

Article

Multi-Index Evaluation of Groundwater Suitability for Irrigation in an Arid and Semi-Arid Agricultural Area: Hydrochemical Indices, IWQI, and GIS Mapping in Armavir Region, Armenia

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Abstract

Groundwater is a principal irrigation water source worldwide; however, its quality is increasingly diminished by rapid urbanization, improper agricultural practices, and accelerating industrial activities. Groundwater management is especially important in areas where soil salinization and erosion are more probable, such as arid and semi-arid zones. In view of this, the Armavir region of the Republic of Armenia was selected as the study area, being an intensively cultivated agricultural zone. The objective of this study was to assess and map the quality of groundwater for irrigation using advanced methods, taking into account both climatic conditions and anthropogenic influences. A total of 72 groundwater samples were collected during the irrigation season from 41 unconfined and 31 confined aquifer wells. Key hydrochemical parameters (pH, EC, TDS, Cl^- , HCO_3^- , CO_3^{2-} , Na^+ , K^+ , Ca^{2+} and Mg^{2+}), irrigation indices (SAR, Na%, MH, RSC and PI), and graphical methods (Gibbs, USSS and Wilcox diagrams) were applied to assess groundwater quality. An integrated assessment was performed using the Irrigation Water Quality Index (IWQI), and spatial distribution was evaluated through geostatistical analysis and GIS mapping. Although certain individual hydrochemical parameters indicated limitations for irrigation in localized areas, particularly within the unconfined aquifer, the integrated IWQI assessment revealed that groundwater predominantly falls within the good to excellent categories across the study area, with more favorable conditions observed in the confined aquifer. These findings constitute an essential prerequisite for counteracting soil salinization and promoting sustainable agricultural development.

Keywords: groundwater; hydrochemical indices; irrigation water quality index (IWQI); GIS mapping; agricultural water management; sustainable agriculture; Armenia

Academic Editor: Kourosh Mohammadi

Received: 23 May 2026

Revised: 9 July 2026

Accepted: 17 July 2026

Published: 21 July 2026

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1. Introduction

Freshwater is a vital resource for all living organisms as it sustains ecosystem structure and functions, regulates biogeochemical cycles, and maintains environmental balance [1]. However, freshwater represents only 3% of global water resources, with the majority stored in glaciers and permanent snow and thus largely inaccessible. Groundwater accounts for approximately 30% of total freshwater resources and constitutes one of the most important water supply sources worldwide [2,3]. Although groundwater resources are crucial, they have undergone dramatic quantitative and qualitative changes globally over the last few decades due to population growth, agricultural expansion, industrial development, and climate change [4–6]. At present, more than 70% of global groundwater abstraction—and an even higher proportion in arid and semi-arid regions is used for agriculture, with almost 38% of irrigated lands relying on groundwater resources [2]. This scale of exploitation poses serious threats to food security, water supply sustainability, climate change resilience, and groundwater-dependent ecosystems. Due to the key role of groundwater in agricultural production, water supply, and functional ecosystems, the Armarir region of the Republic of Armenia was selected as the study area. As one of the most intensively cultivated agricultural regions in the country, this area is predominantly dependent on groundwater resources for irrigation. Natural conditions and climate variability also contribute to the high risk of soil salinization, given the region's hot and dry summers. Moreover, anthropogenic activities such as improper irrigation schemes considerably exacerbate salinization processes [4].

Groundwater quality monitoring is a significant tool for the sustainability of agricultural areas and provides essential data for water management [5–7]. Hydrochemical parameters and indices utilized frequently for assessing irrigation water quality in this context comprised Sodium adsorption ratio (SAR), Sodium percentage (Na%), Magnesium hazard (MH), Residual sodium carbonate (RSC), and Permeability index (PI); however, the availability of inhomogeneous or partial assessment indicators will not predict the quality of water accurately. Therefore, integrated approaches are required. These approaches include graphical techniques—such as Gibbs, USSS, and Wilcox diagrams—that allow for multi-parameter assessment of water quality. As a more comprehensive methodology, the Irrigation Water Quality Index (IWQI) has been proposed as an integrated assessment tool that objectively evaluates irrigation water quality, addressing important drawbacks of individually based hydrochemical indices. The IWQI is based on a methodological framework that includes the normalization of selected parameters, whereby these variables are normalized to a dimensionless scale to reflect their relative contribution to the composite index [8]. Weighting factors are then assigned based on the relative significance of each parameter, derived from either empirical or statistical methods. Multiple formulations of the IWQI have been proposed by different authors, based on the inclusion or exclusion of certain parameters guided by regional hydrochemical characteristics [9]. One of the main advantages of the IWQI over individual indices is its ability to classify water into distinct quality classes according to threshold values defined in relation to performance levels for various uses. In recent years, the application of IWQI has expanded considerably, extending from simple hydrochemical evaluation to its association with agricultural productivity, soil salinization characteristics, and ecosystem stress [10–12]. Spatial mapping is a primary step in groundwater quality evaluation, as it allows spatial generalization and systematic interpretation of point-based hydrochemical data [10]. The heterogeneity of water quality parameters is controlled by hydrogeological structure, aquifer lithology, groundwater flow patterns, and anthropogenic forcing such as irrigation, fertilization, and salinization processes [11]. Mapping this variability enables the identification of spatial patterns, the delineation of regions with elevated salinity or sodium hazard, and

the analysis of their spatial relationships. Such maps facilitate area classification based on irrigation suitability and enable temporal comparisons across seasons or years [13–16].

Groundwater quality monitoring is an integral component of sustainable management strategies, particularly in agricultural regions requiring reliable information on water use and soil salinization prevention [17]. Nevertheless, earlier contributions indicate that regulatory frameworks for groundwater protection tend to be deficient under conditions of unsustainable agricultural systems. The scientific significance of such studies is therefore considerable; equally important is their practical value, as groundwater quality assessment and spatial mapping support the identification of problem areas and provide evidence to inform decisions on agricultural land and water resource management at local scales in risk-prone regions. In such contexts, awareness and the systematic dissemination of information represent essential first steps toward rational water use and sustainable management practices, aimed at enhancing the long-term preservation of groundwater quality and reducing the risk of soil-water system degradation [15,18–20].

Groundwater quality assessment is therefore essential for ensuring the long-term sustainability of agricultural systems in water-scarce regions. Although numerous studies have assessed groundwater quality for irrigation using individual hydrochemical indices, water quality indices, or GIS technologies, such integrated assessments remain limited for high-risk regions in the Republic of Armenia. In this context, the scientific novelty of this study lies in a comprehensive approach to assessing groundwater suitability for irrigation. This approach enables the evaluation of groundwater quality by the Irrigation Water Quality Index (IWQI) which incorporates key hydrochemical parameters (EC, pH, Cl⁻) and indices (SAR, Na%, RSC, MH and PI), with GIS-based spatial analysis. Furthermore, this study provides the first comparative assessment of groundwater from confined and unconfined aquifers in the Armavir region regarding their irrigation suitability, enabling the identification of hydrochemical differences and spatial patterns between them. The obtained results not only contribute to the existing scientific data on groundwater in the region but also serve as a scientific basis for sustainable water resource management and efficient irrigation system planning under arid and semi-arid conditions.

2. Materials and Methods

2.1. Description of the Study Area

The Armavir region is located in the central part of the Ararat Plain in the southwestern part of the Republic of Armenia (Figure 1). It covers an area of 1242 km², representing approximately 4.17% of the country's total land area. The region lies at elevations ranging from approximately 800 to 900 m above sea level and receives no more than 300 mm of annual precipitation. The climate is dry continental, characterized by long hot summers lasting approximately 4–5 months, during which air temperatures frequently reach 40–42 °C [21–23]. In the Armavir region, agricultural land covers approximately 96,516.2 hectares, accounting for about 78.6% of the region's total area. The Armavir region exhibits the highest proportion of arable land and perennial plantations within its agricultural land-use structure compared to all other regions in the Republic of Armenia. Specifically, arable land accounts for approximately 38,236.5 hectares (31.1% of the region's total area), while perennial plantations cover 16,206.7 hectares (approximately 13.2%). The sustainable development of agriculture in the region is fundamentally dependent on the presence and efficient operation of artificial irrigation systems. Leading crop production sectors, including vegetable cultivation, fruit growing, and viticulture, rely on irrigation water supplied by main canals fed by the Hrazdan and Araks rivers, as well as numerous deep boreholes tapping into the Ararat Artesian Basin system. Collectively, these sources constitute the region's primary irrigation infrastructure [22,24].



Figure 1. Location of the study area showing the position of the Armavir region within the Republic of Armenia, the South Caucasus, and the world.

The Ararat Artesian Basin is a natural accumulation area for groundwater, where recharge occurs from the surrounding Ararat and Aragats mountain massifs, as well as the Geghama and Armenian Par mountain ranges. From a hydrogeological perspective, the Ararat Depression is a classic closed intermountain artesian basin, characterized by distinct zones of groundwater recharge, accumulation, and discharge. The Ararat Artesian Basin is characterized by a complex tectonic, geological, and hydrogeological setting. The basin constitutes an intermontane tectonic trough formed within the Araks tectonic zone, which, as a result of subsequent folding processes, has been divided into five second-order structures. In particular, the Armavir region is located within the Hoktemberyan depression and the Sovetashen uplift zones (Figure 2). These structures differ from one another in their geological composition, the thickness of water-bearing rocks, the number of aquifer and aquiclude layers, and their hydraulic properties. Groundwater resources in the Ararat Artesian Basin are formed by atmospheric precipitation, condensation, deep artesian inflow, and, to a lesser extent, surface runoff from the Araks catchment basin [25,26]. The geological structure of the Ararat Plain includes Mio-Pliocene clay-sandstone sediments (N1S), upon which volcanic rocks, lacustrine-fluvial, and alluvial-proluvial formations of Upper Pliocene-Quaternary (N23-Q3) age are deposited, with a total thickness of approximately 400 m. Three aquifers have been identified within these formations: unconfined and confined aquifer complexes, with the latter conventionally divided into two distinct aquifers. The unconfined aquifer is distributed throughout almost the entire basin. It occurs at depths of 0.5–50 m from the surface, where alluvial-proluvial formations are primarily present. The direction of groundwater flow coincides with the relief gradient and is directed toward the Araks River. These waters are concentrated in sandy loam, loam sand and gravel-small pebble deposits [26,27]. The first confined aquifer lies at depths of 50–150 m, characterized by lacustrine-fluvial formations, while the second occurs at depths of 150 m and greater, where volcanic rocks predominate. The two conventionally separated confined aquifers are interconnected by successive complexes composed of permeable and semi-permeable rocks, which exhibit variable thickness and permeability. Together, they form a single integrated aquifer system. The recharge conditions and the formation processes of exploitable groundwater resources for these two confined aquifers are also similar. The basin area is further characterized by high variability in geological-lithological and hydrogeological parameters, particularly regarding the distribution and thickness of aquifers, the diversity of water-bearing rocks, their hydraulic conductivity, transmissivity, water temperature, and the degree of mineralization [26].

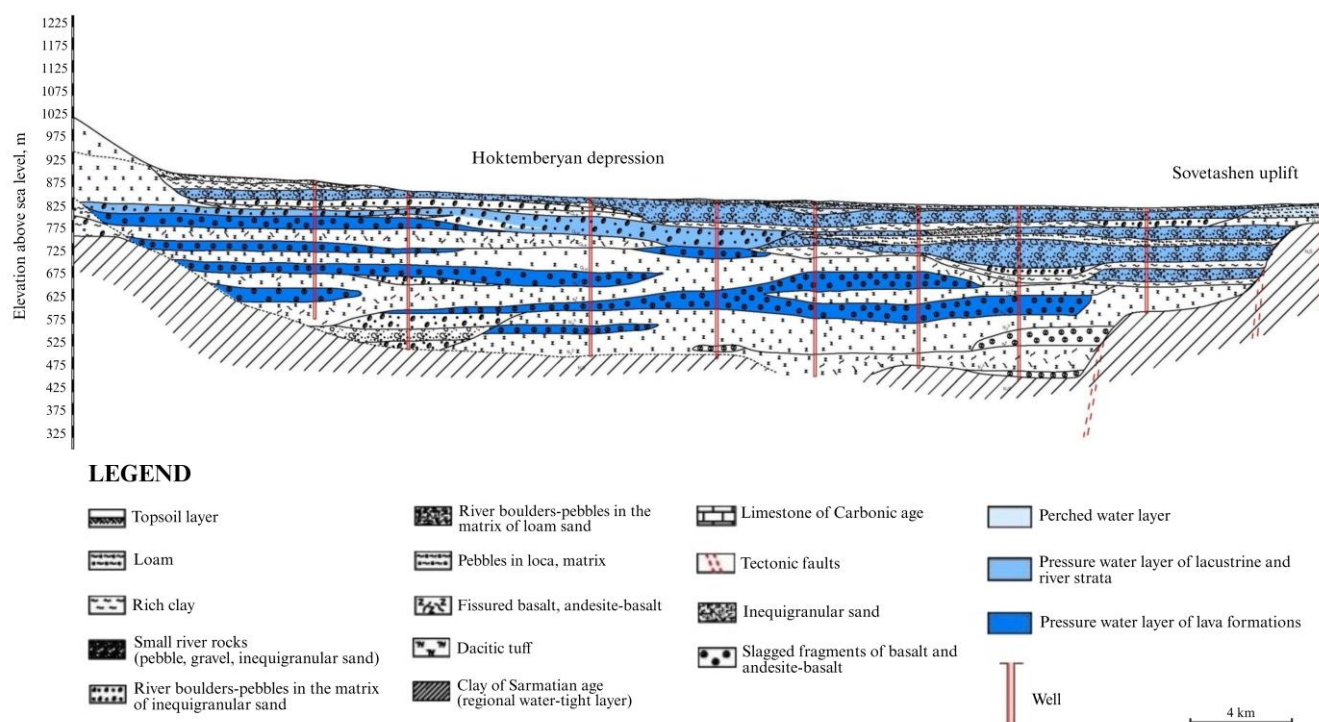


Figure 2. Longitudinal geological-lithological section of the Ararat Artesian Basin.

2.2. Sampling and Laboratory Measurements

Groundwater samples were collected from 72 wells located in intensive agricultural areas of the Armavir region. Of these, 41 wells were obtained from the unconfined aquifer (at depths ranging from 3 to 30 m), and 31 wells were collected from the first confined aquifer (at depths ranging from 100 to 150 m) (Tables S3 and S4). Sampling was conducted monthly during the 2022 and 2023 irrigation seasons (April to October), coinciding with the period of peak agricultural water demand. To ensure the accuracy of hydrochemical analysis, all samples were filtered in situ using 0.45 μm membrane filters. For the determination of cations, samples were immediately acidified with high-purity nitric acid (HNO_3) to $\text{pH} < 2$ to prevent metal precipitation and adsorption on container walls. All samples were stored at 4 $^{\circ}\text{C}$ and analyzed within 48 h.

Electrical conductivity (EC) and Total dissolved solids (TDS) were measured using a portable conductivity meter (MARK-603, VZOR, Nizhny Novgorod, Russia). To ensure measurement accuracy, the instrument was calibrated using standard potassium chloride (KCl) solutions of known conductivity. All EC measurements were automatically temperature compensated to 25 $^{\circ}\text{C}$. The concentrations of potassium (K^+), sodium (Na^+), and calcium (Ca^{2+}) ions were determined by flame photometer (FP-I6431, Bioeuropeak, Jinan, China). To ensure measurement accuracy, the instrument was calibrated using separately prepared standard solutions for each ion. Detection ranges were 0–100 mg/L for K^+ , 0–160 mg/L for Na^+ , and 0–1000 mg/L for Ca^{2+} . Samples that exceeded the maximum detection limit were diluted with deionized water. Calibration curves for each ion were constructed based on standard solutions of known concentrations. The linearity of the calibration curves was evaluated using linear regression ($R^2 > 0.99$). For quality control, reagent blanks and check standards were periodically analyzed to assess background interference and monitor instrument stability. The limits of detection (LOD) were 0.01 mg/L for K^+ and Na^+ , and 2.0 mg/L for Ca^{2+} . Instrument reproducibility was characterized by a coefficient of variation (CV) of less than 3%, and signal drift during measurements did not exceed 3%. For each sampling point, at least two independent replicates were prepared. Each

replicate was measured five times, and the resulting mean value was calculated for further processing.

The pH and the concentrations of chloride (Cl^-) and magnesium (Mg^{2+}) ions were measured using an I-160M (Anatech, Gomel, Belarus) laboratory ion meter. The instrument enables the potentiometric determination of both pH and the concentrations of mono- and divalent ions. For pH measurements, the instrument was calibrated using standard buffer solutions (pH 4.00, 7.00, and 10.00), with automatic temperature compensation applied during measurements. Quantitative determination of Cl^- and Mg^{2+} ions was performed using specific ion-selective electrodes (ISEs). The instrument was calibrated using multi-point standard solutions covering the expected concentration range of the samples, with coefficients of determination (R^2) exceeding 0.99. To ensure method stability and measurement accuracy, check standards were analyzed periodically throughout the measurement process. According to the instrument's technical specifications, the accuracy of pH measurements is approximately ± 0.02 pH units, while the relative errors for the determination of mono- and divalent ion concentrations are $\pm 2.5\%$ and $\pm 5\%$, respectively. All samples were measured at least in duplicate, and the mean values were used for further processing.

Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations were determined by acid-base titration with 0.05 M HCl. To ensure high precision, potentiometric titration was employed to detect the endpoints at pH 8.3 and 4.5 [28]. All measurements were performed no less than five times, and the HCl solution was standardized against primary standards (anhydrous sodium carbonate) prior to analysis. The limit of detection (LOD) for carbonate and bicarbonate ions is 1 mg/L [29].

Data from 2022 and 2023 were aggregated for the analysis, as preliminary statistical testing indicated no significant inter-annual differences, while seasonal variations were found to be the dominant factor; consequently, all analytical results were averaged to provide a representative assessment of groundwater quality.

2.3. Hydrochemical Data Processing and Classification Methods

To assess the suitability of groundwater for irrigation purposes, a combination of computational and hydrochemical analytical methods was applied in accordance with internationally accepted standards. At the first stage of the assessment, the main irrigation water quality indices were calculated, including the Sodium adsorption ratio (SAR), Sodium percentage (Na%), Residual sodium carbonate (RSC), Magnesium hazard (MH), and Permeability index (PI), which are widely used for evaluating irrigation water suitability. At the same time, the main hydrochemical parameters of groundwater were determined, including Electrical conductivity (EC), Total dissolved solids (TDS), pH, and chloride ion (Cl^-) concentration, which play an important role in characterizing water salinity and ionic composition. The above indices were calculated based on the measured ionic composition using standard formulas [4,21,30]. Table S1 presents the groundwater quality classification scheme and corresponding threshold values used in this study.

2.3.1. Calculation of SAR

The calculated SAR values were used to assess irrigation water quality by classifying waters according to the degree of sodium hazard, thereby enabling evaluation of the risks of soil structural degradation and salinization. Elevated SAR values indicate a predominance of sodium relative to calcium and magnesium, which can lead to dispersion of soil particles, deterioration of soil structure, and reduced permeability [31]. Therefore, SAR is considered a key index for evaluating the suitability of irrigation water.

The SAR values were determined by using the following Equation (1) [32]:

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \quad (1)$$

where the given concentrations of ions were reported in meq/L.

2.3.2. Calculation of Sodium Percentage (Na%)

Na% is an important index for assessing the quality of irrigation water, characterizing the relative proportion of sodium ions among the major cations present in the water. It reflects the potential for sodium accumulation in the soil and is used to evaluate water suitability, particularly in terms of its impact on the physicochemical properties of the soil [33].

The Na% values were determined by using the following Equation (2) [34]:

$$Na\% = \frac{(Na^+ + K^+) \times 100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \quad (2)$$

where the given concentrations of ions were reported in meq/L.

2.3.3. Calculation of Magnesium Hazard (MH)

Magnesium hazard (MH) is an important index for assessing irrigation water quality, characterizing the relative proportion of Mg^{2+} to Ca^{2+} ions. High MH values indicate a predominance of magnesium, which can lead to deterioration of soil structure, dispersion of soil colloids, and reduced permeability [35,36].

The MH values were determined by using the following Equation (3) [37]:

$$MH = \frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \times 100 \quad (3)$$

where the given concentrations of ions were reported in meq/L.

2.3.4. Calculation of Residual Sodium Carbonate (RSC)

Residual sodium carbonate (RSC) is an important index for assessing irrigation water quality, characterizing the predominance of carbonate and bicarbonate ions over Ca^{2+} and Mg^{2+} . It is used to evaluate the relative activity of sodium in water and reflects the potential for sodium accumulation in the soil [38]. High RSC values can promote the precipitation of calcium and magnesium, leading to a relative increase in sodium, which may negatively affect soil structure and permeability.

The RSC values were determined by using the following Equation (4) [32]:

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (4)$$

where the given concentrations of ions were reported in meq/L.

2.3.5. Calculation of Permeability Index (PI)

The Permeability index (PI) is an important parameter for assessing irrigation water quality, used to evaluate the impact of water on soil permeability and the soil water-air regime. PI values enable assessment of the potential effects of irrigation water on soil structure and infiltration capacity, as both elevated and reduced values may indicate a risk of altered soil permeability under prolonged irrigation. [39].

The PI values were determined by using the following Equation (5) [40]:

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \quad (5)$$

where the given concentrations of ions were reported in meq/L. It should be noted that the PI is an empirical expression with mixed dimensional units, as the square root term ($\sqrt{HCO_3^-}$) is applied to values expressed in meq/L.

2.4. Graphical Methods in Groundwater Quality Assessment for Irrigation

2.4.1. Mechanisms of Groundwater Chemical Evolution and Weathering Processes (Using Gibbs Diagram and Bivariate Scatter Plots)

The Gibbs diagram is used to identify the main mechanisms controlling the hydrochemical composition of groundwater [41]. It is based on the relationship between TDS and the ratios of major ions ($\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ or $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$) and allows the distinction of the dominant processes influencing water chemistry, including atmospheric precipitation, rock weathering, and evaporation and crystallization. The diagram also enables the assessment of the origin and formation conditions of groundwater [4,42].

While Gibbs diagrams provide a macroscopic overview of the mechanisms governing groundwater chemistry, bivariate scatter plots of major ions are commonly employed to elucidate specific hydrogeochemical processes, such as mineral weathering, ion exchange, and dissolution. This approach facilitates a granular analysis of ionic ratios to identify dominant geochemical pathways within both unconfined and confined aquifers [43,44].

To interpret hydrogeochemical evolution, the following ionic ratios are frequently utilized: the $\text{Na}^+ / \text{Cl}^-$ ratio plot is employed to differentiate between halite dissolution and ion exchange processes. $\text{Ca}^{2+} + \text{Mg}^{2+} / \text{HCO}_3^-$ ratio is used to evaluate the contributions of carbonate mineral weathering (calcite and dolomite) and cation exchange [45].

2.4.2. Application of the United States Salinity Laboratory (USSL) Diagram

Assessments of irrigation water quality were performed combining salinity and sodium hazards using the US Salinity Laboratory (USSL) diagram. A graphical indicator for salinity is the EC, and a graphical indicator of sodium hazard is the SAR. This classification of water samples into the respective C (salinity hazard) and S (sodium hazard) classes enabled the evaluation of their suitability for irrigation and impact on soil physicochemical characteristics [4,32,46,47].

2.4.3. Application of the Wilcox Diagram

The Wilcox diagram was used to assess irrigation water suitability based on the combined evaluation of Sodium percentage (Na%) and Electrical conductivity (EC) [34,35]. The classification was based on a combination of the classical Wilcox method and its modified version, yielding five distinct quality categories: “excellent to good”, “good to permissible”, “permissible to doubtful”, “doubtful to unsuitable”, and “unsuitable” (the boundary values for Na% and EC are presented in Table S1) [48,49]. Using this diagram, water samples were categorized into these quality classes, enabling an assessment of their suitability for irrigation, identification of potential usage limitations, and evaluation of their impact on soil salinity and structural properties under irrigation conditions [47].

2.5. Development of the Irrigation Water Quality Index (IWQI)

The Irrigation Water Quality Index (IWQI) was used to provide an integrated assessment of groundwater suitability for irrigation by combining multiple hydrochemical parameters and indices into a single composite index, taking into account the specific hydrochemical characteristics of the study area [4,50]. IWQI values range from 0 to 100 (Table 1).

Table 1. Classification table according to IWQI value.

Categories	Class I	Class II	Class III	Class IV	Class V
Ranges	>80	60–80	45–60	30–45	<30
Description	Excellent	Good	Permissible	Doubtful	Unsuitable

The Irrigation Water Quality Index (IWQI) methodology generally requires adaptation to account for regional specificities [50,51]. In this study, the IWQI framework was tailored to the hydrogeological conditions and specific challenges of the study area [52]. Specifically, the soil salinization process, which is directly linked to groundwater quality, was taken into account [53]. Consequently, necessary adjustments were made to the classification system to more accurately reflect local conditions [54,55]. During the computation of the IWQI, four main groups of factors were taken into account, which had a harmful effect on soil quality and crop yield. The order of them according to their importance is: influencing the soil salinity (1), influencing the soil infiltration character (2), toxic ions (3), effects on plant physiology (4). For every group, the Weighting factor (Wf) was defined, the aim of which was to show the comparative importance of each group and to clarify the interconnections between the different groups (Table S2) [4,50]. The Wf of each group was calculated by the following Equation (6):

$$Wf_i = \frac{\frac{1}{K_i}}{\sum_{i=1}^n \frac{1}{K_i}} \quad (6)$$

K_i represents a temporary weighting value for each group, ranging from 1 (highly important) to 5 (less important).

For the calculation of IWQI, the following Equation (7) was used:

$$IWQI = \sum_{i=1}^n Wf_i \times \frac{\sum_{m=1}^m QR_i}{m} \quad (7)$$

where IWQI is the Irrigation Water Quality Index, Wf_i is the weighting factor of the n th group, QR_i is the Quality rating of the n th group's m th parameter, and m is the number of parameters in the n th group.

2.6. Geo-Statistical Analysis and Mapping

Geostatistical analysis and mapping were used to assess the spatial distribution of groundwater quality and identify spatial patterns. Inverse distance weighted (IDW) interpolation was performed in the ArcMap 10.x environment using the following settings: power parameter $p = 2$, a variable search radius, and 12 nearest neighboring points. Data were interpolated using the IDW method in ArcGIS 10.4 software. The resulting maps enabled visualization of the spatial variability of hydrochemical parameters and indices and facilitated the identification of high-risk zones for irrigation water use. The IDW technique is a widely used geostatistical interpolation method for predicting spatially distributed parameters in hydrology. It is based on the principle that points closer in space are more similar than those farther apart. The method estimates values at unsampled locations using nearby reference points, assigning weights that decrease with increasing distance. Thus, greater weights are given to nearer points, while lower weights are assigned to more distant ones [21,56].

The IDW is calculated by the following Equation (8):

$$\tilde{Z}(s_0) = \sum_{i=1}^N \lambda_i Z(s_i) \quad (8)$$

where $\tilde{Z}(s_0)$ is the estimated value at point s_0 , and λ_i are the weights assigned to each reference point used in the calculation, and these weights decrease as the distance increases. $Z(s_i)$ is the observed value at reference point s_i , and N is the number of reference points located in the vicinity of the desired point that are used in the calculation.

The weights are determined by the following Equation (9):

$$\lambda_i = d_{i0}^{-p} / \sum_{i=1}^N d_{i0}^{-p} \quad (9)$$

where d_{i0} is the distance between the desired point s_0 and the reference point s_i .

The weights decrease with increasing distance, which is controlled by the coefficient p . The parameter p affects the weighting of reference points; specifically, as the distance between the reference points and the target point increases, the influence (or weight) of the reference points on the target point decreases rapidly. The weights assigned to the reference points used in interpolation must sum to 1, as shown by Equation (10).

$$\sum_{i=1}^N \lambda_i = 1 \quad (10)$$

2.7. Software and Data Analysis

All statistical analyses were conducted using Microsoft Excel 2021 (Microsoft Corp., Redmond, WA, USA) and GraphPad Prism software, version 8.0 (GraphPad Software, San Diego, CA, USA). Graphs were generated using OriginPro 2018 (OriginLab Corp., Northampton, MA, USA). Spatial mapping and geostatistical interpolation were performed using ArcGIS 10.4 (Esri, Redlands, CA, USA).

3. Results and Discussion

3.1. Major Hydrochemical Parameters

Quantitative determination of the ionic composition of groundwater is a fundamental stage of hydrochemical research, enabling the assessment of water quality and its suitability for various uses, particularly for irrigation. The data obtained allow for the analysis of spatial and temporal variations in the major cations and anions, as well as for the identification of natural and anthropogenic factors affecting water quality [57,58]. A statistical summary of the mean seasonal values of selected groundwater hydrochemical parameters is presented in Table 2 (unconfined aquifer) and Table 3 (confined aquifer). In both groundwater aquifers, K^+ exhibited the lowest concentrations among the major ions. In wells of the unconfined aquifer, K^+ concentrations ranged from 2.60 to 35.70 mg/L, whereas in the confined aquifer they ranged from 2.60 to 12.60 mg/L. Comparison of the mean K^+ ion contents of unconfined and confined aquifers using Welch's t -test showed that there was no statistically significant difference between the groups ($t = 1.655$, $df = 56.42$, $p = 0.1035$), although relatively higher mean values were recorded in the unconfined horizon. At the same time, comparison of variances (F-test) indicated a significant difference in the variability of the groups ($F = 5.796$, $p < 0.0001$). These statistical differences, particularly the high variability of ion concentrations in the aquifer, can be explained by the spatial heterogeneity of land use and the local characteristics of irrigation practices [59]. Intensive agricultural activities, which often involve the application of fertilizers, contribute to soil leaching and the infiltration of elements into groundwater [60]. Irrigation return flows and associated evaporation increase the content of dissolved substances in groundwater. Additionally, geochemical processes such as Na-Ca exchange influence the evolution of groundwater composition in the aquifer [59].

Table 2. Statistical analysis of hydrochemical parameters in the unconfined aquifer (number of wells 41).

Parameters	Season	Minimum	Maximum	Mean	Median	Standard Deviation
K^+ (mg/L)	Spring	2.60	27.80	7.37	5.80	4.970
	Summer	2.90	35.70	8.99	6.60	6.768
	Autumn	3.30	32.60	8.48	6.20	6.331
Na^+ (mg/L)	Spring	47.00	502.00	132.10	108.00	88.640
	Summer	52.46	480.50	139.69	104.00	89.308

	Autumn	52.50	462.50	135.29	112.00	84.490
Ca ²⁺ (mg/L)	Spring	3.70	80.10	28.19	30.80	15.991
	Summer	3.80	102.50	40.04	38.00	23.958
	Autumn	3.10	55.80	27.10	29.80	14.304
Mg ²⁺ (mg/L)	Spring	28.40	169.10	69.62	63.70	31.725
	Summer	14.50	131.30	60.87	58.40	29.335
	Autumn	19.90	145.70	63.91	60.80	30.580
Cl ⁻ (mg/L)	Spring	25.30	309.00	105.33	94.60	62.921
	Summer	14.30	240.00	97.58	71.50	62.015
	Autumn	17.10	230.00	87.08	75.90	55.572
HCO ₃ ⁻ (mg/L)	Spring	259.25	1104.10	563.21	518.50	202.165
	Summer	237.90	1024.80	548.52	533.75	190.861
	Autumn	255.10	966.85	548.81	533.75	180.107
EC (µS/cm)	Spring	665.50	3011.00	1530.99	1519.00	560.196
	Summer	599.40	2684.00	1539.29	1566.00	523.850
	Autumn	657.70	2631.00	1500.97	1467.00	467.062
TDS (mg/L)	Spring	323.40	1536.00	764.17	750.00	289.233
	Summer	290.10	1363.00	766.26	779.30	268.570
	Autumn	319.00	1335.00	748.08	729.20	239.802
pH	Spring	6.82	8.41	7.65	7.72	0.409
	Summer	6.87	8.32	7.66	7.76	0.438
	Autumn	6.85	8.39	7.62	7.72	0.415

Na⁺ is the dominant cation in the studied groundwater. Its concentration is primarily controlled by cation exchange processes and anthropogenic influences. Overexploitation of groundwater can disrupt the hydrodynamic balance, promoting the intrusion of more saline waters or the upward migration of sodium-rich waters from deeper horizons, thereby increasing Na⁺ concentrations [37,40]. Na⁺ concentrations in the unconfined aquifer ranged from 47.00 to 502.00 mg/L across different seasons, whereas in the confined aquifer they ranged from 38.50 to 369.00 mg/L. According to the results of Welch's *t*-test, the mean Na⁺ concentration in unconfined and confined groundwater showed no statistically significant difference ($t = 1.814$, $df = 69.32$, $p = 0.0741$), despite higher mean values observed in the unconfined groundwater. Beyond natural water-rock interactions, the observed Na⁺ concentrations are significantly influenced by anthropogenic activities and particularly intensive irrigation. Irrigation return flows, often enriched in salts, facilitate the infiltration of Na⁺ into the groundwater system [61,62]. Furthermore, the cation exchange process, where Na⁺ in the infiltrating water replaces Ca²⁺ and Mg²⁺ adsorbed on the clay minerals of the aquifer matrix, plays a critical role in the hydrogeochemical evolution of the groundwater [63,64]. This process is often exacerbated in areas subjected to groundwater overexploitation, which can alter the hydrodynamic balance and promote the migration of more saline waters from deeper horizons or surrounding areas [65,66]. The seasonal fluctuations, particularly the higher concentrations observed during the spring, suggest a direct link between surface recharge events such as precipitation and irrigation and the mobilization of accumulated salts in the soil profile [67,68].

Table 3. Statistical analysis of hydrochemical parameters in the confined aquifer (number of wells 31).

Parameters	Season	Minimum	Maximum	Mean	Median	Standard Deviation
K ⁺ (mg/L)	Spring	2.60	12.30	7.09	7.00	2.771
	Summer	2.70	12.60	6.31	6.30	2.672

	Autumn	2.90	10.60	6.38	6.70	2.412
Na ⁺ (mg/L)	Spring	38.50	369.00	112.96	89.50	82.898
	Summer	35.80	288.00	93.09	73.40	64.628
	Autumn	37.90	304.00	99.96	80.10	67.651
Ca ²⁺ (mg/L)	Spring	4.00	106.00	42.39	42.20	25.252
	Summer	4.80	76.00	36.50	38.50	19.407
	Autumn	3.10	72.50	33.19	33.80	17.931
Mg ²⁺ (mg/L)	Spring	14.50	117.65	53.35	43.88	27.552
	Summer	16.50	81.70	38.75	30.30	18.310
	Autumn	15.20	88.10	45.85	45.70	20.221
Cl ⁻ (mg/L)	Spring	14.50	123.00	61.03	59.50	33.370
	Summer	11.50	137.00	63.72	59.40	37.729
	Autumn	12.90	129.50	57.05	49.70	31.866
HCO ₃ ⁻ (mg/L)	Spring	198.25	692.35	377.25	347.70	113.612
	Summer	189.10	580.50	352.01	326.35	95.111
	Autumn	195.20	625.25	361.55	336.80	105.679
EC (μS/cm)	Spring	539.10	2623.00	1231.46	1260.00	485.126
	Summer	545.80	2568.00	1227.90	1278.00	463.862
	Autumn	538.20	2562.00	1247.23	1280.00	478.521
TDS (mg/L)	Spring	260.00	1329.00	610.04	623.10	247.851
	Summer	271.20	1304.00	610.27	632.10	236.752
	Autumn	261.70	1347.00	620.03	632.90	244.607
pH	Spring	6.74	8.55	7.72	7.59	0.468
	Summer	6.59	8.59	7.73	7.86	0.542
	Autumn	6.66	8.58	7.71	7.80	0.517

Changes in Ca²⁺ concentrations in groundwater are primarily controlled by the dissolution of carbonate minerals (e.g., calcite and dolomite), ion exchange processes, and variations in hydrodynamic conditions. These variations reflect the combined effects of mineral dissolution and precipitation, ion exchange, and mixing of water masses within the system [63,69]. Ca²⁺ concentrations in the unconfined aquifer ranged from 3.10 to 102.50 mg/L across different seasons, whereas in the confined aquifer they ranged from 3.10 to 106.00 mg/L. The results obtained showed no significant difference in Ca²⁺ concentration between confined and unconfined aquifers ($t = 1.234$, $df = 58.73$, $p = 0.2222$). The lack of statistically significant differences in Ca²⁺ concentrations between the unconfined and confined aquifers may suggest a shared geochemical origin rather than direct hydraulic connectivity. This observation may indicate that both aquifers are influenced by similar carbonate mineral dissolution processes, potentially buffering the chemical composition against vertical variations [70]. Alternatively, the observed patterns might reflect a complex interplay between mineral weathering and ion exchange that masks distinct aquifer-specific signatures [71].

Mg²⁺ is the second most abundant cation in the studied groundwater. It is a key contributor to water hardness, and the Ca²⁺/Mg²⁺ ratio is commonly used to assess water origin and the nature of water-rock interactions. Compared to Na⁺, Mg²⁺ is generally less affected by anthropogenic inputs and shows less pronounced concentration fluctuations, more closely reflecting natural geological conditions [72,73]. Mg²⁺ concentrations in the unconfined aquifer ranged from 14.50 to 169.10 mg/L across different seasons, whereas in the confined aquifer they ranged from 14.50 to 117.65 mg/L. A statistically significant difference was recorded in the Mg²⁺ concentration between confined and unconfined aquifers. The mean Mg²⁺ concentration was higher in the unconfined aquifer ($t = 3.174$, $df = 69.06$, $p = 0.0022$). The statistically significant difference in Mg²⁺ concentrations, with higher mean values observed in the unconfined aquifer, may be attributed to several hy-

drogeological and geochemical factors. In the unconfined aquifer, active water-rock interactions, such as the weathering of silicate minerals, are primary drivers of groundwater chemistry. Additionally, the unconfined aquifer is directly exposed to agricultural return flows and surface runoff, which can introduce magnesium from fertilizers or soil conditioners [65]. Conversely, the lower concentrations in the confined aquifer might reflect a longer residence time and progressive geochemical evolution, where Mg^{2+} is potentially depleted or replaced by Na^+ through cation exchange processes along the groundwater flow path [71].

High Cl^- concentrations can adversely affect soil properties by increasing salinity, which may reduce permeability and impair soil structure. In addition, elevated Cl^- levels can exert toxic effects on plants by disrupting osmotic balance [74]. In the studied groundwater, Cl^- concentrations were higher in the unconfined aquifer, ranging from 14.30 to 309.00 mg/L across different seasons, whereas in the confined aquifer they were lower, ranging from 11.50 to 137.00 mg/L. Analysis of Cl^- distribution revealed significant differences between the investigated aquifers, with higher concentrations observed in the unconfined aquifer. This difference was statistically significant ($t = 3.385$, $df = 65.89$, $p = 0.0012$). According to the Doneen classification [75], 87.8% of groundwater samples from the unconfined aquifer, based on Cl^- concentration, fall into Class I, while 12.2% fall into Class II, the latter showing a limited and localized distribution in the part of the study area extending from the central toward the eastern zone (Figure 3A). In contrast, all groundwater samples from the confined aquifer fall into Class I and are therefore considered excellent for irrigation purposes (Figure 3B). The significantly higher Cl^- concentrations in the unconfined aquifer, compared to the confined one, can be attributed to its greater vulnerability to surface-driven processes. Key mechanisms include evaporative concentration of salts, particularly in areas with high evapotranspiration rates, and the infiltration of irrigation return flows, which often carry concentrated salts from the soil profile [76,77]. Furthermore, the application of fertilizers and other agricultural inputs can contribute to the chloride load in the shallow subsurface [66]. In contrast, the confined aquifer's isolation from these immediate surface inputs likely preserves its lower chloride levels, explaining the statistically significant differences.

Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions are the principal components of the groundwater carbonate system and play a key role in regulating acid-base balance and buffering capacity. Their formation is primarily associated with the dissolution of CO_2 and its interaction with carbonate minerals such as calcite and dolomite [78,79]. CO_3^{2-} was not detected in the groundwater of the study area. HCO_3^- concentrations in the unconfined aquifer ranged from 237.90 to 1104.10 mg/L across different seasons, whereas in the confined aquifer they ranged from 189.10 to 692.35 mg/L, with maximum values in both aquifers observed in spring. Welch's t -test indicated a significant difference in HCO_3^- concentrations between the investigated aquifers ($t = 5.476$, $df = 64.88$, $p < 0.0001$), with higher mean values observed in the unconfined groundwater. The significantly higher HCO_3^- concentrations in the unconfined aquifer suggest enhanced carbonate dissolution, likely driven by higher CO_2 partial pressures in the soil zone, where biological activity is more pronounced [80]. The statistical disparity between the two aquifers indicates that they exhibit distinct hydrogeochemical signatures, with the confined aquifer showing evidence of longer water-rock interaction times and mineral saturation [71].

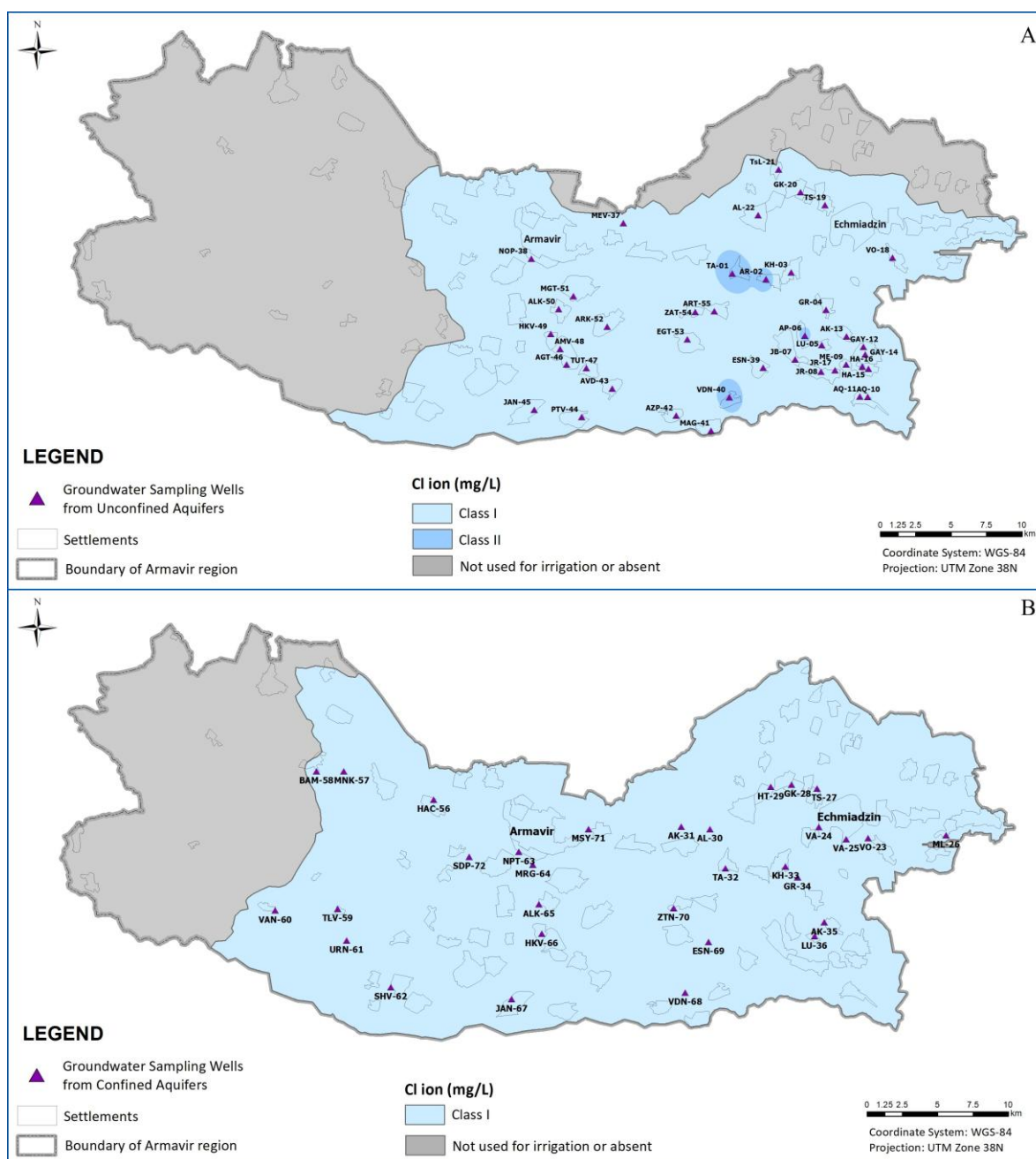


Figure 3. Spatial distribution of Cl^- concentrations in the unconfined (A) and confined (B) aquifers of the Armavir region.

Electrical conductivity (EC) in groundwater is a key parameter for assessing salinity and the overall hydrochemical state of water. There is a direct relationship between EC and salinity: as the concentration of dissolved salts increases, EC values also increase. Therefore, EC is widely used as a rapid and convenient indicator for evaluating water salinity [4,38,81]. EC values varied seasonally, with the highest values in both aquifers recorded in spring. In the unconfined aquifer, EC ranged from 599.40 to 3011.00 $\mu\text{S}/\text{cm}$, whereas in the confined aquifer it ranged from 538.20 to 2623.00 $\mu\text{S}/\text{cm}$. Comparative analysis of EC revealed a significant difference between the aquifers, with higher mean values observed in the unconfined groundwater ($t = 2.495$, $df = 66.55$, $p = 0.0151$). According to the EC classification [34], groundwater in the unconfined aquifer was distributed as follows: 4.9% belonged to the medium salinity water (good category), 85.4% to the high salinity water (permissible category), and 9.7% to the doubtful for irrigation (doubtful category), the latter is mainly confined to localized zones extending from the central-southern

toward the eastern parts of the Armavir region (Figure 4A). In the confined aquifer, 19.4% of groundwater samples were classified as the good category, 77.4% as the permissible category, and 3.2% as the doubtful category. In groundwater from the confined aquifer, the permissible category predominates throughout the study area, whereas the good category is restricted to localized zones, primarily in the central, central-southern, and north-eastern sectors of the Armavir region, and the doubtful category is observed as an isolated patch in the western part (Figure 4B). The observed elevated EC values, particularly in the unconfined aquifer, may reflect the cumulative impact of intensive agricultural practices and evaporative concentration processes [76]. The springtime peak in EC could be attributed to the flushing of accumulated salts from the soil profile into the shallow groundwater system during recharge events [68]. The statistical difference between the aquifers might further imply that the confined aquifer is partially buffered from immediate surface-derived salt loading, although it remains susceptible to long-term hydrogeochemical evolution [65]. It is important to highlight that a study assessing soil salinity levels has been conducted in the study area. The results indicate that in the most vulnerable parts of the region, where groundwater quality was classified as poor based on EC values, processes of salt accumulation and soil salinization are already being observed [82]. These findings demonstrate that secondary soil salinization is emerging as a critical practical concern in the region, highlighting the urgent need for targeted monitoring and sustainable management strategies.

Total dissolved solids (TDS) characterize the total concentration of inorganic salts and a small quantity of organic dissolved in water, including major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anions (Cl^- , HCO_3^-), as well as other dissolved constituents. TDS is widely used to assess the overall mineralization of water and its suitability for irrigation purposes [83]. In the unconfined aquifer, TDS values ranged from 290.10 to 1536.00 mg/L across different seasons, whereas in the confined aquifer they ranged from 260.00 to 1347.00 mg/L. Analysis of TDS revealed a significant difference between the investigated aquifers (Welch's *t*-test, $t = 2.469$, $df = 66.69$, $p = 0.0161$). The significantly higher TDS in the unconfined aquifer likely reflects its greater susceptibility to surface-derived solutes. Fertilizer application and groundwater overexploitation are identified as anthropogenic factors influencing groundwater chemistry [65]. However, the observed TDS range in the confined aquifer indicates that it is also subject to ongoing water-rock interactions, which continue to shape its mineralization over time [80].

pH is a fundamental parameter characterizing the hydrochemical regime of groundwater, reflecting the acid-base balance of the system and controlling chemical reactions and ion exchange processes. It plays a crucial role in regulating the mobility and bioavailability of ions, as well as the interactions and stability of major cations and anions in the aquatic system. From an irrigation perspective, deviations in pH, particularly toward alkaline conditions, can lead to soil degradation and reduced nutrient availability, thereby negatively affecting plant growth and productivity [84,85]. pH values in the unconfined aquifer of the study area ranged from 6.82 to 8.41 across different seasons, whereas in the confined aquifer they ranged from 6.59 to 8.59. No statistically significant difference in pH values was observed between the investigated aquifers ($t = 0.7023$, $df = 57.63$, $p = 0.4853$). According to the Ayers and Westcot classification, groundwater in the unconfined aquifer was distributed as follows: 73.2% belonged to Class I (no restriction on use), and 26.8% to Class II (moderate restriction). Groundwater of Class II is mainly concentrated in the central-southern part of the region and is also present as localized occurrences in the north-eastern areas (Figure 5A).

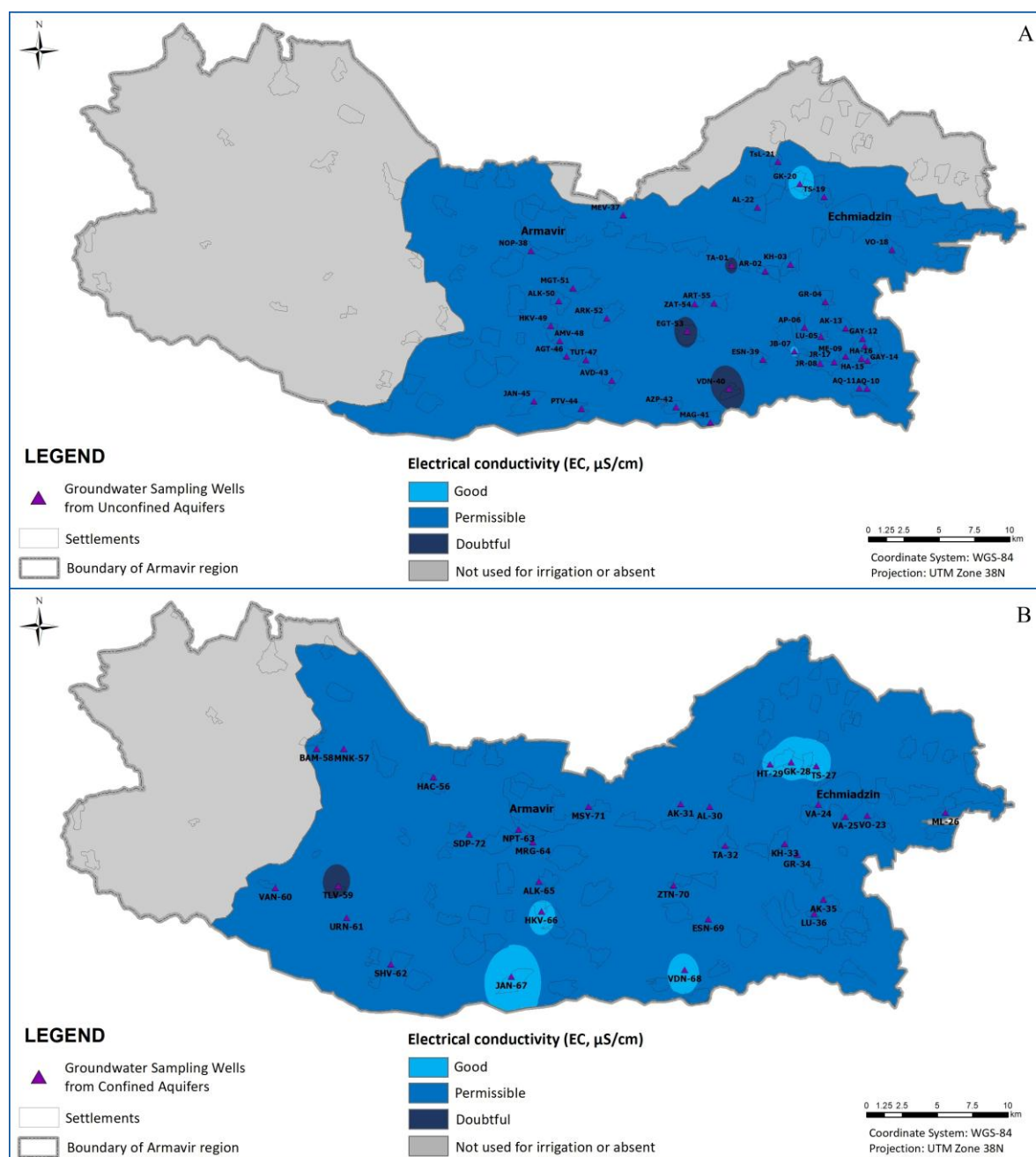


Figure 4. Spatial distribution of EC values in the unconfined (A) and confined (B) aquifers of the Armavir region.

In the confined aquifer, groundwater was classified as 64.5% Class I, 32.3% Class II, and 3.2% Class III (severe restriction on use). In the case of a confined aquifer, Class I groundwater predominates in the region, Class II waters are mainly distributed in the western and central-southern zones, and to a lesser extent in the eastern part. Class III occurs only as localized patches, primarily in the western part (Figure 5B). The lack of statistically significant differences in pH between the two aquifers suggests that both systems are governed by similar buffering mechanisms, primarily the carbonate equilibrium system (CO_2 - HCO_3^- - CO_3^{2-}) [80]. The observed slightly alkaline pH values are typical for groundwater in carbonate-rich sedimentary environments, where the dissolution of minerals like calcite and dolomite acts as a natural pH regulator [86]. While the majority of samples fall within the “no restriction” category, the presence of localized zones with varying quality may indicate areas where specific geochemical conditions such as localized

mineral heterogeneity or anthropogenic influences affect the hydrochemical characteristics [66].

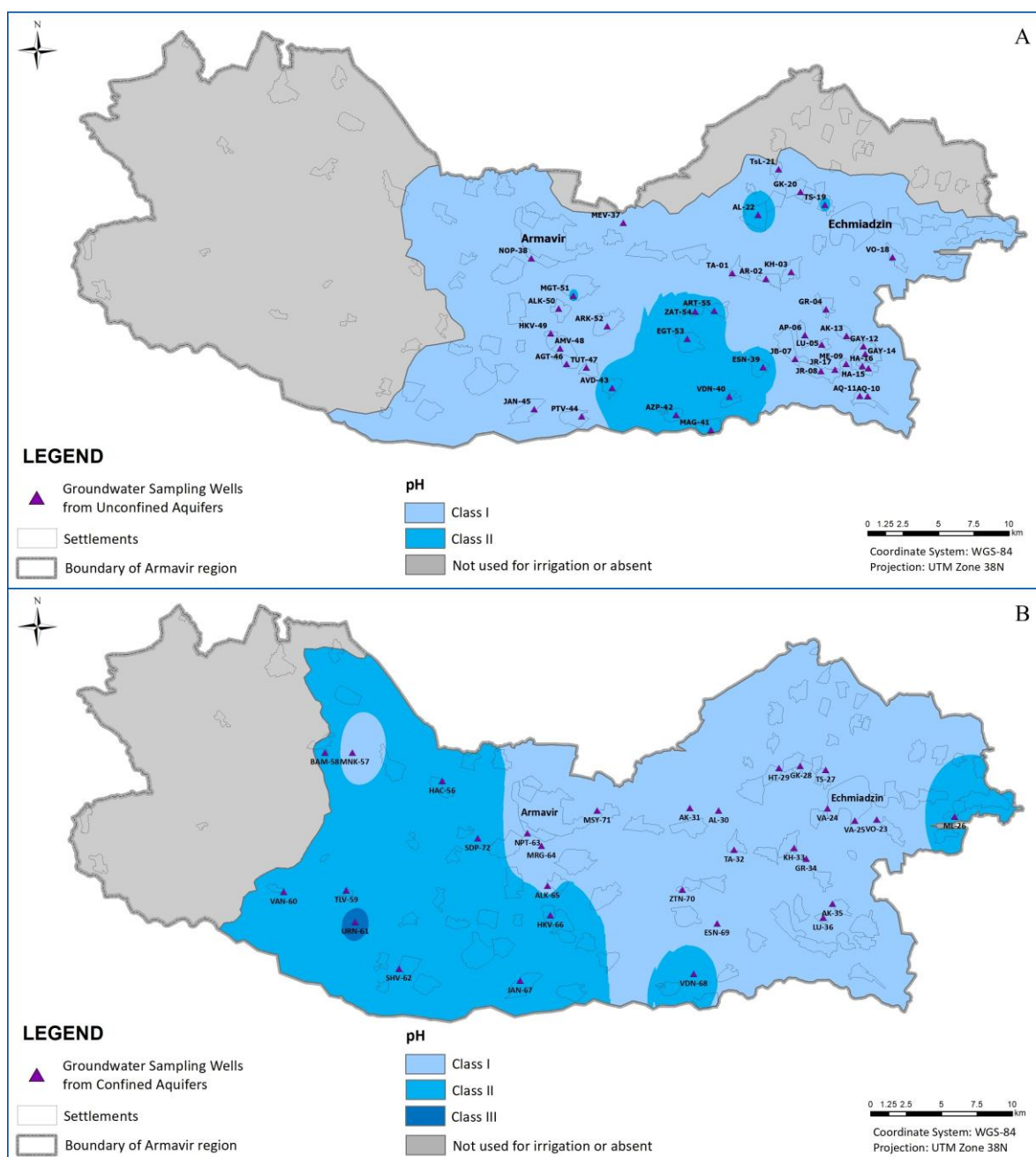


Figure 5. Spatial distribution of pH values in the unconfined (A) and confined (B) aquifers of the Armavir region.

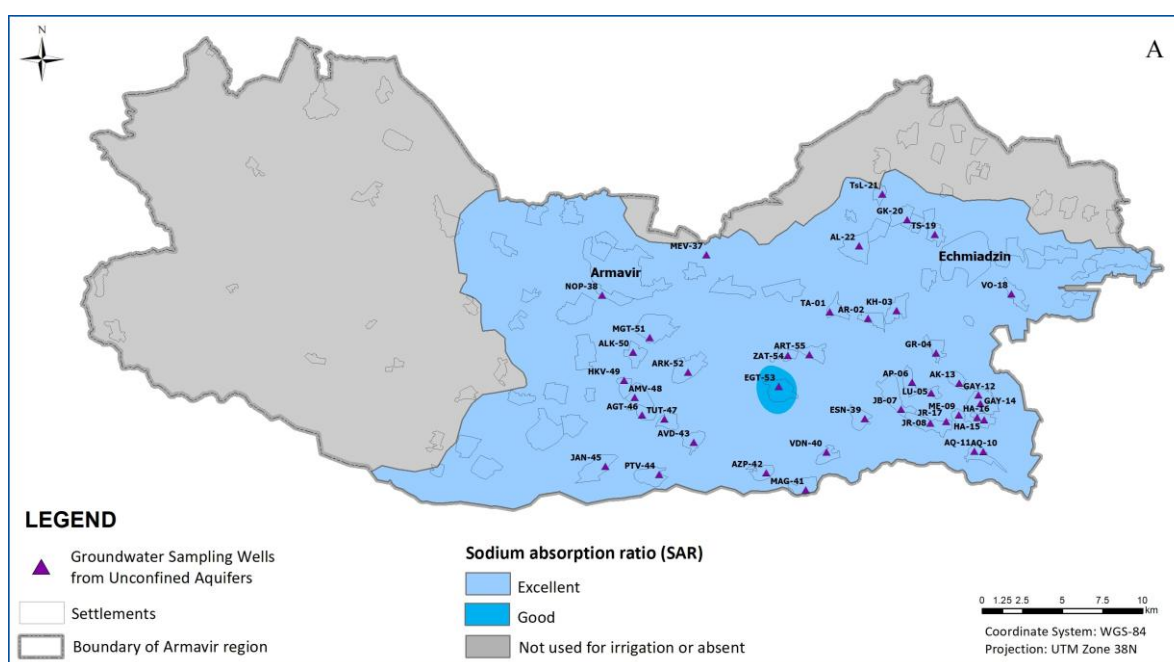
3.2. Irrigation Suitability Indices

3.2.1. Sodium Adsorption Ratio (SAR)

The SAR is widely used as a fundamental index for characterizing the relative predominance of sodium over divalent cations (Ca^{2+} , Mg^{2+}) in groundwater and for evaluating the sodicity hazard of irrigation water. This parameter reflects the intensity of cation exchange processes within the soil-water system, as excess sodium promotes the displacement of calcium and magnesium from soil colloids. As a result, soil aggregate stability is reduced, permeability declines, and hydrophysical properties deteriorate. Therefore, SAR

is a key criterion for assessing irrigation water suitability and its long-term impacts on soil quality [4,84,87,88].

In the unconfined aquifer of the study area, SAR values ranged from 1.491 to 15.490 (Table 4). The majority of groundwater wells (97.6%) were classified as excellent, indicating no sodium hazard, whereas 2.4% were classified as good, reflecting a low sodium hazard, with the latter confined to a small, localized zone in the central-southern part of the region (Figure 6A). In the confined aquifer, SAR values ranged from 1.318 to 7.973 (Table 5), and all groundwater samples were classified as excellent, indicating the absence of sodium hazard throughout the region (Figure 6B). Although the mean SAR value in the unconfined aquifer exceeded that of the confined aquifer, the observed difference did not reach statistical significance ($t = 1.629$, $df = 66.99$, $p = 0.1079$). The prevalence of ‘excellent’ SAR categories across both aquifers suggests that the groundwater in the study area is generally well buffered against sodicity hazards. This stability is largely attributed to the dominance of divalent cations (Ca^{2+} and Mg^{2+}), which effectively counteract the dispersive effects of Na^+ on soil colloids [32]. The absence of a statistically significant difference between the unconfined and confined aquifers indicates a shared geochemical baseline, where carbonate mineral dissolution, specifically calcite and dolomite, consistently provides sufficient calcium and magnesium to maintain low SAR values [89]. However, the slightly higher mean SAR in the unconfined aquifer, while not statistically significant, may reflect the influence of natural water-rock interactions and cation exchange processes that influence solute concentrations in the subsurface [62]. Continuous monitoring is advisable, as the temporal evolution of SAR in similar arid regions has shown increasing trends that can impact irrigation suitability [66].



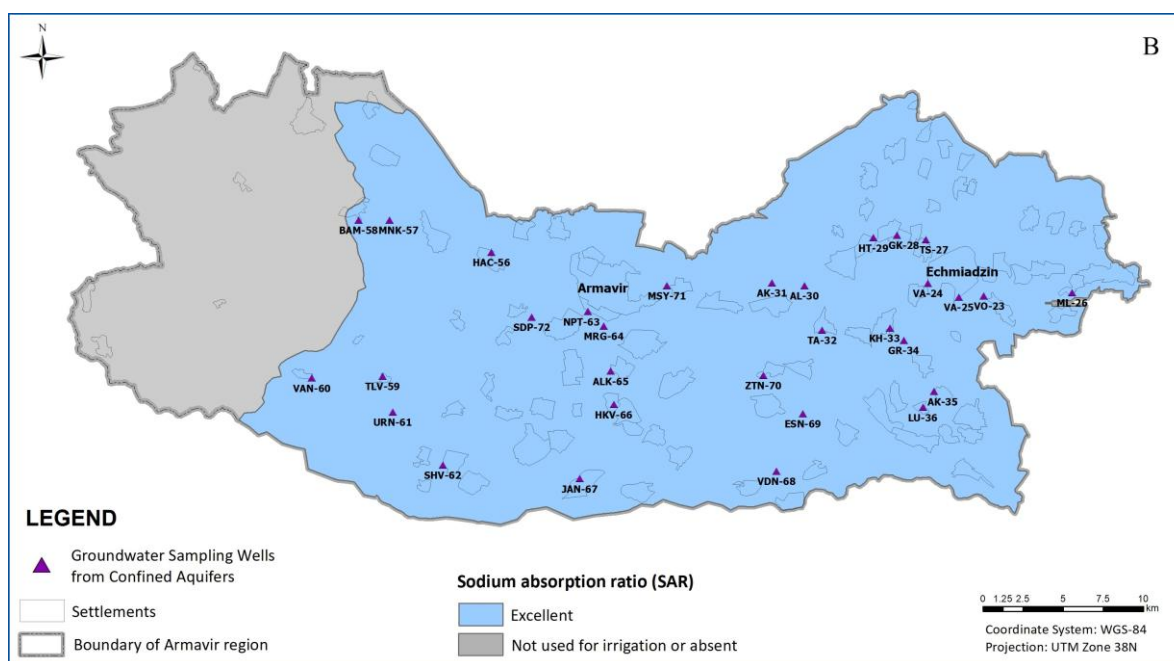


Figure 6. Spatial distribution of SAR values in the unconfined (A) and confined (B) aquifers of the Armavir region.

Table 4. Calculated irrigation water quality indices for the unconfined aquifer.

Well Number	SAR	Na%	MH	RSC	PI	IWQI
TA-01	3.074	37.376	82.146	−8.264	47.532	71.579
AR-02	2.658	41.280	70.841	0.409	61.723	78.902
KH-03	2.214	46.903	70.121	1.103	79.443	88.458
GR-04	1.927	33.284	72.151	−1.907	52.221	79.039
LU-05	2.471	39.002	76.897	0.120	57.443	78.120
AP-06	2.846	36.958	78.323	−3.279	51.160	73.275
JB-07	1.713	41.184	90.970	2.313	83.038	89.320
JR-08	5.051	65.579	93.099	5.168	93.855	84.891
ME-09	3.041	45.269	82.419	−0.313	63.107	79.169
AQ-10	7.616	72.817	91.736	4.046	91.469	79.208
AQ-11	2.916	52.257	92.312	3.614	86.072	86.640
GAY-12	1.643	27.419	74.323	−3.469	45.152	76.926
AK-13	1.723	28.287	75.128	−2.823	46.690	79.086
GAY-14	1.699	31.260	76.883	−1.388	48.368	79.243
HA-15	1.772	32.912	74.175	0.001	57.409	82.935
HA-16	3.157	44.668	74.749	0.989	64.585	78.248
JR-17	2.781	42.392	78.732	0.133	62.948	82.204
VO-18	2.354	46.776	59.328	2.451	79.849	86.332
TS-19	2.802	58.653	85.208	2.372	95.484	88.549
GK-20	2.705	58.932	90.804	2.212	102.448	90.097
TsL-21	2.640	52.431	77.694	2.255	87.897	87.828
AL-22	2.797	52.843	67.561	0.664	79.549	86.746
MEV-37	2.104	40.420	80.858	1.953	70.702	84.312
NOP-38	2.049	37.485	37.419	4.483	69.876	85.311
ESN-39	5.791	63.438	82.263	3.266	82.351	79.076
VDN-40	5.074	51.135	79.524	0.263	65.073	69.182
MAG-41	3.216	45.598	79.270	2.318	66.184	77.465
AZP-42	5.264	55.626	86.073	2.196	71.943	75.189
AVD-43	1.906	42.860	86.822	3.681	83.720	87.442

PTV-44	2.036	31.564	79.954	4.224	55.898	76.888
JAN-45	2.037	34.841	68.442	3.557	63.096	81.179
AGT-46	3.226	50.033	69.530	5.867	81.173	84.104
TUT-47	2.988	42.306	76.155	3.752	65.416	77.991
AMV-48	1.491	32.481	66.571	2.483	64.802	85.232
HKV-49	1.555	30.887	68.745	5.212	67.469	84.188
ALK-50	2.805	39.346	80.063	3.137	61.705	76.306
MGT-51	2.438	40.997	78.136	4.401	70.861	81.902
ARK-52	2.565	35.094	85.452	0.952	54.272	75.948
EGT-53	15.490	85.212	88.465	12.688	101.574	70.528
ZAT-54	7.549	68.047	79.543	9.532	87.634	73.754
ART-55	5.819	63.865	75.798	5.115	84.886	78.565

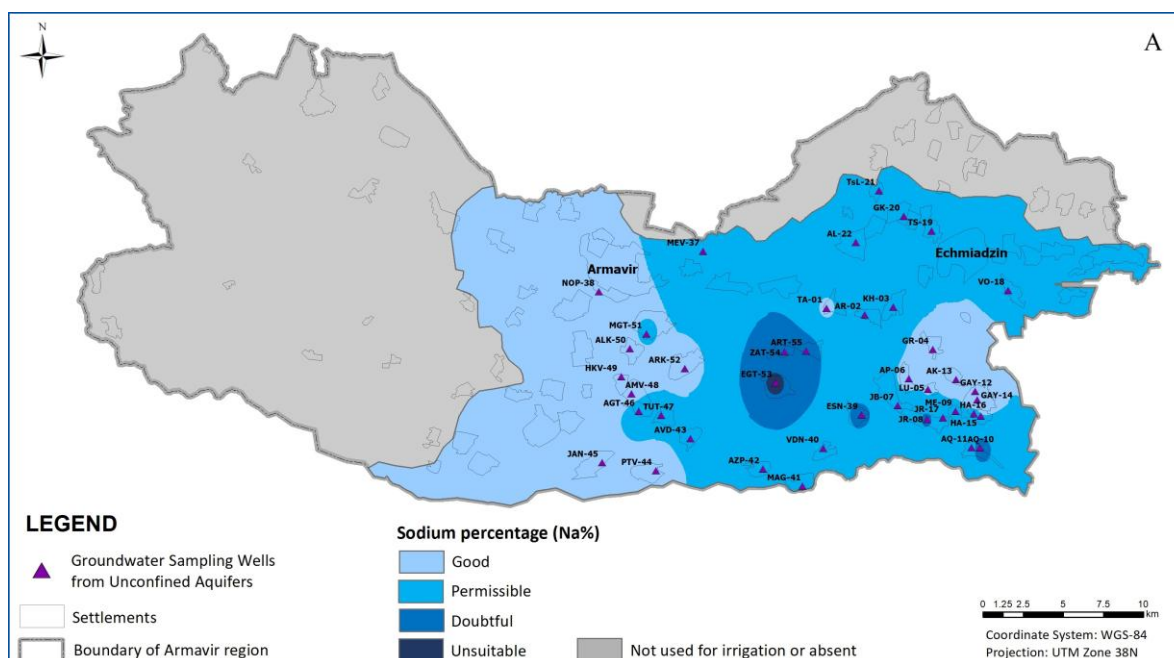
Table 5. Calculated irrigation water quality indices for the confined aquifer.

Well Number	SAR	Na%	MH	RSC	PI	IWQI
VO-23	1.992	41.032	58.402	2.016	73.087	86.215
VA-24	1.370	36.864	77.069	1.240	76.492	89.740
VA-25	1.448	37.454	71.777	1.548	75.614	88.862
ML-26	3.373	48.586	72.843	0.043	67.961	81.565
TS-27	1.728	45.649	88.980	1.012	85.032	90.559
GK-28	1.969	48.150	91.791	0.767	86.204	90.566
HT-29	2.283	51.544	86.847	1.063	88.198	90.768
AL-30	2.292	36.638	73.030	−1.950	55.305	80.634
AK-31	2.126	35.970	72.477	−0.760	57.419	81.500
TA-32	2.264	38.015	76.820	−1.783	57.646	82.750
KH-33	1.501	32.593	66.401	−0.272	58.760	85.951
GR-34	1.511	31.834	67.757	−0.431	57.823	85.493
AK-35	1.418	25.798	80.373	−3.579	44.341	82.389
LU-36	1.653	33.165	75.010	−0.583	58.316	84.629
HAC-56	2.740	43.532	67.744	0.859	66.058	83.017
MNK-57	4.502	51.696	75.525	−3.842	63.296	77.322
BAM-58	3.929	51.568	76.029	−2.012	66.330	80.217
TLV-59	6.113	58.026	62.087	−5.897	66.247	71.399
VAN-60	7.973	70.043	67.395	−1.101	80.883	77.334
URN-61	3.707	57.076	63.379	3.289	85.758	84.030
SHV-62	1.318	31.079	60.000	2.864	71.516	88.389
NPT-63	2.221	40.191	34.363	3.327	68.962	82.711
MRG-64	3.102	50.154	43.549	4.184	78.608	85.363
ALK-65	3.478	56.072	48.574	6.056	90.461	85.803
HKV-66	1.587	42.750	82.492	2.758	95.582	88.822
JAN-67	1.482	41.261	55.581	2.240	93.234	89.744
VDN-68	1.540	41.498	83.424	2.206	91.182	89.107
ESN-69	1.672	29.634	58.412	−3.791	46.810	82.052
ZTN-70	1.956	35.440	58.224	−1.193	57.300	84.138
MSY-71	2.314	37.582	65.782	−0.456	58.405	81.941
SDP-72	3.351	49.933	54.983	0.259	70.404	83.470

3.2.2. Sodium Percentage (Na%)

The Na% characterizes the cationic composition of water by indicating the proportion of Na^+ relative to total cations and the direction of ionic balance. This indicator is particularly important as it reflects the potential of water to contribute to the gradual accumulation of sodium in the soil exchange complex, without explicitly describing the underlying mechanisms. Under conditions of elevated Na%, the potential of soil sodicity increases, which may be accompanied by structural instability and reduced water permeability [33,52].

In the study area, Na% values ranged from 27.419 to 85.212 in the unconfined aquifer and from 25.798 to 70.043 in the confined aquifer (Tables 4 and 5). Although mean Na% values were slightly higher in unconfined groundwater, this difference was not statistically significant ($t = 1.075$, $df = 70.00$, $p = 0.2860$). According to the classification, groundwater in the unconfined aquifer was distributed as follows: 36.6% belonged to the good category, 48.8% to the permissible category, 12.2% to the doubtful category, and 2.4% to the unsuitable category. Na% classification of the unconfined aquifer reveals a clear spatial differentiation, with good-quality groundwater prevailing in the western part, transitioning to permissible in the central zone, while doubtful and unsuitable categories are mainly concentrated in the central-eastern parts, forming distinct high-risk zones (Figure 7A). According to the classification, groundwater in the confined aquifer was distributed as follows: 41.9% belonged to the good category, 54.9% to the permissible category, and 3.2% to the doubtful category. The Na% classification of the confined aquifer reveals a clear spatial pattern, with permissible groundwater predominating in the western part and partly in the northeastern zone, while good-quality water is mainly distributed from the central part toward the eastern areas. Doubtful water occurs only in localized zones, particularly in the southwestern part (Figure 7B).



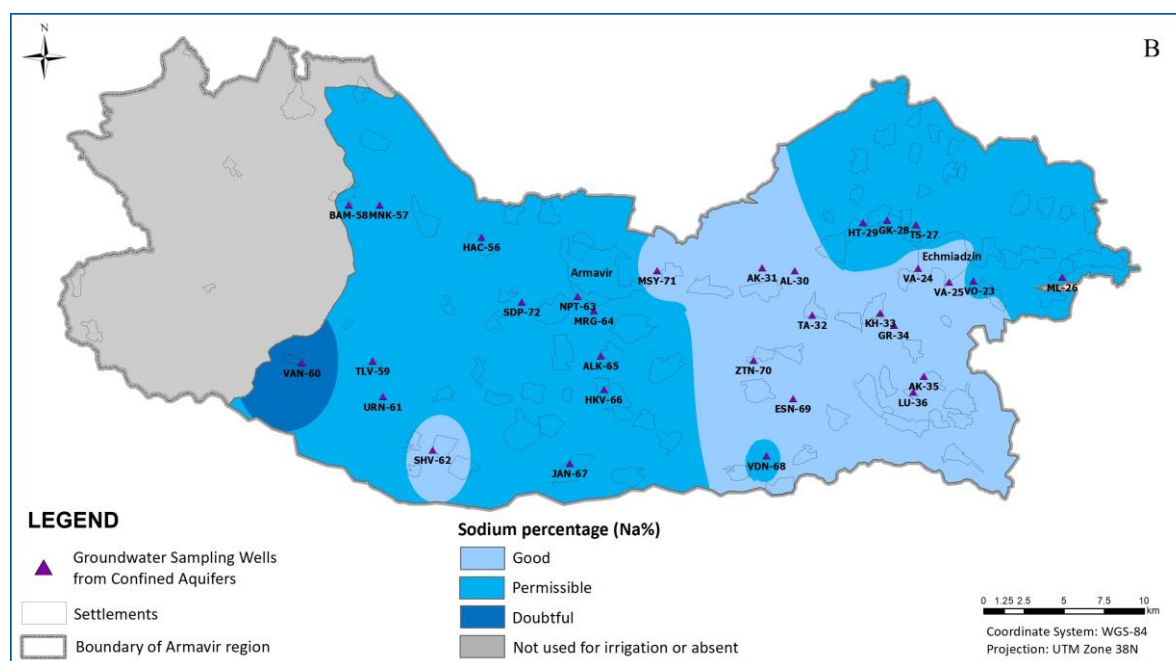


Figure 7. Spatial distribution of Na% values in the unconfined (A) and confined (B) aquifers of the Armavir region.

Monitoring the Na% in groundwater is of critical importance for assessing its suitability for irrigation. The application of groundwater with elevated Na% to agricultural land poses a significant risk of soil sodification, as high concentrations of sodium relative to other cations, particularly calcium and magnesium, promote the dispersion of clay particles within the soil matrix [32]. This dispersion leads to the clogging of soil pores, which subsequently results in reduced hydraulic conductivity and impaired infiltration rates [90,91]. Over time, this structural instability can severely limit crop productivity and necessitate costly land reclamation efforts [92]. The spatial differentiation identified in the study area indicates that a monolithic approach to groundwater use is inappropriate, necessitating the implementation of precision agricultural management. High-risk zones, classified as “doubtful” or “unsuitable,” require specific interventions, such as the application of soil amendments like gypsum to replace exchangeable sodium with calcium, or the selection of salt-tolerant crop varieties to maintain productivity [93–95]. In areas where groundwater quality is marginal, conjunctive use strategies blending poor-quality groundwater with higher-quality surface water or alternating irrigation sources can be employed to manage the cumulative salt and sodium load in the root zone. Furthermore, given that soil structural decline is a gradual process, modeling long-term soil degradation risk based on salinity and sodicity allows for proactive rather than reactive management [96,97].

3.2.3. Magnesium Hazard (MH)

Magnesium hazard (MH) represents the proportion of magnesium relative to the total concentration of divalent cations ($\text{Ca}^{2+} + \text{Mg}^{2+}$) and is used to assess the degree to which the ionic composition of water is biased toward magnesium dominance. This index is important because waters with elevated magnesium levels can gradually alter the composition of the soil exchange complex, reducing the relative contribution of calcium, which plays a key role in maintaining soil structural stability [35,36,38,52]. MH values in the studied groundwater ranged from 37.419 to 93.099 in the unconfined aquifer and from 34.363 to 91.791 in the confined aquifer (Tables 4 and 5). Statistical analysis indicated that

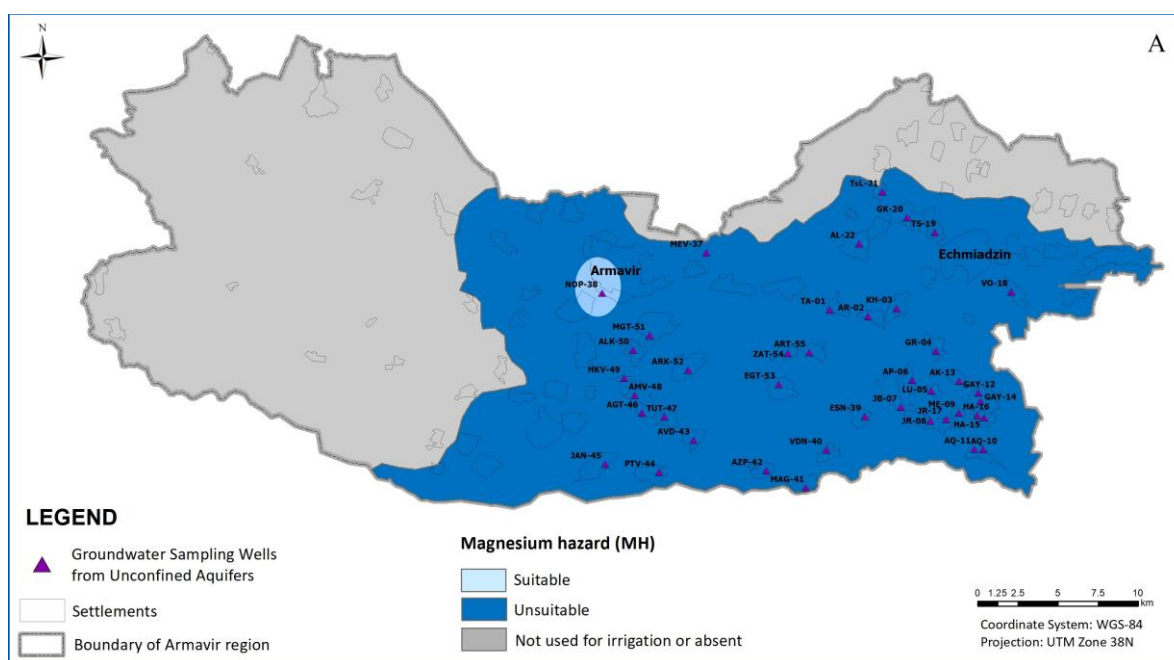
the MH index was sensitive to the aquifer type, as a significant difference was observed between the groups ($t = 3.298$, $df = 54.48$, $p = 0.0017$).

According to the classification, 2.4% of groundwater samples in the unconfined aquifer were categorized as suitable, while 97.6% were classified as unsuitable. The spatial distribution of MH in the unconfined aquifer indicates a clear predominance of unsuitable groundwater across almost the entire study area, with only a small, localized suitable groundwater zone observed in the central part of the region, extending slightly toward the north (Figure 8A). In the confined aquifer, 9.7% of groundwater samples were classified as suitable, whereas 90.3% were classified as unsuitable. Compared to the unconfined aquifer, the confined aquifer exhibits a more extensive zone of suitable groundwater, particularly in the central to northern parts of the region, indicating a relatively lower magnesium hazard (Figure 8B). It should be noted that the high MH values, which classify most samples as unsuitable, reflect the naturally magnesium-rich lithology of the Ararat Plain and do not act as a dominant driver of the integrated IWQI.

The MH is a critical index of potential soil structural degradation. Mechanistically, magnesium (Mg^{2+}) behaves differently than calcium (Ca^{2+}) in the soil matrix. While calcium is highly effective at promoting the flocculation of clay particles, thereby maintaining stable soil aggregates and high hydraulic conductivity, magnesium is less effective in this role [98]. When magnesium dominates the exchange complex, it can promote the disaggregation and dispersion of clay particles, especially in soils with specific mineralogy (e.g., illitic or smectitic clays). This dispersed clay can then migrate and clog soil pores, leading to a significant reduction in saturated hydraulic conductivity and impaired infiltration rates [99].

3.2.4. Residual Sodium Carbonate (RSC)

Within the framework of irrigation water quality assessment, it is important to consider not only the quantitative ionic composition but also the nature of chemical interactions and geochemical processes occurring within the soil-water system. In this context, RSC is particularly important, as it allows evaluation of the impact of the water's chemical environment on soil not only in terms of ionic proportions but also with respect to interaction and precipitation processes [38,88].



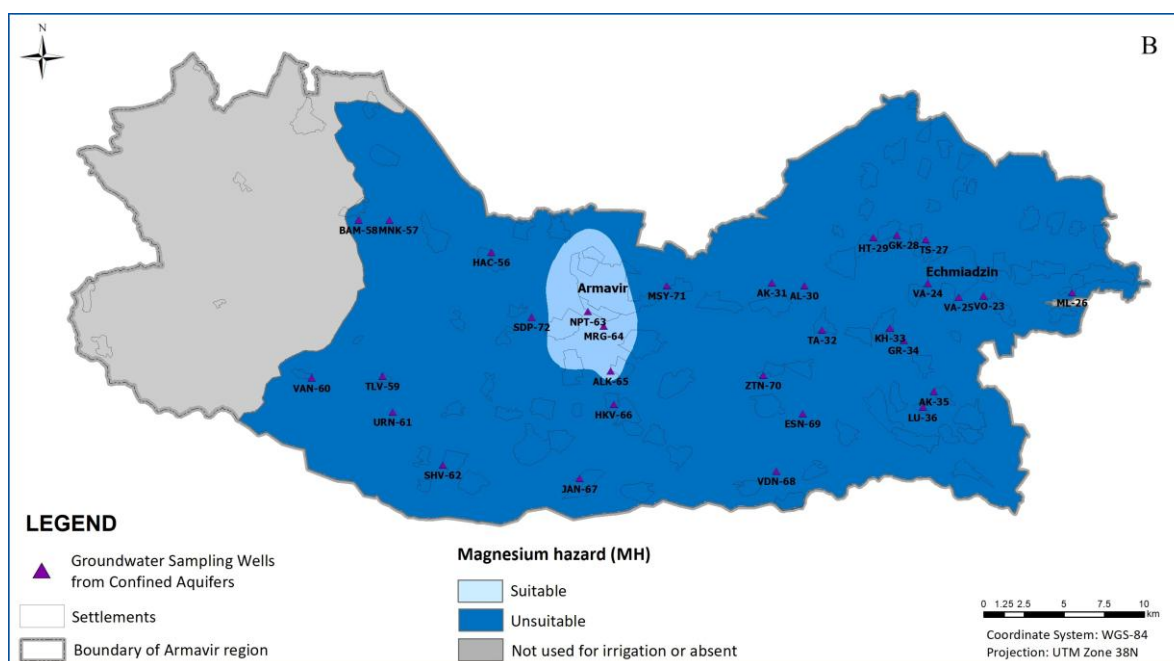


Figure 8. Spatial distribution of MH values in the unconfined (A) and confined (B) aquifers of the Armavir region.

RSC values for the studied groundwater are presented in Tables 4 and 5. In the unconfined aquifer, RSC values ranged from -8.264 to 12.688 . According to the classification, 39.0% of groundwater samples belonged to the good category (generally safe for irrigation), 22.0% to the medium category (marginal for use as an irrigation source), and 39.0% to the bad category (generally unsuitable for irrigation without appropriate management or treatment). The RSC classification of the unconfined aquifer reveals a clear spatial pattern, with good-quality groundwater predominantly distributed in the eastern part, transitioning to medium-quality groundwater in the central zone, while bad-quality water prevails in the western part and occurs in some southeastern areas (Figure 9A). In the confined aquifer, RSC values ranged from -5.897 to 6.056 and were classified as follows: 67.7% belonged to the good category, 12.9% to the medium category, and 19.4% to the bad category. The RSC classification of the confined aquifer indicates that good-quality groundwater predominates across most of the study area, mainly extending from the central part toward the eastern region, as well as occurring in certain areas of the western part. Medium-quality groundwater is primarily distributed from the central zone toward the western part, with additional localized occurrences in the eastern and southern areas. Bad-quality groundwater is mainly concentrated in the central part of the region and occurs as isolated patches in the southwestern areas (Figure 9B). Statistical analysis showed that the RSC index differed significantly between the investigated aquifers ($t = 2.535$, $df = 69.99$, $p = 0.0135$), with higher values observed in the unconfined groundwater. Mechanistically, high RSC indicates an excess of carbonate and bicarbonate ions, which trigger the precipitation of calcium and magnesium as insoluble carbonates in the soil matrix [100]. This precipitation removes soluble calcium and magnesium from the soil solution, thereby increasing the relative proportion of sodium and exacerbating the SAR, which promotes clay dispersion and structural degradation [101].

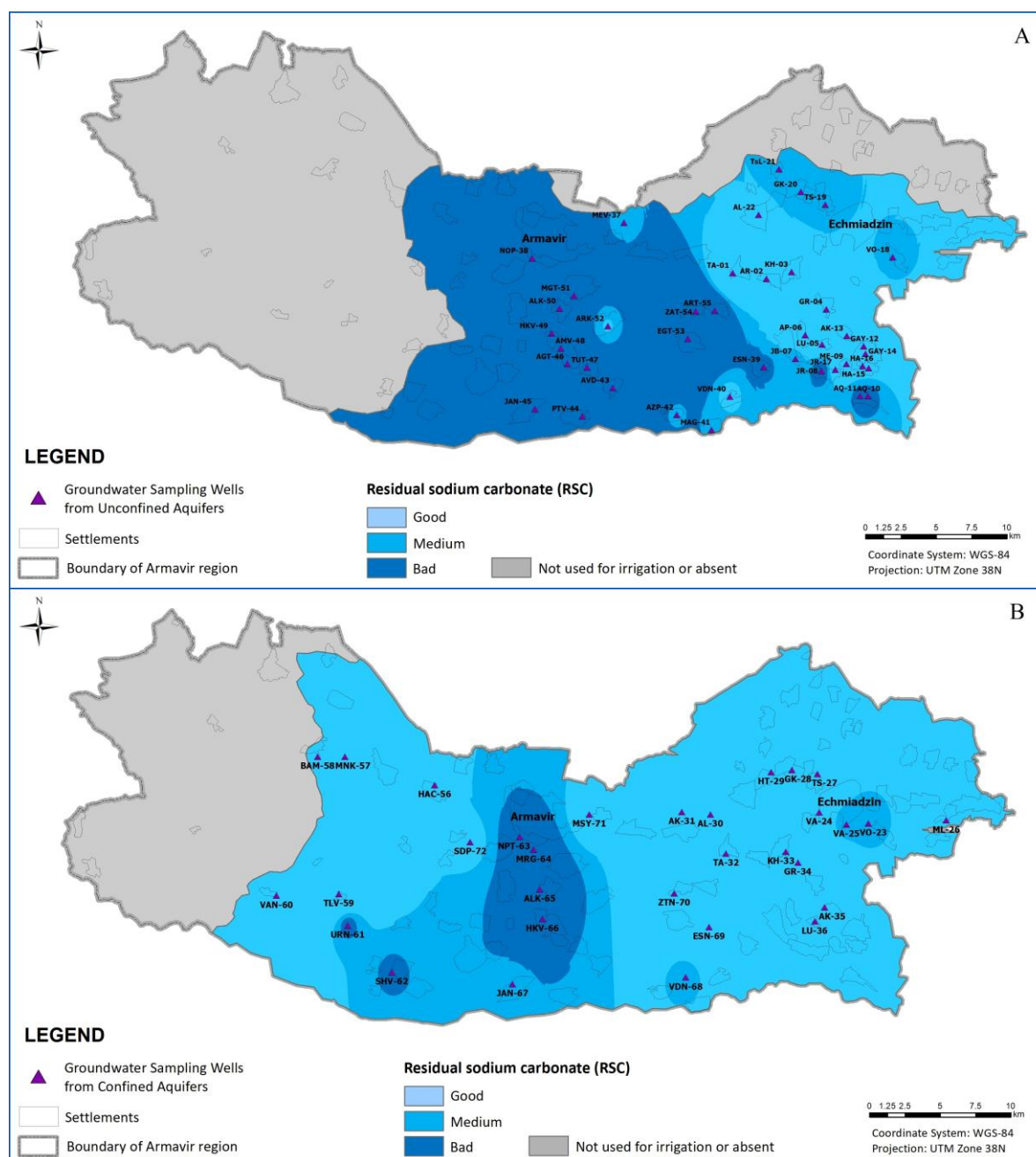


Figure 9. Spatial distribution of RSC values in the unconfined (A) and confined (B) aquifers of the Armavir region.

3.2.5. Permeability Index (PI)

The PI is applied in irrigation water assessment to characterize the effect of ionic composition on soil permeability and water movement within the soil profile. This index is particularly valuable because it integrates the combined effects of sodium and bicarbonate ions with divalent cations (Ca^{2+} , Mg^{2+}), thereby reflecting the likelihood of maintaining or disrupting the soil pore system. The use of the PI is important not only for assessing water quality but also for predicting changes in the soil hydrodynamic regime, thereby enabling evaluation of the long-term impacts of irrigation water [39,88,102]. In the study area, PI values of groundwater ranged from 45.152 to 102.448 in the unconfined aquifer and from 44.341 to 95.582 in the confined aquifer (Tables 4 and 5). The values of the PI index were nearly identical in the confined and unconfined aquifers, and no statistically significant difference was observed between them ($t = 0.037$, $df = 67.78$, $p = 0.9704$).

In the unconfined aquifer, groundwater samples were classified as follows: 39.0% belonged to Class I (good for irrigation), and 61.0% to Class II (suitable for irrigation). The PI classification of the unconfined aquifer indicates that Class I groundwater is mainly distributed in the northeastern and southeastern parts of the region, with additional occurrences in the southern zone. The remaining parts of the region are classified as Class II groundwater (Figure 10A). Groundwater in the confined aquifer was classified as follows: 38.7% belonged to Class I, and 61.3% to Class II. A distinct spatial pattern is observed in the PI classification of the confined aquifer, with Class I groundwater distributed over relatively extensive central-southern, eastern and southern zones and occurring as distinct patches in the northeastern part of the region. All other areas are classified as Class II groundwater (Figure 10B). The observed spatial distribution of PI classes where significant portions of the study area fall into Class II suggests that while the water may be usable, it carries a latent risk of reducing soil permeability over time. This necessitates the adoption of precision irrigation management, such as the application of soil amendments (e.g., gypsum) to counteract the dispersive effects of sodium and bicarbonate, or the implementation of conjunctive use strategies to balance the ionic load [103,104]. Furthermore, as recent studies indicate, the effectiveness of these management strategies is enhanced when PI monitoring is integrated with advanced geochemical modeling and spatial analysis, allowing for site-specific interventions that preserve the soil pore system and ensure long-term agricultural sustainability [105].

3.3. Graphical Evaluation of Groundwater Quality for Irrigation

3.3.1. Assessment of Water-Rock Interaction and Ionic Ratios

The Gibbs diagram is widely used in hydrochemical analysis to identify the dominant natural processes controlling the ionic composition of water. It is based on the relationship between TDS and major ion ratios, enabling the differentiation of systems governed by rock weathering, evaporation-crystallization, or atmospheric precipitation [41,42,106]. Analysis of the Gibbs diagrams indicated that the chemical composition of the studied groundwater is predominantly governed by water-rock interaction processes. In both aquifers, the predominant part of the samples is located in the rock dominance zone, which indicates that the mineralization of water is mainly formed by the processes of dissolution of ions from aquifers and chemical decomposition of soil materials (Figure 11A,B). In the diagram constructed on the basis of the $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ ratio, a significant part of the samples is concentrated in the range of medium and high values, which indicates the relative predominance of sodium and the influence of cation exchange processes. At the same time, most of the TDS values are at the average level, which indicates moderate mineralization of groundwater. In the $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ratio diagram, groundwater is mainly distributed in the low and medium ratio range, which indicates the important role of the hydrocarbon component and confirms the dominance of rock weathering processes.

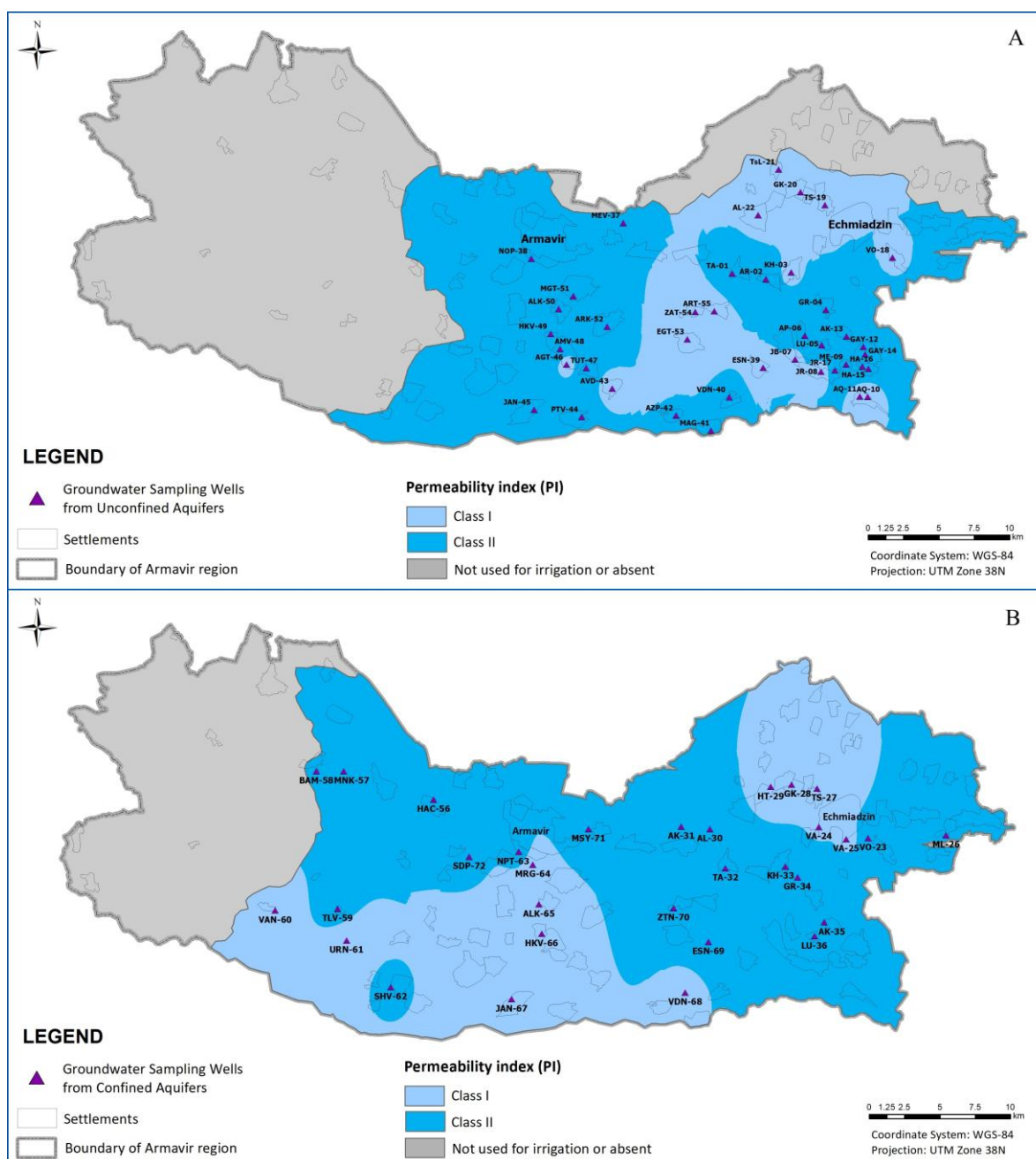


Figure 10. Spatial distribution of PI values in the unconfined (A) and confined (B) aquifers of the Armavir region.

A more detailed explanation of the analysis of rock dominance in the process of formation of the chemical composition of groundwater expressed by the Gibbs diagram is provided by bivariate plots. Analysis of the relationship between Na^+ and Cl^- ions shows that about half of the samples are close to the theoretical 1:1 line of halite (NaCl) dissolution. In the other half, the relative excess of sodium can be attributed to the weathering of sodium-containing silicate minerals and ion exchange (Figure 12a). The weathering process of silicate minerals and ion exchange was relatively more pronounced in the confined aquifer. This suggests that the prolonged groundwater residence time characteristic of confined aquifers facilitates the activation of forward cation exchange processes, during which additional sodium is released from the rock matrix into the aqueous environment (Figure 12c).

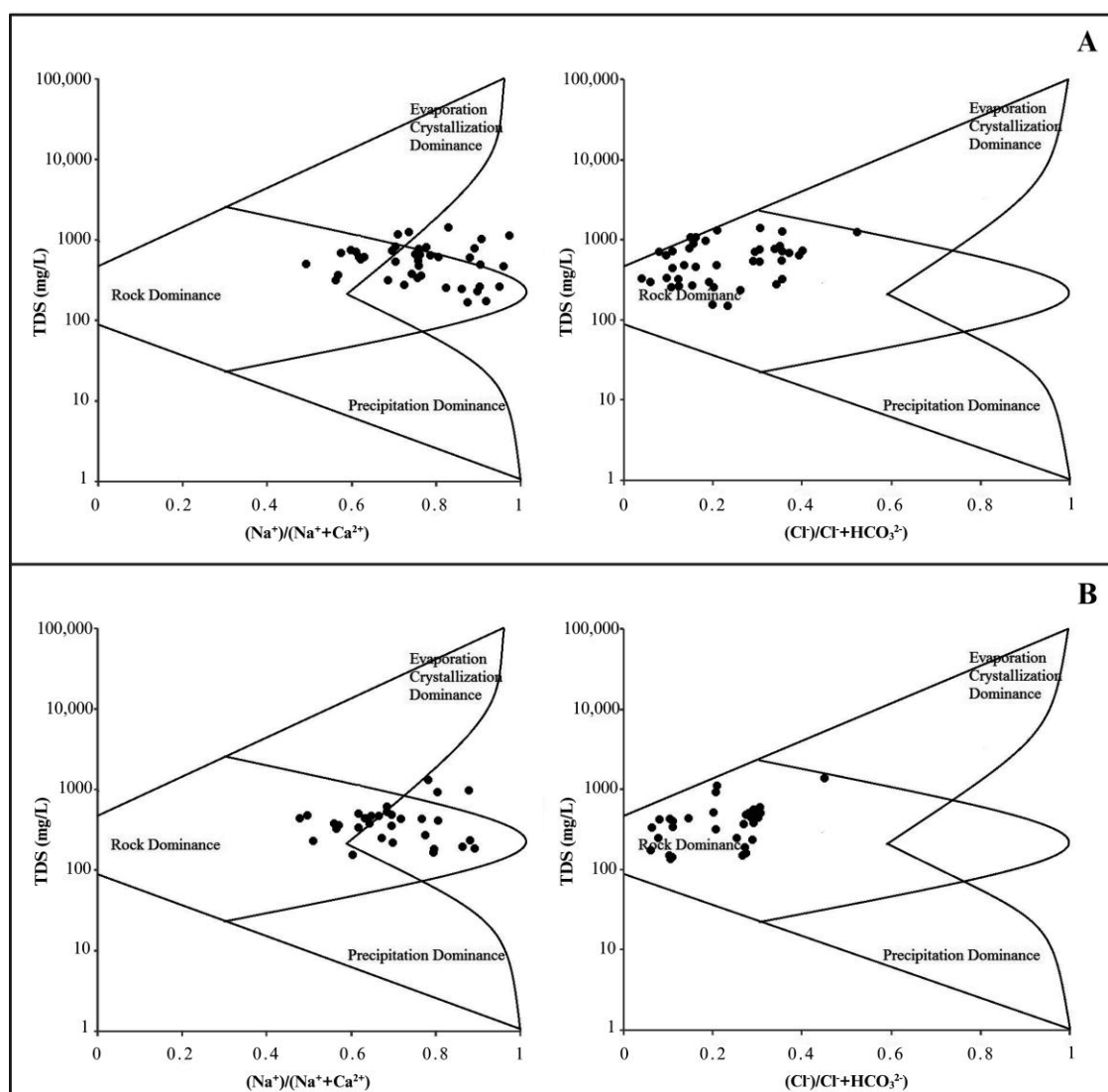


Figure 11. Gibbs diagram for groundwater from the unconfined (A) and confined (B) aquifers of the Armavir region.

The $\text{Ca}^{2+} + \text{Mg}^{2+}$ against HCO_3^- plots show that unconfined and confined aquifers do not differ significantly from each other and that carbonate weathering and ion exchange processes predominate in almost all samples, which confirms the role of carbonate mineral (calcite and dolomite) solution in the formation of alkaline earth cations and bicarbonates (Figure 12b,d).

3.3.2. USSL and Wilcox Diagrams

The USSL and Wilcox diagrams are applied as complementary tools for the comprehensive assessment of irrigation water quality, taking into account the combined effects of salinity and sodium hazard. The USSL approach is based on the relationship between EC and SAR and is primarily used to evaluate risks to soil structural stability. In contrast, the Wilcox diagram, which incorporates EC and Na%, provides a general classification of irrigation water quality. Their combined application enables a more accurate differentiation of water suitability under varying agro-ecological conditions [38,47,88]. Analysis of the USSL classification revealed that, in the unconfined aquifer, 4.9% of groundwater wells fall within the C2-S1 category, 73.2% within C3-S1, 9.7% within C3-S2, 4.9% within C4-S1, 4.9% within C4-S2, and 2.4% within C4-S4. In contrast, groundwater from the confined aquifer is distributed as follows: 19.4% in C2-S1, 71% in C3-S1, 6.4% in C3-S2, and

3.2% in C4-S2. This distribution indicates a predominance of high-salinity (C3) waters with generally low sodium hazard (S1), although the presence of higher salinity and sodicity classes suggests localized risks for soil structure degradation and reduced permeability under irrigation (Figures 13a and 14a).

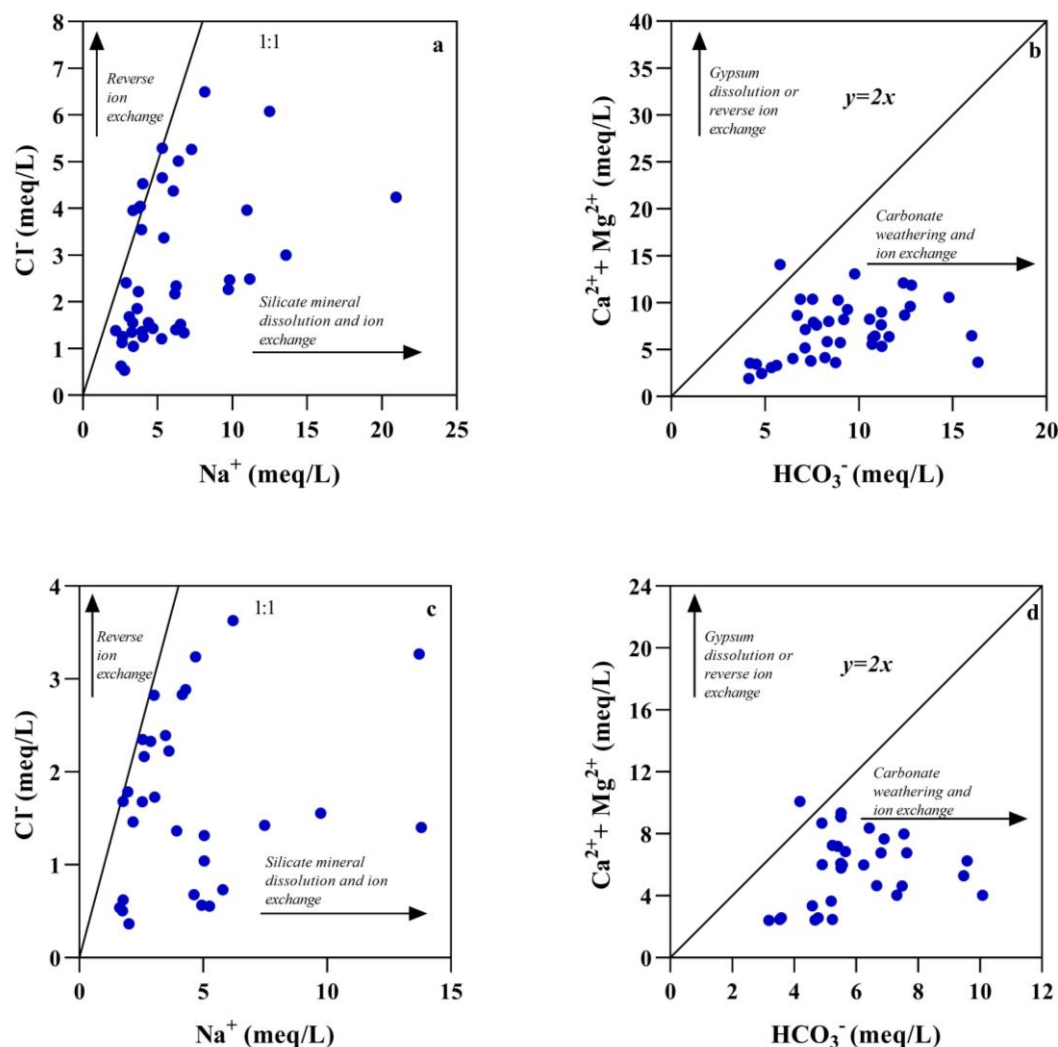


Figure 12. Bivariate plots of: Na^+ (meq/L) against Cl^- (meq/L) for the unconfined aquifer (a), $\text{Ca}^{2+} + \text{Mg}^{2+}$ (meq/L) against HCO_3^- (meq/L) for the unconfined aquifer (b), Na^+ (meq/L) against Cl^- (meq/L) for the confined aquifer (c), and $\text{Ca}^{2+} + \text{Mg}^{2+}$ (meq/L) against HCO_3^- (meq/L) for the confined aquifer (d).

The Wilcox diagram analysis further supports these findings. In the unconfined aquifer, 14.6% of groundwater samples are classified as “doubtful to unsuitable”, 12.2% as “permissible to doubtful”, 68.3% as “good to permissible”, and 4.9% as “excellent to good”. For the confined aquifer, 3.2% of samples fall into the “doubtful to unsuitable” category, 6.4% into “permissible to doubtful”, 67.8% into “good to permissible”, and 22.6% into “excellent to good” (Figures 13b and 14b). Overall, the confined aquifer demonstrates comparatively better irrigation suitability, with a higher proportion of waters in the favorable quality classes. The occurrence of relatively lower-quality groundwater, particularly in the unconfined aquifer, can be attributed to a combination of natural and anthropogenic factors. Natural controls include the region’s arid to semi-arid climatic conditions, high evaporation rates, and lithological characteristics that promote mineral dissolution and salt accumulation. Anthropogenic influences such as intensive agricultural

practices, inefficient or traditional irrigation methods, excessive groundwater abstraction, and the over-application of mineral fertilizers further exacerbate salinization and sodium-related hazards [4,107].

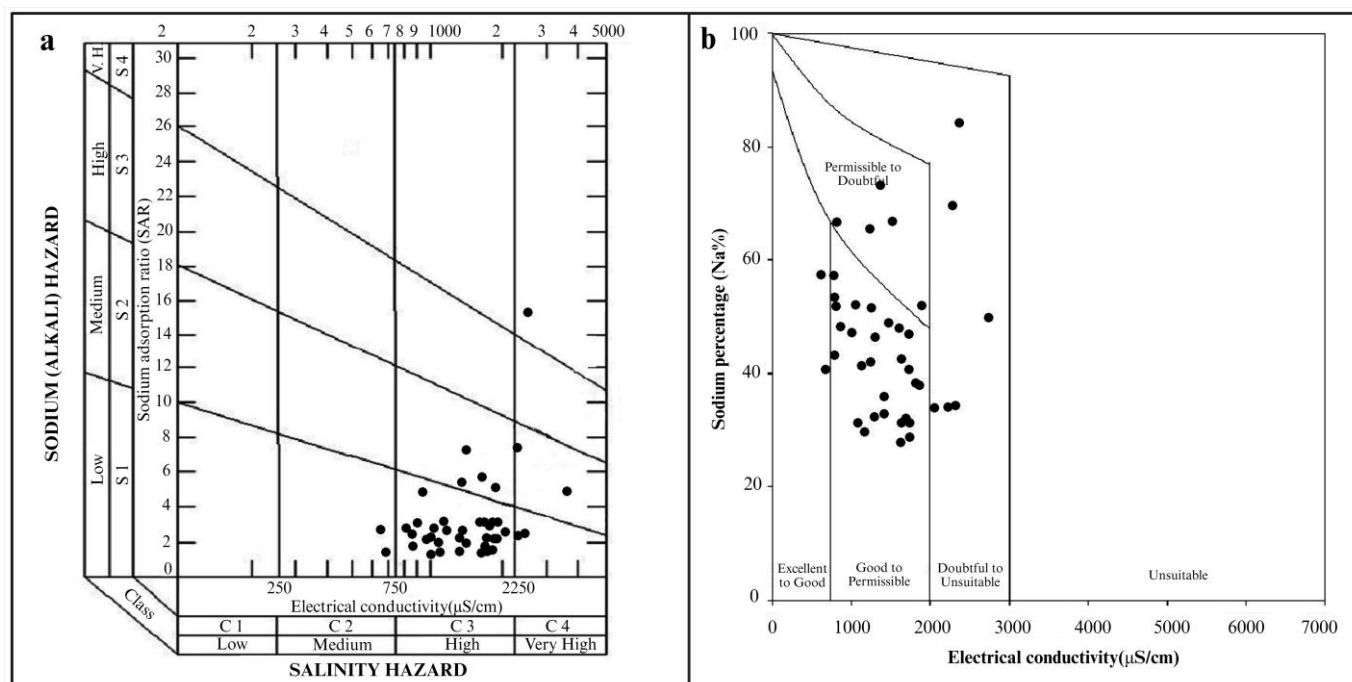


Figure 13. Classification of groundwater from the unconfined aquifer using the USSS (a) and Wilcox (b) diagrams of the Armavir region.

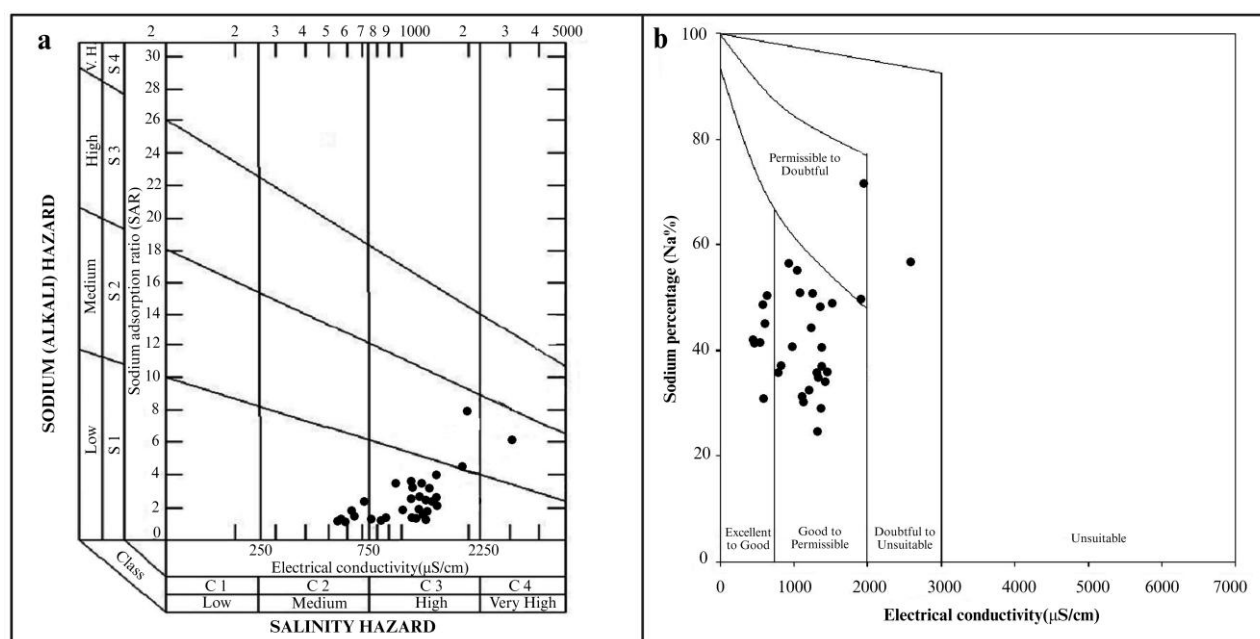


Figure 14. Classification of groundwater from the confined aquifer using the USSS (a) and Wilcox (b) diagrams of the Armavir region.

3.4. Assessment of the Irrigation Water Quality Index (IWQI)

The IWQI was applied as an integrated assessment index to comprehensively evaluate the suitability of groundwater for irrigation by combining key hydrochemical parameters and indices into a single value. It is particularly valuable as it provides a holistic assessment of water quality, taking into account the combined effects of salinity, sodium

hazard, and their potential impacts on soil properties. This approach enables a more precise differentiation of water suitability levels and supports the justification of their effective use [4,15,21]. During the study period, IWQI values in the unconfined aquifer ranged from 69.18 to 90.10, with a mean value of 80.76. In the confined aquifer, IWQI values ranged from 71.39 to 90.76, with a mean value of 84.40 (Tables 4 and 5). Notably, no groundwater samples corresponding to classes III, IV, or V were identified in the study area. Comparison of IWQI values indicated that water from the confined aquifer has more favorable quality characteristics for irrigation purposes than water from the unconfined aquifer ($t = 3.121$, $df = 69.34$, $p = 0.0026$).

According to the IWQI values, groundwater in wells of the unconfined aquifer was classified into two classes. Specifically, 46.34% of the groundwater fell into Class I, while 53.66% was categorized as Class II. It should be noted that a secondary soil salinization process was also observed in areas with the lowest IWQI values [82]. In contrast, the confined aquifer also exhibited two classes, but the distribution differed slightly: 90.30% of the groundwater was classified as Class I and 9.70% as Class II. In the unconfined aquifer, the parameters belonging to Group 1 (salinity) and Group 2 (infiltration) showed the greatest deviation from optimal values, representing the primary drivers of IWQI reduction in this aquifer type. In confined aquifers, the values of the IWQI were relatively high compared to those in unconfined aquifers. However, in certain observation points, the values have decreased due to lower indices in the first group (salinity). According to the map of the unconfined aquifer, groundwater in the central and eastern parts of the province predominantly falls into the excellent (Class I) category. Good quality water (Class II) is found in the central region extending towards the east (Figure 15A). The map of the confined aquifer reveals that most groundwater is in the excellent category, indicating that water extracted from deeper wells is of high quality (Figure 15B). However, only the western part of the region has groundwater classified as good quality water. Groundwater quality deterioration is driven by a combination of active agricultural practices and inadequate water management. Long-term irrigation with water of elevated salinity under the climatic and geohydrological conditions of the Ararat Plain, characterized by low precipitation, high evaporation rates, poor natural drainage, and shallow groundwater levels, can lead to progressive soil salinization and reduced crop yields, and may ultimately render affected lands unsuitable for agriculture. From an economic and agronomic perspective, preventing soil salinization through appropriate water management is considerably more cost-effective than the subsequent remediation of salinized soils. Therefore, engaging farmers in environmental stewardship, particularly with respect to groundwater and soil resource management, is essential, given their central role in both driving and mitigating salinization processes [21,38,107]. The obtained results are consistent with findings from studies in other arid and semi-arid regions, where groundwater suitability for irrigation is primarily limited by factors related to salinization, sodium hazard, and soil infiltration capacity [14,64]. Specifically, a study conducted in the Masis Province, which is adjacent to the study area, also demonstrated that groundwater from the confined aquifer is characterized by higher IWQI values and more favorable irrigation quality compared to that from the unconfined aquifer [4]. Similar patterns of groundwater quality variation and suitability constraints have been documented in studies of arid and semi-arid regions, where hydrochemical characteristics are often influenced by processes such as evaporation, mineral dissolution, and anthropogenic activities [108,109].

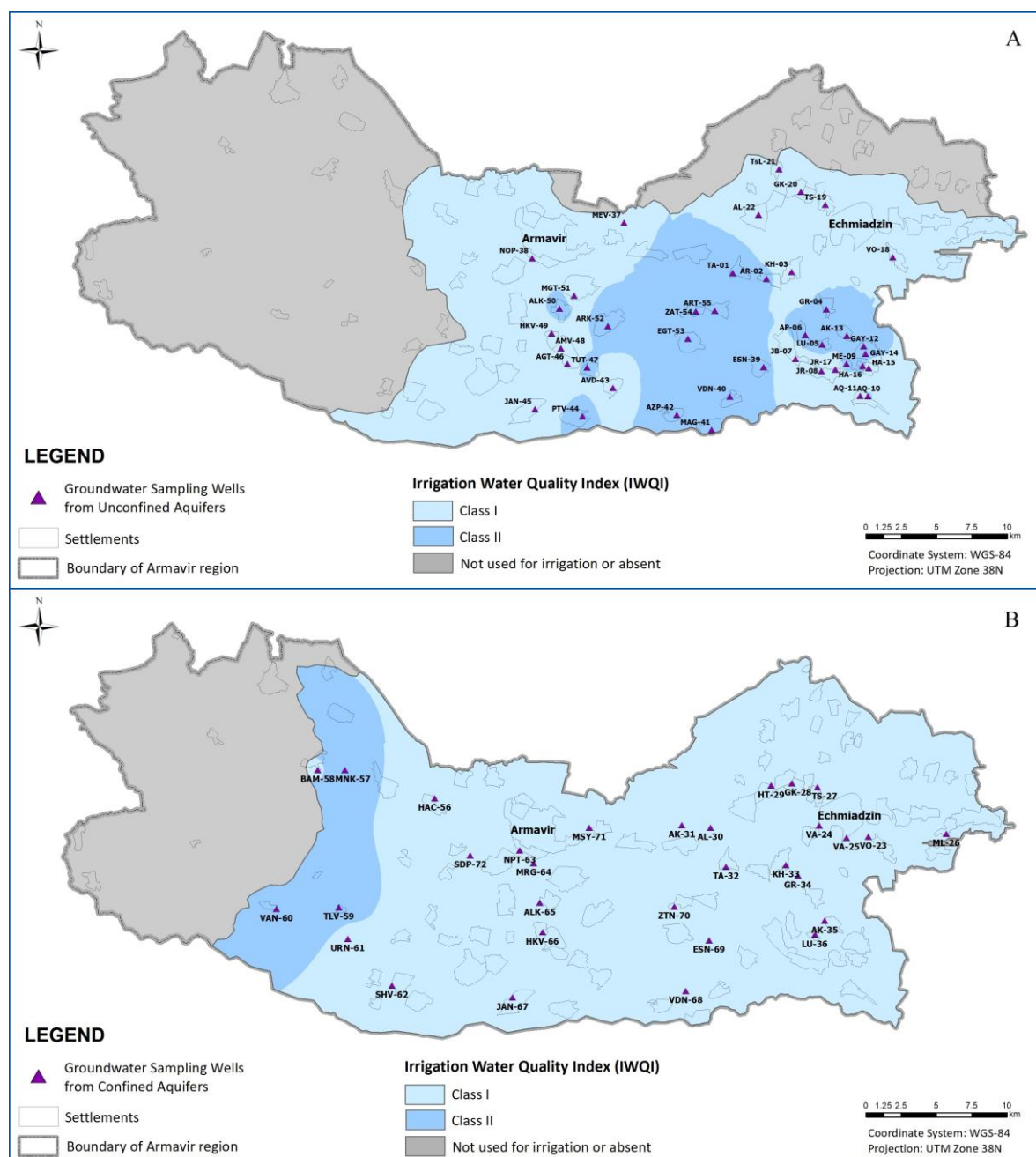


Figure 15. Spatial distribution of IWQI values in the unconfined (A) and confined (B) aquifers of the Armavir region.

4. Conclusions

Analysis of the ionic composition of the studied groundwater revealed that the dominant cation sequence is $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{K}^+$, while among the major anions the prevailing order is $\text{HCO}_3^- > \text{Cl}^-$, with CO_3^{2-} not detected in any sample. In the unconfined aquifer, ion concentrations were generally higher and more variable, reflecting the stronger influence of surface-related processes such as precipitation, irrigation return flows, and soil leaching. In contrast, the confined aquifer exhibited more stable ionic compositions, primarily controlled by deeper hydrochemical processes including water-rock interaction and longer residence times. The assessment of the main hydrochemical parameters (EC, TDS and pH) and irrigation suitability indices (SAR, Na%, MH, RSC and PI), as well as graphical analyses, showed that the irrigable properties of the studied groundwaters, depending on the assessment approach, can differ significantly from each other, which can

lead to improper management of water resources and, as a result, to the degradation of agricultural lands in the region.

In contrast to the above-mentioned diversity of groundwater assessment values, sometimes even contradictory, the IWQI made it possible to give a complete assessment of the irrigable properties. The IWQI results indicate that groundwater in the study area is predominantly classified within the good to excellent categories, with more favorable conditions observed in the confined aquifer. The Irrigation Water Quality Index demonstrated its effectiveness as an integrated tool for evaluating groundwater suitability for irrigation: by combining key hydrochemical parameters into a single composite value, it provides a comprehensive assessment that accounts for salinity, sodium hazard, and their potential impacts on soil properties and crop development. Compared to approaches based on individual indicators, the IWQI offers a more consistent and practically applicable evaluation, enabling clearer differentiation of water quality classes. Moreover, its adaptability to different regional hydrochemical conditions and its capacity to incorporate updated monitoring data enhance its suitability for long-term groundwater management. The spatial mapping results further confirmed the utility of GIS-based approaches for identifying high-risk zones and supporting targeted water management interventions at the local scale.

Despite the comprehensive methodological approach adopted, several limitations of this study should be acknowledged. The dataset spans the irrigation seasons of 2022 and 2023; while seasonal variability was captured through spring, summer, and autumn sampling campaigns, longer-term multi-year monitoring would be necessary to detect inter-annual trends and assess the potential influence of climate variability on groundwater quality dynamics. Sulphate (SO_4^{2-}) concentrations were not included in the hydrochemical dataset, as sulphate levels in the groundwater of the Ararat Plain are generally low due to the predominance of carbonate lithology, and preliminary screening indicated values below the threshold of irrigation concern. Nevertheless, their systematic inclusion in future monitoring campaigns would further strengthen the comprehensiveness of the IWQI calculation.

Future research should expand the monitoring network to other regions of the Ararat Plain to enable a basin-scale assessment of groundwater quality dynamics and facilitate the identification of regional salinity trends. Additionally, coupling groundwater quality assessments with soil salinity monitoring programs and crop yield data would allow a more complete evaluation of the long-term agronomic impacts of irrigation water quality, providing a stronger and more actionable evidence base for sustainable land and water management policy in the South Caucasus region. In parallel with all this, to improve water use efficiency and mitigate groundwater over-abstraction, transitioning to precision irrigation technologies is necessary, as these methods effectively minimize water losses and prevent secondary soil salinization. The active involvement of farmers, water authorities, and policymakers in evidence-based groundwater stewardship represents an essential step toward the sustainable management of this vital resource and the prevention of irreversible soil-water system degradation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18147451/s1>, Table S1: Classifications of the irrigation water quality indices and hydrochemical parameters, Table S2: Groups, weighting factors, and quality rating functions for IWQI parameters, Table S3: General information of unconfined aquifer wells in Armavir region, Table S4: General information of confined aquifer wells in Armavir region.

Author Contributions: A.H., H.K., A.S. and K.G.: conceptualization, methodology, data curation and writing—original draft preparation. A.H., A.G. and K.G.: software and formal analysis and visualization. A.H., H.K., A.E. and K.G.: investigation and resources. A.S.; R.K.S. and M.A.S.: writing—

review and editing and project administration. K.G., A.S. and M.A.S.: validation, supervision and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Higher Education and Science Committee of the Ministry of Education, Science, Culture, and Sports (MESCS) of the Republic of Armenia under research project No. 21AG-4C075.

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: All data are presented in the article. If additional information is needed, it is available from the corresponding author upon reasonable request.

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

Abbreviations

The following abbreviations are used in this manuscript:

EC	Electrical conductivity
GIS	Geographic Information System
IDW	Inverse distance weight
IWQI	Irrigation Water Quality Index
MH	Magnesium hazard
MESCS	Ministry of Education, Science, Culture, and Sports
SAR	Sodium adsorption ratio
PI	Permeability index
RSC	Residual sodium carbonate
TDS	Total dissolved solids
QR	Quality rating
USSL	United States Salinity Laboratory
Wf	Weighting factor

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