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Identification and Validation of Groundwater Potential Zones in Al-Madinah Al-Munawarah, Western Saudi Arabia Using Remote Sensing and GIS Techniques

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Abstract: Groundwater is an essential water resource utilized for agricultural, industrial, and home applications. Evaluating the variability of groundwater is essential for the conservation and management of this resource, as well as for mitigating the reduction in groundwater levels resulting from excessive extraction. This study aimed to define the groundwater potential zones (GWPZ) in Al-Madinah Al-Munawarah, Western Saudi Arabia, utilizing remote sensing and geographic information system (GIS) techniques, alongside meteorological data. Seven thematic maps were produced based on the regulatory characteristics of geology, drainage density, height, slope, precipitation, soil, and normalized difference vegetation index (NDVI). The influence of each theme and subunit/class on groundwater recharge was evaluated by weighted overlay analysis, including previous research and field data. The groundwater potential map was created via the weighted index overlay approach within a GIS. The groundwater potentials were classified into three categories: very poor, moderate, and good zones. The low groundwater potential regions encompass 805.81 km^2 (44.91%) of the research area, located in mountainous basement rocks, characterized by high drainage density and steep gradients. The moderate zones comprise 45.67% of the total area, covering 819.31 km^2, and are situated in low-lying regions at the base of mountainous mountains. Conversely, the favorable zones, comprising 9.42% of the total area, span 169.06 km^2 and are located within the alluvial deposits of the lowlands next to the Wadi Al-Hamd basin and agricultural farms. The results' accuracy was confirmed by overlaying data from 26 wells onto the designated groundwater potential categories, revealing that all wells corresponded with regions of high groundwater potential. The generated map would contribute to the systematic and efficient management of groundwater resources in this area to meet the rising water demands of Al-Madinah. The groundwater potential map is one aspect of groundwater management. It is also very important to assess this potential further via groundwater temporal monitoring, groundwater balance, and modeling.

Keywords: GIS; Groundwater Mapping; remote sensing; sustainable development; water supply

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1. Introduction

Groundwater serves as a substitute for surface water and is a crucial natural resource utilized in home, agricultural, and industrial sectors, contributing to the overall development of a region [1]. The presence, arrangement, and flow of underground water mostly rely on the geological and hydro-geomorphological characteristics of the region [2]. Identifying and assessing regions with significant groundwater potential is essential for establishing the ideal locations for new water extraction wells to meet the increasing demand for water, particularly in areas experiencing low rainfall and water scarcity. The amalgamation of remotely sensed data with geographic information systems (GIS) is very compatible and may be effortlessly integrated with data acquired from traditional and terrestrial measurement instruments [3]. The utilization of high-resolution satellite images is prevalent in groundwater research owing to their exceptional spectral and spatial resolution. These images are utilized to determine the geology, geomorphology, soil composition, lineament density, drainage density, rainfall patterns, and land use for maps that reveal the presence of groundwater [3,4]. Remote sensing and GIS offer several advantages over conventional approaches [5]. These advantages include being time- and cost-effective, as well as providing synoptic coverage.

In recent decades, there has been a rise in the exploitation of groundwater resources, leading to excessive consumption of groundwater. Consequently, a variety of environmental problems have arisen, including a reduction in groundwater levels, exhaustion of water resources, pollution, and degradation of water quality [6]. Scientists globally employ Geographic Information Systems (GIS) and remote sensing techniques to assess the prospective areas for GWPZ. The outcomes of these assessments differ according to the parameters considered in calculating the GWPZ [7,8]. Moreover, the outcomes they achieve may vary based on the diverse elements taken into account when defining these zones. One study demonstrates the use of lineaments for groundwater exploration [9], while other studies explain the utilization of various factors such as geomorphology, land use, geology, drainage density, slope, rainfall intensity, and soil texture [6,10]. The accessibility of satellite data, traditional maps, and accurately adjusted ground truth data has made it easier to provide a foundation for evaluating areas with potential groundwater resources [6]. Furthermore, the outcomes derived from GIS and remote sensing for evaluating GWPZ are deemed trustworthy, as they undergo verification by field surveys.

The Kingdom of Saudi Arabia is experiencing significant pressure on its groundwater resources due to its predominantly arid to semiarid climate, as well as rapid population expansion, urbanization, and industrial development in the country [11,12]. Shallow aquifers in Western Saudi Arabia are predominantly situated in valleys between basement terranes and along coastal areas [13,14]. Nonetheless, the Arabian Shield possesses substantial strata of sedimentary deposits ranging in age from the Paleozoic to the present, which constitute deep aquifers and act as a crucial reservoir of groundwater in the region [15]. The predominant published studies regarding groundwater in the western region concentrated on evaluating groundwater quality and identifying pollution sources. This was accomplished by examining the concentrations of significant cations, anions, and possibly deleterious elements in Western Saudi Arabia and along the Saudi Red Sea coastline (e.g., [16–23]).

Al-Madinah Al-Munawarah is a prominent metropolis in Saudi Arabia that attracts a large number of seasonal visitors due to its pilgrimage. In order to address the increasing need for water in agriculture, industry, and domestics, the authorities have thoroughly investigated, extracted, and developed [24]. The Al-Madinah province contains many aquifers, such as fractured Precambrian bedrock, Paleozoic sedimentary rocks, and alluvial deposits overlaid by recent lava flows [25]. The region is experiencing a water deficit due to very high temperature, semi-arid to extremely arid conditions, poor rainfall, and heavy pumping from groundwater aquifers for agricultural purposes [16,26–28].

Weighted overlay mapping is an effective method for identifying areas with higher groundwater potential. It combines multiple geospatial factors, such as geology, soil type, slope, and drainage density, to help pinpoint regions where groundwater exploration might be more successful. However, it is important to be cautious and recognize that while weighted overlay mapping is a useful tool for identifying GWPZ, it does have limitations. This mapping technique does not provide information about the sustainability of the groundwater resources in those areas or the rates at which groundwater can be sustainably extracted. The objective of this study is to delineate the areas with high potential for groundwater in the Al-Madinah Al-Munawarah region of Western Saudi Arabia using remote sensing and GIS techniques. The main goals are to create theme maps that show the characteristics that affect groundwater potential in the area and to assign weights to each of these thematic maps using the weighted overlay analysis (WOA).

This research introduces a novel approach to groundwater exploration by applying the WOA method combined with GIS and remote sensing data. Unlike many global studies that use all available WOA data, even those with minimal impact, this study focuses on identifying the most influential factors specific to the study area for pinpointing potential groundwater sites. Diverse data sources—including soil, topography, geology, and hydrology—were integrated with remote sensing data in a unique way not previously applied in this region. By developing an optimized model that adjusts criteria weights based on local characteristics, the accuracy in identifying potential groundwater areas was enhanced. Applying this methodology to an area previously unexamined with this approach, our research successfully identified new high-potential groundwater zones, contributing to more effective water resource planning.

2. Materials and Methods

2.1. Study Area

Al-Madinah Al-Munawarah is situated within the latitudes of 24°15′54″ and 24°36′54″ N and the longitudes of 39°29′06″ and 39°50′15″ E (Figure 1). The groundwater resources of Madinah are found in the highly permeable Harrat Rahat region in the east and south, as well as in alluvial deposits to the west, encompassing the core area of Madinah city. The groundwater level is comprised between 535 and 594 m, whereas the water table depth varies between 28 and 93 m [17,29]. Over the past twenty years, Al-Madinah has transitioned from relying completely on its groundwater to relying almost exclusively on desalinated water from the Yanbu desalination plant. The city's groundwater is harnessed for agricultural and industrial purposes. The climate of Al-Madinah city is characterized by an arid climate with a hot and dry atmosphere. During the summer, the weather is scorching, while in the winter, it is relatively chilly. According to [30], the summer temperature typically falls within the range of 25–42 degrees Celsius, while the winter temperature falls within the range of 10–24 degrees Celsius. The majority of precipitation occurs in November, December, and January, with intermittent rainstorms occurring in April [19].

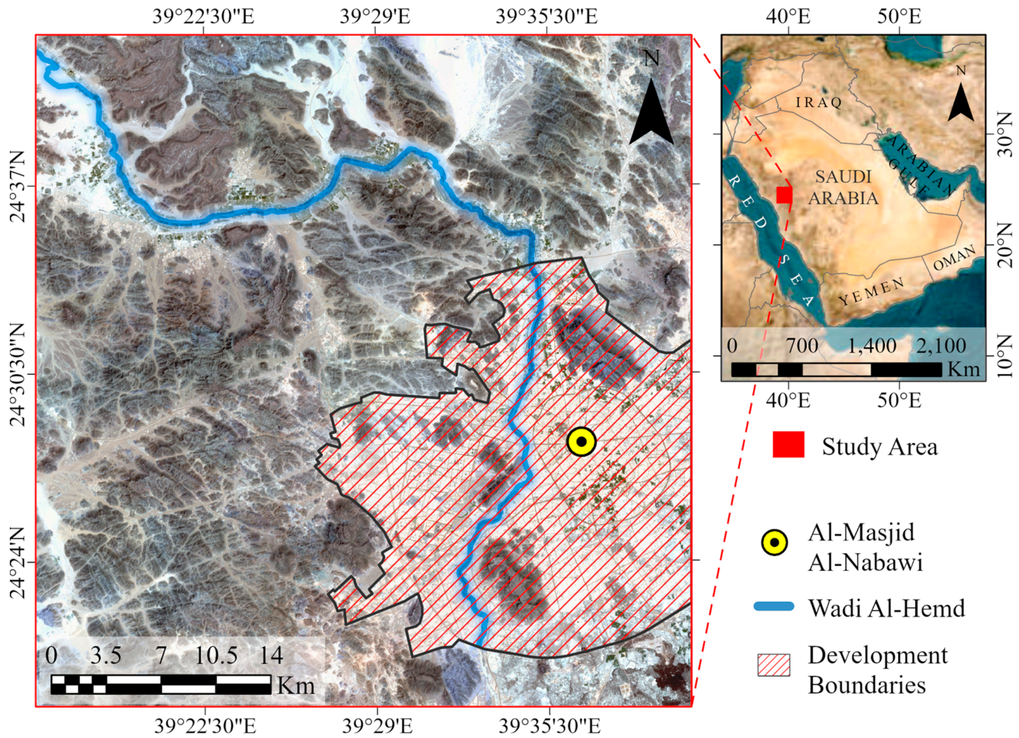

Figure 1. Location map of the study in Al-Madinah Al-Munawarah Province. The smaller map located in the right provides the study area's location in Saudi Arabia.

The Wadi Al-Hamd Basin is recognized as one of the largest basins in the Kingdom of Saudi Arabia, with a total area of 104,679 square kilometers. The Wadi Al Hamd flows in a southeastern to northwestern direction, dividing into two primary valleys. One of these valleys, called Wadi Al-Hamd, continues to flow northwest towards the Red Sea. The other valley, known as Wadi Al Jazl, travels north towards the city of Al Ula. The primary economic activity in this basin is agriculture, which heavily relies on unlicensed and uncontrolled groundwater wells, primarily drilled wells [27]. The precipitation patterns within the basin exhibit temporal and spatial variations. The Wadi Al-Hamd Basin experiences an annual rainfall distribution ranging from 40 mm to 80 mm, with an increasing trend from the northwest to the southeast. The Wadi Al-Hamd is distinguished by the existence of two formations that contain groundwater. The Quaternary aquifer is located in the ancient basins, while the volcanic aquifer covers the southern part of Al-Madinah Al-Munawarah city [25,27].

2.2. Datasets

The study employed a three-phase analytical framework to evaluate GWPZ in Al-Madinah Al-Munawarah, Saudi Arabia. During the preliminary phase, substantial data gathering was conducted, integrating thorough fieldwork, remote sensing data from NASA, and geological information from the Saudi Geological Survey. A 12.5 m resolution Digital Elevation Model (DEM) from Sentinel 1 data was employed to examine the city's topography, encompassing elevation and slope attributes. Geological and soil data elucidated rock composition and permeability—elements affecting water discharge and absorption. Such data were obtained from Geological and soil data were obtained from the Saudi Geological Survey [31]. Precipitation data from the Ministry of Environment, Water, and Agriculture, spanning 2010 to 2024, were analyzed to discern rainfall patterns. The city's drainage network, encompassing wadi systems, was developed from the DEM to evaluate natural drainage patterns.

During the second step, a weighted overlay analysis was performed to delineate possible groundwater zones. To achieve compatibility and precision across all datasets, we implemented several preprocessing steps, including georeferencing, resampling, and normalization. All datasets were standardized to a consistent spatial resolution of 12.5 m. This uniform scale facilitated more accurate overlay and analysis during the weighted overlay mapping process. Each dataset was allocated a weight indicative of its significance in influencing groundwater potential, established through a synthesis of field observations. Field observations within the study area were instrumental in identifying and understanding the characteristics of regions with groundwater presence. By conducting on-site surveys and measurements, we understand the hydrogeological features that influence groundwater occurrence, such as the locations of groundwater, existing wells, types of rocks and soil, and land use practices. The insights gained from these field observations enhance our understanding of the complex interactions between geological and environmental factors affecting groundwater availability in the area and assist us in assigning weights to the datasets and reclassifying them based on their importance. The weighted datasets were amalgamated using ArcGIS Pro to produce a composite GWPZ map, classifying regions into poor, moderate, and good GWPZ (Figure 2).

The concluding step encompassed field verification and remote sensing validation techniques for the GWPZ map. Field validation was performed subsequent to the creation of this map by visiting the study region to evaluate the poor, moderate, and good GWPZ. Farms equipped with groundwater wells should ideally be situated in regions designated as high potential zones, thereby affirming the existence of groundwater in those locales. In contrast, suboptimal potential zones should exhibit an absence of physical indicators of agriculture or groundwater wells. The second method utilized the Normalized Difference Vegetation Index (NDVI), a remote sensing tool, to identify vegetation in the region. Given that vegetative regions presumably employ groundwater wells for irrigation, we utilized this data to ascertain whether the agricultural fields were situated in optimal potential zones or alternative zones, hence corroborating the GWPZ map.

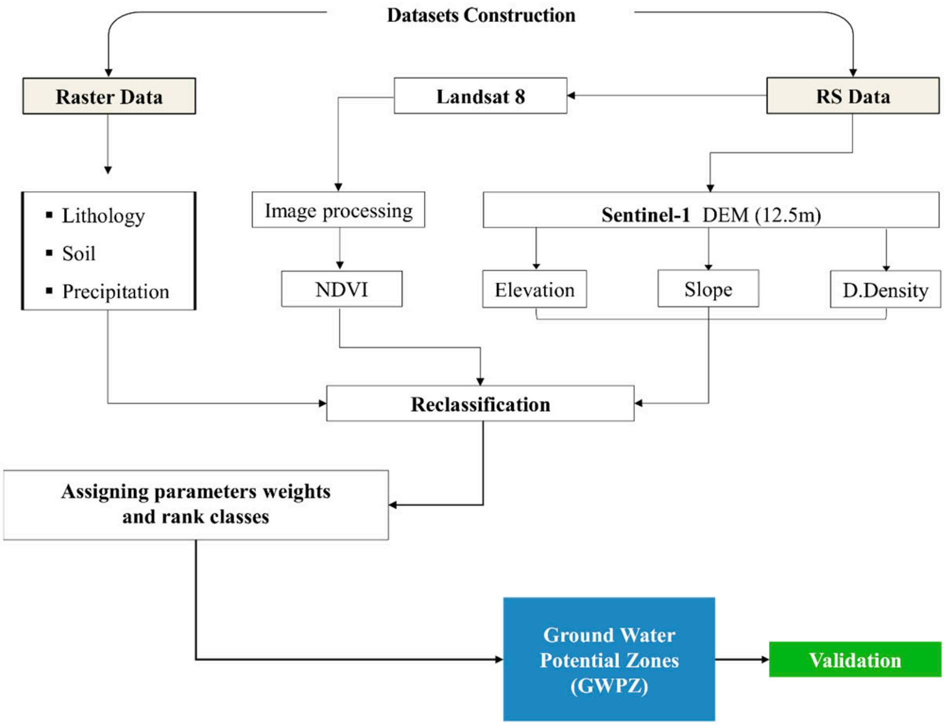

Figure 2. A flow chart outlining how the datasets were utilized to map the GWPZ in the study area.

Table 1 delineates the important factors and rankings for identifying potential groundwater zones. Each aspect was allocated a weight based on its influence on the phenomenon and on previous studies [21,32]. Subsequently, each layer was categorized into five classifications and assigned relative weights. The soil received the lowest weight due to its thin composition, mostly consisting of volcanic fields (Harrat), which restricts its influence on groundwater infiltration. In contrast, drainage density and geology were assigned the most significance due to the influence of fractures, faults, and valley branching in channelling water into subterranean strata. In these classifications, a grade of (5) indicates the highest probability of groundwater presence, whilst a rating of (1) signifies the lowest probability. Following the classification and allocation of weights, a weighted overlay analysis of these layers was performed to generate the final map indicating areas with groundwater potential.

Table 1. The layers utilized in the overlay analysis to identify GWPZ.

Parameter	Weight (%)	Classes	Rank
Slope (Degree)	10	0–6	5
		7–12	4
		13–20	3
		21–28	2
		29–47	1
Precipitation (mm)	15	37–43	1
		44–47	2
		48–51	3
		52–55	4
		56–58	5

Table 1. *Cont.*

Parameter	Weight (%)	Classes	Rank
Elevation (m)	15	489–617	5
		618–695	4
		696–780	3
		781–888	2
		889–1772	1
Lithology	20	Igneous Rocks	2
		Metamorphic Rocks	3
		Sedimentary Rocks	4
Drainage density (km^2)	20	0–0.2	1
		0.3–0.5	2
		0.6–0.7	3
		0.8–1	4
		1.1–1.9	5
Soil	5	Calciorthids	1
		Lava flows	2
		Torriorthents	3
NDVI	15	−0.078–0.065	1
		0.066–0.11	2
		0.12–0.15	3
		0.16–0.20	4
		0.21–0.46	5

3. Results and Discussion

The accessibility of groundwater is chiefly influenced by geology, geomorphology, soil composition, lineament density, drainage density, precipitation patterns, and NDVI. Consequently, all thematic maps pertinent to the study area have been generated, and these maps are delineated below.

3.1. Geology

From a geological perspective, the study area has rock formations that span in age from Precambrian to Quaternary (Figure 3). The Precambrian rocks (Neoproterozoic 900 to 540 Mya) consist mostly of metavolcanic and meta-sedimentary rocks. The Cambrian and Cambrian-Ordovician formations consist of alternating layers of coarse-to-fine-grained sandstones and micro gabbro rocks. Furthermore, there are lava flows from the Tertiary to Quaternary period, as well as deposits from the Quaternary period consisting of sand, gravel, silt, and sabkha units [33–37]. The Wadi Al-Hamd Basin can be divided into three distinct topographical zones [27]. Firstly, there is the Najd Plateau, situated in the eastern part of the basin and ranging in elevation from 750 to 1600 m above mean sea level. Secondly, there is the Hijaz mountain, which spans from sea level in the main channel of the Wadi to over 2000 m on the western side. Lastly, the northern and southern parts of the basin are characterized by the presence of lava flows from Harrat Hirmah and Harrat Rahat. Calciorthids and Torriorthents are the predominant soil types in the study area, particularly within Wadi Al-Hamd (Figure 3). Calciorthids create a layer of soil and have a texture that is sandy to loamy. Torriorthents primarily develop on slopes that are undergoing active erosion. The composition of Torriorthents includes loamy sand, fine sandy loam, sandy loam, loam, or clay loam, as well as their gravelly equivalents [38–42].

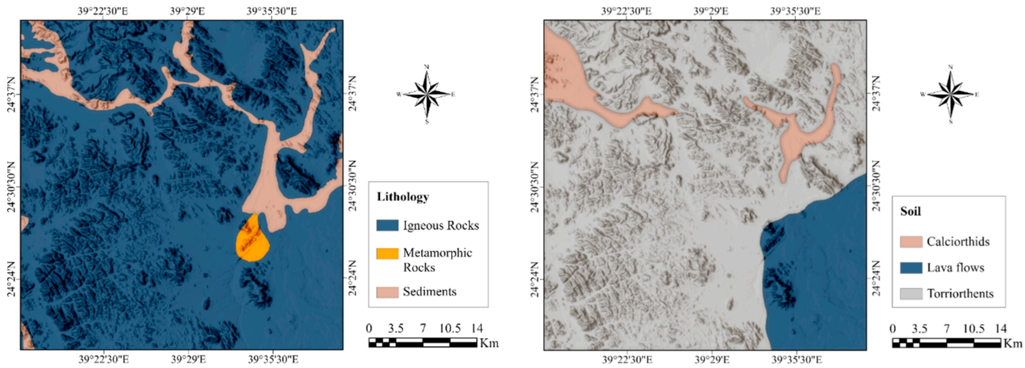

Figure 3. (**left**) A geological map of the various rock formations presents in the study area. The research region predominantly consists of diorite, granodiorite, granite, and granite gneiss rocks, as well as a few sedimentary rocks. (**right**) A map exhibits the arrangement of soil types within the designated area.

3.2. Elevation and Slope

Figure 4 shows that more than 65 percent of the research region is situated at an elevation below 696 m above sea level. The lower-lying topography plays a critical role in the movement of both groundwater and surface water, particularly because it absorbs water from steep slopes that have limited vegetation. Madinah's terrain consists of flat plains, hilly regions, and valleys. Typically, the altitude of the ground in the plains varies from 600 m to 620 m above mean sea level (AMSL). The city contains mountainous regions located in the north, south, and west, ranging in elevation from 800 m to 1500 m above mean sea level (AMSL). The topography of the region exhibits an east-to-west slope, which continues until it reaches the Al-Aqiq valley [19]. The research area exhibits a diverse range of altitudes, with the highest point reaching an elevation of 1272 m above mean sea level (AMSL) in the southwestern region and the lowest point measuring 489 m AMSL in the northern half, specifically in the main stretch of Wadi Al Hamd. The study area's elevation was divided into five unique groups ranging from 489 to 617 m above mean sea level (AMSL) to 889 to 1272 m AMSL (Figure 4). The majority of the research region has slopes that are less than 13 degrees. Wadi Qana and Wadi Aqiq are expansive wadis located in the Al-Madinah region. The Wadi Aqiq flows in a northerly direction and converges with Wadi Qana in the eastern region of the Al-Madinah area. The outlets of the Madinah basin converge and continue as a single main valley, referred to as Wadi Al Hamd [17]. The study region was divided into five categories based on the slope values: 0 to 6°, 7 to 12°, 13 to 20°, 21 to 28°, and 29 to 74° (Figure 4).

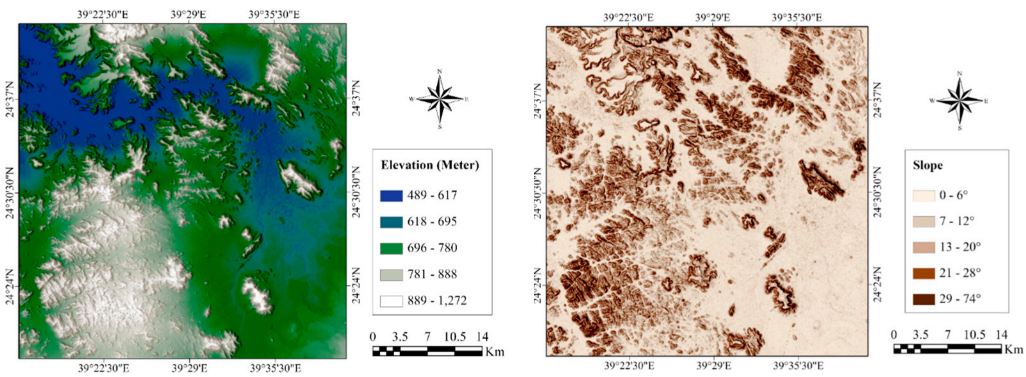

Figure 4. (**left**) A map depicting the digital portrayal of the surface elevation of the study area, showing a range from 489 to 1272 m above mean sea level (AMSL). (**right**) A map illustrating the various slopes found in the study areas. The gradient in the lower class ranges from 0 to 6, while in the higher class it spans from 29 to 74.

3.3. Drainage Density and Stream Network

Wadi Al-Hamd originates in the northwestern region, where it flows through elevated mountain ranges. As it progresses, minor tributaries join the main channel at sharp angles, forming a dendritic drainage pattern. The wadi then turns eastward before continuing southeast, eventually reaching the southeastern part of Al-Madinah. The land in the study region was classified into five categories, ranging from 0–0.2 to 1.10–1.90 km/km^2. The downstream areas showed a high drainage density along the elevation (Figure 5). However, specific regions located further upstream have a higher density of drainage. The study region encompasses five stream orders, ranging from first order in the high highlands and descending to the fifth order when they converge in the main wadi, such as Al-Hamd. According to [43], a low drainage density is a reliable predictor of high potential for groundwater.

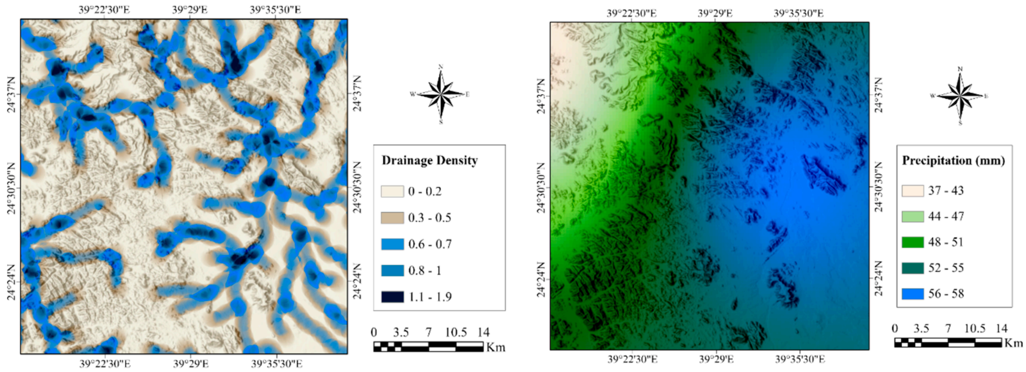

Figure 5. (**left**) The map displays the five classifications of drainage density in the study region, with values ranging from 0 to 0.20 (km/km^2) for the lowest classification and from 1.10 to 1.90 (km/km^2) for the highest classification. (**right**) A map illustrating the precise distribution of precipitation levels within the studied area. The highest recorded measurement was 58 mm, while the lowest recorded measurement was 37 mm.

3.4. Rainfall

Al-Madinah Al-Munawarah has an arid climate but experiences increased precipitation from November to January. It is characterized by low rainfall, high temperatures, and an overall dry environment. Rain typically falls in sporadic bursts during November, December, March, and April. The average annual rainfall in the Madinah area is approximately 40.1 mm. The measured rate of infiltration ranges from 0.13 to 1.01 cm/min. The average daily temperatures fluctuated between 27 and 43 °C during the months of July and August and between 10 and 25 °C in December and January [17]. The yearly maximum precipitation is 52.9 mm. The research area experiences little variation in the annual precipitation rate. The eastern portion of the study region has a greater amount of precipitation on a yearly basis. Thiessen polygons were used to verify meteorological data by considering the distribution of stations. The data were classified into five intervals ranging from 37–43 to 55–58 mm/year (Figure 5).

3.5. NDVI

The normalized difference vegetation index (NDVI) is a calculated value derived from measurements of reflectance in the visible and near-infrared sections of the electromagnetic spectrum. It is used to assess the amount of plant cover in a given area [44]. It quantifies this disparity, offering an assessment of the density and state of vegetation. From a quantitative perspective, areas with high plant coverage will exhibit positive values, whereas areas with soil and non-vegetation coverage will have slightly fewer positive values [45,46]. The fluctuation in the water table is influenced by several elements, including the intensity and amount of rainfall, the ability of rocks and soil to absorb water, the depth of groundwater above sea level, the shape of the land, the process of water evaporation and plant transpiration, and the amount of water discharged from wells [47]. The groundwater table may exert control over vegetation succession and cover patterns [48]. The land in the area was classified into five categories based on the NDVI values: −0.078–0.065, 0.066–0.11, 0.12–0.15, 0.16–0.20, and 0.21–0.46 (Figure 6). The minimum NDVI value recorded was −0.078, indicating the presence of bare or soil land in hilly regions with no vegetation cover [49]. The highest recorded NDVI value was 0.46, indicating the extent of vegetation coverage by palm trees in the agricultural lands located in Wadi Al-Hamd. The vegetation in the east–west expansion of Wadi Al-Hamd significantly increased in density.

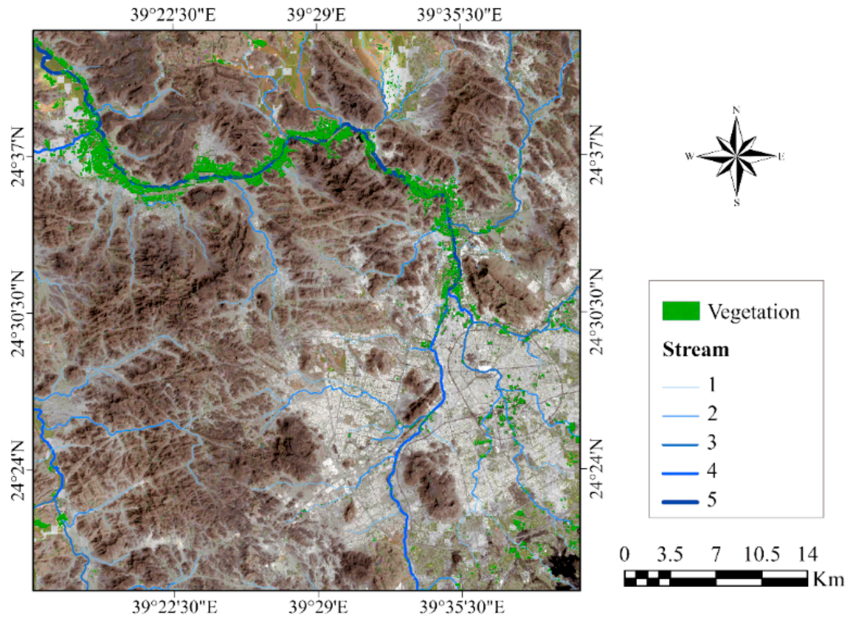

Figure 6. The study area encompasses five stream orders, ranging from first order in the high highlands to the fifth one in wadi Al-Hamd. The highest recorded NDVI value was reported in the east–west expansion of Wadi Al-Hamd.

3.6. Groundwater Potential Zones Map

The Wadi Al-Hamd Basin is the largest Wadi in the Al-Madinah Al-Munawarah Province. Previous studies described the groundwater resources of the Wadi Alhamd Basin and Al-Madinah Al-Munawwarah region as being defined by two primary aquifers: an alluvial Quaternary aquifer and a volcanic aquifer. The alluvial aquifer is situated along the recent basin, composed mainly of gravel, sand, and clay from erosion processes, while the volcanic aquifer extends through the southern part of Al-Madinah Al-Munawwarah city and includes the weathered basalt flows of Harrat Rahat, consisting of Tertiary and Quaternary lava flows [25,27]. These two hydrogeological units are hydrologically interconnected on a regional scale and function as unconfined to semi-confined aquifers. The weathered basalt unit acts as a secondary aquifer, whereas the primary groundwater source is the sub-basaltic alluvial deposits. Studies indicate that the depth of groundwater ranges from 30 to 90 m below the surface (Figure 7). Additionally, there are two buried wadis beneath the Rahat volcanic area containing alluvial deposits exceeding 50 m in thickness, with the average thickness of the alluvial unit varying from 15 to approximately 40 m, reaching up to 50 m at the center of Wadi Alhamd [25].

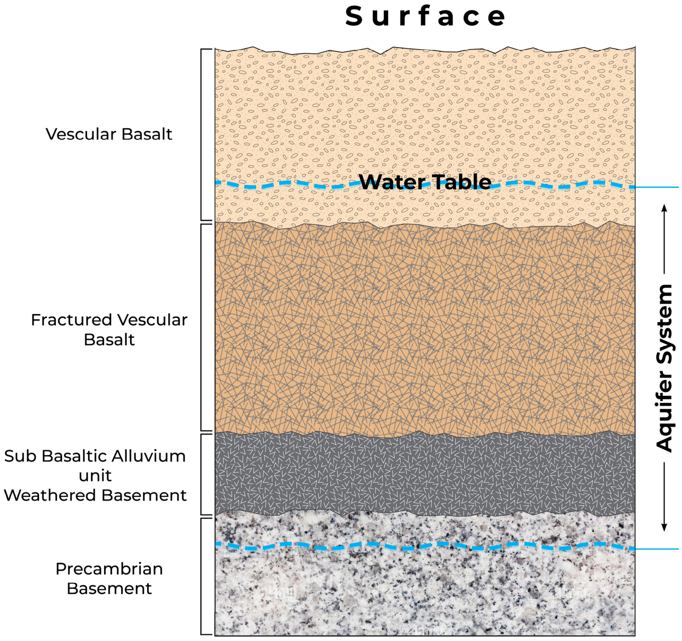

Figure 7. Geological cross-section of an aquifer system in the Wadi Al-Hamd Basin (modified after [25]).

The groundwater table depth in the Wadi Al-Hamd Basin ranges from 2 m to 200 m. The significant variety in depth can be primarily related to the differences in ground topography, types of aquifers, and their distribution [27]. The shallow groundwater is found in the southeastern and northeastern parts of the Wadi, but the deeper water tables are located in a north-south direction in the center area of the Wadi. This alignment corresponds to the presence of Tertiary and Quaternary (lava flows) formations. All findings were confirmed through on-site visits to the study area, specifically the agricultural farms located in the Wadi Al-Hamd basin. Groundwater samples were obtained from 26 wells around the Wadi (Figure 8) and subsequently analyzed for their depths and chemical composition in order to facilitate further investigation.

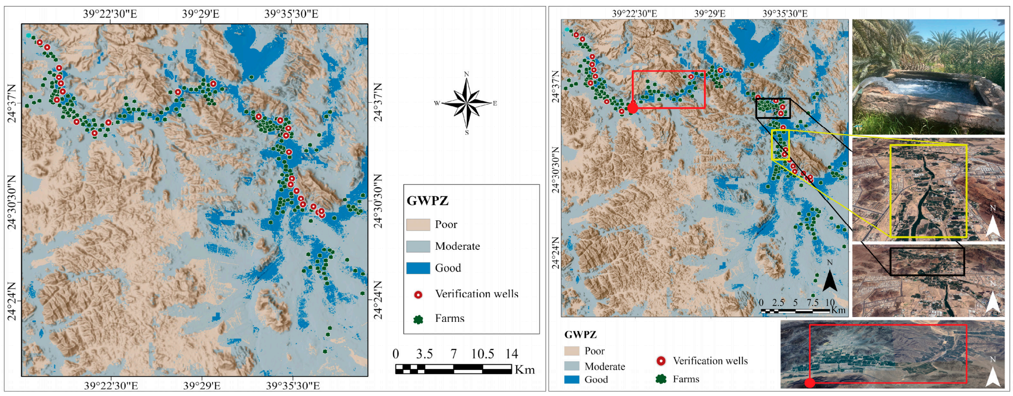

Figure 8. GWPZ resulting from the weighted overlay analysis.

Rainfall is identified as the main source of recharge for these two aquifers, contributing to both groundwater replenishment and surface runoff. Discharge predominantly occurs through production wells used for irrigation and domestic water supply. The hydrochemistry and types of groundwater are influenced by the area's rock-forming minerals, such as gypsum, anhydrite, and halite, as well as precipitation and reverse ion exchange processes. The lithology, precipitation, altitude, gradient, and drainage density characteristics significantly influence the recharge, occurrence, and accessibility of groundwater in this study.

Although the predominant rock types in the research area are igneous and metamorphic, characterized by poor porosity, they possess extensive fractures and foliation that facilitate the infiltration and percolation of rainwater. Thus, the fractures and foliations have a crucial role in increasing permeability, recharge rates, and groundwater potential [50]. Conversely, slope, soil texture, and elevation are considered important due to their individual responsibilities. The mountains in the research area include steep slopes, which result in a substantial amount of runoff. This is because the steep gradients facilitate a fast downward movement of precipitation, which reduces the time available for infiltration and replenishing the saturated zone [51]. The main soil types found in Wadi Al-Hamd are Calciorthids and Torriorthents. These soils have textures ranging from sandy to loamy or clay loamy, which facilitate the rapid movement of surface water into an aquifer system [48].

The catchment in the study area is categorized into three classifications according to its groundwater potential: very poor/poor, moderate, and good. The regions with extremely poor or poor potential encompass 805.81 km^2 of the research area, accounting for 44.91% of the total. The places are situated in the upstream segment of the watershed, particularly inside the hilly sections of the basement. The moderately groundwater-potential zones, covering an area of 819.31 km^2 (45.67%), are situated in low-lying areas at the base of mountainous regions. These zones are characterized by moderate slopes, permeability, and productivity. Conversely, the areas with good potential for groundwater cover a total of 169.06 km^2 (9.42%) and are located in Wadi Al-Hamd and its accompanying date farms, which consist of sandy loam and sandy clay loams. Good GWPZs are identified by their low drainage density, low terrain, and low slope.

Understanding how our groundwater potential mapping information would be utilized is crucial within Saudi Arabia's water resource management policies. In the Kingdom, all groundwater is considered national property managed by the government, and wells require permits from the Ministry of Environment, Water, and Agriculture. Our study provides valuable insights that can assist in permitting by identifying areas with high groundwater potential.

While a database of permitted wells exists, unpermitted or illegal wells may still be present, particularly in remote or inaccessible areas where on the ground monitoring is challenging. Remote sensing and GIS analyses employed in our study are instrumental in detecting unauthorized wells by identifying farms and agricultural activities that may not align with official records. By analyzing satellite imagery and spatial data, we can detect changes in land use patterns and vegetation indices indicating the presence of unauthorized groundwater extraction. This is important because illegal wells are often associated with unregulated farming practices that can lead to over-extraction and depletion of groundwater resources.

The challenges in identifying and validating GWPZ in the study area include the inadequate long-term and continuous monitoring, especially in remote areas, which creates uncertainty in assessing groundwater availability. The region's complex hydrogeology, due to fractured bedrock, leads to heterogeneous aquifer properties, complicating predictions of groundwater flow and storage capacity. Additionally, restricted recharge from the arid climate and minimal precipitation, combined with excessive abstraction, contribute to groundwater depletion.

4. Conclusions

This work delineated the GWPZ in Al-Madinah Al-Munawarah Province, Western Saudi Arabia, employing weighted overlay analysis that integrated seven thematic layers: geology, elevation, slope, soil, drainage density, rainfall, and NDVI. The study region was classified into zones of extremely poor, poor, moderate, and good groundwater potential. The research indicated that drainage density, slope, and soil were the principal factors influencing GWPZ in the examined region. The groundwater potential map was overlaid with the groundwater table elevation and the locations of the existing well fields. The existing well fields are located in regions with favorable groundwater potential. These data validate the precision of the map generated in this study. This study demonstrates the application of remote sensing and GIS methodologies to rapidly and effectively integrate surface and subsurface data. This integration may assist in pinpointing prospective sites for the future installation of groundwater well fields. This analysis, however, does not provide information about the sustainability of the groundwater resource and maximum pumping rates that could be abstracted in the long-term. Additional hydrogeological studies, including groundwater level monitoring and flow modelling, are essential to accurately evaluate groundwater resources' sustainability. Advanced geophysical techniques should be applied to precisely map subsurface structures, providing a deeper understanding of aquifer characteristics and groundwater potential. Artificial recharge projects should be initiated to strengthen the reliability of predictions for GWPZ, along with efforts to develop public and institutional capacity for long-term sustainability.

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