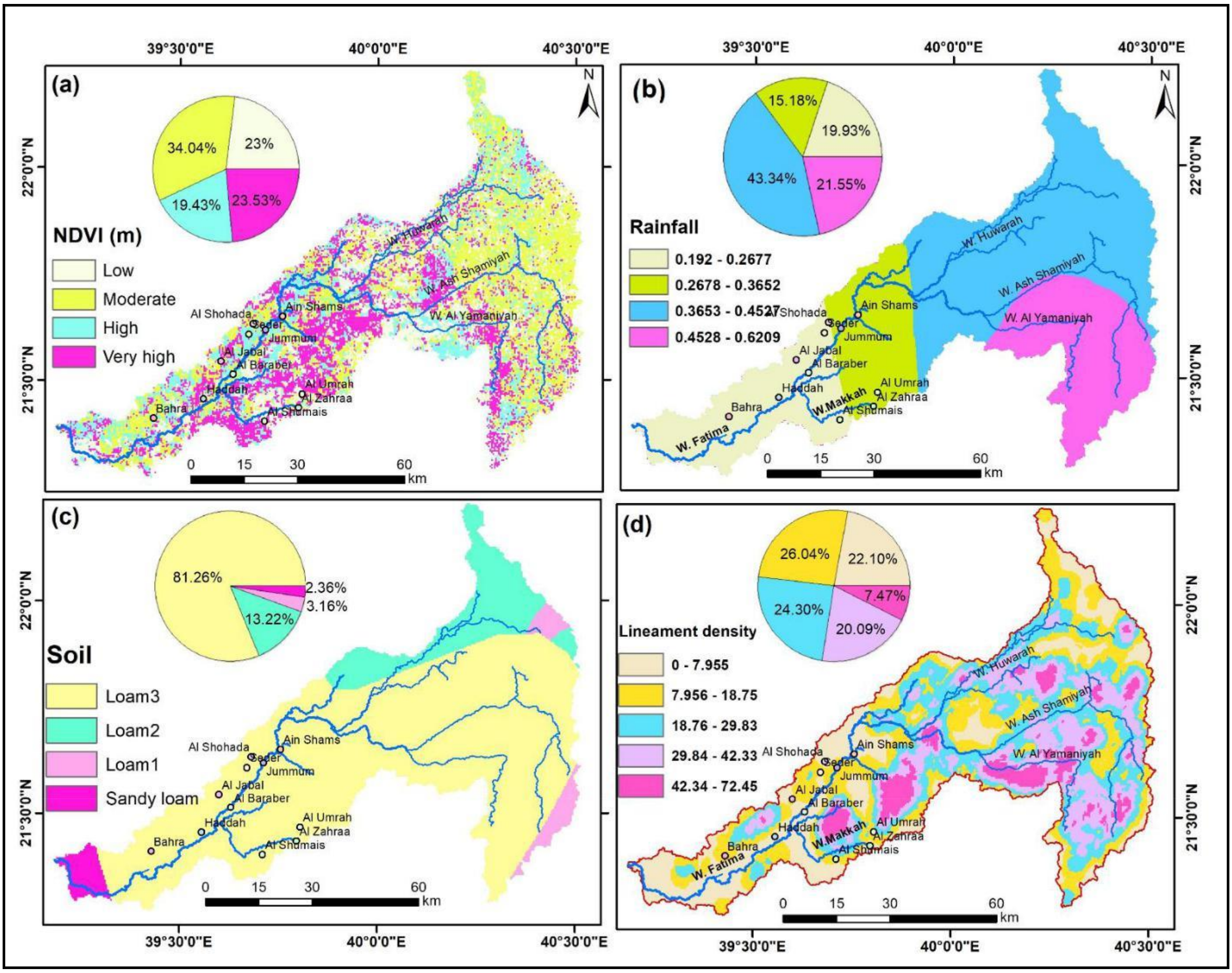


Figure 6. (a) NDVI; (b) Rainfall; (c) Soil; (d) Lineament density.

4.11. Rainfall

Precipitation is one of the essential hydrologic components that has been recognized as a significant source of aquifer recharge and a primary source of groundwater availability, especially in arid areas (Guru et al., 2017; Avand et al., 2020; Magesh et al., 2012; Shekhar & Pandey, 2015). Rainfall percolation within the soil promotes the shallow aquifers to be recharged, and the precipitation significantly affects percolation (Adiat et al., 2012). The upstream of the Wadi Fatimah basin receives an annual rainfall of 300 to 360 mm (Al Sefry et al., 2003). Rainfall patterns and intensity control the water availability in any basin. In order to identify groundwater potential zones and to recharge aquifers hydrologically, rainfall is one of the most important components (Abdelkareem et al., 2012 and 2022).

The eastern part (high elevation) receives approximately greater precipitation yearly than the western (low height). The possibility of groundwater in a given geographical area increases due to precipitation (Hong & Abdelkareem, 2022; Jaafarzadeh et al., 2021). Using rainfall data from the TRMM satellite, investigators may monitor, document, and measure the precipitation patterns for the watershed under consideration. The mean annual rainfall over the study area was interpolated depending on the Kriging method. Five categories for the rainfall intensity map (Fig. 6b) are 0.192 – 0.267, 0.267 – 0.365, 0.365 -0.452, and 0.452 – 0.620, covering 19.93, 15.18, 43.34, and 21.55, respectively.

Due to its geographical characteristics, located in western Saudi Arabia, Wadi Fatimah is frequently subjected to flash flood storms due to excessive, highly intense rainfall. During flood periods, the portion of infiltrating water that reaches the water table is considered the most important source of the local alluvial aquifers recharge in arid and semi-arid regions (Morin et al., 2009; Dahan et al., 2007). Figure 5 shows the areas recently subjected to rainfall storms in Wadi Fatimah. Alshehri and Abdelrahman (2023) calculated a coarse drainage texture of 0.059 within the Wadi Fatimah basin, promoting additional groundwater recharge from precipitation during flood periods and the rainy season. The recharge of the local alluvial aquifer in the area was confirmed by the rise in water levels along the wadi after the rainfall period (Al Sefry et al., 2003). In addition, the amount of infiltrating water into the aquifer was calculated to occur at a rate of roughly 72 mm/y (Alyamani & Hussein, 1995) and 85 mm/y (Memon & Kazi, 1984).

Figure 7. Rainfall accumulation during the rainstorm.

4.12. Soil

The soil texture is another effective element for determining places appropriate for recharging processes. Regarding groundwater recharge and agricultural production, soil type is a crucial factor. Thus, knowledge of soil texture is crucial for understanding invasion rats (Jaafarzadeh et al., 2021). The sort of soil has a major impact on the flow volume and infiltration (Bera et al., 2020). Sand is an example of fine-grained, well-sorted soil whose infiltration rate is lower than coarse-grained soil (Senanayake et al., 2016; Abdelkareem et al., 2012). Rocks' porosity, permeability, and geometrical characteristics are thus significant in determining a region's GPZs. The dimensions, shape, and arrangement of soil grains and the pore structures connected to them can have a major impact on water transport (Opp & Bodenkörper, 2011). Sandy soil has a rapid rate of infiltration; more-coarse, loamy soil with a high sand content has been given higher importance; and fine soil with a smaller rate of infiltration owing to a greater amount of clay has been allocated low priority (Shekhar & Pandy, 2015). The studied basin is characterized by sandy loam to loam of different proportions of sand, silt, and clay (Fig. 4c). Thus, it is classified into sandy loam, loam 1, loam 2, and loam 3, ordered from high to infiltration capacity and covering 2.36, 3.16, 13.22, and 81.26, respectively.

4.13. Lineaments

Lineaments have a significant impact on groundwater circulation and storage, as well as how surface runoff gets absorbed into the ground (Subba Rao 2009). Groundwater recharge systems, as well as movement directions, are controlled by fracture and fault systems. The fracture and fault systems are controlling the groundwater recharge systems and movement directions. They are linear features that promote secondary porosity. Geologic characteristics known as lineaments are linear or curved and have a major role in the development and transport of groundwater in crystallized terrain. The infiltration of surface runoff and replenishment of the hard-rock aquifer are caused by lineaments, including cracks, fissures, and joints, which often form because of tectonic stress/strain. Many authors have highlighted that a high lineament density leads to a high well output by using the connection between the presence of groundwater and lineaments (Achu et al. 2020; Hung et al. 2005). The area is classified into five classes (Fig. 4d) including 0 – 7.95, 7.95 – 18.75, 18.76 – 29.83, 29.84 – 42.33, and 42.34 – 72.45, respectively.

4.14. Groundwater prospective map GPZs

The GPZs were established by combining elevation, slope, curvature, drainage density, distance to river, TWI, rainfall, TRI, NDVI, soil, and lineaments data from satellite pictures, hydrologic, and geologic. According to the likelihood of GW, the area was separated into different six zones (Fig. 6). The six categories are excellent (10.98 %), very high (21.98 %), high (24.99 %), moderate (21.44 %), low (14.70 %), and very low (5.91 %). The region with the highest potential is now clearly visible. The GW recharge zones are supported by sand and gravel, depressions, and a high flat or gentle slope in this area. The gathered wells confirmed the GPZs in order to validate the estimated model. Additionally, places with vegetation and agricultural activities are connected with good groundwater potential zones. Zones with a high slope, elevated ranges, and low density have little infiltration. Dams in this range would make it possible to capture water and protect the downstream areas as well as newly growing urban areas (Souissi et al., 2018). Zones with well-sorted sand that promote high porosity variations reveal high infiltration capability.

According to the computational models, high-ranking probabilities are consistent with the well location and vegetated areas. As a result, abundant spring sites coincident with the area of high to excellent potentiality, which doesn't display more springs from "Low" potential zones. The GWPZ map of the research area is confirmed through the ROC curve (Fig. 9). The usefulness of the system's assessment is shown by the fact that the AUC can be utilized to define the system's ability to properly anticipate both the occurrence of "groundwater" and its absence from the system. Values for the AUC range from 0 to 1 (Fig. 9), with lower values denoting beneficial predictions and higher values denoting more reliable estimations. The AUC for the model is 0.73, which indicates improved accuracy. As multiple wells are compatible with the zones of high prospective, the field investigations verified the GWPZ map. Several farms also correlate with those zones (Fig. 8). Based on the Sentinel-2 band combined 12, 8, 3, in R, G, and B, accordingly, vegetation and water resources make up the majority of the extremely high to extreme GWPZs (Fig. 9).

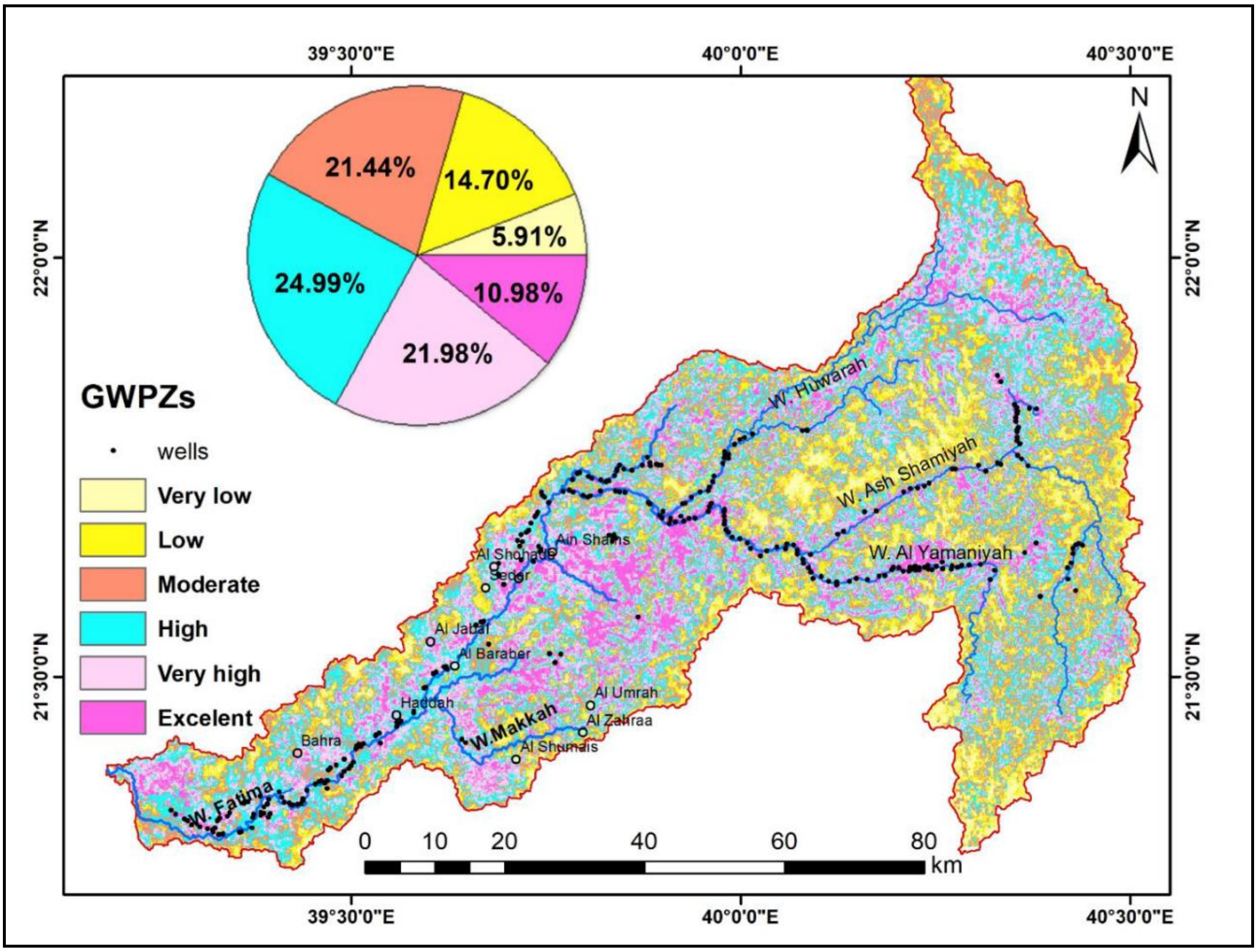


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Figure 8. Groundwater prospective zones. 375

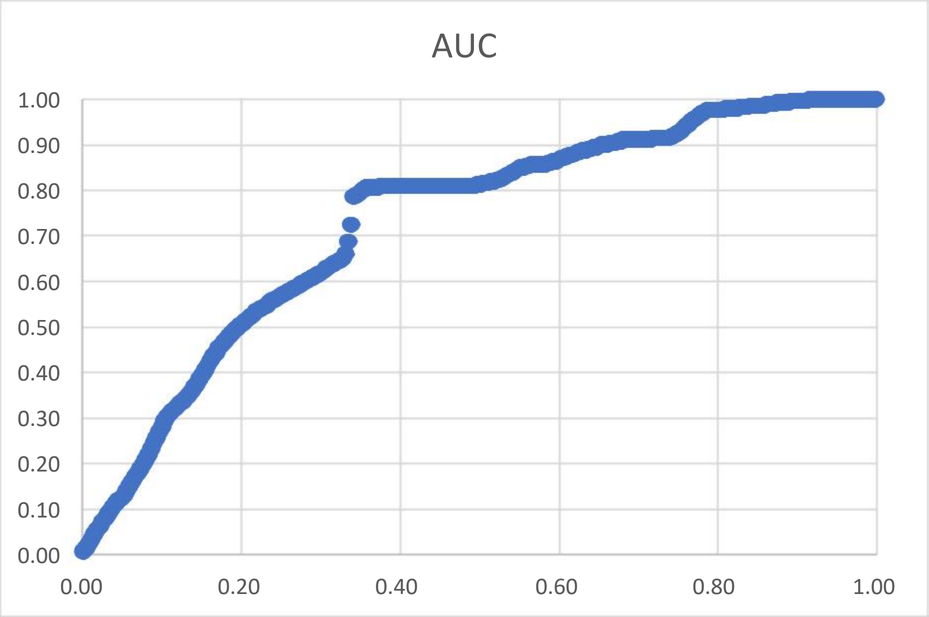

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Figure 9. AUCs of predicted GWPZ model (AUC: 0.73). 377

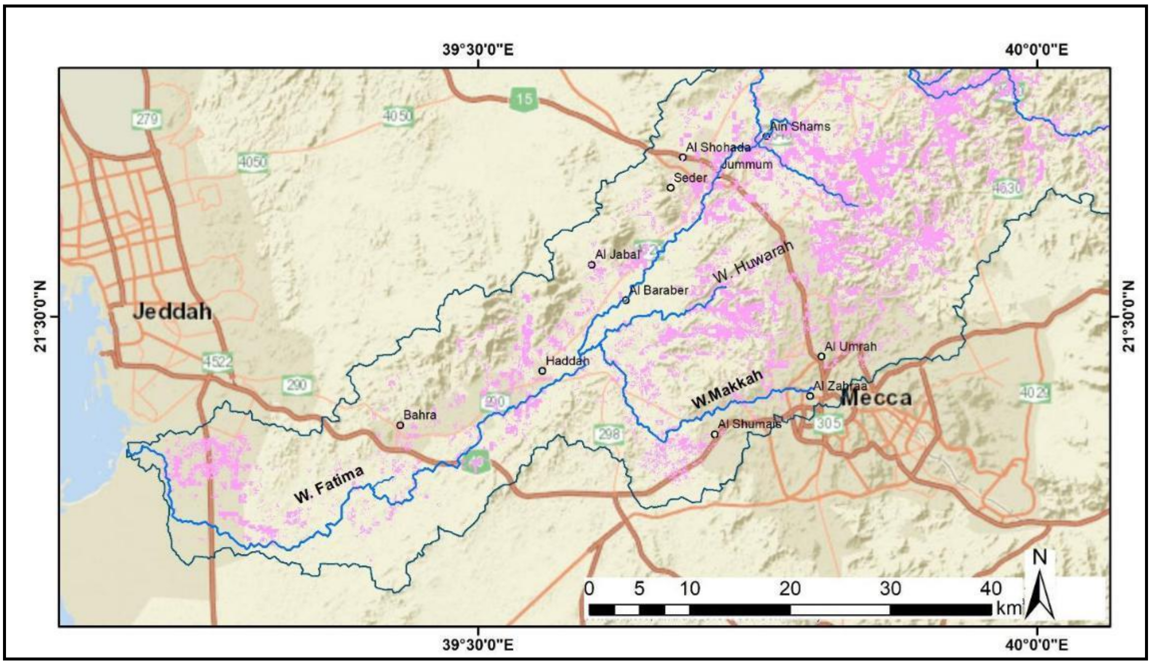

Figure 10. Excellent groundwater prospective zone overlain by main roads,streams and watershed.

5. Discussion

Wadi Fatima's geologic and topographic setting in western Saudi Arabia promotes the rainfall conditions at the elevated upstream areas that drain to the Red Sea at Jeddah city. Such a setting gave it a promising area for water harvesting and accumulation. The applied model utilized multi-criteria of topography, meteorology, geology, structures, and hydrology parameters. Areas of high potentiality are consistent with zones of low topography, high lineament density, and flat to gentle slopes (Li et al., 2023; Zhu & Abdelareem, 2021). Additionally, areas with loose sediments in the downstream and highly vegetated areas would promote infiltration and minimize runoff (Sun et al., 2023).

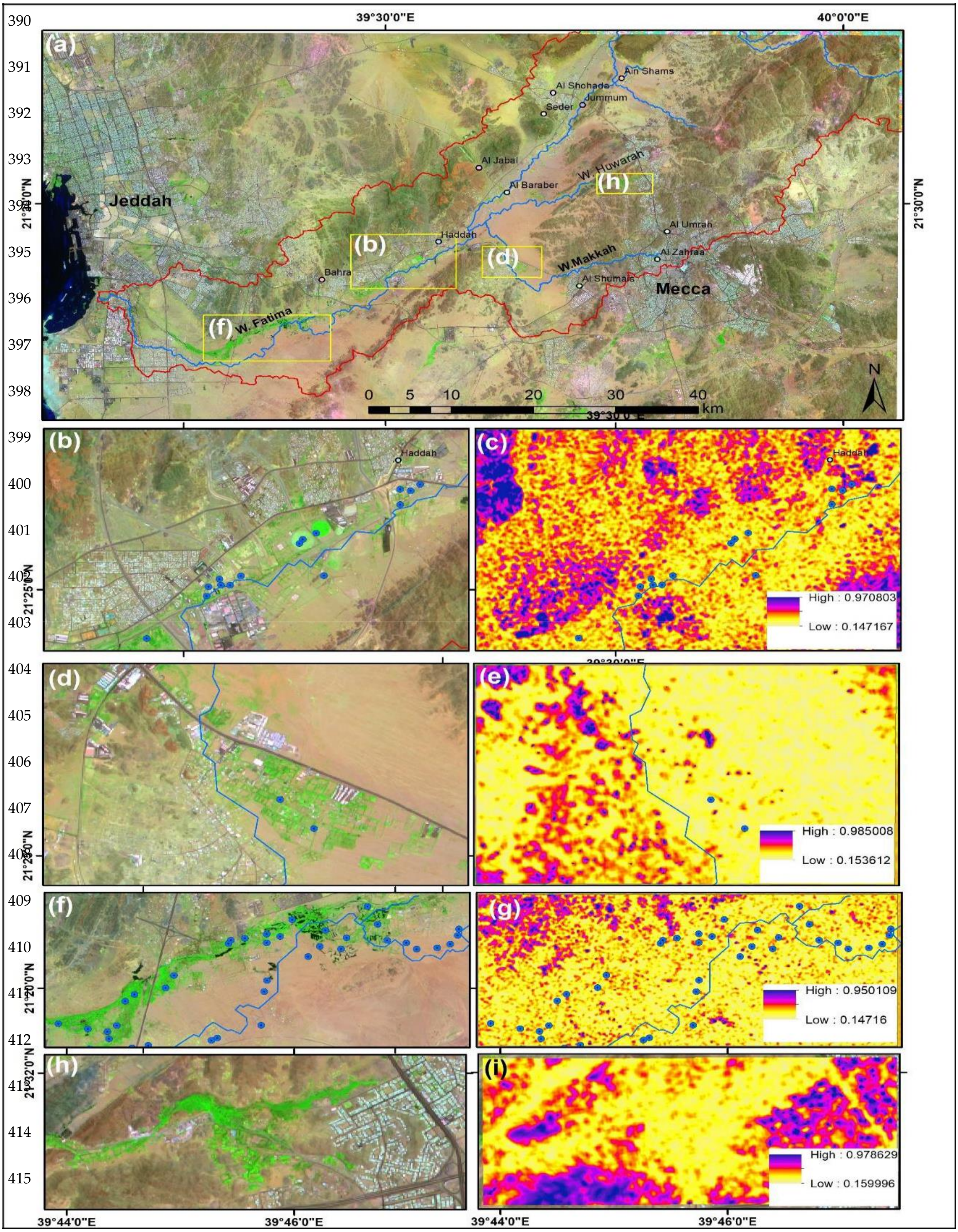

Figure 11. Sentinel-2 12, 8, and 3 of the studied basin that overlain by well locations; (b, d, f, h) Sentinel-2 image subset; (c, e, g,i) In SAR CCD.

The wet and moist soil in these locations is another effect of the high TWI values [Beven et al., 1979; Sun et al., 2023]. This suggests that groundwater has accumulated in these areas. The combined data in a GIS model allowed highlighting such promising areas consistent with groundwater sites. Such source of water allowed the reclamation of land for diverse agricultural purposes and the development of new settlements at the down- and midstream areas (Fig. 11). Sentinel-1 imagery employing InSAR CCD data proves significant variations in LU/LC, particularly in the context of agricultural and other human activities in the essentially downstream region.

The validity of the developed model was verified against the field observations, previous geophysical investigations, well yield, and the location of groundwater wells that present in areas with the highest potential of groundwater occurrence in the study area. The results of the GWPZ map are consistent with geoelectric results (Alshehri & Abdelrahman,2023) which implied high potential amounts of groundwater at the shallow groundwater aquifer in Wadi Fatimah. Additionally, the highest density of wells, along with the high transmissivity values of the shallow aquifer, range between 300 m2/d and 1800 m2/d (Al Sefry et al., 2003), while the storativity values are averaged at 0.06, and the specific yield values ranged from 0.12 to 0.2 ((Sen, 1995; Dawson & Istok, 1991). These values indicate that the aquifer yields range from mid to high potential and water accessibility to the wells. According to Al Sefry et al. (2003) and based on the aquifer testing and geophysical surveys, the estimated groundwater volume is around 42x106m3. Thus, the verification proved that the GWPZ generated from GIS techniques is reliable and representative.

6. Conclusions

Groundwater is a vital water source for sustainable development, particularly for dry and hyper-arid regions. Remote sensing imagery and GIS techniques were efficiently merged to uncover, assess, and monitor exploration data for water resources in varied climatic conditions. In order to determine probable zones of groundwater potentiality, W. Fatima, located in the Makka region, is explored using GIS and satellite imagery methods. Many GIS maps that show the geology, geomorphic, climatic, and hydrologic conditions have been processed, normalized, and revealed the groundwater potential zones, which are categorized into five zones: excellent (10.98%), very high (21.98%), high (24.99%), moderate (21.44%), low (14.70%), and very low (5.91%). Overall, investigating the GWPZ area utilizing GIS and remote sensing methods is extremely beneficial to sustainability and decision-makers. The GWPZ map was tested and compared to the receiver operating characteristic (ROC) curves and field data, locations of existing wells, and thickness of the water-bearing formations inferred from geophysical data. Thus, the verification proved that the GWPZ generated from GIS techniques is reliable and representative.

Author Contributions: Mohamed Abdekareem: Conceptualization, Methodology, writing original draft, writing review and editing software, Investigation, validation. **Fathy Abdalla:** Conceptualization, Methodology, writing original draft, writing review and editing software, Investigation, Analysis, Validation. **Fahad Alshehri:** Conceptualization, Methodology, Validation, Investigation Formal Analysis, Project Funding, Supervision, Project management. **Chaitanya B. Pande:** Writing original draft, Writing review-editing, Investigation and Formal analysis. All authors were involved in the intellectual elements of this paper.

Acknowledgments: The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through project no. (IFKSURC-1-7315).

Funding: The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through project no. (IFKSURC-1-7315).

Data Availability Statement: The data are not publicly available due to further research.

Conflicts of Interest: The authors declare no conflict of interest.

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