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Assessing Groundwater Quality and Diagnosing Nitrate Pollution in the Sidi Allal Region: A GIS-Based Approach Utilizing the Groundwater Pollution Index

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Abstract: Groundwater is a critical resource for various human activities, yet it faces contamination risks from agricultural, industrial, and domestic sources. This study aimed to evaluate groundwater in Morocco's Sidi Allal region using the groundwater pollution index (GPI) and diagnose nitrate pollution. The study included 45 groundwater wells from the study area, and physicochemical parameters such as pH, electrical conductivity, cations, and anions were examined in the laboratory. The geographic information system (GIS) was used to determine the spatial distribution of groundwater quality parameters. The groundwater pollution index and nitrate pollution index (NPI) were determined. The inverse distance weighting method (IDW) was used to create a spatial distribution map. The results indicated that the calculated GPI values ranged from 0.856 to 7.416, with an average of 2.06. About 40% of groundwater samples were highly polluted and unsuitable for drinking. The NPI values ranged between −0.74 and 10.5, with an average of 5.1. About 64% of the total groundwater samples were considered highly polluted according to the NPI classification, suggesting that the groundwater was unsuitable for drinking purposes. The spatial distribution map revealed the availability of appropriate groundwater in the central area of the study area and inappropriate groundwater near the Esbou River and Nassour Canal. The findings of this study revealed high concentrations of nitrates in groundwater samples in the central part of the study area, indicating that this increase in nitrates may be due to intensive use of nitrogen fertilizers in agricultural activities and sewage waste.

Keywords: groundwater pollution index; groundwater; inverse distance weighting (IDW); nitrate pollution index

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1. Introduction

As of 2019, the World Health Organization (WHO) reported that around 2.2 billion people globally primarily rely on groundwater as their main source of drinking water. This represents about 31.5% of the global water supply for domestic, agricultural, and industrial uses [1,2]. In certain regions, particularly arid and semi-arid areas, the sole source of freshwater is groundwater. Groundwater serves various essential purposes but is significantly overused for irrigation, which can potentially result in contamination. Responsible management is crucial to ensure the long-term availability of these resources and prevent pollution [3–5].

As populations expand and industrial and agricultural activities grow, the need for water resources intensifies. This heightened demand often results in the overextraction of groundwater, meaning that more groundwater is being pumped out than can be naturally replenished. This overextraction occurs when the rate at which water is withdrawn from underground aquifers exceeds the rate at which these aquifers can be refilled by natural processes like rainfall and percolation. Overextraction can cause water tables to drop, which may lead to land subsidence, reduced well yields, and increased energy costs for pumping, all of which can jeopardize the sustainability of groundwater as a reliable water source. Sustainable water management practices are crucial to address this challenge [6]. Overpumping can cause the water table to drop, and in extreme cases, can result in the depletion of groundwater resources. Moreover, human activities such as improper disposal of industrial waste, agricultural runoff, and use of fertilizers and pesticides can contaminate groundwater, making it unsafe for human consumption. This can also lead to ecological problems, such as the destruction of aquatic habitats and biodiversity loss [7].

Water pollution can have serious adverse effects on human and animal health. Polluted water can contain harmful chemicals, pathogens, and other contaminants that can cause a range of health problems, from mild illnesses to life-threatening diseases, with symptoms such as diarrhea, vomiting, and stomach cramps. It can also cause skin rashes, respiratory problems, and neurological effects. Long-term exposure to certain contaminants in water, such as lead or arsenic, can lead to chronic health problems, including cancer and developmental disabilities [6,8,9]. Groundwater resources in Morocco are facing increasing threats from anthropogenic activities, particularly those related to agriculture. The intensive use of fertilizers and pesticides in agriculture can lead to the contamination of groundwater, which can have serious consequences for human health and the environment [10].

In recent years, calculating the groundwater pollution index (GPI) has become increasingly popular as a tool to evaluate and classify water quality from various sources, including agriculture and industry. The GPI is a numerical value that provides a comprehensive overview of the overall quality of water resources based on multiple water quality parameters [11,12]. The groundwater pollution index provides a comprehensive overview of the quality of water resources with many mathematical models used to calculate the GPI. It is used to determine the suitability of water for drinking purposes in many countries in which one of the main challenges is to adapt cost-effective pollution control strategies for groundwater [13,14].

The main objective of this study was to evaluate groundwater in the Sidi Allal Tazi region using the groundwater pollution index (GPI), nitrogen pollution index (NPI), and geographic information system (GIS) to classify and identify contaminated wells. In addition, the purpose of this study was to identify wells that have suitable water quality for drinking and irrigation drinking purposes, with the aim of promoting effective management of groundwater resources in the Sidi Allal Tazi region in Morocco.

2. Materials and Methods

2.1. Location of Study Area

The study area, Sidi Allal Tazi, is a Moroccan city in the Rabat-Sala-Kenitra region, situated between the Ben Mansour coastal region and Sebou River in northwestern Morocco. It is located between latitude 34.51 degrees north and longitude −6.32 degrees west (Figure 1). Its climate is characterized by warm summers and relatively mild conditions, with an average annual temperature of 20 °C. The region receives an average annual rainfall of 520 mm, with July being the driest month (0 mm) and December being the wettest (114 mm). The coldest month is January, with an average temperature of 12.4 °C [15,16]. The hydrogeological structure of the aquifer system in the coastal zone of the Moroccan Al-Rabat-Sale-Kenitra region can be described as consisting of two distinct layers:

- The upper layer is a sandy-grassy surface layer with a thickness ranging from 5 to 10 m in the inner dunes and 20 to 30 m in the dune cordon. Within this layer, the water table is relatively shallow in the interior dunes, ranging from 2 to 10 m in depth, and deeper in the littoral cord, reaching depths of 10 to 40 m.
- The second layer, situated at greater depths (>50 m), is significantly thicker compared to the first layer and mainly comprises clays. Hydraulic communication between these

two layers occurs through a red clay-sandy screen, with a thickness that varies from 10 to 20 m.

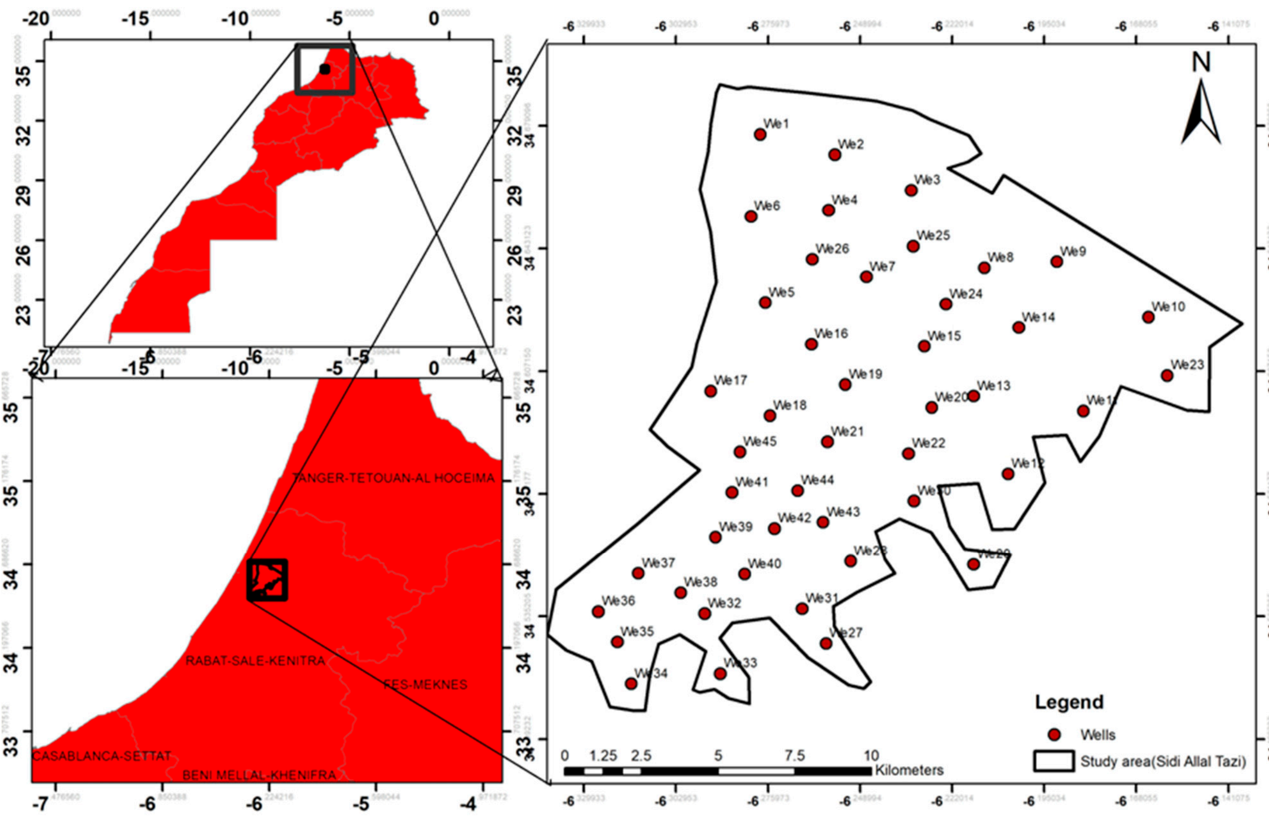

Figure 1. Location of study area.

2.2. Well Samples

Well samples were obtained from 45 wells in the region of Sidi Allal Tazi in Morocco; the wells in the study area exhibit depths ranging from 6 to 20 m. This region, situated between the Sebou River and Nador Canal in the Sidi Allal area, is in close proximity to agricultural lands. Water samples were collected from wells from different locations in the study area in June 2020. Afterward, the samples were transported to the laboratory in a 4 °C cooler for analysis. All samples underwent analysis for twelve physicochemical parameters, including electrical conductivity (EC), temperature, pH, and chemical parameters like cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-). These parameters were analyzed using standard procedures, as recommended by APH [17]. Table 1 summarizes the methods for measuring all variables.

Table 1. Methodologies used to determine the physicochemical parameters.

Parameter	Unit	Method Used
Electrical Conductivity EC	(µs/cm)	Conductivity meter (INOLAB cond720)
pH	_	pH meter (INOLAB pH7110)
Calcium	(meq/L)	Photometry a flame
Sodium	(meq/L)	Volumetric dosage
Potassium	(meq/L)	Volumetric dosage
Magnesium	(meq/L)	Photometry aflame
Chloride	(meq/L)	Nephelometric method
Bicarbonate	(meq/L)	Conductivity meter (INOLAB cond720)
Sulfate	(meq/L)	pH meter (INOLAB pH7110)
Nitrate	(meq/L)	Sulphanilamide method

2.3. Determination of Groundwater Pollution Index

Subba Rao developed the groundwater pollution index (GPI), an indicator that uses several chemical and physical factors to evaluate the quality of drinking groundwater [18]. The process of assessing drinking water quality using the GPI involves several steps. In the initial step, the relative weight (RW) of the parameter analyzed, ranging from 1 to 5, was determined. This determination was based on the parameter's importance in assessing water quality and its impact on human health, as indicated in Table 1. The next step involved evaluating the weight parameter (Wi) for each water quality variable to assess its relative contribution to the overall quality of groundwater samples. This evaluation was performed using Equation (1). The third step included calculating the parameter concentration (Sp) for each analyzed water quality variable. This calculation involved dividing the content (C) of each variable in each water sample by the permissible limit set for that variable. In this study, the permissible limits provided by the World Health Organization (WHO, 2011), referred to as Si in Equation (2), were used [19]. The fourth step in the GPI method was to compute the quality of groundwater (Qw) by multiplying the weight parameter (Wi) with the parameter concentration (Sp) for each analyzed water quality variable (Table 2) [20–22]. This calculation was performed using Equation (3). The final step in the PGI assessment involved summing all the overall quality (Ow) values per sample. This summation was accomplished using Equation (4).

$$\mathrm{Wi} = \mathrm{RW}/\sum \mathrm{RW} \tag{1}$$

$$\mathrm{Sp} = (\mathrm{C}/\mathrm{Si}) \tag{2}$$

$$\mathrm{QW} = \mathrm{Wi} \times \mathrm{Sp} \tag{3}$$

$$\mathrm{GPI} = \Sigma \mathrm{QW} \tag{4}$$

Table 2. The sum of relative weights and World Health Organization (WHO) standards.

Chemical Parameter	Unit	WHO Standard (2011)	Relative Weight	Weight Parameter
				WI = ∑ni = 1 wi
pH		7	3	0.10
Ca^{2+}	mg/L	75	2	0.07
Mg^{2+}	mg/L	50	2	0.07
Na^{+}	mg/L	200	4	0.14
K^{+}	mg/L	12	1	0.03
HCO_3^{-}	mg/L	120	3	0.10
Cl^{-}	mg/L	250	4	0.14
SO_4^{2-}	mg/L	250	5	0.17
NO_3^{-}	mg/L	50	5	0.17
			∑wi = 29	∑wi = 1.00

2.4. Determination of Nitrate Pollution Index (NPI)

The nitrate pollution index (NPI) is a measure of potential nitrate pollution of groundwater. It is a numerical index that is used to assess the risk of nitrate pollution in a given area based on factors such as soil type, climate, land use, and agricultural practices [23]. Water pollution with nitrates has become a serious problem in the world due to the deterioration of groundwater quality. The NPI was calculated using Equation (5).

The NPI can be calculated using Equation (5):

$$\mathrm{NPI} = (\mathrm{Cs} - \mathrm{HAF})/\mathrm{HAF} \tag{5}$$

where Cs is the concentration of nitrate in groundwater, and HAF is the background nitrate concentration in groundwater that is considered to be the human-acceptable value (20 mg/L).

NPI is utilized in assessments of groundwater quality. The value is an important reference in evaluating groundwater quality. Generally, higher NPI values indicate more significant nitrate pollution and higher health risks [24]. The classification of groundwater according to the NPI is shown in Table 3.

Table 3. Classification of nitrate pollution index (NPI).

Values of NPI	Type of Pollution
<0	Clean
0–1	Light
1–2	Moderate
2–3	Significant
>3	Very significant

2.5. Gibbs Diagram

The Gibbs diagram, as proposed by Gibbs in 1970 (Equations (6) and (7)), was utilized to evaluate various aspects of groundwater chemistry, specifically examining (a) the prevalence of evaporation-driven processes, (b) the dominance of precipitation-related influences, and (c) the impact of rock–water interactions [25]. This assessment was conducted separately for cations and anions, with concentrations represented in milliequivalents per liter.

For cations, the Gibbs calculation was performed as follows:

$$\text{Gibbs I} = Na^{+} + K^{+}/(Na^{+} + K^{+} + Ca^{2+}) \quad (6)$$

For anions, the Gibbs calculation was conducted as follows:

$$\text{Gibbs II} = Cl^{-}/(Cl^{-} + HCO_3^{-}) \quad (7)$$

3. Results and Discussion

Table 4 provides a statistical summary of the values obtained from the 45 wells, which were then compared with the standards set by the World Health Organization [19].

Table 4. Analytical results of groundwater quality parameters.

Variable	Minimum	Maximum	Mean	Standard Deviation	Variation Coefficient	Skewness	Kurtosis
EC [µS/cm]	874	7640	2582	1704	67.95	1.5	1.51
pH	6.6600	8.0000	7.2413	0.2517	3.48	0.09	1.22
Ca^{2+} [mg/L]	89.20	300.80	171.86	50.9	29.62	0.4	−0.32
Mg^{2+} [mg/L]	10.69	293.30	41.07	42.37	103.16	5.03	29.6
Na^{+} [mg/L]	63.7	1274.8	306.2	325.2	106.23	1.66	2.04
K^{+} [mg/L]	3.590	13.050	8.138	2.646	32.51	−0.12	−1.19
HCO_3^{-} [mg/L]	200.0	848.5	403.7	138	34.18	1.57	3.05
Cl^{-} [mg/L]	98.0	1900.1	524.8	540	102.91	1.42	0.82
SO_4^{2-} [mg/L]	47.9	661.2	128.9	101.8	78.99	3.84	17.58
NO_3^{-} [mg/L]	5.3	229.5	114.6	71.9	62.75	0.07	−1.18
PIG	0.731	7.063	1.883	1.137	55.25	2.64	10.37
PNI	−0.738	10.476	4.729	3.555	75.17	0.07	−1.13

3.1. Hydrochemistry

The pH levels ranged between 6.66 and 8, with an average of 7.21. As observed in Figure 2, the spatial distribution of hydrogen ions in the study area fell within acceptable limits. The parameters analyzed included electrical conductivity, which refers to the water's ability to conduct an electric current. The electrical conductivity values of the groundwater samples varied, ranging from 874 to 7640. The average value across all samples was found to be 2582. As per Moroccan standards, 29 samples from wells were permissible and 16 samples from wells were not permissible for domestic use (Figure 3). Additionally, Table 5 displays the classification according to Handa (1969), revealing that 16% of the sampled locations were in a questionable state, posing concerns for both drinking and irrigation purposes [26].

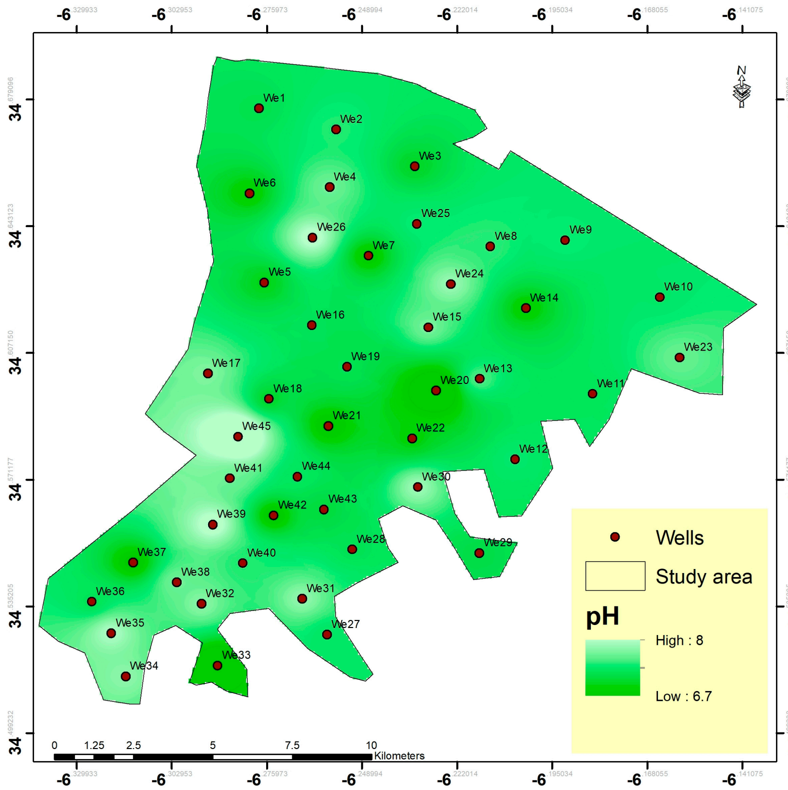

Figure 2. Spatial distribution map of pH.

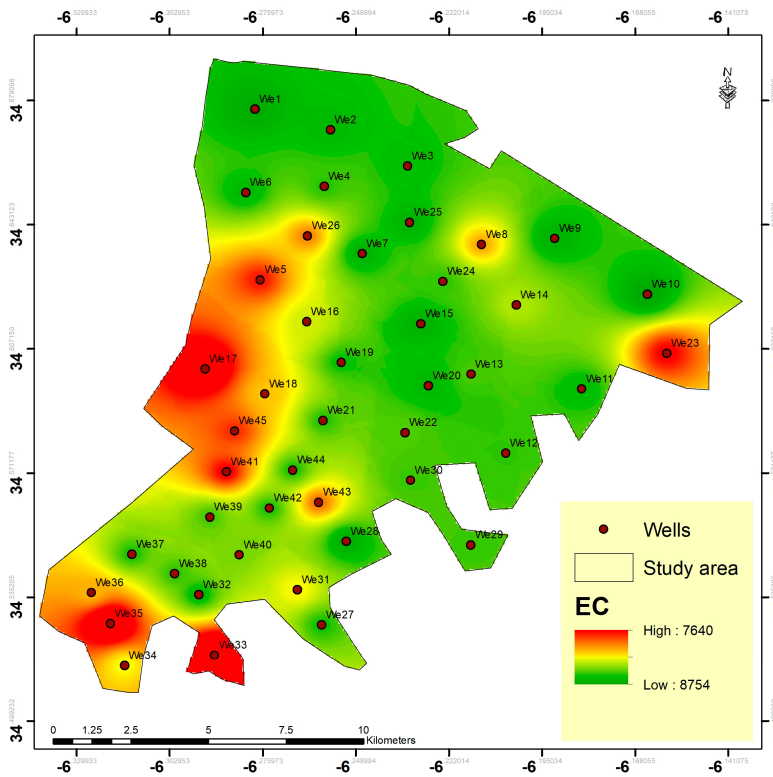

Figure 3. Spatial distribution map of electrical conductivity.

Table 5. Classification of groundwater based on electrical conductivity (EC).

EC (μS/cm) Range	Water Type	Classification	No. of Samples	% of Samples
0–250	Low	Excellent	0	0%
251–750	Medium	Good	0	0%
751–2250	High	Permissible	29	64.4%
2251–6000	Very high	Doubtful	13	28.9%
6001–10,000	Extensively high	Poor	3	6.7%

The distribution of major cations and anions is shown in Table 4. It was observed that the levels of most of the wells were slightly above the maximum limit allowed by the World Health Organization (WHO, 2011). Based on the results presented in Figures 4 and 5, the predominant ions in the study samples were Na^+, Cl^-, and HCO_3^-. The orders of dominance of the cations and anions were $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ > and $Cl^- > HCO_3^- > NO_3^- > SO_4^{2-}$, respectively. Calcium is a vital ion in drinking water, essential for the formation and upkeep of healthy bones and teeth [27]. In the present investigation, the concentrations of calcium varied from 89.20 to 300.80 mg/L, with an average value of 171.86 mg/L. Approximately 75.5% of the sites sampled were within the allowable limits of the samples, while 24.5% were within permissible limits as per the WHO guidelines (Figure 4). Magnesium is another essential element for maintaining a healthy immune system, strong bones, and blood glucose levels [28]. In the study area, the concentrations of magnesium ranged from 10.69 to 293.30 mg/L, with an average concentration of 41.07 mg/L. According to WHO standards, 98% of the sampled locations were deemed suitable and 2% were found to be unsuitable for drinking purposes (Figure 4). Increased concentrations of magnesium in groundwater can be attributed predominantly to the existence of limestone and gypsum in geological formations [29]. The sodium concentrations in the study area displayed a range from 63.7 to 1274.8 mg/L, with an average concentration of 306.2 mg/L. Approximately 65% of the sample locations exceeded the permissible sodium levels in groundwater (Figure 4). Consistent consumption of groundwater with elevated sodium levels can lead to health issues, including hypertension, heart disease, and the formation of kidney stones [30]. The sources contributing to the increased sodium concentrations in the study area may include irrigation and leaching from rainfall, intrusion of sewage effluent, and the presence of brackish water in aquifers [31]. In the study area, the concentrations of potassium ranged from 3.590 to 13.050 mg/L, with an average of 8.138 mg/L. Only two well samples were found to be contaminated, exceeding the recommended standard limit for drinking purposes as per WHO guidelines. The nitrate concentrations in the study area exhibited a range between 5.3 and 229.5 mg/L, with an average of 114.6 mg/L. A total of 29 sample locations were identified as highly contaminated zones within the study area, according to WHO standards, and about 64.4% of the samples fell within permitted limits for drinking purposes (Figure 5). Elevated nitrate levels in the study region were attributed to various anthropogenic activities, including modern agricultural practices, uncovered septic tanks, open landfills, and waste disposal from residents. The primary sources of bicarbonate in groundwater are the presence of alkaline earth metals and the dissolution of minerals [32]. In the study area, bicarbonate levels ranged from 200.0 to 848.5 mg/L, with an average of 403.7 mg/L. According to WHO standards, about 82% of the collected samples fell within permissible limits, and 17% of samples fell within permissible limits for drinking purposes (Figure 5). The chloride concentrations in the study area had a range of 98.0 to 1900.1 mg/L, with an average of 524.8 mg/L (Figure 5). Approximately 29% of the sampled locations met the acceptable limits, while the other 71% were within the permissible range recommended by WHO standards. Regarding sulfate concentrations, they varied from 47.9 to 661.2 mg/L, with an average of 128.9 mg/L. Among the samples, 44 well locations were considered acceptable, and 1 well fell within the permissible sulfate concentration limits for drinking purposes (Figure 5). All sampled locations complied with WHO standards for sulfate concentration, except for one location.

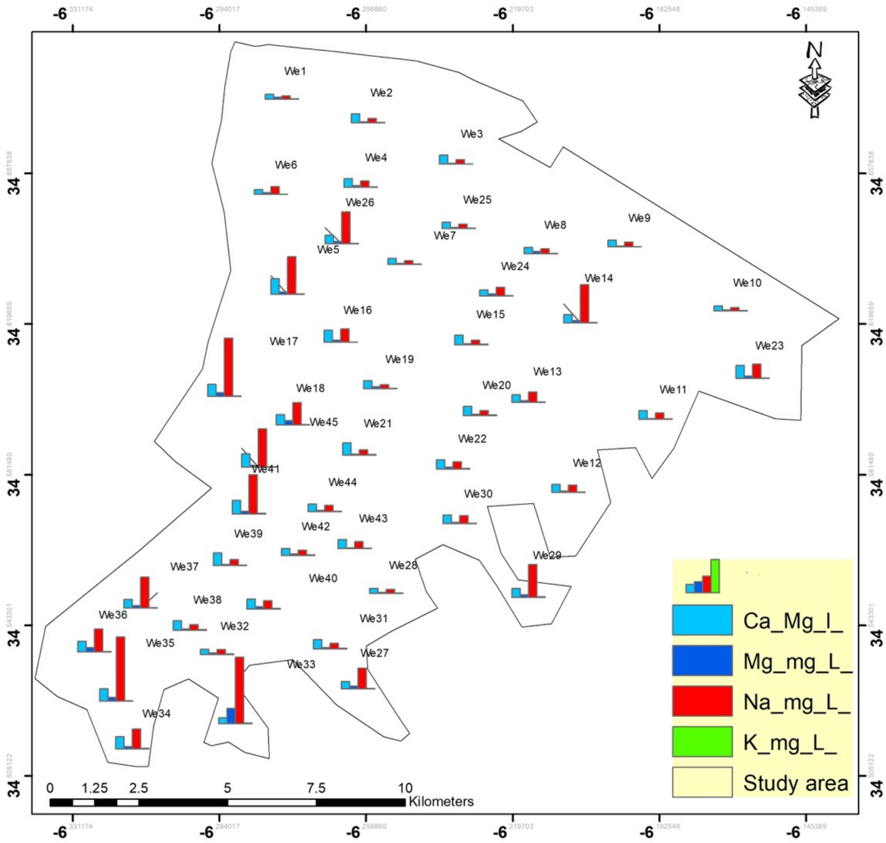

Figure 4. Spatial distribution map of cations.

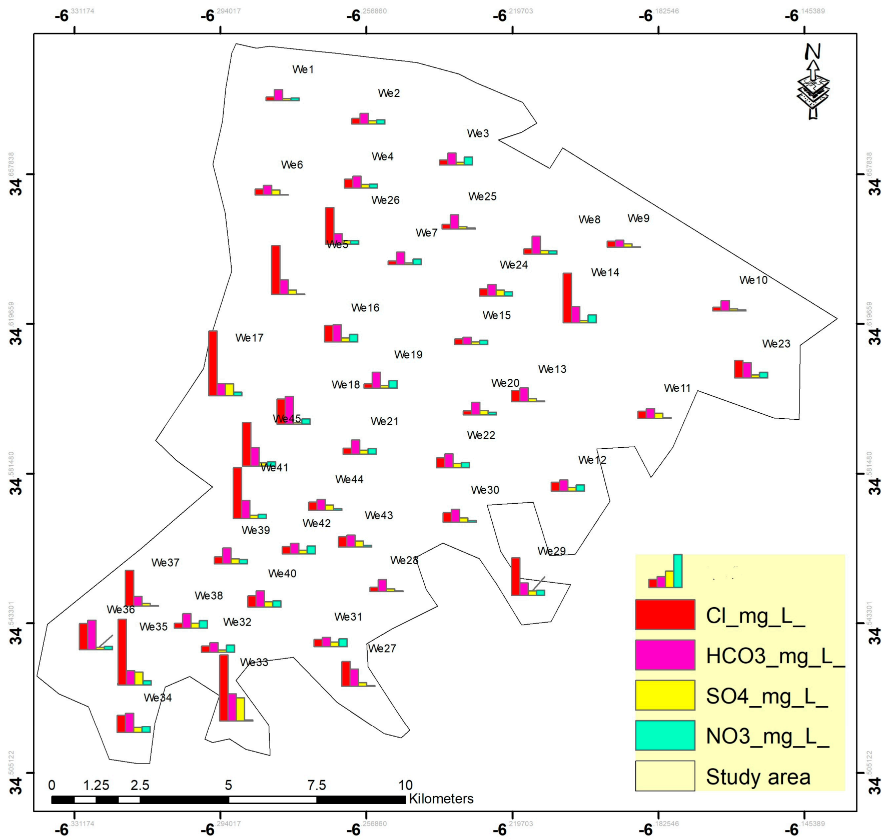

Figure 5. Spatial distribution map of anions.

3.2. Piper Plot

The composition of groundwater can be subject to various influences, such as the extent of rock-mineral weathering, prevailing climatic conditions, redox reactions, geological and hydrogeological configurations, as well as human activities [33]. In the study area, piper plot analysis revealed that the combination of Na^+ and Ca^{2+} cations was greater than the presence of Mg^{2+} cations, and in terms of anions, Cl^-, HCO_3^-, NO_3^-, and SO_4^{2-} exceeded the levels. Figure 6 illustrates that approximately 55.6% of the samples fell into the mixed Ca^{2+}–Mg^{2+}–Cl^- category, 40% belonged to the Na^+–Cl^- category, and 4.4% of the sample locations represented the Ca^{2+}–HCO_3^- water type. Figure 6 indicates that the Ca^{2+}–Mg^{2+}–Cl^- category was more prevalent than the Na^+–Cl^- category, and it surpassed the Ca^{2+}–Mg^{2+}–HCO_3^- category. The diagram suggested that rock–water interactions, base ion exchange processes, and the nature of the aquifer play significant roles in shaping the characteristics of groundwater in the study area.

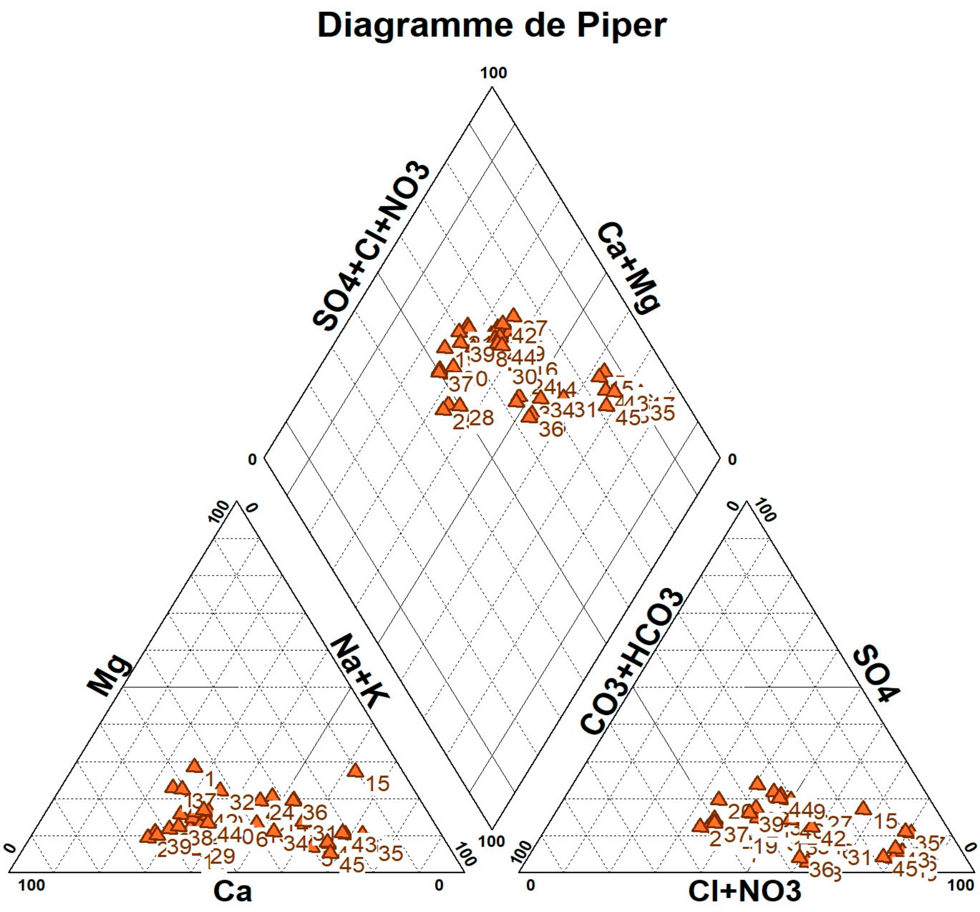

Figure 6. Piper plot of sampling wells.

3.3. Gibbs Plot

The Gibbs diagram, originally developed by Gibbs in 1970, employs two ratios to analyze groundwater chemistry. The first ratio $[(Na^+/(Na^+ + K^+ + Ca^{2+})]$ represents cations, while the second ratio $[Cl^-/(Cl^- + HCO_3^-)]$ represents anions [25]. These ratios are plotted against total dissolved solids (TDS) to assess groundwater chemistry. Figure 7 illustrates that a significant portion of the water samples fell within the evaporation-crystallization zone, resulting in increased salinity due to higher levels of Na^+ and Cl^- in comparison to the increase in TDS. However, a few samples demonstrated the influence of rock mineral dissolution on the chemical composition of groundwater.

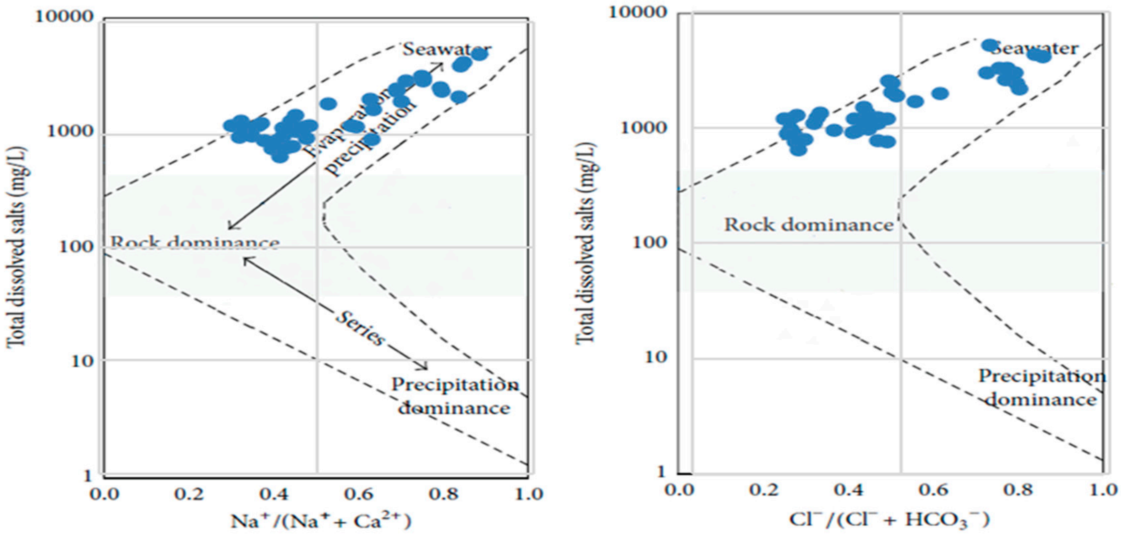

Figure 7. Gibbs diagram of groundwater.

3.4. Nitrate Pollution Index (NPI)

In the study area, the spatial distribution of the NPI values ranged between −0.74 and 10.5, with an average of 5.1 (Table 4). According to the NPI classification presented in Tables 4 and 6, about 8% of the study samples were good "clean" groundwater (NPI < 0) and 16% of wells had light pollution ($0 \leq$ NPI < 1), indicating a low level of contamination, 6% of wells had moderate pollution ($1 \leq$ NPI < 2), indicating a moderate level of contamination, 4% of wells had significant pollution ($2 \leq$ NPI < 3), indicating a high level of contamination, and 64% of wells had very significant pollution (NPI ≥ 3), indicating a very high level of contamination, as shown in Table 6 and Figure 8. It can be inferred that the excessive nitrate content of the water in the study area is mainly because it is an agricultural area where farmers excessively use high-nitrogen fertilizers, in addition to pollution of the surface water surrounding the study area, such as the Sebou River and Nador canal that feed these wells. Figure 8 shows the distribution of NPI values in the study area. The wells close to the Sebou River and Nador Canal were the most polluted by nitrates from the study area. The findings from a study carried out in the Sidi Slimane region, Morocco [34], indicated that the pollution of water extracted from wells surpassed both Moroccan and global standards to a significant extent.

Table 6. Classification of nitrate pollution index (NPI).

Classification of NPI	Type of Pollution	Number of Wells	%
<0	Clean	4	8
0–1	Light	7	16
1–2	Moderate	3	6
2–3	Significant	2	4
>3	Very significant	29	64

Sources of Nitrate

Nitrate contamination in any region is likely to spread due to several sources, such as using organic nitrogen fertilizer, intensive use of synthetic fertilizer, overuse of pesticides, extended leaks in wastewater infrastructure, etc. High nitrate concentrations in well water can have severe health effects, particularly on infants and children, who are more susceptible to methemoglobinemia. Additionally, it can cause environmental impacts by promoting the growth of aquatic plants and algae, leading to eutrophication in lakes [35]. The nitrogen cycle represents a series of chemical reactions through which nitrogen is converted into various forms that can be used by plants and other organisms [36].

$CO(NH_2)^2$, also known as urea, is a nitrogen-containing compound that can be used as a fertilizer. When urea is applied to soil, it can be hydrolyzed by the enzyme urease to form ammonium (NH_4^+) and carbon dioxide (CO_2). The reaction is as follows [37]:

$$CO(NH_2)^2 + 2H_2O \rightarrow 2NH_4^+ + CO_3{}^{2-}$$

The ammonium ions can then be converted to other forms of nitrogen through a series of reactions. In the first step, ammonium reacts with water to form ammonium hydroxide (NH_4OH):

$$NH_4^+ + H_2O \rightarrow NH_4OH$$

Next, ammonium can be oxidized to nitrite (NO_2^-) by nitrifying bacteria in soil:

$$NH_4^+ + 2O_2 \rightarrow 2NO_2^- + 2H^+ + 2H_2O$$

Finally, nitrite can be further oxidized to nitrate (NO_3^-) by other nitrifying bacteria:

$$NO_2^- + O_2 \rightarrow NO_3^-$$

Nitrate is the form of nitrogen that is most commonly taken up by plants. Under aerobic conditions, nitrate can also be further transformed into nitrogen gas (N_2) by denitrifying bacteria:

$$2NO_3^- + 10H^+ \rightarrow N_2 + 5H_2O$$

Overall, the nitrogen cycle plays a crucial role in the cycling of nitrogen in the environment and is essential for plant growth and ecosystem functioning [38]. In the study area, the high concentration of nitrates in water samples showed that there is excessive use of fertilizers due to agricultural and human activities in this area, which has negative effects on water quality and health.

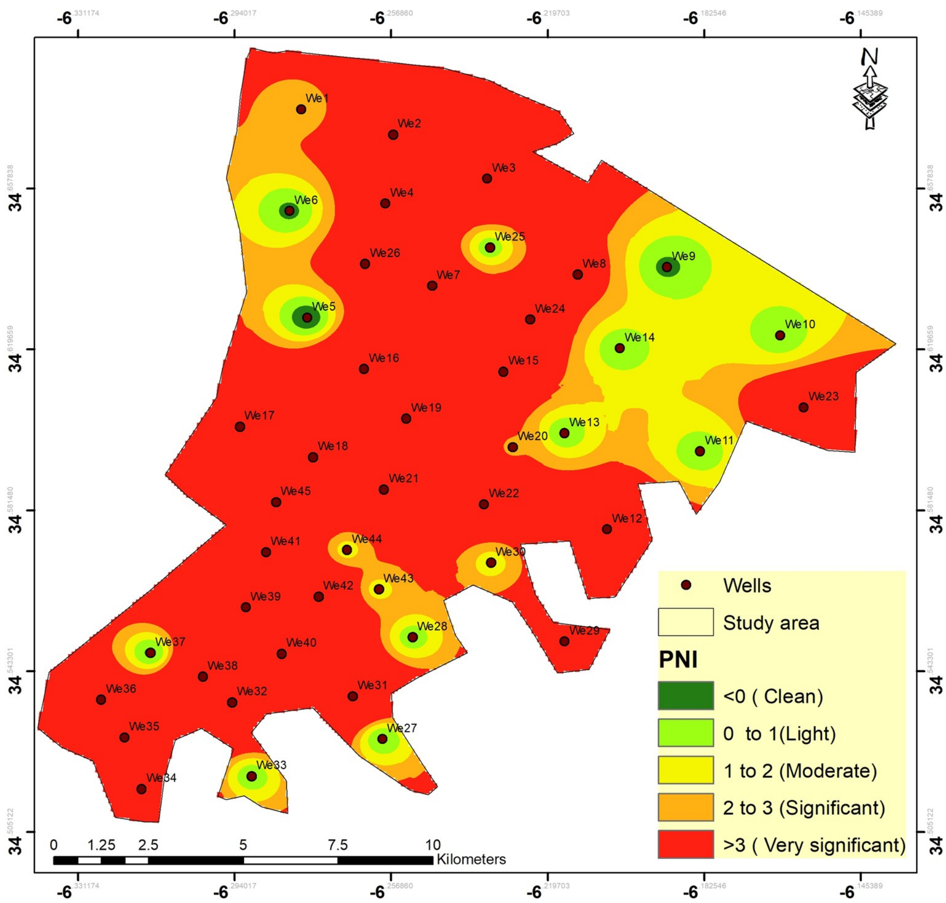

Figure 8. Spatial distribution of the nitrate pollution index (NPI).

3.5. Groundwater Pollution Index (GPI)

The GPI provides a consolidated measure representing the overall rate of groundwater pollution, considering the combined influence of various chemical factors on groundwater quality [30]. The GPI has been developed to condense extensive physicochemical data into a single value, offering valuable information about the overall groundwater quality. Furthermore, the application of the GPI aids in the evaluation of water chemistry to determine its fitness for consumption. The values of GPI ranged between 0.856 and 7.416, with an average score of 2.06 (Table 4). The GPI findings revealed that 7% of the groundwater samples belonged to the 'insignificant pollution' category, with only 2 groundwater samples considered highly suitable for drinking. Furthermore, 26% of the samples were classified as 'low pollution,' while another 26% fell under the 'moderate pollution' category for drinking purposes. In addition, 18% and 22% of the samples were designated as 'high pollution' and 'very high pollution,' respectively (Tables 7 and 8 and Figure 9). The GPI findings revealed that the vast majority of groundwater within the study area was not suitable for drinking. When considering the geographical distribution of the GPI, the map demonstrated that the southern and western regions of the study area exhibited elevated pollution levels, with many wells displaying high to very high pollution levels (Figure 9). Consequently, it is strongly advised to not directly consume water from this area for drinking purposes. The findings from studies carried out in the Sidi Slimane and Sidi Allal regions [16,34] indicated that the pollution of water extracted from wells surpassed both Moroccan groundwater standards to a significant extent.

Table 7. Classification of groundwater pollution index (GPI).

Range of GPI	Classification	N	%	Purpose
<1.0	Insignificant pollution	3	7	Drinking and irrigation
1.0–1.5	Low pollution	12	26.5	Drinking and irrigation
1.5–2.0	Moderate pollution	12	26.5	Irrigation
2.0–2.5	High pollution	8	18	Irrigation
>2.5	Very high pollution	10	22	Proper treatment is required for any kind of usage

Table 8. The results of NPI and GPI.

Name	NPI	GPI	Name	NPI	GPI
We1	2.60	1.34	We23	7.00	2.23
We2	5.00	1.28	We24	5.39	1.79
We3	10.48	1.64	We25	0.39	1.14
We4	4.76	1.58	We26	4.38	2.58
We5	−0.74	2.46	We27	0.09	2.12
We6	−0.24	1.25	We28	0.39	1.01
We7	7.00	1.43	We29	6.50	2.86
We8	4.00	1.80	We30	1.51	1.39
We9	−0.21	0.86	We31	10.06	1.70
We10	0.36	0.86	We32	9.01	1.73
We11	0.39	0.94	We33	0.26	7.42
We12	7.85	1.66	We34	7.61	2.45
We13	0.15	1.36	We35	5.15	4.10
We14	10.36	3.34	We36	4.03	3.22
We15	5.14	1.13	We37	−0.24	2.13
We16	10.28	2.40	We38	10.14	1.89
We17	4.11	3.80	We39	5.29	1.60
We18	6.63	3.24	We40	7.75	2.08
We19	10.04	2.05	We41	5.39	3.14
We20	2.86	1.23	We42	10.46	1.84
We21	6.78	1.54	We43	1.51	1.20
We22	6.61	1.85	We44	1.51	1.28
			We45	5.05	2.69

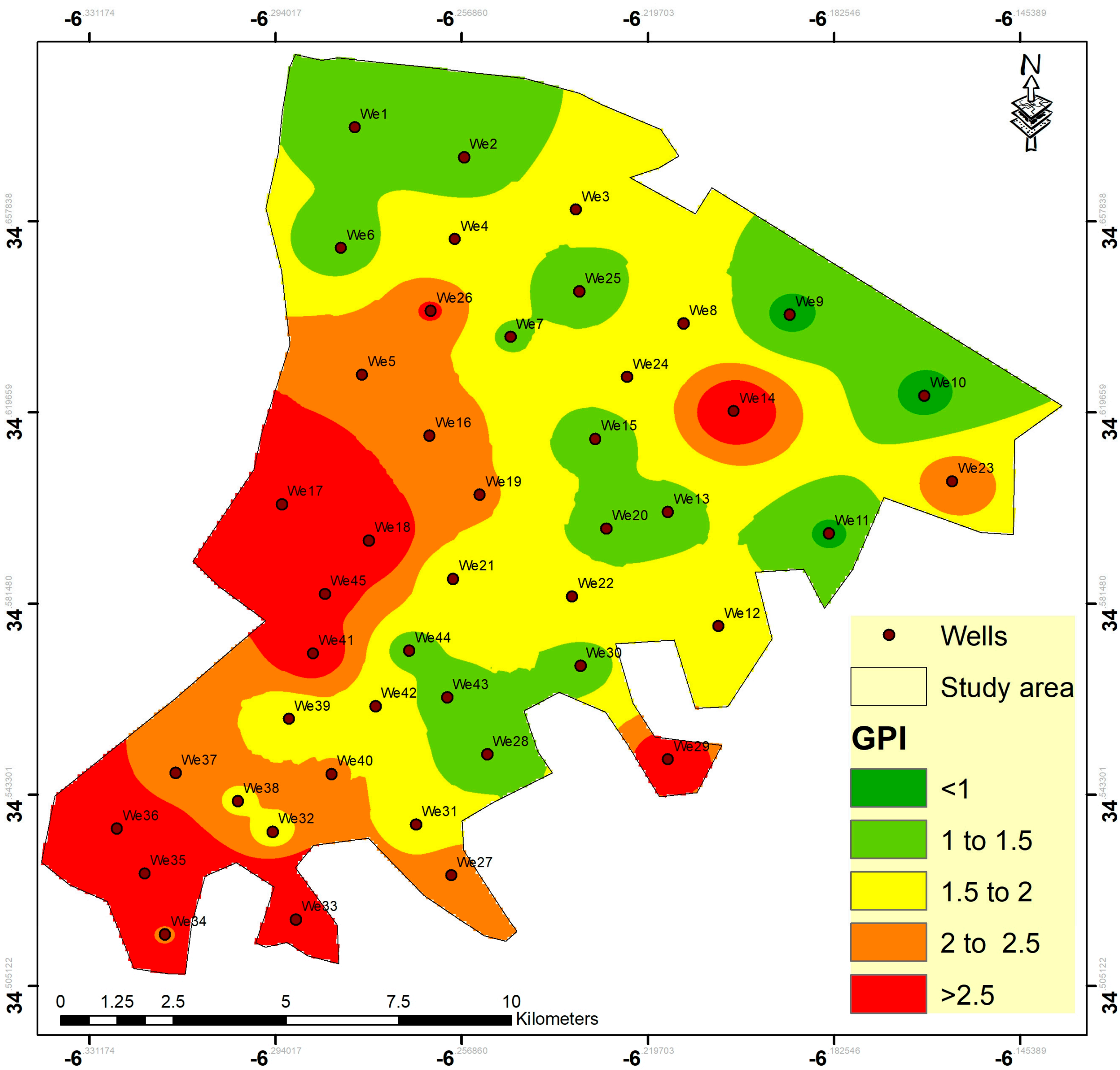

Figure 9. Spatial distribution of GPI.

4. Conclusions

Based on the physical and chemical attributes of the analyzed samples, the findings indicate notable distinctions in the primary ions and salinity of the groundwater samples collected in Sidi Allal Tazi, Morocco. The predominant orders of the cations and anions are as follows: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ for cations and $Cl^- > HCO_3^- > NO_3^- > SO_4^{2-}$ for anions. Based on the Gibbs diagram, a significant portion of the water samples fell within the evaporation-crystallization zone, resulting in increased salinity due to higher levels of Na^+ and Cl^-. However, a few samples demonstrated the influence of rock mineral dissolution on the chemical composition of groundwater. The GPI values varied between 0.856 and 7.416, with an average of 2.06. Approximately 7% of the groundwater samples were categorized as having 'insignificant pollution,' while only 2 groundwater samples met the criteria for being highly suitable for drinking. Additionally, 26% of the groundwater samples were classified as 'low pollution,' while 26% were categorized as 'moderate pollution' for drinking purposes. Moreover, 18% and 22% of the samples were identified as 'high pollution' and 'very high pollution,' respectively. Therefore, it is not recommended to consume water directly from this area. The nitrate pollution index values ranged between −0.74 and 10.5, with an average of 5.1. About 64% of wells had very significant pollution ($NPI \geq 3$). The findings indicate the presence of high concentrations of nitrates in the water samples collected, which indicates excessive use of fertilizers resulting from agricultural and human activities in this region. This activity seriously affects water quality.

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