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Groundwater Characteristics' Assessment for Productivity Planning in Al-Madinah Al-Munawarah Province, KSA

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Abstract: In recent times, drilling groundwater wells for irrigation, domestic, and industrial uses is increasing at a high rate in Saudi Arabia, meaning that groundwater is becoming a primary water resource. In the study region, over-exploitation and unsustainable performance severely deteriorate groundwater. Therefore, it is important to monitor the groundwater levels and quality as well as to detect the hydraulic parameters in order to plan and maintain groundwater sustainability. Knowledge of aquifer hydraulic parameters and groundwater quality is essential for the productivity planning of an aquifer. Therefore, this study carried out a thorough analysis on measured depth to groundwater data (2017 and 2022), borehole pumping test records, and chemical analysis of the collected water samples, especially in the presence of overexploitation and scarcity of recharge scale. To accomplish this aim, measurements of 113 groundwater wells (including 103 water samples) and analysis of 29 pumping tests between step and long-duration tests were made of all aquifer characteristics. These parameters consist of well loss, formation loss, well efficiency, specific capacity, transmissivity, hydraulic conductivity, resulted drawdown, and physiochemical parameters. Thematic maps were generated for all parameters using the geographic information system (GIS) and diagrams to strategize the groundwater productivity in Al-Madinah Al-Munawarah Province. The estimated hydraulic parameters are highly variable. Four distinct portions were identified for aquifer potentiality based on these varying ranges. Both the north and east of the region are good for groundwater productivity due to good aquifer materials, whereas the southwestern and western portions have relatively poor values. The analyzed groundwater was categorized as fresh to slightly salty water, with two primary chemical types identified showing a prevalence of mixed NaCl and Ca-Mg-SO_4/Cl water. Finally, groundwater productivity assessment predicts that the aquifers can support the Al-Madinah Al-Munawarah Province demand for several years if certain well distributions are adopted and for a few hours/day of pumping rate. The maps that have been created can be examined to aid in making decisions related to hydrology.

Keywords: groundwater; aquifer potentiality; pumping tests; hydraulic characteristics; hydrochemistry; GIS

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Citation: Masoud, M.; El Osta, M.; Al-Amri, N.; Niyazi, B.; Alqarawy, A.; Rashed, M. Groundwater Characteristics' Assessment for Productivity Planning in Al-Madinah Al-Munawarah Province, KSA. *Hydrology* **2024**, *11*, 99. https://doi.org/10.3390/hydrology11070099

Academic Editor: Kristine Walraevens

Received: 21 May 2024
Revised: 1 July 2024
Accepted: 5 July 2024
Published: 8 July 2024

1. Introduction

During the last several decades, groundwater abstraction is increasing due to urban populations, with 70% attributed to irrigated agriculture [1]. Groundwater is crucial for public health, with more than 74% of the global population depending on it for fresh drinking water [2]. Therefore, monitoring freshwater resources is essential, mainly in semi-arid and arid countries like KSA, which are highly dependent on groundwater resources [3,4]. Globally, unsustainable groundwater extraction and climate change pose a threat to groundwater-dependent ecosystems, particularly in dry lands, affecting vegetation due to changes in groundwater quantity, quality, and distribution [5]. New groundwater management strategies and productivity planning are crucial for reestablishing global economies, as the quantity and quality of groundwater supply management will significantly influence many of them in the future.

Efficient hydrological exploration and management at both local and regional scales depend on the importance of groundwater potential and quality [6]. Quantitative description of aquifers is essential for maximizing subsurface natural resources. Studies on aquifer geometry and properties as well as groundwater quality are essential for correct decision-making in groundwater resource development [7]. In addition, the estimation of aquifer characteristics for example the hydraulic conductivity and transmissivity can assist in determining if aquifer conditions are suitable for groundwater productivity for domestic, agricultural, and industrial purposes, thus aiding in addressing water resource scarcity challenges [8,9]. Borehole pumping test (BPT) analysis is a widely used method for calculating hydraulic parameters in borehole sites, providing a quantitative evaluation of aquifer conditions [10].

Urbanization and intensive farming have increased the demand for groundwater in the desert areas of Saudi Arabia [11]. Al-Madinah Al-Munawarah, a megacity in Saudi Arabia, experiences a notable influx of people coming from rural areas and seasonal visitors. The ongoing rise in water usage raises the need for groundwater, requiring the discovery and development of more groundwater aquifers. Accordingly, defining groundwater characterizations based on hydrogeological parameters and hydrochemical aspects is crucial for effective use, protection, and prediction of alteration in groundwater behaviors for productivity planning in Al-Madinah Al-Munawarah Province. Aquifer mapping, pumping tests, and water quality can simplify groundwater management planning, implementation, and monitoring, enhancing irrigation services and promoting groundwater resource sustainability [12]. Therefore, understanding parameters like porosity, hydraulic conductivity, transmissivity, groundwater flow, well performance (including well loss, formation loss, well efficiency), and physiochemical parameters is crucial for assessing groundwater aquifers [13,14].

The over-exploitation of groundwater in certain regions in Al-Madinah Al-Munawarah has prompted a concern for scientific and judicious resource management and conservation. For this, the task of this work involves assessing groundwater resources and planning their use to meet crop water requirements without excessive groundwater table lowering. The research employed both pumping tests analysis and chemical analysis of water samples to cheaply and efficiently characterize the aquifer system in the study area. Analyzing pumping test results along with other hydrogeological and hydrochemical data is essential for creating aquifer characterization programs to promote sustainable groundwater usage.

2. Site Description

The province of Al-Madinah Al-Munawarah is situated in the Hejaz region of Western Saudi Arabia along the Red Sea coast, about 340 km north of Makkah, and has an area of 151,990 km^2 (Figure 1a). The groundwater aquifer has been utilized as an essential source for agriculture activities in the basins of the province where surface water is scarce. Groundwater originates from different aquifers containing basalt lavas, alluvium, and weathered basement, with three well fields serving as part of the Al-Madinah water supply. The study area is classified as a dry region, with the average yearly rainfall calculated at 70 mm. Rainfall typically increases east to west, with occasional stormy periods and lasting a few minutes (Figure 1b). The eastern study area close to the Red Sea has a gentle topography between 0 and 300 m above mean sea level, while high elevation areas between 1000 and 1800 m were observed towards the Tabuk, Hail, Al Qassim, and Ar Riyad regions (Figure 2a). Geological and hydrogeological investigations in the Al-Madinah region have been conducted, with detailed mapping by [15–18]. These studies showed that the primary geological formations in the Al-Madinah region include fractured igneous and metamorphic rocks, sedimentary rocks, wadi fill deposits, and lava flows (Harrat) as shown in Figure 2b. The majority of basins in the study region consist of Precambrian basement rocks that underwent folding, metamorphism, granitization, and intrusion before the Cambrian period [15]. The geology of the region is well understood, but its hydrogeological data are limited in distribution. The inventory of 113 drilled wells, 29 pumping tests, and 103 water samples have been used to expand the limited database of the groundwater aquifer in the region.

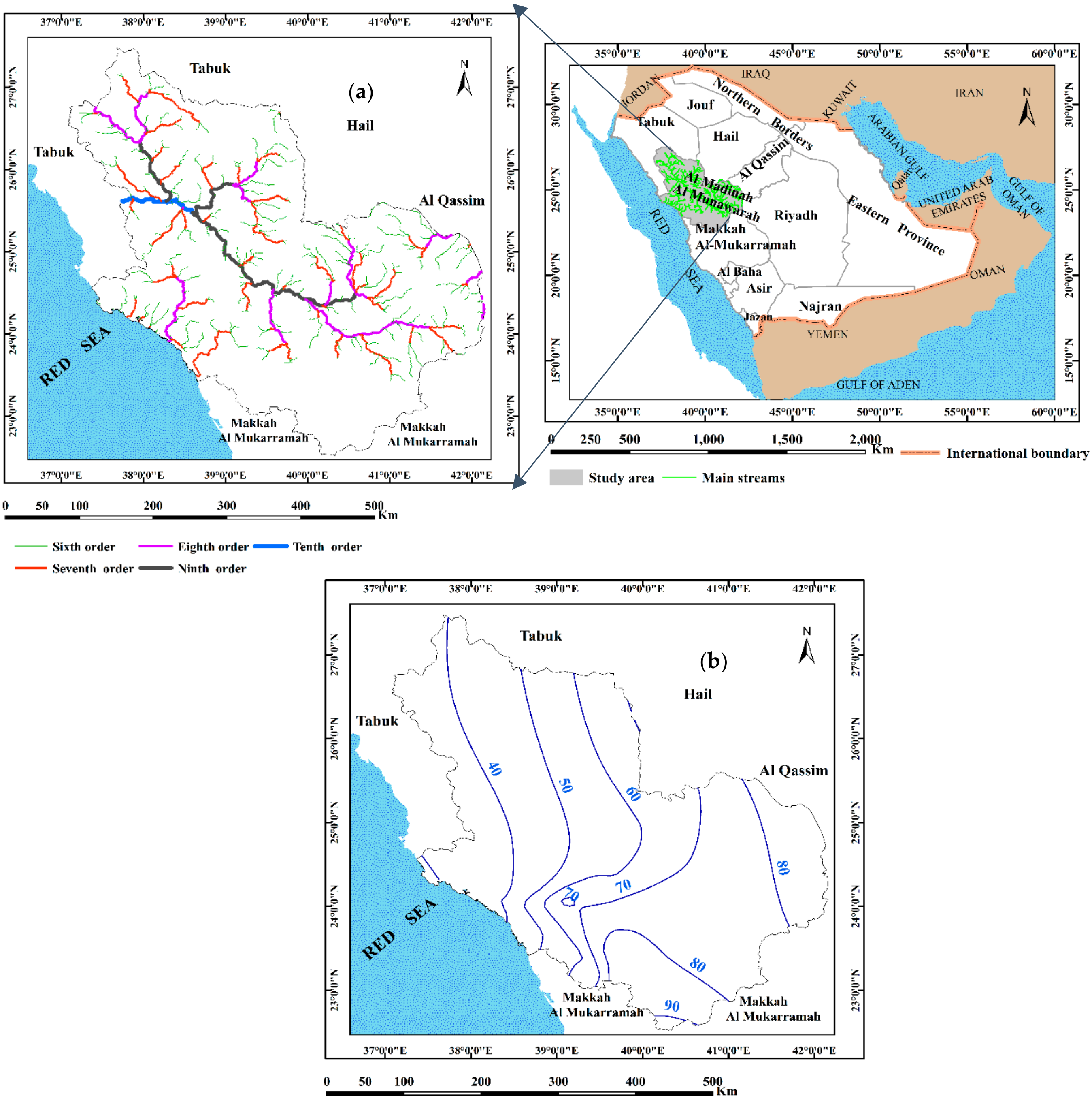

Figure 1. Location map of Al-Madinah Al-Munawarah Province (**a**) and annual rainfall distribution map (**b**).

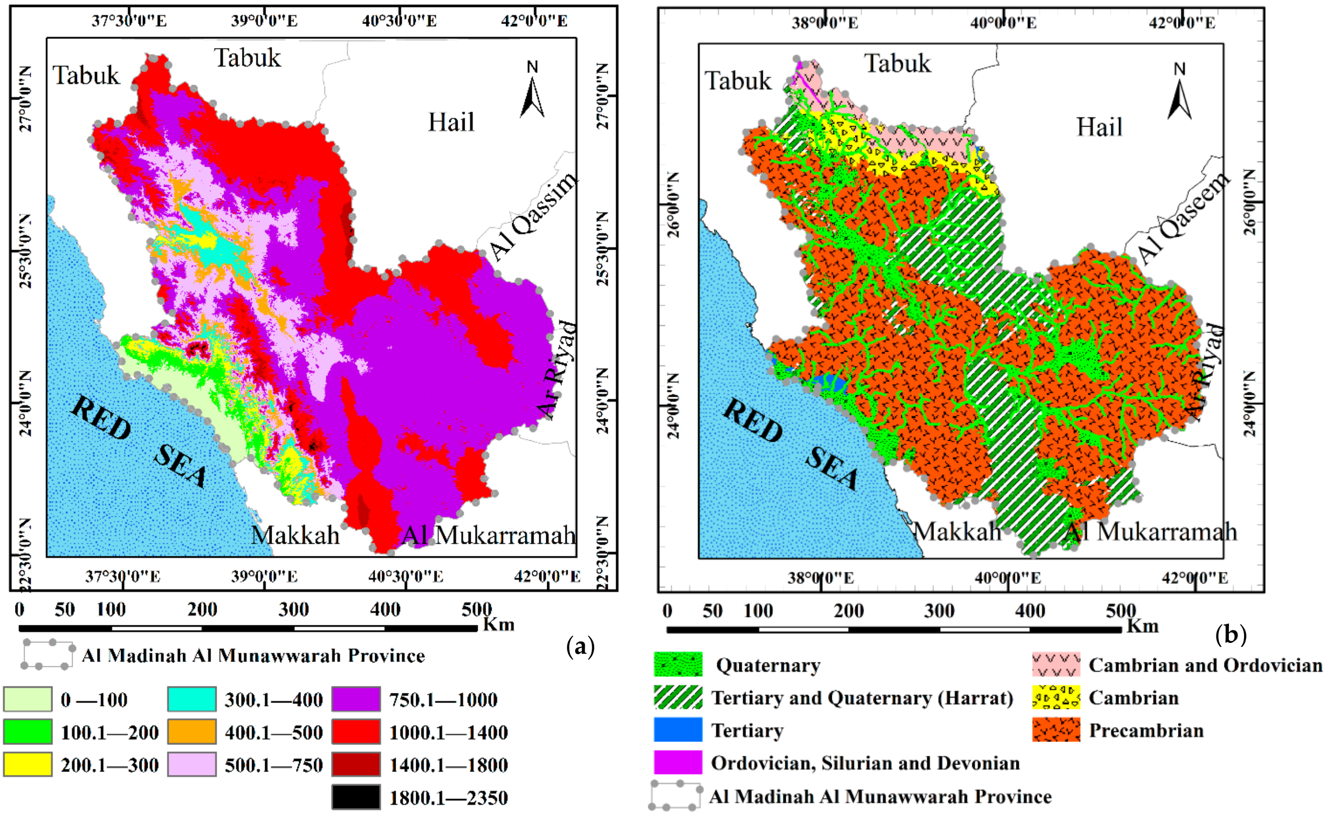

Figure 2. Digital elevation model (DEM) in meters (**a**), and geological map (**b**) of Al-Madinah Al-Munawarah Province.

3. Materials and Methodology

We employed a range of fieldworks and techniques to achieve the target of this study, which is to assess the features of groundwater for productivity planning and sustainable development, including the following:

- Creating a list of the 113 currently drilled groundwater wells.
- Conducting measurements of groundwater depth in 113 wells from 2017 to 2022.
- Storing information from hydrological and drilling reports, such as screen and pump sizes and locations, in archives.
- Collecting 29 pumping tests data between step and long-duration tests by collaboration with the groundwater sectors and drilling companies in KSA (Figure 3a).
- Gathering 103 distinctive groundwater samples for chemical examination (Figure 3b).
- Performing field measurements of total dissolved solids (TDS), electrical conductivity (EC), pH, and temperature (T °C) with multi-parameter probes and devices.
- Conducting chemical analysis of 103 groundwater samples in an accredited laboratory using various methodologies. Major ions, minor and trace elements were obtained. Ion chromatography determined the concentrations of numerous parameters, whereas the amounts of CO_3^{-2} and HCO_3^- were determined through titration; meanwhile, ICP-OES was utilized for the detection of trace and heavy elements. Equation (1) shows that the charge balance error (CBE) validates the analytical error of determined ion concentrations (meq/L^{-1}) falling within a 5% range.

$$\text{CBE} = \frac{\sum \textbf{Cations} - \sum \textbf{Anions}}{\sum \textbf{Cations} + \sum \textbf{Anions}} \times 100 \quad (1)$$

- The pumping tests data from 29 boreholes were analyzed using the AQUIFER TEST program to examine how withdrawals interact with flow and well behavior. Various hydraulic parameters such as well loss, formation loss, well efficiency (γ), transmissivity (T), hydraulic conductivity (K), and specific capacity (Sc) were calculated using different methods and equations by [19–23]:

$$S = BQ + CQ^2 \quad (2)$$

S equals the intended drawdown of water level (m), Q equals the flow rate (m^3/h), B represents the loss coefficient due to formation (h/m^2), and C represents the loss coefficient due to the well (h^2/m^5). The decline in a pumped well (S) is caused by the rate of drop from formation loss (BQ) and reduction from well loss (CQ^2). Once the well discharge rate is divided by the drawdown, the equation above is altered to the following equation:

$$S/Q = B + CQ \quad (3)$$

Nonetheless, the subsequent formula could also be employed to determine the efficiency percentage of a well at any given pumping rate:

$$\gamma = BQ/(BQ + CQ^2) \quad (4)$$

where (γ) is equivalent to the well efficiency percentage.

$$T = 2.3\ Q/4\ \Pi\ \Delta S \quad (5)$$

$$K = T/H \quad (6)$$

$$Sc = Q/\Delta S \quad (7)$$

T represents transmissivity (m^2/day), Q refers to the discharge rate (m^3/day), π = 3.1415926535, ΔS indicates the variation in water-level drop in one logarithmic cycle (m), K is the hydraulic conductivity (m/day), H is the thickness of aquifer (m), and ΔS represents the total drop in water levels.

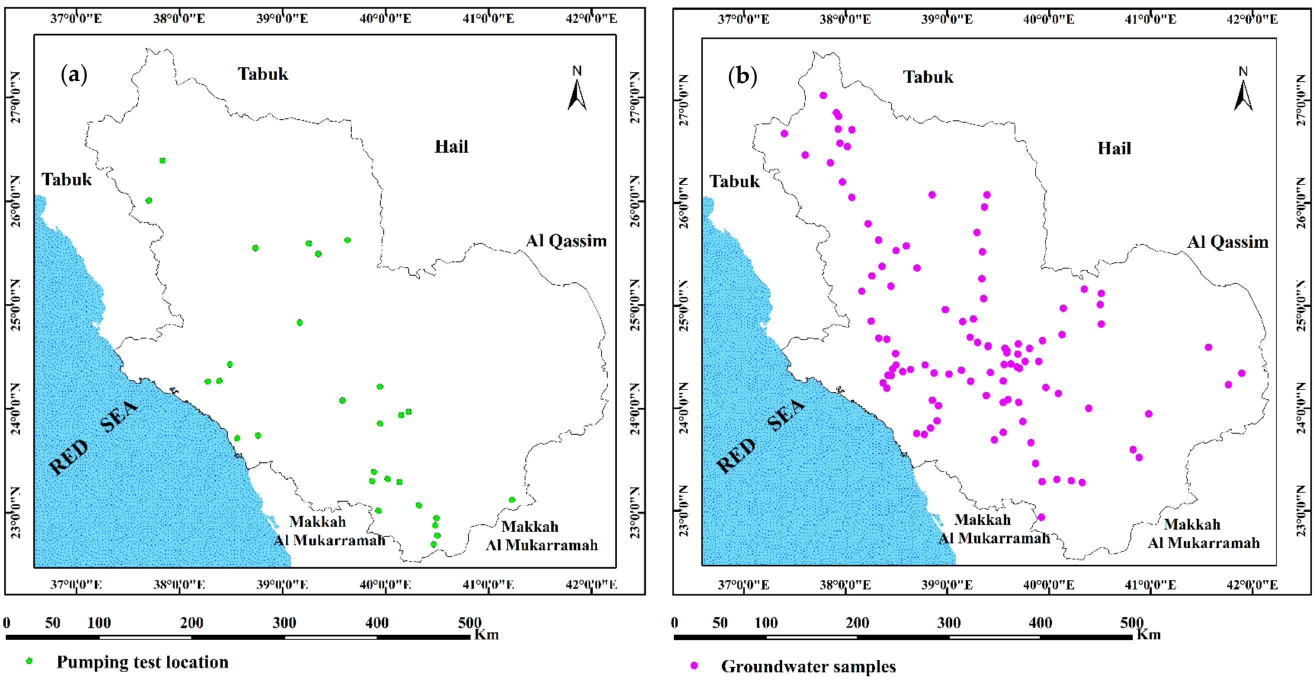

Figure 3. Location maps of pumping tests (**a**) and groundwater samples (**b**) in Al-Madinah Al-Munawarah Province.

- In order to identify the chemical characteristics of groundwater and the primary mechanism influencing its chemistry, AquaChem (2014.2) software was utilized to create

diagrams for Chadha, total ionic salinity (TIS), Gibbs, and US Salinity Laboratory Staff, as well as to evaluate hazards based on salinity and sodium adsorption ratio [24–26].
- Thematic maps are created using GIS (10.2) and Surfer (12), incorporating hydrogeological data such as water tables, salinity, and the aquifer resulted drawdown using the Kriging method. According to [27–29]., many types of interpolations have been applied to create these maps, and Kriging was the most suitable and matching method with the measured data.

The specifics of these mentioned stages are emphasized and examined in the subsequent sections.

4. Results and Discussion

4.1. Hydrogeological Characteristics

4.1.1. Groundwater Aquifer System

Groundwater aquifers within the region provide the Al-Madinah water supply, primarily for agricultural activities. The aquifer extraction began in the 1970s, and between 1990 and 2000, different well fields were constructed to supply water to Al-Madinah Province [30]. Groundwater is located in three aquifers consisting of the upper weathered section and fractured Precambrian basement rocks (less than 5 m-thick), Tertiary and Quaternary (Harrat) rocks, and Quaternary alluvial deposits overlaid by recent basalt lavas flows' eroded basement (Figures 2b and 4). Al-Madinah Al-Munawarah Province is experiencing a water scarcity issue caused by excessive extraction from underground aquifers and minimal precipitation, which has led to declining water levels and quality deteriorating [31,32]. Therefore, it is important to comprehend the hydrogeological and hydrochemical features of groundwater aquifers for effective productivity planning in the region. The geology of the region is well understood, but the hydrogeological data are limited. In this work, groundwater table for the years 2017 (31 wells) and 2022 (113 wells), 29 well pumping tests' information, and chemical analyses of 103 groundwater samples are conducted to evaluate the groundwater conditions in the research area.

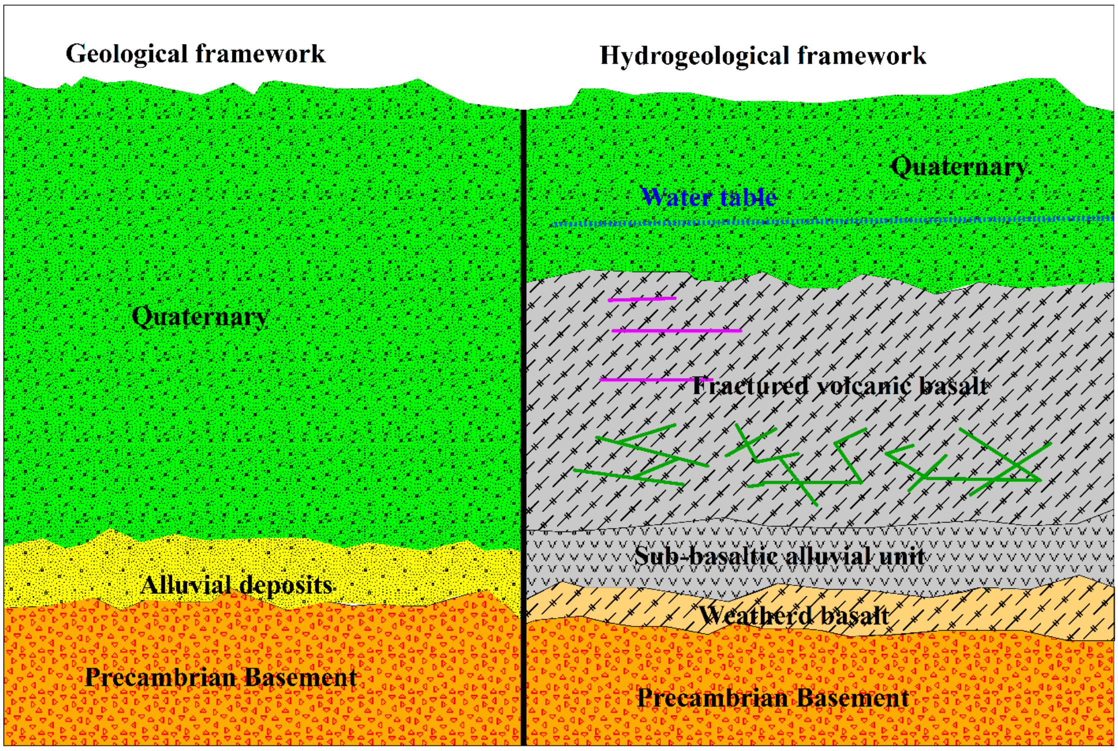

Figure 4. Groundwater aquifers' distribution in Al-Madinah Al-Munawarah Province modified after [27].

4.1.2. Groundwater Levels Distribution and Movement

The bottom of the weathered basement is where the groundwater aquifer begins, with a free water surface at the top and some semi-confined areas caused by low permeability materials and lava and inter-lava hydraulic changes. Over time, runoff, recharge from rainfall, and underground groundwater flow from the south beyond the study region, have all contributed to the accumulation of groundwater in the aquifer system. According to [30], the system's overall groundwater flow direction is north and northwest, with historical discharge to the Ayn er Zerqa springs at Al-Madinah and alluvium in the Wadi Al-Hamdh (north) and Al-Aqiq (west). In this study, the thickness of the aquifer system was estimated from the well log data to be in the range from 57 to 327 m and the depth to water level varied from 10.57 to 177 m from the ground surface. Consequently, the groundwater head distribution maps have been based initially on the depth to water data marks for the years 2017 (31 wells) and 2022 (113 wells) as shown in Figures 5a and 5b, respectively. From these figures, certain hydrogeological features are apparent. In the extreme south of the region, the groundwater head indicates northwesterly flows in the year 2017 and southwesterly flows in the year 2022 as a result of declining heads and yields in the southern well fields. Declines of up to 2 m in the groundwater levels were observed in the south over a period of about 5 years. In the north, the heads accord with flow to the southwest in the direction of the down gradient of the region, demonstrating that the rainfall recharges the system along this boundary. Heads in the central part of the region indicate a westerly groundwater flow consistent with the presence of the Red Sea drainage point for the aquifer system in that region.

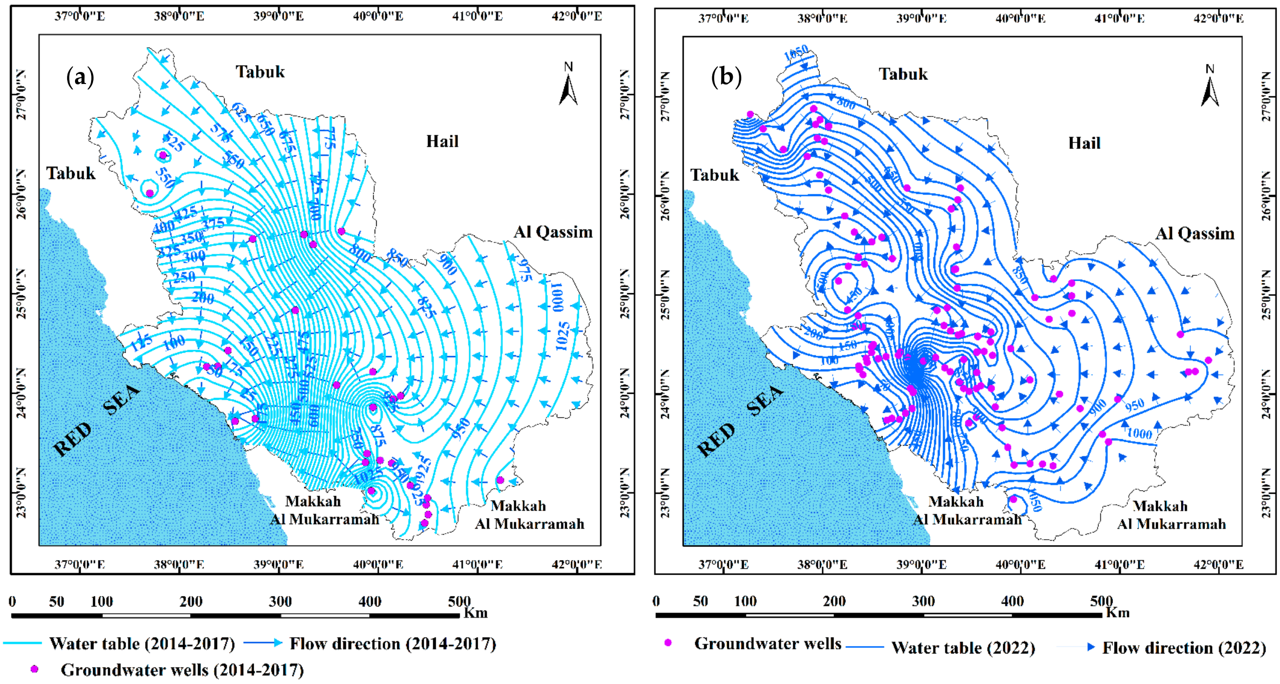

Figure 5. Maps for groundwater head distribution and flow directions for the years 2017 (**a**) and 2022 (**b**) in Al-Madinah Al-Munawarah Province.

The groundwater abstraction rate prior to 1970 is incomplete, but annual discharge in the Al-Madinah region was 34 million m^3/year in 1979 [33]. Since 1992, both the number of drilled wells and the annual abstraction from different aquifers have increased, producing 15,695,000 m^3/year [30]. Otherwise, in 2007, Ref. [30] surveyed 60 groundwater wells with an estimated discharge rate of 21 million m^3/year. Accordingly, current heavy abstraction has occurred in Al-Madinah Al-Munawarah Province producing declines in the groundwater levels in the year 2022, where the zero line was moved inland (Figure 5b).

4.1.3. Well Performance and Hydraulic Parameters

Estimating the groundwater well performance and hydraulic characteristics of any aquifer system is critical for quantitative groundwater flow information, contaminant transport modeling, and assessing the groundwater productivity planning. On the basis of the above theories and methods, the hydraulic properties were estimated using pumping tests (step and long-duration tests) performed on specific well locations. Concerning our work, the acquired pumping test measurements was analyzed throughout a cross of 29 drilled wells (Figure 3a) in order to provide quantitative information of the in situ well performance and hydraulic characteristics of the region under the aquifer formation. Advanced plotting techniques and the Aquifer test 2016 program were utilized for the examination of step and constant pumping based on Equations (2)–(7). Figure 6a,b shows the analytical solutions and observations for both step and long-duration tests in a well, for instance. The hydraulic parameters were estimated and are detailed in Table 1a,b. Analysis of the step pumping tests results indicated that the observed well loss (CQ^2) and formation loss (BQ) fall within the range of 0.01–23.53 and 0.0001–12.31, respectively. Alternatively, the mean efficiency (γ) across all stages ranges from 27.6% (Well No. 21) to 78.86% (Well No. 14). These findings suggest that the drilled wells in Al-Madinah Al-Munawarah Province have significant well losses and varying degrees of well efficiency, ranging from low to high. The poor well performance in the area may be due to a somewhat blocked gravel interstice surrounding the well-screen or screen hole, along with the accumulation of fine material during early well development [10]. This can also be caused by the precipitation of minerals in the pipes, for which it is recommended to estimate the precipitation rates of the main minerals. On the other hand, the specific capacity (Sc) can be calculated in each step by dividing its discharge rate by its drawdown. It is an extremely significant number that can be utilized to determine the ideal pumping rate from the production well and to create an appropriate schedule for well maintenance [34]. Therefore, this parameter (Sc) is one of the significant indices for constructing a groundwater aquifer productivity potential map (GAPPM) in the region. As listed in Table 1a, Sc ranges widely from 2.63 to 59.33 m^2/h, with a mean value of roughly 19.68 m^2/h. Sc accuracy is influenced by a number of variables, such as the discharge rate, constancy of pumping rate, and well design [34].

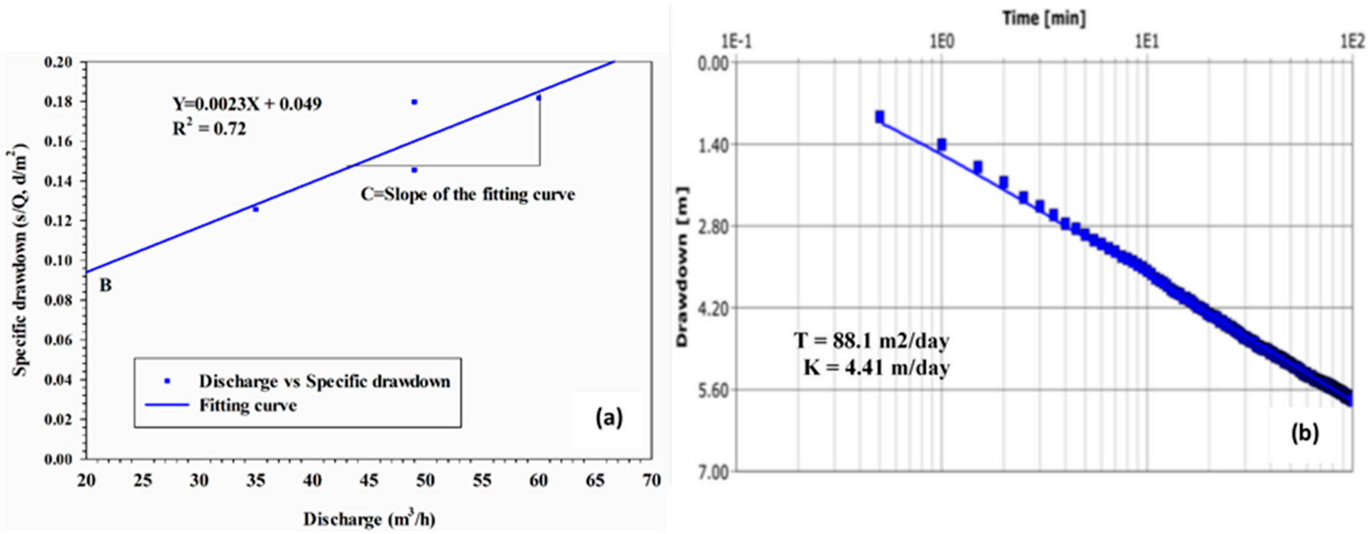

Figure 6. Example of the step drawdown (**a**) and long-duration (**b**) pumping test analysis for Well No. 1 in Al-Madinah Al-Munawarah Province.

Table 1. (**a**) Calculated well performance parameters from step drawdown pumping test analysis. (**b**) Calculated aquifer hydraulic parameters from long-duration pumping test analysis.

(a)

Well No.	Step Pumping Test Analysis									
	Step No.	Draw-Down S (m)	Discharge Q (m^3/h)	Formation Loss Coef. B (h/m^2)	Well Loss Coef. C (h^2/m^5)	Formation Loss (BQ)	Well Loss (CQ^2)	Well Efficiency (γ) %	Average of (γ) %	Specific Capacity Sc (m^2/h)
1	1	4.4	35.00	0.049	0.0023	1.72	2.82	38.98	31.71	6.47
	2	7.13	49.00	0.049	0.0023	2.40	5.52	33.67		
	3	8.81	49.00	0.049	0.0023	2.40	5.52	27.25		
	4	10.91	60.00	0.049	0.0023	2.94	8.28	26.95		
3	1	16.41	47.38	0.27	0.002	12.79	4.49	77.96	70.97	2.63
	2	20.97	55.76	0.27	0.002	15.06	6.22	71.79		
	3	27.32	68.22	0.27	0.002	18.42	9.31	67.42		
	4	31.74	78.44	0.27	0.002	21.18	12.31	66.73		
8	1	17.28	31.54	0.0119	0.0003	0.38	0.30	35.41	52.30	37.48
	2	25.44	41.94	0.0119	0.0003	0.50	0.53	47.08		
	3	32.88	49.86	0.0119	0.0003	0.59	0.75	55.97		
	4	50.16	63.00	0.0119	0.0003	0.75	1.19	70.73		
14	1	16.41	47.376	0.30	0.0019	14.21	4.49	86.61	78.86	2.63
	2	20.97	55.764	0.30	0.0019	16.72	6.22	79.78		
	3	27.32	68.22	0.30	0.0019	20.47	9.31	74.91		
	4	31.74	78.444	0.30	0.0019	23.53	12.31	74.14		
16	1	3.95	17.39	0.18	0.0027	3.13	0.82	79.25	75.00	4.17
	2	5.60	23.22	0.18	0.0027	4.17	1.45	74.53		
	3	6.78	26.82	0.18	0.0027	4.82	1.94	71.11		
17	1	0.57	42.876	0.01	0.0000	0.56	0.08	97.79	77.12	59.33
	2	1.6	95.328	0.013	0.000043	1.24	0.39	77.45		
	3	2.12	99.72	0.013	0.000043	1.30	0.43	61.15		
	4	2.77	153.648	0.01	0.000043	2.00	1.02	72.11		
21	1	1.2	24.012	0.02	0.0023	0.48	1.33	40.02	27.60	13.79
	2	2.33	32.004	0.02	0.0023	0.64	2.36	27.47		
	3	3.43	38.988	0.02	0.0023	0.78	3.50	22.73		
	4	4.58	46.008	0.02	0.0023	0.92	4.87	20.09		
22	1	0.98	24.98	0.0219	0.0007	0.55	0.44	55.83	51.13	23.35
	2	1.29	29.99	0.0219	0.0007	0.66	0.63	50.91		
	3	1.69	36.00	0.0219	0.0007	0.79	0.91	46.65		
23	1	1.05	60.012	0.0106	0.0001	0.01	0.0001	60.60	49.50	46.66
	2	2.06	96.984	0.0106	0.0001	0.01	0.0001	49.90		
	3	2.63	119.592	0.0106	0.0001	0.01	0.0001	48.20		
	4	3.82	141.012	0.0106	0.0001	0.01	0.0001	39.13		

(b)

Well No.	Long-Duration Pumping Test Analysis				Aquifer Potentiality Based on T Values Gheorghe Classification [34]
	Discharge (Q) (m^3/Day)	Resulted Drawdown (m)	Transmissivity T (m^2/Day)	Hydraulic Cond. K (m/Day)	
1	1071.40	8.77	88.20	4.41	Moderate potential
2	38.02	18.00	0.0198	0.08	Negligible potential

Table 1. *Cont.*

Well No.	Long-Duration Pumping Test Analysis				Aquifer Potentiality Based on T Values Gheorghe Classification [34]
	Discharge (Q) (m^3/Day)	**Resulted Drawdown (m)**	**Transmissivity T (m^2/Day)**	**Hydraulic Cond. K (m/Day)**	
3	36.30	12.00	105.40	9.30	Moderate potential
4	26.00	3.44	0.30	0.25	Negligible potential
5	52.70	6.43	95.40	8.30	Moderate potential
6	570.30	16.00	3.60	0.14	Very low potential
7	155.50	15.00	2.30	0.76	Very low potential
8	1486.10	2.20	1330.00	32.10	High potential
9	162.40	56.40	5.83	0.044	Low potential
10	228.10	38.90	7.07	0.063	Low potential
11	3652.10	2.03	1123.2	19.01	High potential
12	174.50	33.40	7.14	0.0533	Low potential
13	1007.40	27.20	6.48	0.051	Low potential
14	3326.40	38.50	45.10	0.29	Low potential
15	95.00	20.33	7.48	0.044	Low potential
16	1512.00	29.90	45.10	0.29	Low potential
17	1002.20	26.60	50.10	0.53	Moderate potential
18	648.00	7.70	112.30	0.69	Moderate potential
19	3378.30	3.20	1244.20	6.13	High potential
20	3628.80	0.85	33,696.00	302.4	High potential
21	1710.70	0.70	32,832.00	216.0	High potential
22	1047.20	40.50	26.50	0.34	Low potential
23	1105.90	4.30	915.80	18.66	High potential
24	864.00	1.80	2505.60	23.33	High potential
25	3404.20	4.20	2160.00	38.88	High potential
26	155.50	69.90	5.70	0.042	Low potential
27	3888.00	4.95	145.20	1.56	Moderate potential
28	1451.50	58.14	178.00	1.89	Moderate potential
29	561.60	20.70	32.74	0.23	Low potential

(b)

Sen [35] classified the well productivity into three categories based on Sc values: medium productivity (between 1.8 and 18 m^2/h), low productivity (less than 1.8 m^2/h), and high productivity (more than 18 m^2/h). As a result, the region's production wells had a medium to high productivity. Therefore, if designed and built properly, wells with a high specific capacity can have a strong discharge capability and minimal drawdown [13]. According to Abdul Mogith et al. [36], a well with a low specific capacity is suggestive of a poor design like a pump in the wrong location, a screen that is too short, or blockages in the screen, leading to a rapid decline in water levels. Therefore, it is crucial to develop and improve well construction to ensure the longevity of the aquifer and enhance the output and productivity of the groundwater supply in the region.

Otherwise, the results of constant tests (Table 1b) showed a large variation in the transmissivity (T) of the groundwater aquifer, where the lowest and greatest values of T that characterize fall between 0.0198 and 33,696.00 m^2/day with an average value of about 2647.5 m^2/day. Therefore, the main factors governing the variation in T values and aquifer potentiality are the rapid lateral changes in facies, the varying types and thickness of aquifers, and the complicated geological formations (Table 1b). The high T values suggest the occurrence of good aquifer rock forming minerals there and a high potential for productivity planning in the region [37].

On the other hand, the hydraulic conductivity represented by K indicates the rock's capacity to convey fluids under a hydraulic gradient unit [38]. In the research, the estimated values of K listed in Table 1b varied from 0.042 to 302.4 m/day, with an average value of approximately 23.65 m/day. It was noted that the groundwater aquifer system in the area consists mostly of various geological formations such as a weathered part and fractured basement, Harrat, alluvial deposits, recent basalt lava flows. Hence, the precise K values suggest that the aquifer has considerable groundwater potential, as evidenced by its quick recovery time.

4.1.4. Resulted Drawdown Patterns and Aquifer System Potentiality

This study may be the first to investigate how the aquifer system in the investigated region responds hydrologically to a constant pumping rate. The objective is to determine whether a unique resultant drawdown may allow the limited extent and geometry of the aquifer to be established, along with the well's location within the aquifer system. In general, most of the aquifer height loss and drawdown rise happened in the first 100 days from discharge. Figure 7a illustrates the range of average resultant decline in groundwater level due to constant pumping from 29 groundwater wells to be from 0.7 to 69.90 m. Within the research area region, the central and southern portions of the region exhibit higher drawdown values, whilst the northwestern part displays lower values. The small aquifer thickness, high discharge rates, adjacent several wells, and low hydraulic characteristics are the reasons for the high drawdown in the region.

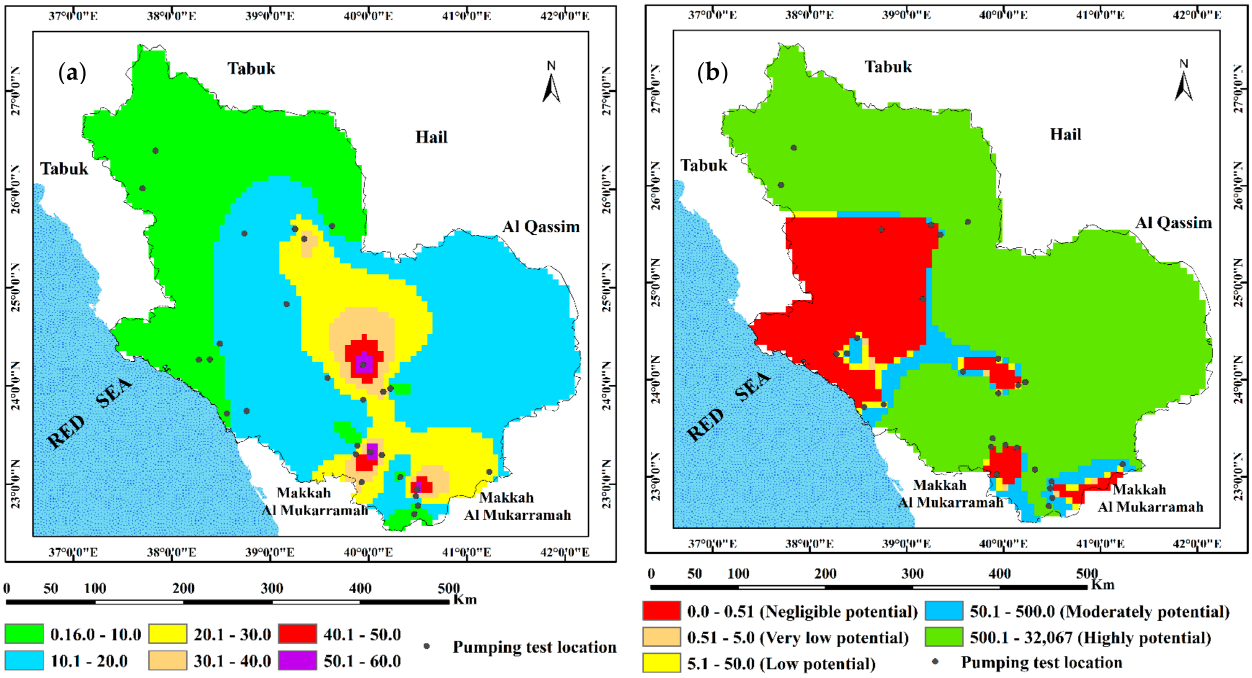

Figure 7. Resulted drawdown patterns (**a**) and aquifer system potentiality (**b**) distribution maps in Al-Madinah Al-Munawarah Province.

On the other hand, the obtained values of the hydraulic characteristics were then imported into a Geographic Information System and gridded, contoured, and color-coded into ranges to produce the aquifer system potentiality map as shown in Figure 7b. A general idea of distributions throughout the region can be obtained by using this map. Four distinct portions can be identified for potentiality based on varying ranges. Groundwater productivity is high in the northern and eastern parts of the region due to the features of aquifer materials, while the southwestern and western areas show lower values.

Ultimately, the expected outcomes of managing groundwater are modeled as exploitation increases due to higher water needs in the region. Accordingly, managing the groundwater of the aquifer system is vital to prevent substantial decreases in water levels and deterioration in quality. The determined characteristics of the aquifer are important for decision-makers and provide initial information for drilling water wells and assessing groundwater suitability for agriculture.

4.2. Descriptive Hydrochemistry of Groundwater

Assessing the quality of groundwater and its suitability for various purposes is the second crucial aspect in planning the groundwater productivity in Al-Madinah Al-Munawarah, aiming for sustainable development. Consequently, the hydrochemical properties of the groundwater were evaluated using the statistical findings (minimum, maximum and average) of the chemical analysis of 103 water samples detailed in Table 2.

Table 2. Average concentration of various groundwater quality parameters (for 103 samples).

Parameter	Unit	Minimum	Maximum	Average	WHO Standard for Drinking [39]
pH	-	6.64	8.50	7.61	6.50–8.50
EC	µS/cm	582	14,050	3631	1000
TDS	mg/L	261	8628	2236	500
Na^+	mg/L	41.90	1754.58	464.63	200
Ca^{2+}	mg/L	16.08	854.01	216.29	75.0
Mg^{2+}	mg/L	1.99	550.64	71.52	35.0
K^+	mg/L	6.39	75.60	11.55	12.00
$CO_3{}^{2-}$	mg/L	3.00	51.00	15.2	100.00
$HCO_3{}^-$	mg/L	48.80	1256.60	185.18	120.00
Cl^-	mg/L	13.42	3186.35	579.20	250.00
$SO_4{}^{2-}$	mg/l	35.05	3143.55	789.07	250.00
$NO_3{}^-$	mg/L	0.07	359.47	65.08	45.00
$PO_4{}^{3-}$	mg/L	0.01	5.16	0.37	6.00
I^-	mg/L	0.011	1.27	0.076	0.001–0.07
Br^-	mg/L	0.06	5.82	0.68	Less than 1.0
F^-	mg/L	0.02	3.90	0.61	Less than 1.0
SiO_2	mg/L	5.45	130.22	26.08	5.00–25.00
TH	mg $CaCO_3$/L	81.64	4395.00	833.76	500.00
ALK.	mg/L	44.99	1029.78	170.30	30.00–400.00
SAR	meq/L	1.337	30.09	7.075	10.00–26.00

4.2.1. Assessment of the Physico-Chemical Parameters

In general, the distribution of physico-chemical parameters in groundwater is significantly influenced by the aquifer-matrix, recharge source, and groundwater flow direction. Based on the new information, the mechanisms and processes that regulate the area's groundwater quality were categorized. In the study region, the pH values found in the groundwater samples were noted as ranging from 6.46 to 8.5 with an average value of 7.61. According to these findings, the groundwater may have been somewhat alkaline, and all of the samples fell between the permissible range of 6.5 and 8.5 (Table 2). This slightly alkalinity behavior in groundwater could be attributed to CO_2 loss, precipitation, and the dissolution of minerals in the basalt rocks in the region. The average EC and TDS readings were 3631 µS/cm and 2236 mg/L, respectively. These metrics typically represent the concentration of electrically conductible dissolved ions, which varies with temperature and the availability of soluble salts in the geology of the region [40]. A map was created to show where higher salinity areas are located based on the total dissolved solids (TDS) levels in the region (Figure 8). The map indicates a rise in TDS levels in the south and southeast portions of the region, with the groundwater classified as fresh to brackish water based on Freeze and Cherry's classification [41] (Table 3). The lithological characteristics, changes in the facies of the water-bearing formation, and rainfall lead to variations in salinity and water type in the region. The fresh groundwater type (in 35 samples) is observed in the northeast and some scattered areas in the central portions of the region. The brackish water type can be found in different parts of the region (in 68 samples) and is suitable for irrigation depending on the plant species that can tolerate this level of salinity. Consequently, overusing groundwater for farming in the study area could lead to rising water levels and degraded groundwater quality.

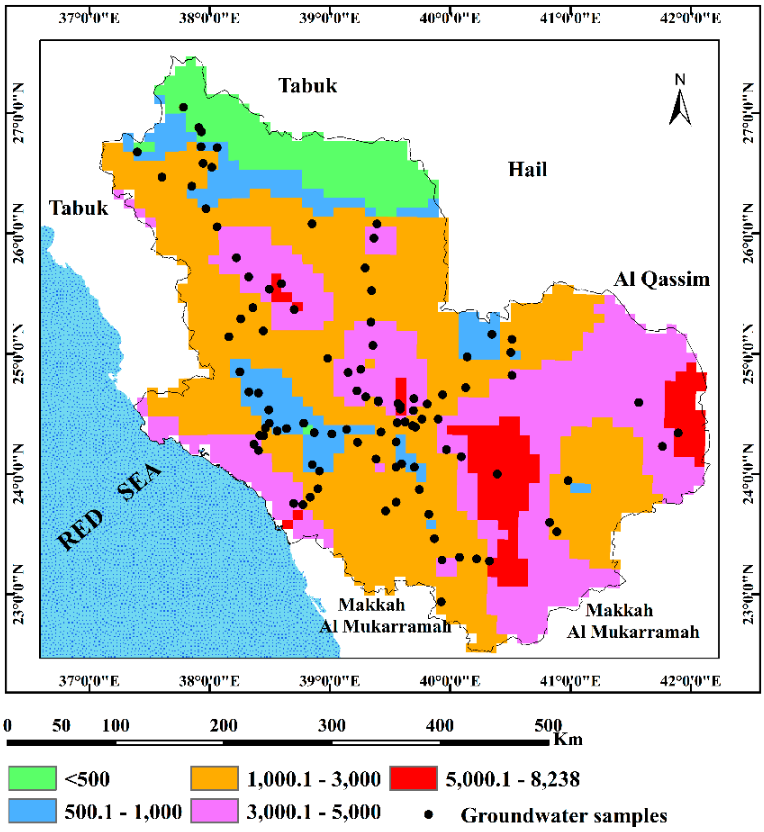

Figure 8. Distribution map of the total dissolved solids (TDS).

Table 3. Groundwater classification according to Freeze and Cherry [41].

Category	TDS (mg/L)	Groundwater Samples
Fresh	<1000	35 samples (34%)
Brackish	1000–10,000	68 samples (66%)
Saline	10,000–100,000	-
Brine	100,000	-

Otherwise, the total hardness (TH) and alkalinity (Alk) in sampling sites (64% of the total 103 samples) and (1.5% of the total water samples), respectively, exceeded the reference value of TH and Alk for drinking purposes.

4.2.2. Assessment of the Hydrogeo-Chemical Parameters

Cations: The main cations can be settled in a hierarchical order primarily depending on their concentration measured in the region: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ (in 75% of the total samples); $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ (in 25% of the total samples). However, confirming with the previous literature by [42,43], the present study reported the Na^+ predominance concentration phenomena. The exchange of Ca^{2+} for Na^+ in Na-earth deposits, along with calcium replacing sodium, may play a role in the observed phenomenon. Furthermore, Na^+ exceeded the limit standard for the WHO [39] which was recorded as more than 200 mg/L in the bulk of water samples (80%). This study revealed that the Ca^{2+} concentration exceeded the WHO's permissible limit of 75 mg/L in 77% of the sampling sites. Typically, Ca^{2+} is present in groundwater as a result of the natural dissolution of carbonate rocks such as limestone and dolomites, as well as silicate minerals like plagioclase [44]. The Mg^{2+} levels in groundwater extended from 1.99 to 550.64 mg/L, with a mean value of 71.52 mg/L. Similarly for Ca^{2+}, about 77% of total sample sites were found to be above the prescribed limit of the WHO (35 mg/L), where the same mineral sources can be used to enrich it in groundwater. Regarding the K+ levels in the groundwater, most groundwater samples (72%) were discovered to be under the recommended limit of 12 mg/L according to a report [39] (Table 2).

Silica (SiO_2): The concentration of SiO_2 varies between 5.45 and 130.22 mg/L, with an average of 26.08 mg/L. We observed about 42 samples (40% of the total samples) above the allowed limit (25 mg/L). The only source of silica in groundwater is the interaction between groundwater and rock. The silica that results from the chemical weathering of silicate minerals in rocks and sediments is dissolved by the circulating groundwater [45].

Anions: Based on the results of chemical analysis, Cl^- is the major anion in 62% of the total sample sites followed by $SO_4{}^{2-} > HCO_3{}^- > NO_3{}^- > CO_3{}^{2-} > PO_4{}^{3-} > Br^- > I^- > F^-$, while it was found that $SO_4{}^{2-}$ and $HCO_3{}^-$ are the major anions in 29% and 9% of the total water samples, respectively. Recent studies carried out by [42,46] have shown a comparable pattern of anion accessibility in the groundwater in the north, central, and south parts of Al-Madinah Al-Munawarah Province. The results revealed a range of Cl^- from 13.42 to 3186.35 mg/L. Higher Cl^- values in 69% of the sample sites may be attributed to salt suspension, soil permeability, and fertilizers from the farming areas [46]. On the other hand, the $SO_4{}^{2-}$ levels ranged from 35.05 mg/L to 3143.55 mg/L in groundwater samples, with most exceeding the 250 mg/L reference limit due to gypsum dissolution in the soil layer. In the case of $HCO_3{}^-$ concentration, it exhibited a range between 48.80 and 1256.60 mg/L. The replacement of sodium with calcium in sodium-rich deposits may result in an increased dissolution of carbonate minerals in groundwater [42]. While $PO_4{}^{3-}$ concentrations were diverse between 0.01 and 5.16 mg/L and were detected within the reference limit (6.00), the $NO_3{}^-$ values (from 0.07 to 359.47 mg/L) consistently exceeded the WHO reference limit (45.00 mg/L) throughout 44% of the sampling locations in the study region. Otherwise, the distribution map for $NO_3{}^-$ concentrations in groundwater of the aquifer system (Figure 9) indicates that many portions of the province exhibits high nitrate ranks especially in the southern part. The higher $NO_3{}^-$ at many samples locations will be because of the widespread utilization of nitrate fertilizer in agricultural practice; various methods, such as precipitation, rivers, and watering systems, contribute to the penetration of soil nitrate into the aquifer. Additionally, the results for $NO_3{}^-$ are consistent with most of the earlier research conducted in the western region of KSA as demonstrated by [43,47,48]. The presence of $NO_3{}^-$ is evidence for using fertilizers in agricultural activities.

In the case of I^-, Br^-, and F^- concentrations, they exceeded the reference limit of the WHO [39] across (11%), (19%), and (18%) of the total sampling sites, respectively. The relatively high values of these elements are mainly attributed to seawater intrusions especially in the drilled wells nearby the Red Sea.

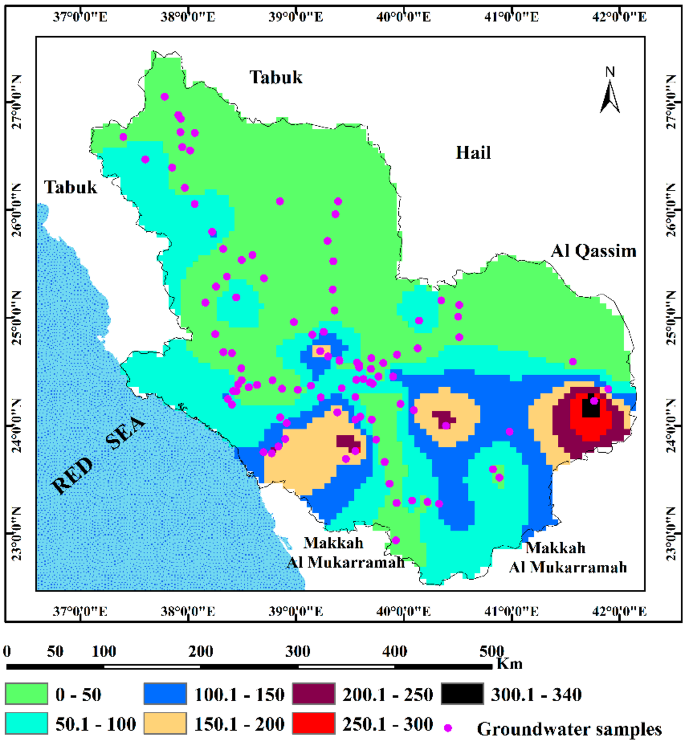

Figure 9. Distribution map of nitrate concentration (mg/L) in Al-Madinah Al-Munawarah Province.

4.2.3. Hydrogeochemical Features and Regulating Mechanism

The research goal is to identify the chemical assembly of groundwater in the aquifer system and to provide a theoretical framework for understanding the source and distribution of different types of groundwater uses. The current hydrogeochemical facies (HF) employed Modified Piper (after Chadha) [24], total ionic salinity (TIS), Gibbs [25], and US Salinity Laboratory Staff [26] diagrams. Figures 10a–c and 11 display the outcomes of the HF of groundwater quality in the region. The displayed Chadha diagram (Figure 10a) identifies the main cations and anions as well as in the groundwater types in the region. Two primary hydrochemical features were distinguished with the prevalence grading of combined NaCl (Field 3) and Ca-Mg-SO_4/Cl (Field 2) water classifications. These occurrences show that alkali metals exceeded alkaline earth metals and strong acidic anions exceeded weak acidic anions. The primary causes of the various types of water are the reverse ion-exchange developments and the disillusion of rock-forming minerals of the aquifer system.

To determine the changes in salt content in groundwater in the specific province, a TIS diagram was utilized. This diagram involved plotting Cl^- concentrations against the combined concentrations of HCO_3^- and SO_4^{2-} (in meg/L) as shown in Figure 10b. For groundwater samples, the majority (approximately 53% of samples) present a TIS between 0 and 40 meq/L line. In total, 26% of the groundwater samples exhibit relatively high levels of TIS between 40 and 80 meq/L. Furthermore, 21% of the samples on the plot are higher than the threshold of 80 meq/L for TIS, showing high salinity levels and low groundwater quality.

The Gibbs evaluation advised that the region could be notably encouraged via means of different factors together with geological formations, rainfall, evaporation, and anthropogenic activities [49]. The results of the Gibbs evaluation revealed that evaporation and rock–water interaction are the primary natural processes governing the groundwater chemistry in the study area. The increased presence of Na^+ and Cl^- ions in the region, resulting from excessive fertilizer use in agriculture, is also believed to be contributing to the leaching of secondary salts and the higher TDS levels observed.

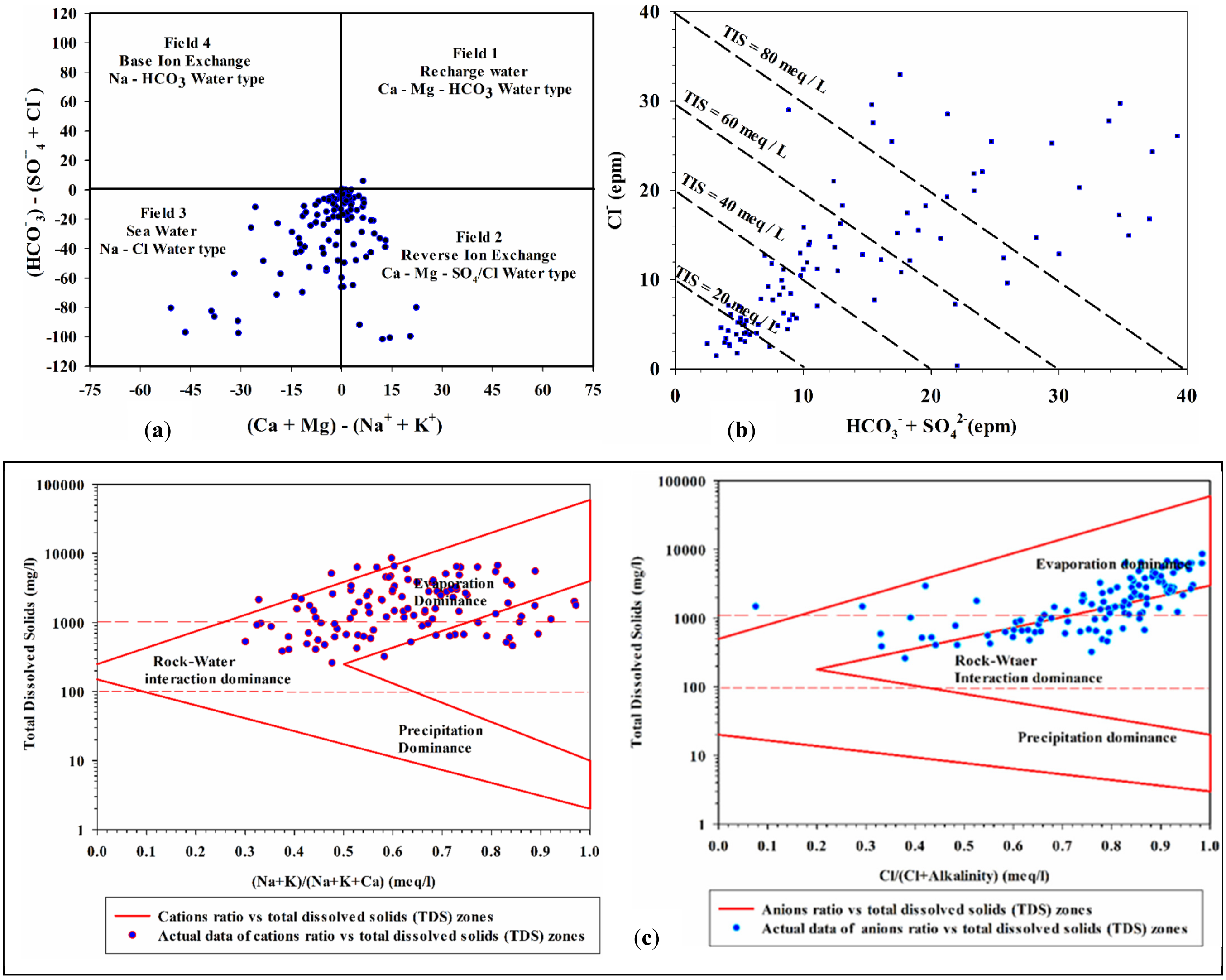

Figure 10. Modified Piper after Chadha (**a**), total ionic salinity, TIS (**b**), and Gibbs (**c**) diagrams for groundwater features and regulating mechanisms in Al-Madinah Al-Munawarah Province.

In addition, groundwater samples were analyzed using the US salinity diagram from 1954 to determine their suitability for irrigation based on SAR and EC values (Figure 11). As shown in Figure 10, about 43.0% was under the (C2-C3) S1 category which shows a low sodium hazard and a medium to high salinity threat. This groundwater can be used to irrigate clay soil, and crops that can withstand salt should be selected. At the same time, half of the groundwater samples fell within C4 (S1-S2-S3-S4) with levels of sodium ranging from low to very high, along with very high salinity risks. Only crops that are tolerant to salt should be watered with groundwater in these fields, especially in the water samples from the C4-S3 and C4-S4 fields. The remaining 7.0% of the total samples were under the C3-S2 category stating a combined high salinity to medium sodium hazard (Figure 11). The high to very high hazard was dominated especially in the southeast of Al-Madinah Al-Munawarah Province.

The research results suggest that alongside overseeing groundwater levels, aquifer productivity, and groundwater quality, it is important for local authorities to control proposed well drilling in the province by setting limits on daily pumping rates and distances between wells to ensure effective groundwater management within the region. This involves restricting the amount of water withdrawn daily from the production wells to ensure an optimum safe yield.

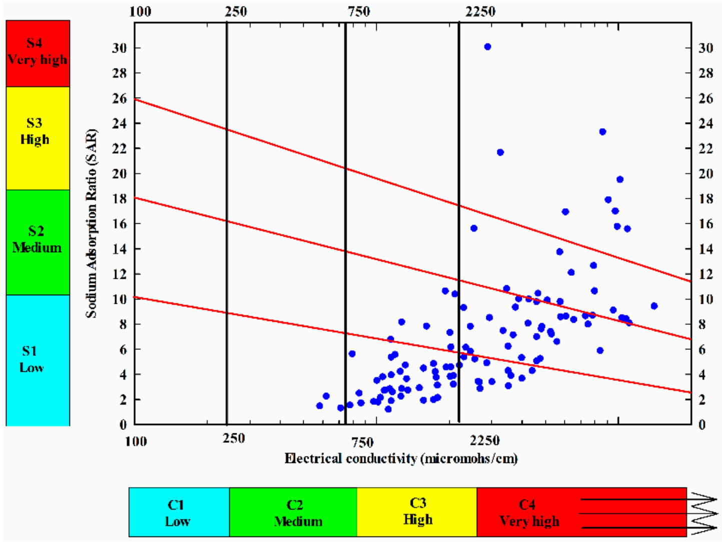

Figure 11. US salinity graph for groundwater hazard in Al-Madinah Al-Munawarah Province.

5. Conclusions

Monitoring groundwater levels, water quality, and conducting pumping tests (of both short and long duration) is an essential method for evaluating the productivity of the aquifer system in Al-Madinah Al-Munawarah Province, KSA. The thickness of the aquifer system is estimated to range from 57 to 327 m, the depth to water level varies from 10.57 to 177 m, and the groundwater head indicates northwesterly flows in the year 2017 and southwesterly flows in the year 2022. As a result, declines of up to 2 m in the groundwater level were observed in the southern portion of the region over a period of about 5 years. The results obtained from analyzing step-pumping tests demonstrated that the measured well loss (CQ2) and formation loss (BQ) were located in the range of 0.01–23.53 and 0.0001–12.31, respectively. Otherwise, the average well efficiency (γ) and specific capacity (Sc) ranged widely from 27.6%–78.86% and from 2.63 to 59.33 m^2/h, respectively. The relatively poor to medium production wells' performance in the region could be attributed to the partially blocked gravel spaces surrounding the well-screen, with the accumulation of fine material during the initial phases of well construction. Alternatively, the outcomes of constant pumping tests revealed significant variation in the transmissivity (T) and hydraulic conductivity (K) of the groundwater aquifer, with values ranging from 0.0198 to 33696.00 m^2/day and 0.042 to 302.4 m/day, respectively. The anticipated drawdown due to pumping was observed to be to be from 0.7 to 69.90 m. Four distinct portions can be identified for aquifer potentiality in the region, with the northern and eastern parts being favorable for groundwater productivity because of good aquifer materials.

Assessing groundwater quality and its appropriateness for various purposes is another key aspect to consider when planning for groundwater productivity in the region. In brief, the mean EC and TDS measurements were 3631 µS/cm and 2236 mg/L, respectively. The examined groundwater was classified as fresh to slightly salty water with a mixture of NaCl and Ca-Mg-SO_4/Cl as the dominant categories. Evaporation and the interaction of rocks with groundwater are the main natural processes that govern the groundwater chemistry in the studied province. The southeast of Al-Madinah Al-Munawarah Province experienced predominantly high to very high water quality hazards. Hence, it is significant to regularly assess the water quality in the area to ascertain its suitability for various purposes, particularly due to excessive use.

Author Contributions: M.E.O., M.M., N.A.-A., A.A., B.N. and M.R. proposed the concept of the research; B.N., M.M. and M.E.O. supported the resources and fieldwork; M.M., M.E.O., N.A.-A., A.A., B.N. and M.R. supported the software, methodology, and writing—original preparation and review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: No human or animal study was conducted during the present research.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are provided as tables and figures.

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

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