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Evaluation of Groundwater Quality Using the Water Quality Index (WQI) and Human Health Risk (HHR) Assessment in West Bank, Palestine

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Abstract: Access to clean and safe water is extremely important, not only in Palestine but also worldwide. In the West Bank, groundwater is particularly valuable because of its scarcity and inaccessibility, and, due to the nature of the area's aquifers, is currently regarded as being at high risk of pollution. Moreover, the water quality in this area is also of wide concern, with its effects being directly linked to human health. Certain parts of the West Bank groundwater suffer from high concentrations of nitrate and potassium. In total, 38.8% of nitrate and 10% of potassium concentrations in well samples exceed the permissible limit set by the WHO and PSI, and, therefore, health problems arise as a limiting factor for life quality and welfare in this region. Moreover, 87.7% of samples are classified as having very hard water. To evaluate the well water in the study area, an assessment was conducted based on the WQI and HHR. Therefore, 49 samples were taken from a group of wells distributed across the study area during the year 2021. The physico-chemical parameters of each sample were analysed. The WQI values showed that 78% of the well samples were of good quality. Moreover, in the classification of the water based on a Piper diagram, 65% of the groundwater was determined to be calcium–magnesium–bicarbonate-type water. Likewise, health risk assessments were evaluated for fluoride and nitrate in drinking water for adults, children, and infants. The main values of the estimated total hazard index (THI) obtained from the analysed data on the health risk assessments revealed a diverse effect on the local population based on age category. The ranges of THI in all sampling locations varied considerably and extended from 0.093 to 3.01 for adults, 0.29 to 3.08 for children, and 0.302 to 3.21 for infants. These results widely indicate that infants are more exposed to health risks.

Keywords: groundwater contamination; physico-chemical parameters; water quality index (WQI); total hazard index (THI); Piper diagram; West Bank

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1. Introduction

Groundwater remains a major and extremely important source of drinking water around the world. In fact, groundwater supplies around 33% of the world's freshwater needs [1]. Groundwater is becoming increasingly vital in low-precipitation regions that already suffer from water scarcity and uneven distribution [2,3]. In the West Bank, where the majority of the water supply is provided by groundwater, access to safe drinking water is crucial [4]. The Mountain Aquifer is an important water source, the importance of which is widely attributed to both the quantity and high quality of its freshwater [5]. It is mainly composed of karstic and permeable limestone and dolomite formations of the Cenomanian and Turonian ages [6]. Karsts are the fractures and joints in rocks that form conduits and caves. These formations can store groundwater. Moreover, the flow can be rapid through fractures that have been enlarged by dissolution [7]. However, the biggest threat to the water quality in the Mountain Aquifer is pollution due to wastewater and agricultural activity [8]. Various groups of well-known factors related to groundwater pollution in different regions of the world have been studied and detailed, including rapid population growth, untreated sewage, leaking septic tanks and domestic waste, increased industrialization and the overuse of fertilizers in agricultural activities, the dissolution of minerals and the interactions between water and rocks, the evaporation of groundwater, and changes in land cover and changes that occur in the natural environment [9–11].

Groundwater pollutants can be attributed to either inorganic metals, including total dissolved salts (TDSs), heavy metals, cations, and anions, or pathogens, such as bacteria, viruses, and parasites [12,13]. Over the past few decades, groundwater quality has become a serious dispute worldwide, leading to extensive research on quality and health risk assessments carried out by countries such as India, China, and Tunisia [14–16]. Furthermore, 80% of the health risks are connected to the consumption of contaminated water [17]. Zohud [18] reported that limited studies have been conducted on the extent of the health risks associated with the groundwater in the West Bank. Elevated nitrate (NO_3^-) levels surpassing 50 mg/L can result in potential health risks [19]. Rising nitrate levels in groundwater are hazardous to human health and can impact haemoglobin, potentially causing methemoglobinemia disorder, which mainly affects the health of infants and children [20]. The fluoride (F^-) in groundwater usually helps to promote dental health by reducing dental caries when consumed in small doses, while large doses may result in fluoride toxicities [9,21]. The F^- concentration has been found to be within the permissible level in the West Bank, but not in the Gaza Strip [22,23]. The chloride (Cl^-) in groundwater may originate from natural sources or anthropogenic sources, such as wastewaters, cesspits, and fertilizers [24,25]. When the Cl^- concentration rises in groundwater, it develops a saline flavour, which may cause diarrhoea to allergic individuals [26]. Hejaz [27] reported that the Cl^- concentration in the groundwater of the northern West Bank is below the permissible level of 250 mg/L, but that 18% of the NO_3^- concentration is above the permissible level of 50 mg/L. However, Daghara [28] reported that 24% of Cl^- and 21% of NO_3^- concentrations are above the permissible limit in the springs of the West Bank. A high level of sulphate (SO_4^{2-}) in groundwater causes a bitter flavour and may cause diarrhoea, which can lead to dehydration and put infants at severe risk [29]. The minerals in water are essential for the development of the human body, but only when found within the permissible limits [30,31]. Mahmoud [22] reported that there are three main hydrochemical facies in the West Bank: freshwater, freshwater mixed with another water type, and an extreme water type. Using a variety of water quality parameters, the water quality index (WQI) is a useful tool for evaluating water quality [32]. These parameters have been assigned weights according to their importance and health effects [33]. However, we are aware that, in our region, the groundwater quality typically deteriorates during the dry season and improves during the rainy season. Therefore, we deliberately selected the dry season for our study.

This study aimed to (1) analyse the hydrogeochemical properties and hydrochemical facies of the groundwater, as well as their formation mechanisms, and to assess the groundwater quality in the northern West Bank; (2) use the WQI to assess the drinking groundwater quality; and (3) to determine the extent to which the fluoride and nitrate concentrations pose a non-cancerous health risk to adults, children, and infants. Finally, there is a lack of studies evaluating groundwater quality using the WQI and HHR in the West Bank, which makes this study extremely significant. Nonetheless, the outputs of this study are important for stakeholders, including researchers, decision makers, and policymakers, and it will also facilitate the management of water resources and enhance the protection and sustainability of groundwater in the West Bank, Palestine. This is anticipated to be necessary to confront the increasing water scarcity in the coming years.

2. Materials and Methods

2.1. Study Area

The West Bank is a Palestinian territory located in the Mediterranean Region, west of Jordan. It is surrounded by the Dead Sea and the Jordan River on the east and by Israel on three sides. It has a total area of 5860 km^2 and a population of approximately 3,100,000 registered in 2020. The West Bank rocks contain a complex sequence of limestone, dolomite, chalk, and marl [7]. The climate of the West Bank is Mediterranean, which fluctuates from 250 mm of rain in the east and southeast to more than 500 mm in the west (Figure 1). The climate is characterised by cold and rainy winters, and it gradually becomes hot and dry during the summer. The average annual rainfall in the study area is between 450 and 650 mm [34], with a gradual distribution that increases from the east and west towards the mountain areas, where a large amount of this rainfall leaks out to feed the groundwater, and the rest runs into the nearest valleys. The study area is formed by the governorates of the northern West Bank; these include Nablus, Qalqilya, Jenin, Tulkarm, Tubas, and Salfit, which had total populations of about 400,000, 120,000, 335,000, 200,000, 65,000, and 80,000 in the year 2020, respectively [35].

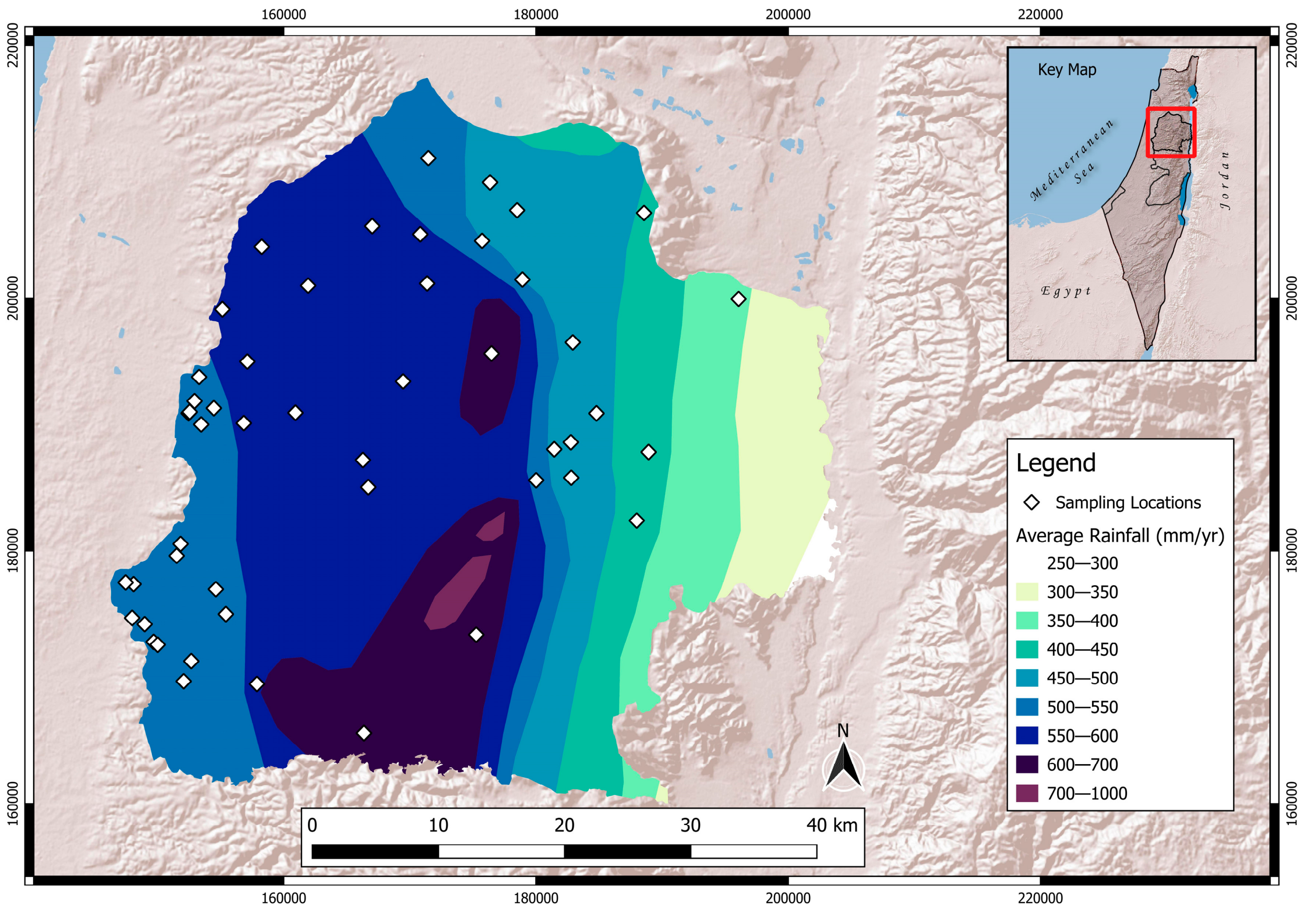


Figure 1. Annual rainfall distribution for the study area.

The Mountain Aquifer is split into three sections: the Eastern, Northeastern, and Western Aquifers (Figure 2). While portions of the Northeastern Aquifer and the Eastern Aquifer flow eastward towards the Jordan River, portions of the Northeastern Aquifer and the Western Aquifer flow westerly towards the Mediterranean Sea [36,37]. The study area is divided into two main aquifers, the Western and Northeastern Aquifers. The governorates of Tulkarm, Qalqilya, Salfit, and the northern part of Nablus are located in the western basin, while Jenin, Tubas, and the southern part of Nablus are located in the northeastern basin. Chalk, dolomite, and limestone from the Upper Cretaceous to Tertiary era make up the majority of the Mountain Aquifer [25]. Due to extensive fracturing and karst channels, the limestone and dolomite rock formations possess relatively high hydraulic conductivities, while marl rocks, characterised by limited fracturing, exhibit significantly lower hydraulic conductivity [38].

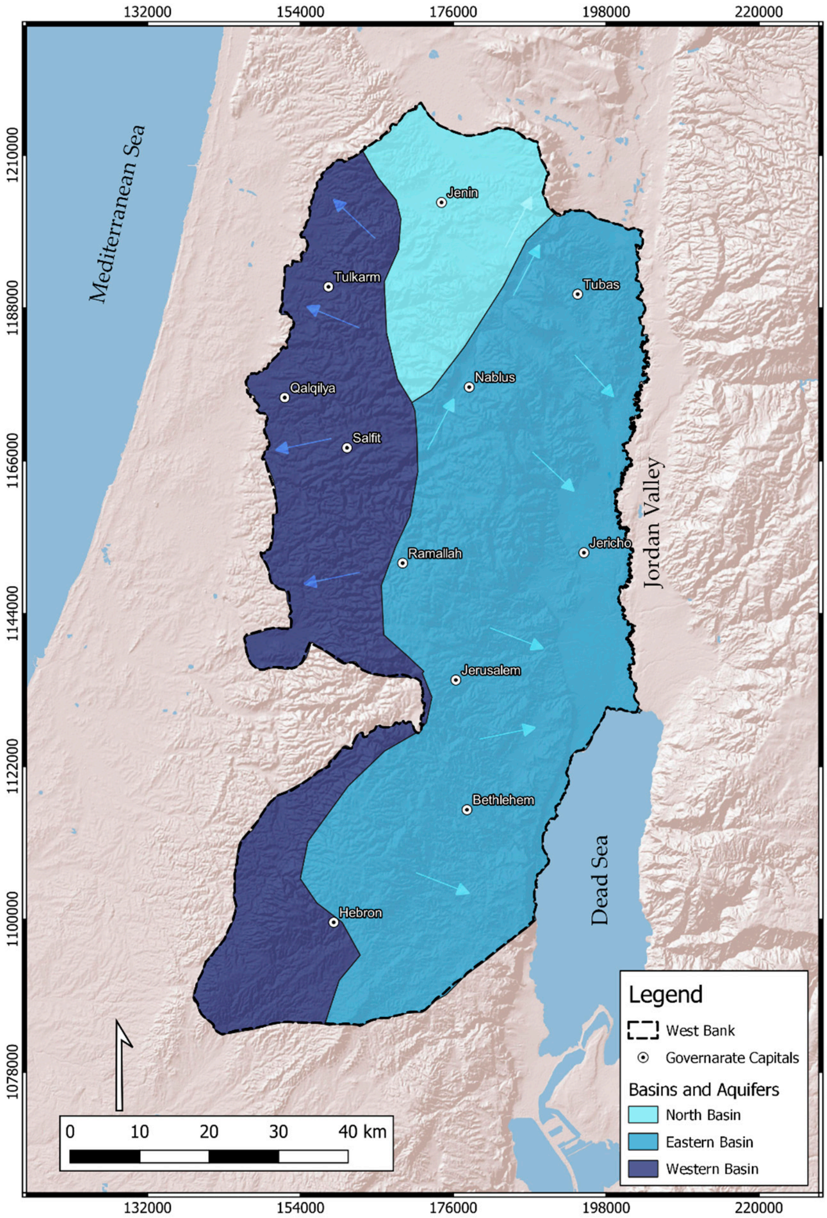


Figure 2. Extent and location of the main aquifer system in the West Bank.

2.2. Groundwater Sampling and Analysis

A total of 49 groundwater samples were collected from the northern part of the West Bank (Figure 3) during the year 2021. Following the WHO guidelines [39], the following parameters were tested: pH, electrical conductivity (EC), total dissolved solids (TDSs), total hardness (TH), chloride, sulphate (SO_4^{2-}), nitrate (NO_3^-), fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), zinc, barium, lead, arsenic, copper, cadmium, aluminium, iron, manganese, chromium, and nickel. The samples were analysed for different physico-chemical parameters following standard methods [40,41].

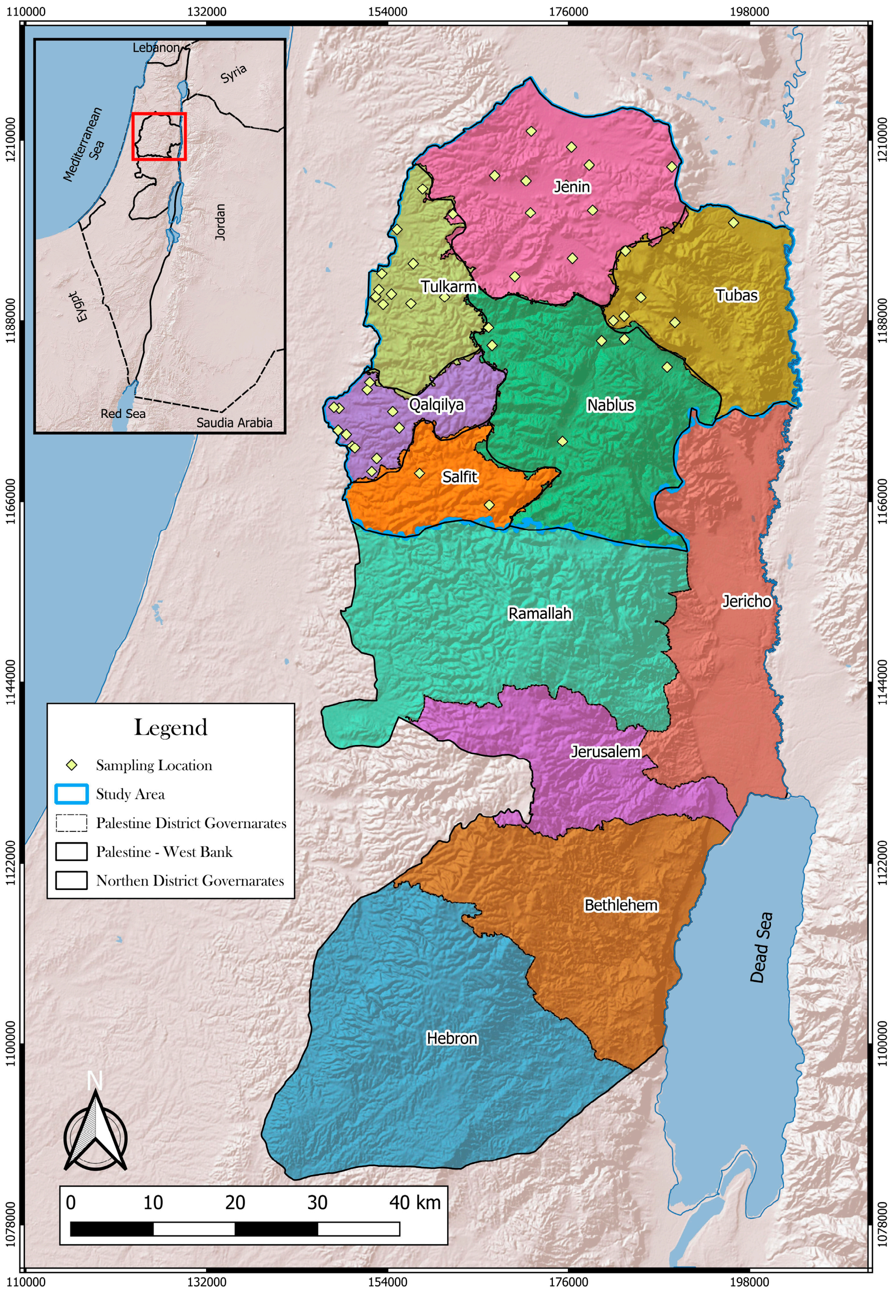


Figure 3. Location map of groundwater samples from different governorates of the study area.

EC, salinity, and pH were measured using an HQ40 portable meter [42]. TDSs were determined by filtering a measured volume of the sample through a standard glass fibre filter [43]. The concentrations of nitrate, sulphate, and fluoride in the water were determined using a UV spectrophotometer [42]. The concentrations of physico-chemical parameters and heavy metals in the water were quantified using an optical emission spectrometer (optima 7300 dv) [42]. The TH of the water was determined via titration with a standard solution of ethylene diamine tetra acetic acid (EDTA), which is a complexing agent [42]. Cl^- was estimated via $AgNO_3$ titration [42]. HCO_3^- was estimated using the volumetric technique, employing hydrosulphuric acid (H_2SO_4), along with phenolphthalein and methyl orange indicators [44].

2.3. Methods

2.3.1. Water Quality Index (WQI)

As it serves as an effective tool for evaluating groundwater quality, the water quality index (WQI) is commonly used worldwide to assess groundwater suitability for drinking [3,45]. In the process of determining the water quality index (WQI), the initial stage involved computing the parameter weights by using Equation (1), as shown in Table 1. Each of these parameters was attributed a weight (wi) ranging from 1 to 5, reflecting its significance and impact on health [33].

$$\mathrm{Wi} = \mathrm{wi} / \sum_{i=1}^{n} \mathrm{wi} \quad (1)$$

$$\mathrm{Qi} = (\mathrm{Ci}/\mathrm{Si}) \quad (2)$$

$$\mathrm{SIi} = \mathrm{Wi} \times \mathrm{Qi} \quad (3)$$

$$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{SIi} \quad (4)$$

where Wi = the relative weight;

wi = the weight assigned to each specific parameter;

n = the count of parameters.

Moving to the third phase, the calculation of the quality rating scale (Qi) was carried out [46] using Equation (2).

where Qi = the quality rating;

Ci = the concentration of each chemical parameter in each water sample in mg/L;

Si = taken from the PSI guidelines for each chemical parameter.

Table 1. Relative weights of chemical parameters in groundwater wells in study area.

Chemical Parameter	Weight (wi)	Wi (wi/∑wi)	PSI
pH	3	0.083	6.5–7.5
TDS	4	0.111	500
TH	2	0.056	500
Ca^{2+}	3	0.083	75
Mg^{2+}	2	0.056	50
Na^{+}	3	0.083	200
K^{+}	2	0.056	10
Cl^{-}	3	0.083	250
SO_4^{2-}	4	0.111	250
NO_3^{-}	5	0.139	50
F^{-}	5	0.139	1.5
Total	36	1	

Eventually, the water quality sub-index (SIi) of each chemical parameter was computed using Equation (3), and the whole WQI was determined using Equation (4), where SIi denotes the sub-index associated with the ith parameter, while Qi represents the rating determined by the concentration of that specific parameter. The variable 'n' corresponds to the overall count of parameters. As a result, the calculated WQI values were sorted into five different categories [9,47].

2.3.2. Human Health Risk (HHR) Assessment

It is good to carry out a health risk assessment to estimate HHR on the basis of ingestion [48]. A health risk assessment method proposed by the USEPA, which has proven to be an effective tool to evaluate health risk [1], was used and adapted through this work. Nevertheless, this study primarily focused on the oral consumption of drinking water as the key pathway of exposure. The health risk assessment centred on the concentrations of fluoride (F^{-}) and nitrate (NO_3^{-}) as the chosen parameters. The USEPA considered these two parameters as non-carcinogenic risks for human health [48,49]. The average daily dosage (CDI) of F^- and NO_3^- ingested from groundwater in the study area was calculated as part of an exposure assessment using Equation (5) [48]:

$$CDI = \frac{CW \times IR \times ED \times EF}{BW \times AT} \quad (5)$$

where

CDI = the average daily dose of ingestion of F and NO_3 (mg/kg/d);
CW = the F^- and NO_3^- concentrations in the water (mg/L);
IR = the ingestion rate (L/day);
EF = the exposure frequency (365 days/year);
ED = the exposure duration (years);
BW = the average body weight (kg);
AT = the average exposure time in years (body weight × 365).
The symbol values are shown in Table 2.

Table 2. Symbols and their values for adults, children, and infants [48,50,51].

Symbol	Value for Adults	Value for Children	Value for Infants	References
IR	2.5 L/day	0.78 L/day	0.3 L/day	USEPA 2014 [50]
ED	64 years	12 years	<1 year	WHO 2013 [40]
EF	365 days/year	365 days/year	365 days/year	USEPA 2014 [50]
BW	57.5 Kg	18.5 Kg	6.9 Kg	USEPA 2014 [50]
AT	23,360 days	4380 days	365 days	USEPA 2014 [50]

The reference dosage served as a quantification of chronic non-carcinogenic hazards [52]. Adverse toxic effects are more likely to manifest when the exposure dose of the specific contaminant surpasses this reference dosage. Typically, this comparison is expressed through the calculation of a hazard quotient (HQ), as outlined in Equation (6):

$$HQ = \frac{CDI}{RfD} \quad (6)$$

where

RfD = the reference dose for a non-carcinogenic pollutant through the oral intake pathway, which is 0.04 mg/kg/d for F and 1.6 mg/kg/d for NO_3 [52]. Based on Equation (6), the total hazard index (THI) of a non-carcinogenic pollutant is computed using Equation (7):

$$THI = \sum_{i=1}^{n} HQi \quad (7)$$

3. Results

The statistical data of the samples from the 49 wells are shown in Table 3. The pH values of the sampled groundwater wells were found to vary from 7.1 to 8.3, showing properties that are almost neutral to slightly alkaline, and this slightly reflects the water–rock interactions. These pH values fall under the permitted limits of drinking water regulations [26,46], and they are in line with those in two different studies in the same study area [22,27]. When the pH is > 8, the water is usually unsuitable for effective chlorine disinfection, but if the value goes below 6.5, pipe erosion starts to increase [27]. In the West Bank, the predominant rock formation is a carbonaceous one, which is reflected in the water's alkaline quality [6]. The EC values of the wells ranged from 504 to 1261 µS/cm, with a mean of 829.6 µS/cm. All groundwater samples that were collected had an electrical conductivity value within the permissible limit. Moreover, the TDSs of the groundwater ranged from 292 to 731 mg/L, with a mean of 477.4 mg/L; all samples had values within the normal range for drinking water. The high level of TDSs in the well samples is widely attributed to the leaching of salts from soil and cesspit tanks, which could potentially infiltrate the groundwater [53–56]. The anion concentrations displayed the following trend: $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > F^-$. However, the cation concentrations displayed the following order: $Ca^{2+} > Na^+ > Mg^{2+} > K^+$. Testing for total alkalinity is crucial for assessing alterations in water alkalinity resulting from human activities [57]. The alkalinity of the tested groundwater wells in the study area was classified as most desirable according to the WHO [17]. The HCO_3^- concentrations of the groundwater samples ranged from 165 to 420 mg/L, with a mean of 312.5. This reflects the karst and carbonate nature of the rocks in the study area. The total hardness (TH) values of the sampled groundwater wells ranged from 260 to 540 mg/L, with a mean of 358. It is clear that 2% of the groundwater exceeded the permissible limit set by the WHO and PSI. According to the TH categorization of groundwater, 87.7% of the samples were classified as having very hard water (Table 3). These values are in line with those of a previous study by Hejaz [27], but they considerably shift from the values found in Mohamad's work [22]. Groundwater that exceeds the limit of 300 mg/L is considered to be very hard water [58]. Hard waters can affect water heaters, boilers and cooking utensils, distribution pipes, and well pumps, and more soap is required to wash clothes [59,60]. The Ca^{2+} concentrations in the analysed samples extended from 53 to 135 mg/L, with a mean value of 86.8. The permissible limit of Ca^{2+} in drinking water is 75 mg/L according to the WHO, but 63.3% of the samples exceeded the permissible limit. The Mg^{2+} concentrations within the analysed samples extended from 14.6 to 54 mg/L, with a mean of 32.6; 71.4% of the studied wells exceeded the allowable limit of the WHO (30 mg/L). Since limestone and dolomite are basic components of the rocks in the study area, their dissolution due to rain introduces certain amounts of calcium and magnesium into the groundwater. The Na^+ concentrations in the groundwater wells ranged from 15.5 to 131 mg/L, with a mean of 39.9; these levels are below the permissible limit of PSI standards. According to the concentration of Na^+, which was less than 200 mg/L, the groundwater in the study area is safe to drink [26]. The potassium level in the groundwater spanned from 0.1 to 27.7 mg/L, with an average of 4.2. It is evident that 10.2% of the analysed samples exceeded the permissible limit set by the WHO. In the study area, the natural sources of K^+ in the groundwater are mainly K^+-bearing rocks, which are usually found in small quantities because of their slow weathering rate. However, human activities, such as wastewater discharge and fertilizer use, are considered important sources of K^+ [61]. A recent study revealed that agricultural practices have a significant negative impact on groundwater quality, which is observed in high concentrations of NO_3^-, K^+, and EC [62]. The Cl^- concentrations ranged from 26 to 249 mg/L, with a mean of 71.2. The Cl^- concentrations are within the drinking water regulations' approved levels. The maximum values of Cl^- and Na^+ were recorded in Jenin well ID (18–20/008), which, again, reflects the effect of human activities (e.g., wastewater discharge, cesspit leakage, and fertilizer use) as additional sources of these substances. The SO_4^{2-} levels ranged from 0 to 65 mg/L, with a mean of 25.5. All of the results fall within the acceptable ranges for drinking water. The F^- concentrations ranged from 0 to 0.7 mg/L, with a mean of 0.28. All results are within the permissible limits of drinking water. The NO_3^- levels ranged from 0.5 to 110 mg/L, with a mean of 40.6. It is clear that 38.8% of the samples exceeded the permissible limit set by the WHO and PSI. The high NO_3^- concentration is mainly caused by agricultural activities (e.g., fertilizer leaching), wastewater discharge, and septic tank leakage [1]. Mahmoud [22] reported that there are seasonal differences in the concentrations of NO_3^- and NH_4^{2+} in groundwater, which increase in the dry season and decrease in the wet season. Moreover, he found that the PO_4^{3-} as P in groundwater ranged from 0 to 3 mg/L. The majority of heavy metal concentrations (e.g., chromium, copper, manganese, lead, cadmium, nickel, aluminium, and arsenic concentrations) in all of the examined samples were discovered to be below the detection threshold of the utilised analytical methods. This means that all concentrations were found to be within the drinking water regulations' approved levels; hence, the groundwater in the study area is considered to be free from metal toxicity.

Table 3. Statistical summary of chemical composition of groundwater in the study area.

Parameters/Unit	Mean	Std. Dev.	Min	Max	PSI	WHO
pH	7.47	0.18	7.1	8.3	6.5–8.5	6.5–8.5
EC µS/cm	829.6	175.1	504	1261	-	-
TDS mg/L	477.4	100.2	292	731	1000	1000
NO_3^- mg/L	40.6	27	0.5	110	50	50
F^- mg/L	0.28	0.12	0	0.7	1.5	1.5
SO_4^{2-} mg/L	25.5	12.6	0	65	200	250
Cl^- mg/L	71.2	39.9	26	249	250	250
Ca^{2+} mg/L	86.8	17.9	53	135	100	75
Mg^{2+} mg/L	32.6	6.6	14.6	54	100	30
K^+ mg/L	4.2	5.6	0.1	27.7	10	-
Na^+ mg/L	39.9	21.1	15.5	131	200	200
TH mg/L	358	61.8	260	540	500	500
HCO_3^- mg/L	312.5	46	165	420	-	-

3.1. The Dominant Water Type

A Piper diagram was built and plotted for all analysed wells within the study area, with the aim of classifying the groundwater types (Figure 4). Table 4 shows the groundwater types. In total, 63.3% of the groundwater wells were classified as (Ca-Mg-HCO_3); 34.7% as (Ca-Mg-HCO_3-Cl), (Ca-Mg-Na-HCO_3-Cl); (Ca-Na-HCO3-Cl); and 2% as (Na-Ca-Mg-Cl-HCO_3) (Na-Ca-Cl-HCO_3). Based on the fundamental geochemical characteristics of the constituent ionic concentrations, a Piper trilinear diagram is a useful visual tool for classifying groundwater, and it elaborates the association and variation among the various types of groundwater [1,22,63]. Furthermore, defining the geochemical characteristics and chemical relationships in the groundwater in the study area in more detail is considered widely helpful. Cation and anion concentration categories can be found in different zones known as hydrochemical facies [64]. The extensive use of fertilizer in the area of recharge for the aquifers of different lithological environments shows a modified groundwater hydrochemical composition, causing it to be notably different from what is expected in normal conditions driven by water–rock interactions and other natural processes [1]. Despite the lithological differences, NO_3 contamination homogenises the overall hydrochemistry, making it difficult to perform the geochemical interpretation required for any evaluation study of groundwater resources [65].

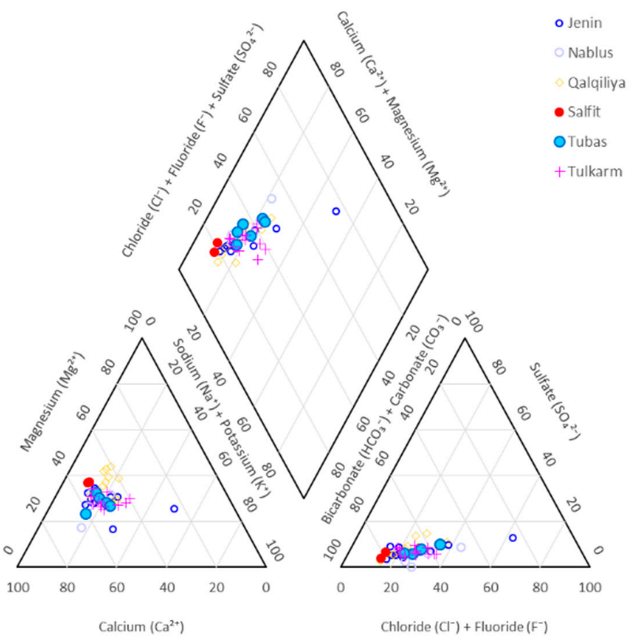


Figure 4. Piper diagram of groundwater sampling area.

Table 4. Categorization of water based on Piper diagram [66,67].

Sl. No.	Water Types	Number and Percentage of Groundwater Source
A	Normal earth alkaline water with prevailing bicarbonate	(31) 63.3%
B	Normal earth alkaline water with prevailing bicarbonate and sulphate or chloride	-
C	Normal earth alkaline water with prevailing sulphate or chloride	-
D	Earth alkaline water with increased portions of alkalis with prevailing bicarbonate	(17) 34.7%
E	Earth alkaline water with increased portions of alkalis with prevailing sulphate and chloride	-
F	Alkaline water with prevailing bicarbonate	-
G	Alkaline water with prevailing sulphate or chloride	(1) 2%

3.2. Water Quality Index in Groundwater

The WQI was classified into five categories, namely excellent, good, poor, very poor, and unsuitable for drinking [47]. Forty-nine groundwater samples and their WQI values are shown in Table 5. The WQI values of the sampled wells ranged from 0.43 to 0.90, of which 77.6% and 22.4% were within the good water and excellent water quality classes, respectively (Table 6). Importantly, all analysed samples were found to be suitable for drinking purposes. Human activities, including the extensive use of fertilizers, wastewater discharge, and cesspit leakage, have affected the groundwater quality of the study area [1,22]. These findings are in line with those of a previous study by Ibrahim and Marei in Jenin in the West Bank [68].

Table 5. Concentration values of physio-chemical analysis of the analysed groundwater samples. WQI assessment results are also provided.

Well_ID	F	NO_3	pH	SO_4	TDS	TH	Cl	Ca	Mg	Na	K	WQI
15–19/017	0.38	68.40	7.45	32.50	558.00	372.00	83.10	87.40	37.33	50.00	19.13	0.82
15–19/018	0.44	72.40	7.36	40.10	626.00	387.00	104.70	90.50	39.16	66.64	24.21	0.90
15–19/046	0.22	63.00	7.54	24.00	545.00	410.00	84.80	106.30	35.10	47.00	11.00	0.76
15–19/006	0.25	71.30	7.27	20.92	543.00	382.80	82.20	93.40	33.95	44.70	10.16	0.75
15–19/001A	0.28	80.00	7.55	29.30	431.00	314.00	55.10	75.64	30.60	30.70	3.34	0.67
15–19/004A	0.29	51.50	7.26	25.90	434.00	373.20	49.70	95.03	33.00	29.70	1.80	0.61
15–20/008	0.40	55.00	7.38	20.50	538.00	411.60	98.88	109.90	33.32	50.36	4.53	0.72
15–19/047A	0.28	32.00	7.60	16.30	400.00	315.80	56.00	79.50	28.50	31.00	0.80	0.51
15–19/028	0.18	43.55	7.69	21.40	320.00	268.10	35.20	66.15	25.00	18.84	0.50	0.48
16–20/005	0.34	26.32	7.35	17.00	387.00	317.60	53.70	85.55	25.25	27.75	1.68	0.50
16–19/002	0.37	40.15	7.24	21.10	455.00	350.50	76.80	94.00	28.12	40.88	2.86	0.60
15–19/010	0.33	48.00	7.61	20.38	510.00	338.60	63.00	91.76	30.21	35.92	0.10	0.61
14–17/043	0.20	59.00	7.31	17.90	460.00	310.00	53.00	72.00	32.00	33.00	1.30	0.59
14–17/044	0.20	65.00	7.32	27.30	466.00	331.00	50.00	80.00	31.00	25.00	0.95	0.62
14–17/001	0.20	110.00	7.50	54.00	556.00	420.00	68.00	90.00	43.00	39.00	2.00	0.84
15–17/012	0.30	45.00	7.57	20.00	443.00	355.00	45.00	71.00	42.00	29.00	2.50	0.59
15–17/004	0.17	63.00	7.70	21.00	499.00	345.00	50.00	65.00	40.00	39.00	6.40	0.66
15–17/007	0.17	31.00	7.40	16.00	415.00	365.00	37.00	90.00	31.00	28.00	1.10	0.52
15–16/003	0.20	51.00	7.50	20.00	415.00	320.00	47.00	65.00	34.50	30.00	3.10	0.57
15–18/004	0.20	70.00	7.55	27.00	415.00	310.00	45.00	57.00	36.00	25.00	4.50	0.62
15–17/019	0.20	19.00	7.50	7.00	370.00	270.00	30.70	53.00	32.00	19.00	3.80	0.43
14–17/021	0.28	60.00	7.30	27.00	496.00	351.00	67.00	85.00	33.80	36.00	1.70	0.64
14–17/034	0.30	82.00	7.40	48.00	658.00	406.00	125.00	97.00	39.00	67.00	3.00	0.82
14–17/052	0.21	91.10	7.50	30.00	550.00	355.20	70.60	83.00	36.00	37.00	27.70	0.89
17–20/050Q	0.70	0.50	7.55	35.00	496.00	670.00	89.00	81.00	35.00	60.00	2.50	0.58
17–19/009	0.42	10.00	7.60	30.00	385.00	335.00	39.00	75.00	31.50	25.00	1.90	0.47
17–20/052J	0.45	3.00	7.30	35.00	478.00	398.00	59.90	95.00	35.00	40.00	3.00	0.53
17–20/033J	0.32	69.00	7.40	52.00	715.00	480.00	160.00	135.00	28.00	100.00	6.00	0.87
17–20/051J	0.37	14.00	7.41	34.00	645.00	499.00	125.00	120.00	46.10	69.00	3.50	0.68
17–20/053	0.31	25.00	7.30	19.00	472.00	395.00	54.00	99.00	30.00	38.00	3.00	0.56
17–21/035	0.17	14.50	7.10	13.00	495.00	449.00	54.00	105.00	39.00	30.00	1.50	0.53
18–20/008	0.21	2.70	8.20	65.00	690.00	295.00	249.00	55.00	25.40	131.00	7.00	0.62
16–19/012	0.35	21.00	7.50	17.00	406.00	349.00	43.00	90.10	25.00	24.00	1.20	0.49
16–20/006	0.20	87.00	7.20	17.00	587.00	481.00	75.00	121.00	38.00	41.00	9.00	0.83

Table 5. *Cont.*

Well_ID	F	NO_3	pH	SO_4	TDS	TH	Cl	Ca	Mg	Na	K	WQI
17–20/051A	0.42	32.00	7.15	23.00	470.00	399.00	55.00	100.00	32.70	35.00	2.20	0.59
18–18/066	0.28	33.90	7.41	23.40	432.00	362.40	59.60	104.20	24.83	32.56	1.83	0.56
18–19/006	0.32	26.06	7.45	39.50	503.00	379.00	98.00	97.60	32.90	52.50	1.68	0.60
18–18/083	0.31	21.22	7.41	19.70	415.00	345.60	64.10	85.55	32.04	30.55	2.02	0.51
Tu_W_001	0.34	23.10	7.71	20.00	393.00	334.70	52.37	81.10	32.10	29.00	3.46	0.52
Tu_W_002	0.35	19.44	7.42	25.70	425.00	333.50	67.73	82.42	31.02	39.79	2.40	0.52
18–18/068	0.31	26.20	7.47	37.90	502.00	381.20	97.52	98.34	33.00	52.71	1.77	0.60
18–18/039	0.25	56.50	7.62	45.00	731.00	540.00	169.00	121.00	54.00	71.00	2.50	0.85
17–17/003	0.00	19.36	7.60	16.20	361.00	264.00	48.00	67.00	24.30	23.50	1.70	0.42
18–18/038	0.17	20.13	7.50	21.00	492.00	324.00	84.00	80.00	30.10	40.50	1.80	0.51
18–18/037	0.16	12.75	7.60	15.00	411.00	280.00	55.00	88.00	14.60	30.70	1.70	0.43
16–18/003A	0.00	12.87	7.60	0.00	348.00	260.00	45.00	64.00	24.30	20.20	1.60	0.38
16–18/004	0.40	22.74	7.70	8.00	374.00	268.00	52.00	72.00	21.40	23.40	2.10	0.47
Sa_W_001	0.18	9.60	7.70	10.00	292.00	293.00	26.00	65.00	30.00	15.50	1.10	0.39
Sa_W_002	0.55	7.00	7.30	22.00	382.00	350.00	35.50	87.00	38.00	19.00	1.60	0.49

3.3. Human Health Risk Assessment

The calculated values of the non-carcinogenic health risks from ingestion for adults, children, and infants in the study area are presented in Table 6. The HQ_{NO3} values of the samples ranged from 0.014 to 2.99 for adults, with a mean of 1.102; from 0.013 to 2.87 for children, with a mean of 1.057; and from 0.014 to 2.99 for infants, with a mean of 1.102. However, 46.9% of adults, children, and infants are considered to be at high risk. According to the distribution of the hazard quotient HQ_{NO3} values, the western basin of the study area's groundwater is particularly significantly contaminated, with NO_3^- being the result of agricultural practices, cesspit tanks, and insufficiently treated wastewater, raising serious health concerns. In addition to NO_3^-, F^- is another element of concern, which is widely distributed in the Earth's crust. The HQ_F values of the groundwater samples extended from 0 to 0.21 for adults, with a mean of 0.042; from 0 to 0.73 for children, with a mean of 0.297; and from 0 to 0.76 for infants, with a mean of 0.309. HQ_F was found to have the highest values in infants, followed by in children, with the lowest values in adults. However, all values of HQ_F were <1, indicating low or no health risk for F in the analysed groundwater samples.

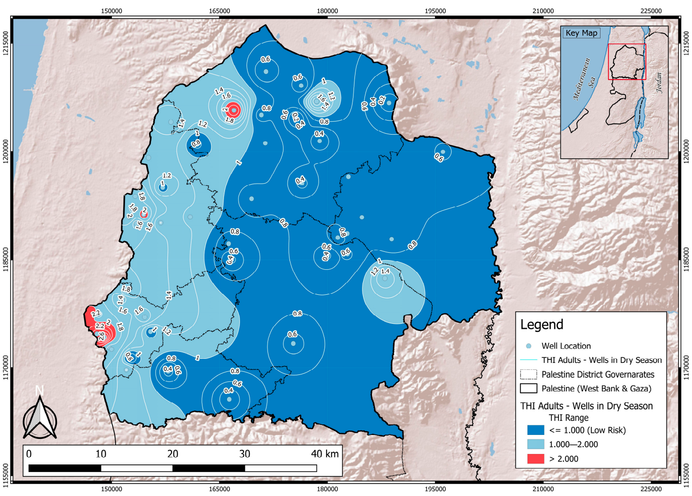
Table 6. Assessment results of human health risk according to computed HQ and THI of fluoride and nitrate ingestion in the study area.

Well_ID	Adults			Children			Infants		
	HQ_F	HQ_{NO3}	THI	HQ_F	HQ_{NO3}	THI	HQ_F	HQ_{NO3}	THI
15–19/017	0.06	1.86	1.92	0.40	1.78	2.18	0.41	1.86	2.27
15–19/018	0.08	1.97	2.05	0.46	1.89	2.35	0.48	1.97	2.45
15–19/046	0.02	1.71	1.73	0.23	1.64	1.87	0.24	1.71	1.95
15–19/006	0.03	1.94	1.96	0.26	1.86	2.12	0.27	1.94	2.21
15–19/001A	0.03	2.17	2.21	0.29	2.09	2.38	0.30	2.17	2.48
15–19/004A	0.04	1.40	1.44	0.30	1.34	1.64	0.32	1.40	1.71
15–20/008	0.07	1.49	1.56	0.42	1.43	1.85	0.43	1.49	1.93
15–19/047A	0.03	0.87	0.90	0.29	0.83	1.13	0.30	0.87	1.17
15–19/028	0.01	1.18	1.20	0.19	1.14	1.32	0.20	1.18	1.38
16–20/005	0.05	0.72	0.77	0.35	0.69	1.04	0.37	0.72	1.08
16–19/002	0.06	1.09	1.15	0.39	1.05	1.43	0.40	1.09	1.49
15–19/010	0.05	1.30	1.35	0.34	1.25	1.59	0.35	1.30	1.66
14–17/043	0.02	1.60	1.62	0.21	1.54	1.75	0.22	1.60	1.82
14–17/044	0.02	1.77	1.78	0.21	1.69	1.90	0.22	1.77	1.98
14–17/001	0.02	2.99	3.01	0.21	2.87	3.08	0.22	2.99	3.21
15–17/012	0.04	1.22	1.26	0.31	1.17	1.49	0.33	1.22	1.55
15–17/004	0.01	1.71	1.72	0.18	1.64	1.82	0.18	1.71	1.90
15–17/007	0.01	0.84	0.85	0.18	0.81	0.99	0.18	0.84	1.03
15–16/003	0.02	1.39	1.40	0.21	1.33	1.54	0.22	1.39	1.60
15–18/004	0.02	1.90	1.92	0.21	1.82	2.03	0.22	1.90	2.12
15–17/019	0.02	0.52	0.53	0.21	0.50	0.70	0.22	0.52	0.73
14–17/021	0.03	1.63	1.66	0.29	1.56	1.86	0.30	1.63	1.93

Table 6. *Cont.*

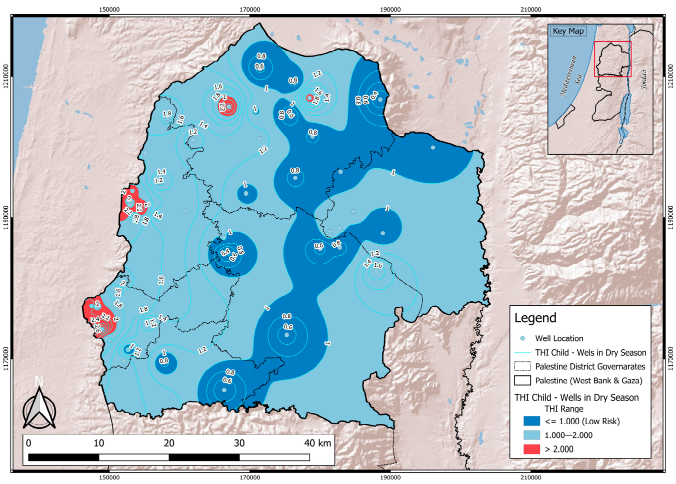
Well_ID	Adults			Children			Infants		
	HQ_F	HQ_{NO3}	THI	HQ_F	HQ_{NO3}	THI	HQ_F	HQ_{NO3}	THI
14–17/034	0.04	2.23	2.27	0.31	2.14	2.45	0.33	2.23	2.55
14–17/052	0.02	2.48	2.49	0.22	2.37	2.59	0.23	2.48	2.70
17–20/050Q	0.21	0.01	0.23	0.73	0.01	0.74	0.76	0.01	0.77
17–19/009	0.08	0.27	0.35	0.44	0.26	0.70	0.46	0.27	0.73
17–20/052J	0.09	0.08	0.17	0.47	0.08	0.55	0.49	0.08	0.57
17–20/033J	0.04	1.88	1.92	0.33	1.80	2.13	0.35	1.88	2.22
17–20/051J	0.06	0.38	0.44	0.39	0.36	0.75	0.40	0.38	0.78
17–20/053	0.04	0.68	0.72	0.32	0.65	0.98	0.34	0.68	1.02
17–21/035	0.01	0.39	0.41	0.18	0.38	0.56	0.18	0.39	0.58
18–20/008	0.02	0.07	0.09	0.22	0.07	0.29	0.23	0.07	0.30
16–19/012	0.05	0.57	0.62	0.36	0.55	0.91	0.38	0.57	0.95
16–20/006	0.02	2.36	2.38	0.21	2.27	2.48	0.22	2.36	2.58
17–20/051A	0.08	0.87	0.95	0.44	0.83	1.27	0.46	0.87	1.33
18–18/066	0.03	0.92	0.96	0.29	0.88	1.18	0.30	0.92	1.23
18–19/006	0.04	0.71	0.75	0.33	0.68	1.01	0.35	0.71	1.06
18–18/083	0.04	0.58	0.62	0.32	0.55	0.88	0.34	0.58	0.91
Tu_W_001	0.05	0.63	0.68	0.36	0.60	0.96	0.37	0.63	1.00
Tu_W_002	0.05	0.53	0.58	0.36	0.51	0.87	0.38	0.53	0.91
18–18/068	0.04	0.71	0.75	0.32	0.68	1.01	0.34	0.71	1.05
18–18/039	0.03	1.54	1.56	0.26	1.47	1.73	0.27	1.54	1.81
17–17/003	0.00	0.53	0.53	0.00	0.50	0.50	0.00	0.53	0.53
18–18/038	0.01	0.55	0.56	0.18	0.52	0.70	0.18	0.55	0.73
18–18/037	0.01	0.35	0.36	0.17	0.33	0.50	0.17	0.35	0.52
16–18/003A	0.00	0.35	0.35	0.00	0.34	0.34	0.00	0.35	0.35
16–18/004	0.07	0.62	0.69	0.42	0.59	1.01	0.43	0.62	1.05
Sa_W_001	0.01	0.26	0.27	0.19	0.25	0.44	0.20	0.26	0.46
Sa_W_002	0.13	0.19	0.32	0.57	0.18	0.76	0.60	0.19	0.79

The total hazard (THI) values of the analysed wells varied by the category of age, with the values extending from 0.093 to 3.01 for adults, with a mean of 1.144; from 0.29 to 3.08 for children, with a mean of 1.354; and from 0.302 to 3.21 for infants, with a mean of 1.411 (Table 6). However, the THI results of the groundwater samples for the total non-carcinogenic risk that exceeded the acceptable limit (i.e., THI > 1) were as follows: 46.9% for adults, 61.2% for children, and 67.4% for infants. The order of THI values for the different age categories (i.e., infants > children > adults) was also depicted in the spatial distribution of these values and variations in the health risk of the groundwater wells within the study area (Figure 5a–c). These results confirm that infants are more vulnerable than adults and children to non-carcinogenic risks due to toxicity. This is primarily because they consume more water per unit of body weight than adults and children [69].

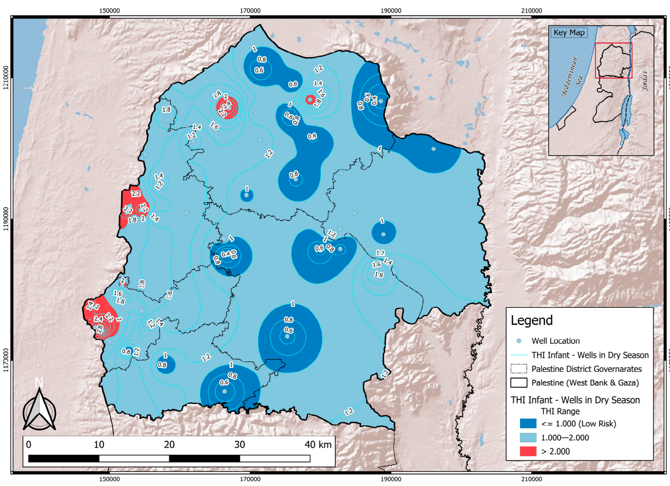


(a)

Figure 5. *Cont.*



(b)



(c)

Figure 5. (**a**) Zoning map of health risk of groundwater for adults. (**b**) Zoning map of health risk of groundwater for children. (**c**) Zoning map of health risk of groundwater for infants.

4. Conclusions

The monitoring of groundwater is crucial, especially in regions grappling with water scarcity. This study utilised three measurement tools (the WQI, HHR, and Piper diagrams) to evaluate groundwater quality. Since each tool covers a specific aspect of water quality, the results offer a broad and comprehensive understanding of the water quality and its impact on the local population.

The main results and conclusions can be summarised as follows:

- The pH values of the groundwater samples were found to vary from 7.1 to 8.3, showing properties that are almost neutral to slightly alkaline. Based on the classification of groundwater according to TDS, 67.3% of the samples fell into the desirable category, while 32.7% were categorised as permissible for drinking. The total hardness values of the groundwater samples ranged from 260 to 540 mg/L; 2% of the groundwater samples exceeded the permissible limit set by the WHO. Moreover, 87.7% were classified as very hard water. The levels of K^+ in the groundwater varied from 0.1 to 27.7 mg/L; notably, 10.2% of the examined samples exceeded the permissible limit set by the WHO. The NO_3^- levels ranged from 0.5 to 110 mg/L, with a mean of 40.6. It is clear that 38.8% of the samples exceeded the permissible limit set by the WHO.

However, the Cl^- and Na^+ concentrations were found to be within the permissible limit set by the WHO.

- The ionic dominance pattern of the groundwater showed the following order for anions: $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > F^-$. Moreover, it showed the following order for cations: $Ca^{2+} > Na^+ > Mg^{2+} > K^+$. The predominant water type in this region is fresh water (calcium–magnesium–bicarbonate), which is suitable for drinking. This type can mainly be attributed to the hydrogeological facies of groundwater, determined by natural processes, such as rock weathering, leaching, and evaporation. However, water types such as (Ca-Mg-Na-HCO_3-Cl), (Ca-Na-HCO_3-Cl), (Na-Ca-Mg-Cl-HCO_3), and (Na-Ca-Cl-HCO_3) may be influenced by anthropogenic factors, such as wastewater, cesspits, and agricultural fertilizers. Consequently, these water types may not be suitable for drinking.
- Based on the water quality index (WQI), 77.6% and 22.4% of samples fell into the 'good' and 'excellent' water classes, respectively, indicating that the groundwater is suitable for drinking.
- No health risk was found for fluoride (F^-) in the analysed groundwater samples. The non-carcinogenic risk of NO_3^- ranged from 0.093 to 3.01 for adults, from 0.29 to 3.08 for children, and from 0.302 to 3.21 for infants. Our study indicates that the younger age group is more vulnerable to NO_3^- toxicity than the oldest age group. However, the health risk associated with NO_3^- was 46.9% for all ages. Therefore, more efforts are needed to reduce the nitrate NO_3^- levels in the groundwater of the study area. Moreover, the development of appropriate methods for the protection of groundwater catchments in the West Bank is crucial and could have beneficial implications for groundwater quality and sustainability.

Recommendation:

Achieving proper groundwater quality cannot be ensured unless effective management of pollution sources is in place. The construction of dams to collect and harvest rainwater and the subsequent injection into the subsurface to replenish groundwater significantly contribute to reducing the concentrations of NO_3^- and other chemicals in the aquifer. Furthermore, mixing groundwater sources with high NO_3^- levels with those that possess low NO_3^- levels has proven to be an efficient strategy for addressing this concern. This method is effective in mitigating the issue by diluting the NO_3^- concentration in the produced groundwater.

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