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Evaluation of the Radon Levels in the Groundwater Wells of Qatar: Radiological Risk Assessment

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Abstract: The objective of this work is to give a holistic overview of the groundwater quality in Qatar in terms of its radon levels and provide a radiological risk assessment of elevated radon levels on human health. This study covered the analysis of groundwater collected from various locations throughout Qatar and maps using ArcGIS followed by a radiological risk assessment of radon in Qatar. There is no extensive study reported to investigate radon activity levels in groundwater across Qatar and their health effects. The radon level measurements of the Qatari groundwater ranged between 2.7 ± 0.2 and 60.7 ± 13.4 Bq/L with a mean value of 20.6 Bq/L, which is greater than the US EPA's maximum contamination level (11 Bq/L). About 65% of the studied samples exceeded the US EPA's MCL guidelines. The mean total annual effective dose due to radon inhalation and ingestion was 0.056 mSv/y, which is below the WHO reference level of 0.1 mSv/y. The radon radiological risk study through inhalation and ingestion clearly revealed that the contribution of the inhalation dose was higher than the ingestion dose.

Keywords: groundwater; Qatar; radon; radioactive; naturally occurring radioactive material; effective dose

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1. Introduction

The exposure of humans to natural radiation has been widely studied and reported in the literature due to its drastic consequences on human health [1,2]. Radon 222, radium 226 and radium 228 are the most reported elements in the literature to be present at various levels in groundwater and to cause natural radiation [3]. Radon has attracted the attention of researchers the most and is probably considered the main source of human exposure to radiation due to its gaseous state which allows it to travel from rocks and enter our bodies through inhalation (air) and ingestion (water) [4]. The characteristic high solubility of radon in water makes radon transfer easy from underlying rocks and soil to groundwater. The most prominent exposure comes from the isotope of ^{222}Rn, which has a half-life of about 3.82 days [5]. It was reported that 69% of the total annual effective dose is attributed to radon and its decay products [6,7]. As stated by the world health organization (WHO), there are no identified threshold levels below which radon can be safe [8]. It was reported that radon increases the risk of lung cancer even at low concentrations; in fact, low and moderate radon concentrations were found to account for the majority of radon-induced lung cancer when compared with high radon concentrations as more people are exposed to low radon concentrations [9]. It was estimated that radon kills between 10,000 and 20,000 people by lung cancer annually in the USA alone [10]. Radon is the decay product of the parent radium, which is found in rocks, and can diffuse or dissolve in water reaching the surface of the earth [11]. Several studies have reported health effects of radon exposure on humans. The breakdown of radon into its daughters is accompanied by the emission of highly ionizing energetic alpha radiation which, in turn, damages the living cells when radon gas is inhaled [12]. The highly ionizing alpha particles emitted by deposited short-lived decay products of radon Polonium-218 and Polonium-214 can interact with the biological tissue in the lungs, leading to DNA damage that is considered an important factor in the carcinogenesis process.

Qatar is an arid peninsula, surrounded by the Arabian Gulf from the northern, eastern and western sides and bordered by Saudi Arabia from the southern side. In total absence of natural surface water resources, rainfall is the sole source for aquifer recharge; however, annual rainfall in Qatar is one of the world's lowest (80 mm), whereas the annual natural evaporation is about 2000 mm [13]. The two main aquifers in Qatar (Rus Formation and Abu Samra aquifers) have salinity levels ranging between 600 and 15,633 mg/L [14–16]. The geological rock formation in Qatar is dominated by limestone karstic formations [17]. While domestic applications in Qatar are met by seawater desalination [18,19], groundwater is extensively used for agriculture and husbandry in order to support the socio-economic sectors in the country [14–19]. Due to inefficient irrigation systems, the hot climate in Qatar and absence of well water metering, groundwater abstraction has skyrocketed, risking the viability of these strategic water reserves [20]. Currently, 36% of the agricultural demand of water is met by groundwater extraction [20,21]. Keeping in mind the arid nature and hot climate of the country, the high abstraction rate of groundwater has been reported to drastically reduce its quantity and quality [22–25]. In general, groundwater is more likely to contain naturally occurring radioactive materials (NORMs) when compared to surface water due to its contact with rocks and soils in the aquifers, which are responsible for the enrichment of groundwater with NORMs [26].

The monitoring of radon in groundwater around the world is well covered in the literature [3,27–50]. The radon levels in groundwater wells vary from one place to another. Table 1 shows the radon levels in groundwater in various parts of the world. Rangaswamy [51] investigated the radon level in the Shimoga district (India) and found the radon concentration to be between 3.10 ± 0.25 and 38.50 ± 1.54 Bq/L with a mean value of 13.60 ± 1.12 Bq/L. About 48% of the surveyed drinking water samples exceeded the US EPA's maximum concentration level (MCL) of 11 Bq/L. Mehra [52] analyzed the radon level in the groundwater, which is used for drinking, in Punjab (India). They found the radon level to be between 2 and 6.6 Bq/L. El-Sharkawy [53] investigated the radon level in private groundwater wells in Tabouk and Al-Sharqiyah (Saudi Arabia) using RAD7 and found the range of the radon in the groundwater to be 5.5–11 Bq/L. As seen in Table 1, the radon levels in groundwater around the world showed some elevated levels that are above the EPA's MCL; hence, the aim of the present work is to give an overview of the radon levels in groundwater and estimate their health effects. Moreover, reviewing the literature has not shown any previous reported work evaluating the radon levels in the groundwater wells across the map of Qatar. Furthermore, no radiological risk assessment which may occur as a result of the exposure to radon gas from groundwater in Qatar has been performed. Hence, the need to carry out this work is important for the country. Despite having few studies reporting the natural radioactivity in Qatari soil [54,55], to the best of our knowledge, there is no holistic study in the literature covering the variation in radon levels in the groundwater wells of Qatar and presenting a radiological risk assessment for exposure to radon. Given the fact that a significant part of the groundwater in Qatar is being used extensively for irrigation without any treatment, it would be beneficial to evaluate the radon levels in the groundwater wells of Qatar and investigate their radiological hazards.

Table 1. Studies from literature reporting radon levels in groundwater globally and regionally.

Country	Radon Level (Bq/L)	Annual Mean Effective Dose (µSv/y)	Reference
Saudi Arabia	0.8–9.1	2.8–33.4	[37]
China	12–41	30–140	[36]
India	0.2–27.3	0.73–99.7	[38]
Saudi Arabia	5.5–11		[53]
United Arab Emirates	0.05–1.8	22.7	[39]
Saudi Arabia	1.45–9.15		[29]
Saudi Arabia	0.9–35.4	17	[27]
Saudi Arabia	1.7–4.3	28.9 ± 2.12	[40]
Saudi Arabia	0.04–67.4		[3]
Iraq	2–4.1	7.9–15.	[33]
Palestine	1.5–23.4		[41]
UAE and Oman	0.2–17		[42]
Iran	0.5–49	40–43	[43]
Iran	4.7–31.5		[44]
Iraq	8.02–11.7	309–451	[45]
Jordan	6.2		[46]
Iraq	0.36–1.5		[34]
Bangladesh	0.36–15.7	1.0–42.9	[47]
Malaysia	7.4–89.1	0–39.2	[35]
Nigeria	0.95–112		[48]
Romania	0.5–129.3		[49]
South Korea	0–300		[50]
Kenya	0–371		[32]

2. Materials and Methods

2.1. Sampling Locations Selection

Sites containing groundwater sampling wells were selected based on the geographic location and well basin type, and the usage of the water from the well (agricultural, domestic, industrial). Forty-eight sampling sites were selected, as shown in Figure 1. The forty-eight groundwater wells were selected from a list reported by Schlumberger's water services (SWS) in 2009, which conducted an inventorial study to identify and locate the 8500 groundwater wells of Qatar along with their GPS coordinates.

2.2. Physical-Chemical Properties Measurement

In order to study the factors affecting the groundwater quality, some important parameters must be determined first such as pH, TDS and temperature. A hanna multi-parameter (Woonsocket, RI, USA) was used to measure the above-mentioned parameters on field. Before taking the measurement, the probes were calibrated and rinsed with deionized water and the groundwater sample.

The total dissolved solids (TDS) of the groundwater samples were estimated from the given secondary electrical conductivity (SEC) using the below equations:

$$\text{TDS} = 0.65 \times \text{SEC—for SEC values below 5000 µS/cm} \quad (1)$$

$$\text{TDS} = 0.70 \times \text{SEC—for SEC values above 5000 µS/cm} \quad (2)$$

The correlation coefficients were taken from the SWS report, which developed these equations after analyzing the relationship between TDS and SEC for groundwater in Qatar from 1971 to 2009 [56].

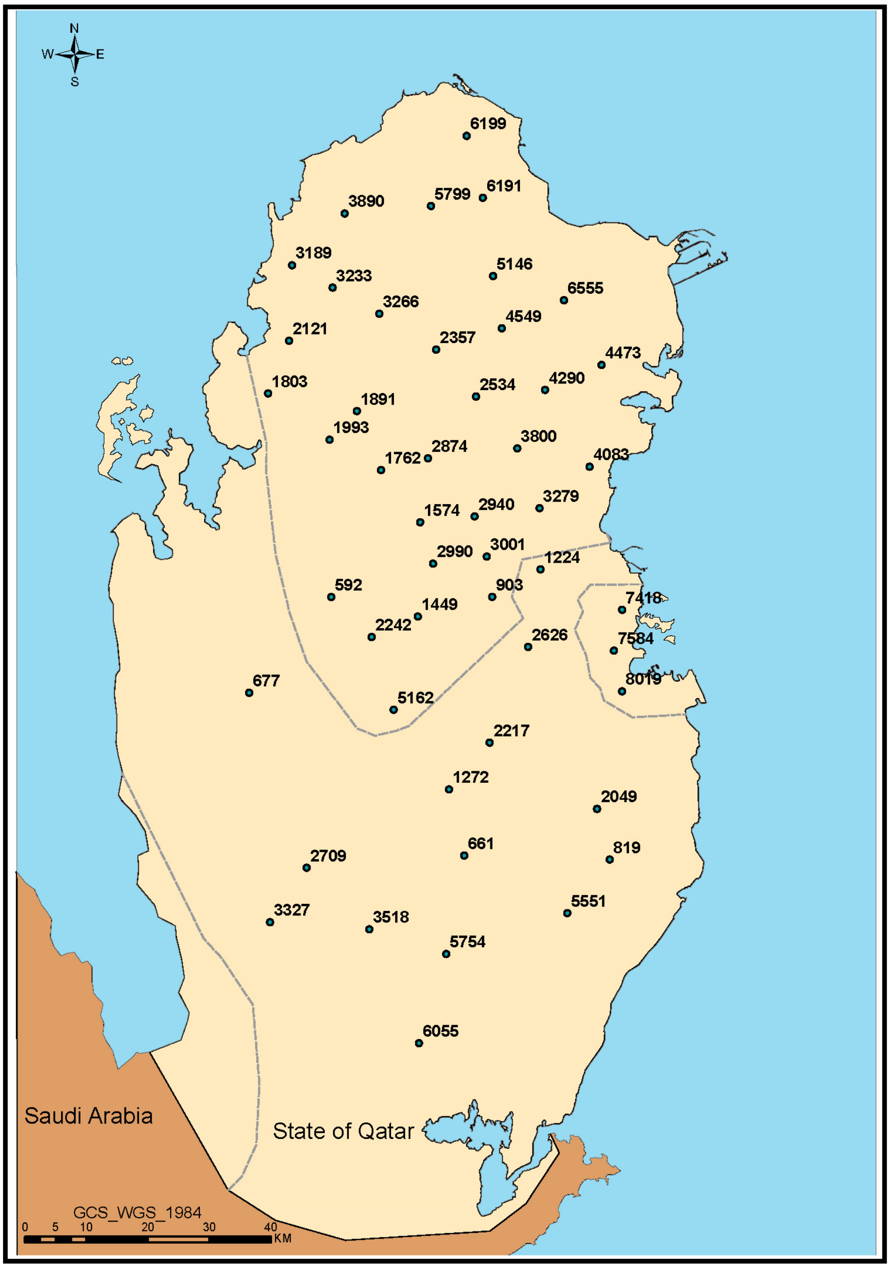


Figure 1. Sample locations of groundwater wells across Qatar.

2.3. Radon Levels Measurements

Radioactivity measurement instruments such as RAD7 (from Durridge, Billerica, MA, USA) with the RAD H_2O accessory for radon measurements as well as gamma survey meters for gamma dose measurements (Geiger counter and scintillator detectors) were used in the present work. Figure 2 shows the RAD-7 used in the present work. The RAD7 H_2O is an accessory to the RAD7 detector that enables the measurement of radon in water over a concentration range below 1 Bq/L. The range for RAD7 is 0.37 Bq/L to 14,800 Bq/L. The lower limit of detection is less than 0.3 Bq/L. The equipment is portable and battery operated. An accurate measurement of radon in water could be performed within an hour of taking the sample. The RAD H_2O gives results after a 30 min analysis with a sensitivity that matches or exceeds that of liquid scintillation methods. During the five minutes of aeration, more than 95% of the available radon was removed from the water.

Figure 2. RAD7 with the RAD H_2O accessory.

Field gamma radiation measurements of soil, scales, precipitation and sludge in and around water tanks were performed using a Geiger counter. For field Radon measurements in water, the samples were analyzed instantly at the sampling location, so the result did not require decay correction. The RAD H_2O uses a standard, pre-calibrated degassing system and pre-set protocols built into the RAD7, which give a direct reading of the radon concentration in the water sample itself. The air in the gas phase in the vial was pumped into the radon detector after being dried in the drying column. The radioactive aerosols in the gas phase were captured by a filter unit attached to the inlet of the radon detector. The sample size of 250 mL corresponds to the RAD7's built-in Wat-250 protocol. The pump ran for five minutes, aerating the sample and delivering almost 95% of available radon to the detection chamber.

2.4. Sampling Procedure

Water sampling for radon measurements was conducted taking into consideration that the sample is representative of the water column at the site rather than stagnant water in the well. Hence, the groundwater was pumped for an adequate amount of time (at least 15 min) to ensure removing the stagnant water from pipes and having a representative sample. Triplicate samples were collected from each well and the average value was reported in the present work.

The measurement of physical parameters such as pH, temperature and SEC was carried out in situ using multi-parameter instrument. In order to avoid loss/leak of radon gas from groundwater, the groundwater samples did not come into contact with air. A tube was inserted in the well faucet in order to fully fill the 250 mL vial by forcing the water to flow on the inner wall of the vial. The vial was filled completely with groundwater and closed air-tight with the container cap in order to prevent escape of the radon gas to the atmosphere.

2.5. Radiological Risk Assessment

The annual effective doses for ingestion and inhalation can be estimated using Equation (3), which was introduced by UNSCEAR in 2000 [57]:

$$AED_{Wig} = C_{RnW} \times C_W \times EDC \quad (3)$$

where AED_Wig is the effective dose for ingestion, CRnW is the radioactivity concentration in water (Bq/L), C_W is the weighted estimate of water consumption and EDC is the effective dose coefficient for ingestion (3.5×10^{-9} Sv/Bq). The weighted estimate of water consumption (C_W) was assumed to be 60 L/year, as reported in literature [31] and assumes that the end user will consume 60 L of water annually [58].

The annual effective doses for inhalation (AED_{Wih}) can be calculated using Equation (4):

$$AED_{Wih} = C_{RnW} \times R_{aW} \times F \times O \times DCF \quad (4)$$

where R_{aW} is the ratio of radon in air to radon in water (10^{-4}), F is the equilibrium factor between radon and its progenies (0.4), O is the average indoor occupancy time per individual (7000 h/y) and DCF is the dose conversion factor for exposure to radon (9×10^{-9} Sv/Bq/h/m^3) [58].

3. Results and Discussions

3.1. Physico-Chemical Parameters (pH and SEC)

Table 2 lists the pH, EC and TDS of the studied wells across the map of Qatar. The analyzed groundwater wells in the present study showed a TDS between 711.7 ± 34 and 31535 ± 175 mg/L. The obtained results are shown as iso-concentration maps in Figure 3. The TDS of the groundwater can be used to give an indication about the suitability of the water for drinking or irrigation purposes. Three are 46 and 37 exceedances to the Qatar drinking standards and Qatar crop irrigation guidelines, respectively. This means that 96% of the samples were greater than the WHO drinking water guidelines of 1000 mg/L and 77% of the samples were higher than the Qatar crop irrigation guidelines of 2000 mg/L. Moreover, 27 groundwater locations with a TDS greater than 3000 mg/L were observed, which constitute 56% of the total number of groundwater samples analyzed. As seen in Table 3, about 56% of the studied groundwater wells can be categorized as "unfit for drinking and irrigation purposes" [59]. Furthermore, in the present study, it was observed that 12 groundwater wells had TDS values above 9000 mg/L, which was found in the literature to describe "very saline" water [60]. In the present study, it was found that the highest TDS values were observed around the capital of Qatar and the most populous city (Doha) due to the substantial extraction of groundwater. Due to over pumping, the area which can be used for drinking or irrigation in Qatar is shrinking over time. The area underlain by freshwater in Qatar has been reported to decline over time. In 1971, the area underlain by freshwater with TDS below 1000 mg/L was estimated at 15% of the total country area. In 2009, the area was estimated at 2%. Likewise, the area underlain by freshwater with TDS < 3000 mg/L between 1971 and 2009 was estimated at 25% and 16%, respectively [56]. The groundwater TDS profile shown in the present work shows the increase in the salinity of groundwater in Qatar. The presence of red areas close to the shoreline with TDS as high as 22,650 mg/L could be attributed to (1) groundwater over pumping, (2) seawater intrusion and (3) upconing of saline and brackish water from lower layers below the fresh groundwater areas [56]. Upconing describes the upward movement of brackish/salt water in a cone-shaped manner through a freshwater–brackish water interface due to the freshwater over pumping above the interface [61,62]. Upconing is widely reported in the literature to cause well salinization in coastal aquifers [63,64].

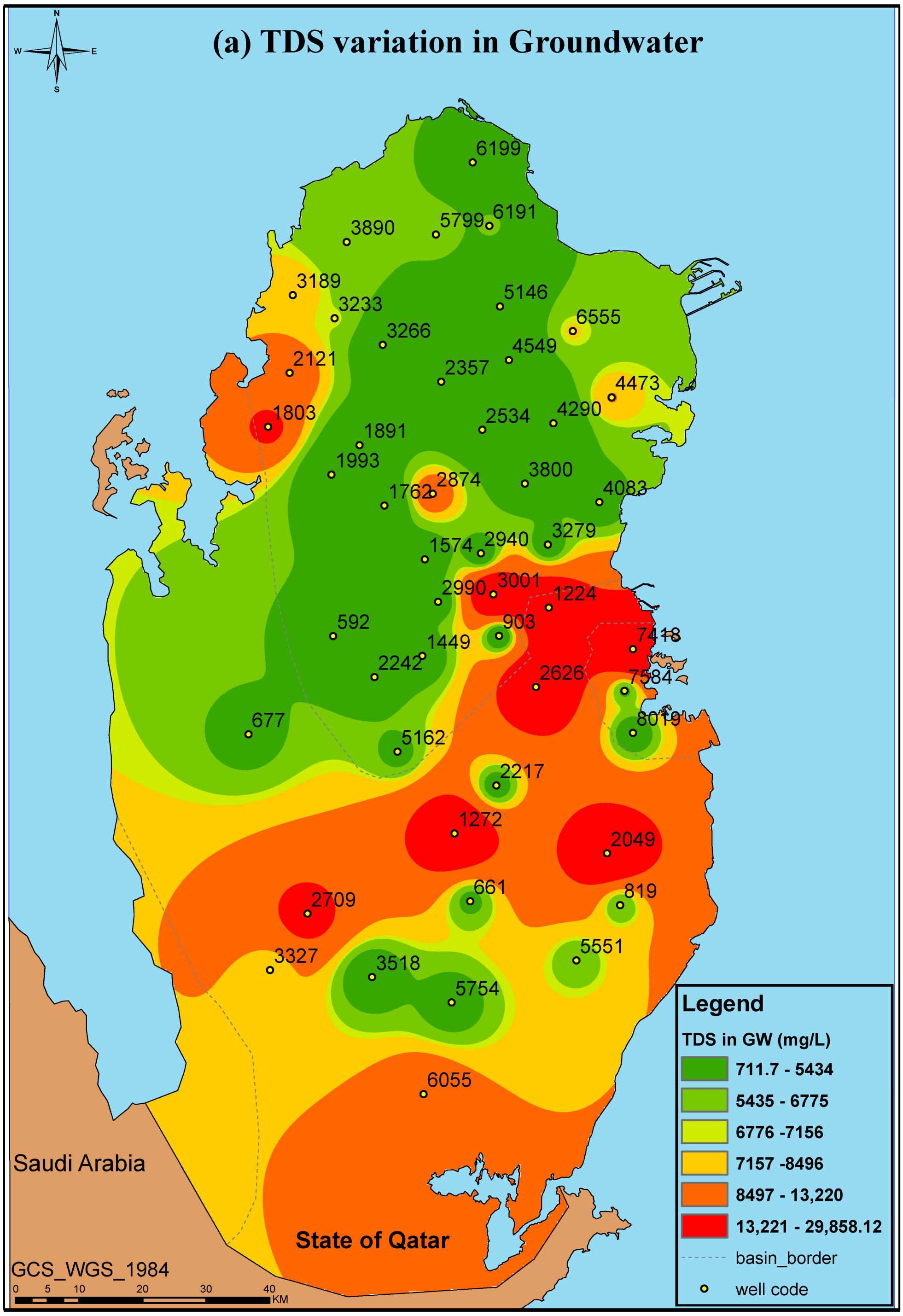
With regard to pH, the pH of all the studied samples was found to almost fall within the WHO/Qatari drinking water standards of 6.5–8. The physical parameters evaluated in the present work were found be in good agreement with the results published in the literature; for instance, Shomar [65] reported the pH range of the groundwater in Qatar to be 6.94–8.22, whereas that of the TDS was 11–14,959 mg/L.

Table 2. Physico-chemical parameters of the surveyed groundwater wells.

Well ID	pH	EC (mS/cm)	TDS (mg/L)
592	7.99 ± 0.31	3.68 ± 0.23	2392 ± 150
661	7.74 ± 0.11	6.60 ± 0.02	4620 ± 14
677	7.77 ± 0.04	6.84 ± 0.08	4785 ± 53
819	7.58 ± 0.13	10.88 ± 0.02	7616 ± 14
903	7.79 ± 0.00	6.66 ± 0.11	4659 ± 74
1224	6.24 ± 0.65	41.70 ± 20.85	14,595 ± 146
1272	7.80 ± 0.15	5.23 ± 0.10	3658 ± 67
1449	7.82 ± 0.15	4.13 ± 0.08	2680 ± 51
1574	7.72 ± 0.04	2.50 ± 0.06	1625 ± 39
1762	7.82 ± 0.10	1.32 ± 0.05	711.7 ± 34
1803	6.82 ± 0.79	26.15 ± 2.15	18,305 ± 1505
1891	7.95 ± 0.19	1.64 ± 0.04	1068 ± 24
1993	7.96 ± 0.14	3.29 ± 0.03	2135 ± 23
2049	6.36 ± 2.75	36.63 ± 21.87	25,641 ± 1530
2121	7.44 ± 0.09	19.43 ± 0.05	13,601 ± 35
2217	7.84 ± 0.00	6.56 ± 0.04	4592 ± 28
2242	7.48 ± 0.38	3.35 ± 0.01	2178 ± 6.5
2357	7.83 ± 0.05	2.61 ± 0.06	1693 ± 34
2534	8.01 ± 0.12	1.34 ± 0.01	874 ± 9.1
2626	7.79 ± 0.09	6.11 ± 0.08	4277 ± 56
2709	7.54 ± 0.00	25.40 ± 0.10	17,780 ± 70
2874	7.90 ± 0.06	1.80 ± 0.02	1169 ± 12
2940	7.80 ± 0.08	4.25 ± 0.02	2760 ± 16
2990	7.80 ± 0.00	4.26 ± 0.14	2767 ± 88
3001	7.75 ± 0.02	4.86 ± 0.06	3159 ± 39
3189	7.74 ± 0.02	12.73 ± 0.20	8911 ± 140
3233	7.64 ± 0.02	10.56 ± 0.08	7390 ± 53
3266	7.71 ± 0.07	2.26 ± 0.09	1414 ± 6
3279	6.41 ± 3.21	4.35 ± 2.18	1413 ± 14.1
3327	7.44 ± 0.25	12.32 ± 0.37	8624 ± 259
3518	7.77 ± 0.12	3.68 ± 0.07	2389 ± 42
3800	7.75 ± 0.13	2.49 ± 0.09	1615 ± 55
3890	7.79 ± 0.08	9.62 ± 0.14	6730 ± 95
4083	7.97 ± 0.13	4.86 ± 0.05	3159 ± 33
4290	7.86 ± 0.09	2.55 ± 0.03	1658 ± 20
4473	7.82 ± 0.02	13.80 ± 0.19	9660 ± 133
4549	7.93 ± 0.10	2.95 ± 0.22	1918 ± 143
5146	7.93 ± 0.21	3.19 ± 0.07	2073 ± 46
5162	7.73 ± 0.30	6.94 ± 0.01	4858 ± 7
5551	7.79 ± 0.09	8.92 ± 0.01	6240 ± 10.5
5754	7.77 ± 0.11	5.22 ± 0.04	3651 ± 31.5
5799	7.65 ± 0.06	9.08 ± 0.14	6352 ± 95
6055	7.64 ± 0.03	19.42 ± 0.21	13,591 ± 144
6191	7.87 ± 0.07	7.80 ± 0.04	5465 ± 32
6199	7.83 ± 0.04	12.85 ± 0.06	8995 ± 42
6555	7.82 ± 0.06	11.46 ± 0.19	8019 ± 130
7418	7.34 ± 0.12	45.05 ± 0.259	31,535 ± 175
7584	7.82 ± 0.18	7.87 ± 0.04	5510 ± 50
8019	7.74 ± 0.03	4.61 ± 0.07	2993 ± 49
Statistical Analysis			
Min	6.24	1.32	711.7
Max	8.01	45.05	31,535
Mean	7.65	9.42	6094
Standard Deviation	0.40	9.91	732

Table 3. Categorization of water according to their salinity in TDS [59,60].

Category	TDS (mg/L)
Desirable for drinking	<500
Permissible for drinking	500–1000
Useful for irrigation	1000–3000
Unfit for drinking and irrigation	>3000
Very saline	>9000



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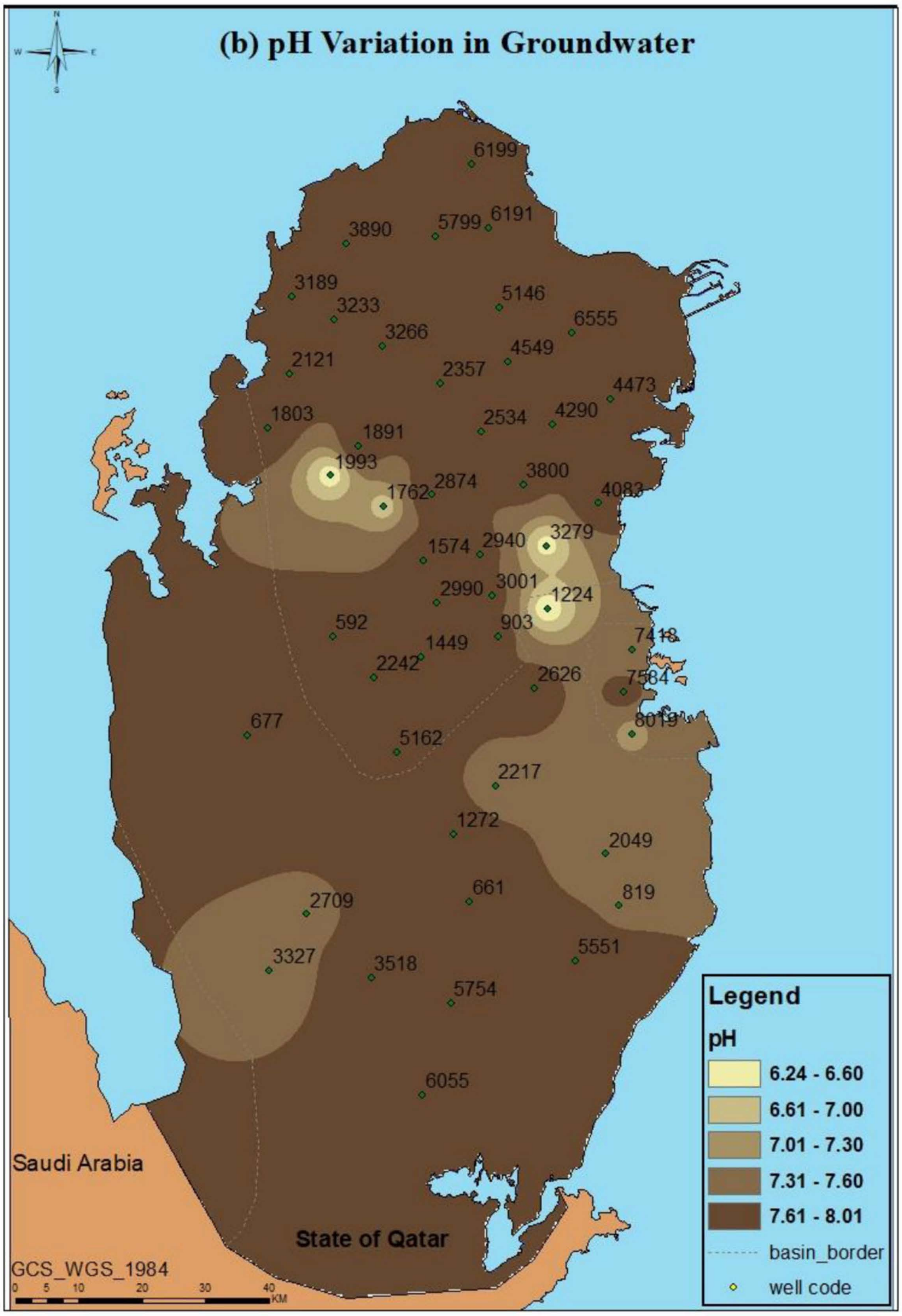

Figure 3. Spatial variations in TDS (**a**) and pH (**b**) in groundwater in Qatar.

3.2. Radon Measurements

Table 4 lists the radon concentration (in Bq/L) in the studied groundwater wells while Table 5 shows the statistical analysis of the present study. The radon concentration values ranged between 2.710 ± 0.205 and 60.700 ± 13.400 Bq/L. The analysis of radon levels in the 48 groundwater samples studied in the present work showed 32 exceedances of the US EPA's maximum contamination level (MCL) of 11 Bq/L.

Table 4. Radon levels in the groundwater wells analyzed in this work.

Well Code	Radon Bq/L	Well Code	Radon Bq/L
592	5.57 ± 0.64	3001	55.50 ± 1.40
661	16.50 ±0.22	3189	7.550 ± 1.720
677	5.16 ± 0.69	3233	11.00 ± 1.710
819	41.90 ± 2.81	3266	21.200 ± 2.070
903	2.71 ± 0.20	3279	20.900 ± 0.907
1224	52.40 ± 2.63	3327	8.550 ± 0.217
1272	12.40 ± 1.50	3518	12.600 ± 0.422
1574	28.90 ± 0.925	3800	14.500 ± 1.120
1762	45.30 ± 1.32	3890	16.100 ± 0.970
1803	11.900 ± 0.948	4083	18.300 ± 1.880
1891	58.800 ± 2.760	4290	17.400 ± 1.790
1993	49.400 ± 4.010	4473	18.500 ± 1.100
2049	60.700 ± 13.400	4549	9.00 ± 0.441
2121	9.870 ± 0.889	5146	17.700 ± 2.540
2217	6.900 ± 0.764	5162	15.600 ± 1.560
2242	14.400 ± 1.380	5551	39.100 ± 3.220
2357	10.500 ± 0.563	5754	15.300 ± 1.910
2534	11.00 ± 2.370	5799	14.500 ± 1.250
2537	10.50 ± 2.370	6055	15.600 ± 0.485
2626	4.870 ± 0.623	6191	18.900± 1.040
2709	10.800 ± 1.110	6199	17.200 ± 1.840
2874	37.200 ± 2.860	6555	7.500± 0.665
2940	44.00 ± 2.240	7418	8.590 ± 0.999
2990	27.20 ± 1.40	8019	11.100 ± 1.030

This accounts for 65% of the studied samples. According to the world health organization (WHO) [66], water sources with radon levels above 100 Bq/L must be treated by means of aeration or an activated carbon system. In the present study, it was found that all of the studied samples had radon levels below the WHO action level.

Figure 4 shows the radon level maps developed by ArcGIS, while Figure 5 shows a bar chart diagram depicting the distribution of radon activity levels in the present study. As can be seen, about 48% of the studied samples had an average radon activity level between 10.1 and 20 Bq/L. The radon level in the groundwater samples studied in the present work was found to fall within the levels reported in the literature (Table 1 and Figure 6). However, the radon levels were found to be higher than the levels found in some parts of the world, such as India, China, Palestine, Iran, Iraq and Saudi Arabia. For instance, the radon level in the groundwater of Iraq was studied by Alawy [33], who surveyed groundwater wells in Karbala. The radon level range in the studied wells was 2–4.1 Bq/L. Althoyaib [29] carried out a study to survey NORM levels, including radon levels, which were determined using RAD7 H_2O, in 19 different groundwater wells in Saudi Arabia. The average level of the radon was reported between 1.45 ± 1.19 and 9.15 ± 1.55 Bq/L. Similarly, El-Sharkawy [53] investigated the radon level in private groundwater wells in Tabouk and Al-Sharqiyah (Saudi Aarabia) using RAD7 and found the range of the radon in the groundwater to be 5.5–11 Bq/L. Likewise, Murad [26] studied the radon level of 12 groundwater wells along the border between UAE and Oman. The reported Rn level in the studied wells was between 0.2 and 17 Bq/L. Furthermore, Al Zabadi [41] carried out similar work in order to study the radon level in groundwater wells of Palestine. In their study, an RAD7 instrument was used to determine the radon level in the groundwater samples collected from wells in Palestine. The range of radon level in the surveyed samples was between 1.5 and 23.4 Bq/L and the average was 6.9 Bq/L. Somashekar [38] studied the activity of radon in 30 groundwater wells in Varahi and Markandeya in India. The study also estimated the annual effective dose exposure. The activity concentration of the studied samples ranged between 0.2 and 27.3 Bq/L.

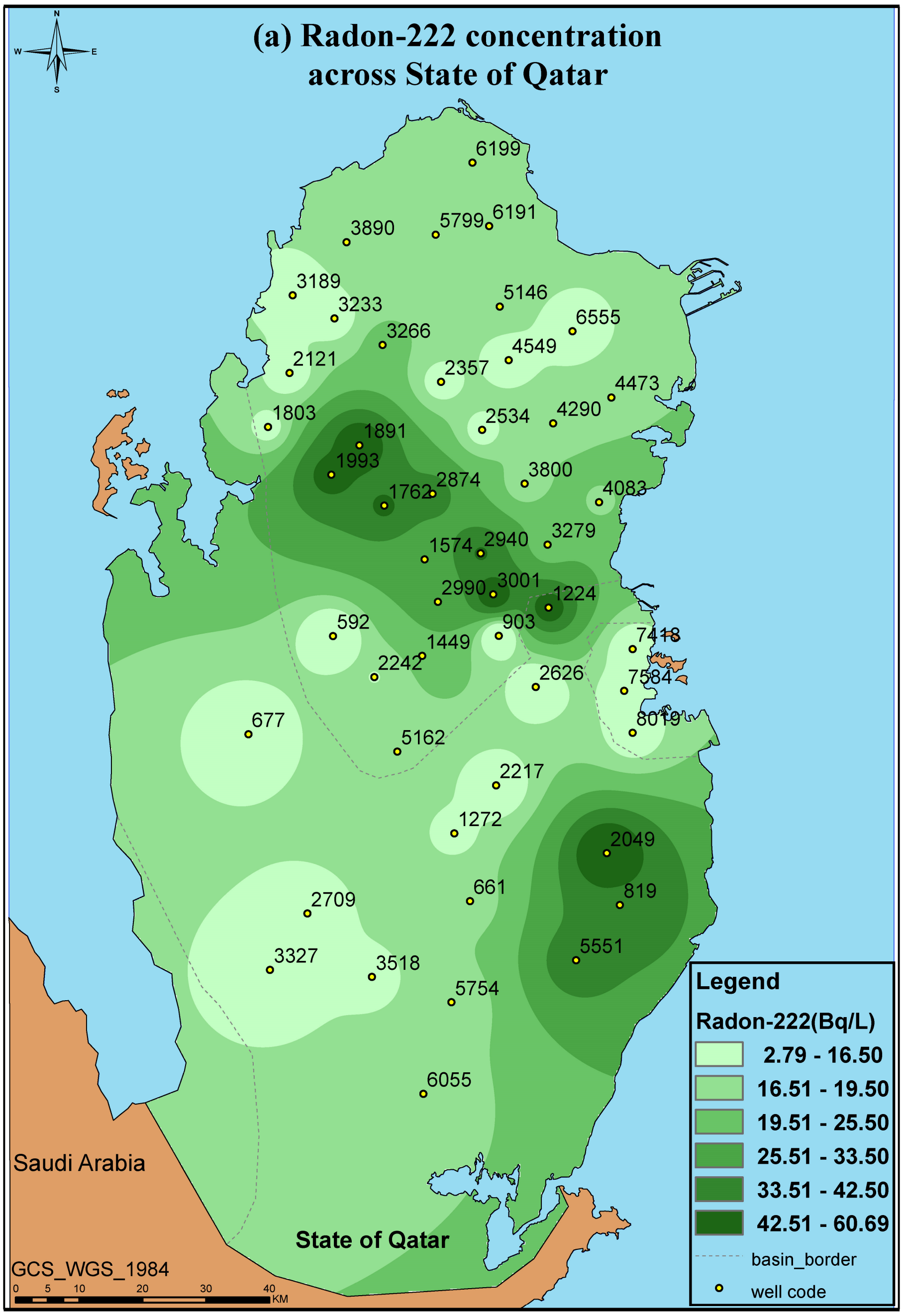

Figure 4. *Cont*.

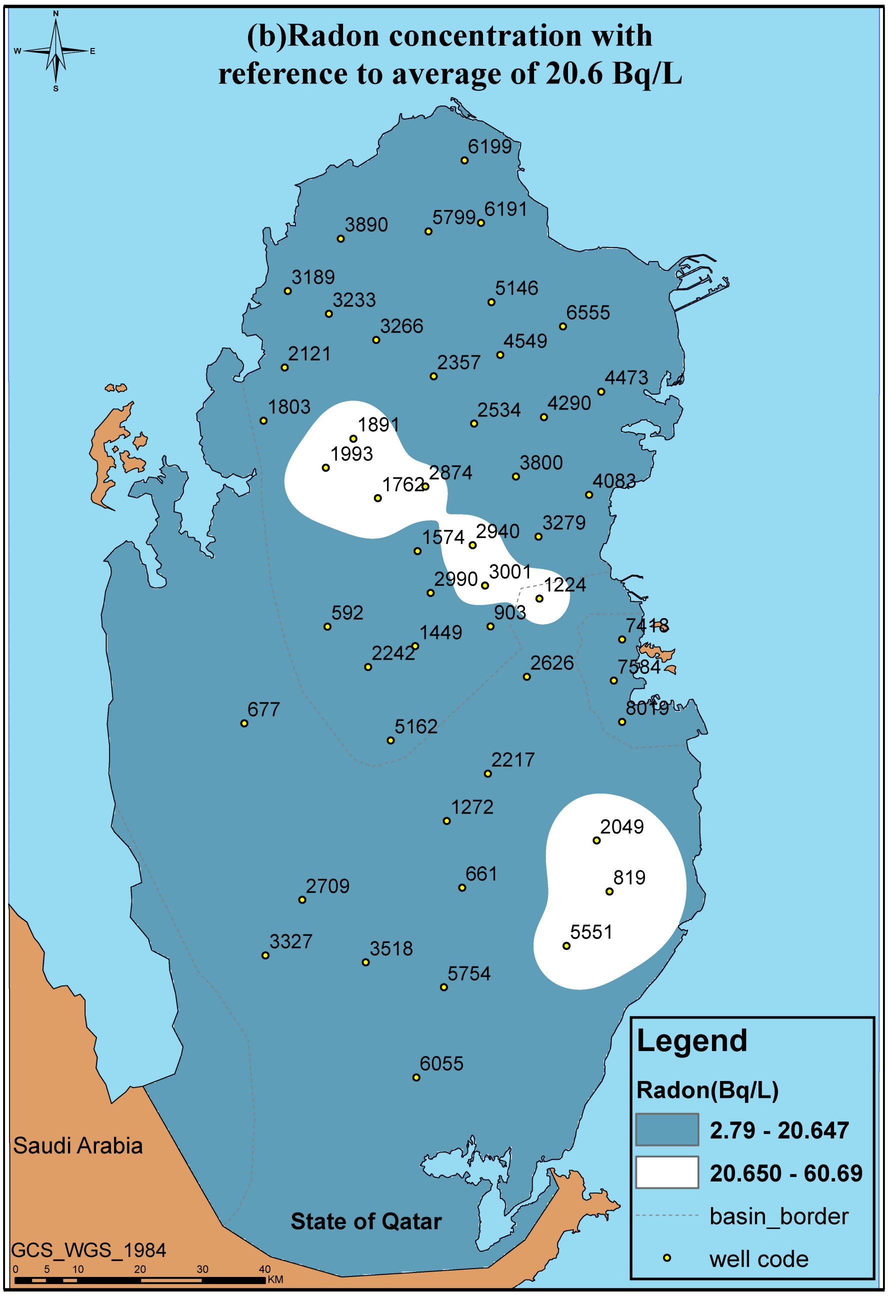

Figure 4. Interpolated maps of radon concentrations in groundwater, created by IDW method.

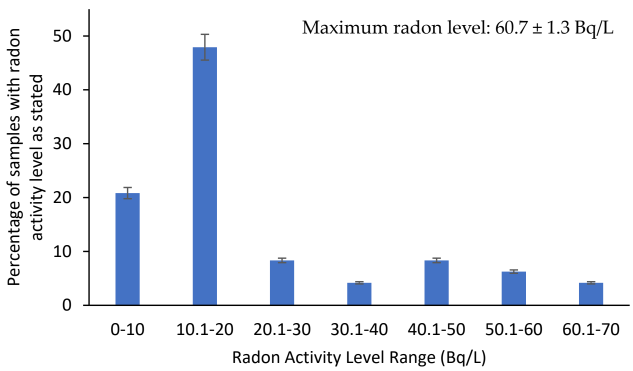

Figure 5. Distribution of radon in groundwater samples in the present study.

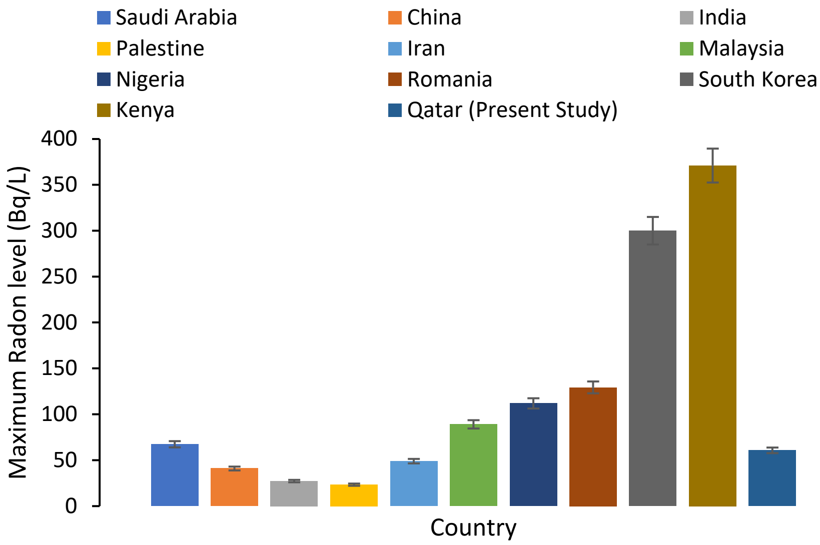

Figure 6. A schematic depicting the radon levels in the present work in comparison with the other studies reported in the literature.

In the present study, the elevation in the concentration of radon in some of the groundwater wells more than others might be attributed to the presence of sandstone formations that have more contact with basement rocks. This resulted in an accumulation of radioactive materials in the sandstone formation and hence increased the activity level of radon in the groundwater. Moreover, the slight elevation in radon levels in the present study could be attributed to a terrestrial source of natural radiation which results from the presence of natural radiation sources in the rocks such as uranium-235, uranium-238 and thorium-232 decay chains [67,68]. Al Sulaiti [54,55] investigated the natural radioactivity levels in Qatar and determined the activity levels of uranium-235, uranium-238 and thorium-232 decay chains in soil. In their work, they found out the level of uranium-238 in one sample to have a mean of 213.97 $\pm$ 1.3 Bq/kg, which was way higher than the world average value of 35 Bq/kg [69] and higher than the uranium-238 levels reported in the literature in Kuwait and Oman [70–72]. Moreover, the investigative work conducted by Deeba on radon in groundwater in Bangladesh also attributed the presence of radon in groundwater to the existence of radium in soil and bedrock around the aquifer [47]. This finding can be supported by the study conducted in Qatar, which reported a radium-226-equivalent level of 228.2 $\pm$ 9.4 in Qatar [54,55]. In another study, Al-Kinani [73] evaluated naturally occurring radioactive materials (NORMs) in soil samples collected in Qatar and found that the activity level of radium-226 in three samples was higher than the NORMs' level exempted by the State of Qatar. This was also confirmed by Hahn, who attributed the presence of radon in groundwater to be generated from radioactive materials, such as uranium in the sedimentary bedrock (such as limestone and shale), which give rise to the formation of radon in groundwater [74]. These findings were observed to agree with several studies that investigated the level and sources of radon in groundwater in the region, such as in Saudi Arabia [3,29,40,75].

The correlation between the radon and the physicochemical characteristics of the groundwater were investigated by plotting the relationship between radon vs. pH and TDS for all the studied groundwater samples. Figure 7a,b shows the scattered data points which did not provide any conclusive correlation between radon and the physicochemical characteristics. This can be supported by observing the coefficients of determination (R^2) for both plots, which were 0.067 and 0.094. The lack of correlation between radon and the physicochemical characteristics was well reported in the literature. For instance, Rahimi [44] investigated the level of radon in groundwater in Iran and found that the level of radon is not correlated with the physicochemical characteristics. They reported the coefficient of determination to be as low as 0.005.

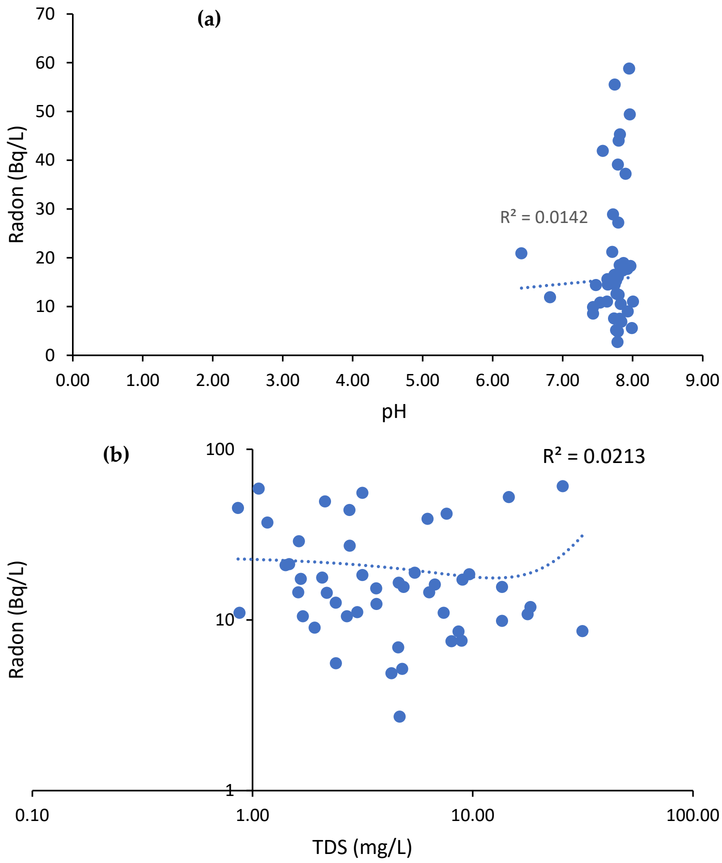

Figure 7. The correlation between radon gas concentration in groundwater and (**a**) pH and (**b**) TDS (logarithmic axis).

Table 5. Radon guideline/standards exceedances.

Number of Samples Measured	48
Min	2.710 ± 0.205
Max	60.700 ± 1.3400
Mean	20.647
Standard Deviation	15.724
US EPA's MCL Standard (Bq/L) [76]	11
Number of Exceedances	32
UNSCEAR Standard (Bq/L) [58]	40
Number of Exceedances	8
WHO Drinking Water Standard (Bq/L) [66]	100
Number of Exceedances	-

3.3. Radiological Risk Assessment

The radiological assessment aims to evaluate the dose and risk to humans from exposure to a radioactive material [77]. Once the activity level of a radioactive material is known, the estimation of the dose and risk can be carried out by doing a careful assessment regarding the exposure to the public [77]. The radiological risk assessment associated with radon can be estimated from Equations (3) and (4). The dose from radon can be divided into two parts: (1) ingestion and (2) inhalation. The annual mean effective doses for ingestion and inhalation were calculated according to parameters introduced by the UNSCEAR report [58] and are calculated as follows:

$$\text{Annual mean effective dose for ingestion } (\mu\text{Sv/y}) =$$

$$\text{Rn}^{222} \text{ conc. } (\text{Bq/L}^1) \times 60 \text{ ly}^{-1} \times 10^{-3} \text{ m}^3 \text{ l}^{-1} \times 3.5 \text{ nSvBq}^{-1}$$

$$= 20.64 \times 60 \times 10^{-3} \times 3.5 \times 10^{-9}$$

$$= 4.328 \ \mu\text{Sv/y}$$

$$\text{Annual mean effective dose for inhalation (mSv)} =$$

$$\text{Rn}^{222} \text{ conc. (Bq/L)} \times 10^{-4} \times 7000 \text{ hy}^{-1} \times 0.4 \times 9 \text{ nSv } (\text{Bqhm}^{-3})^{-1}$$

$$= 20.64 \times 10^{-4} \times 7000 \times 0.4 \times 9 \times 10^{-9}$$

$$= 51.947 \ \mu\text{Sv/y}$$

The estimated radiological risk through inhalation and ingestion of radon in Qatar is illustrated in Table 6. The total mean annual effective dose ranged between 7.4 and 165.7 µSv/y. The WHO's recommended reference level for the annual effective dose received from drinking water consumption was reported at 0.1 mSv/y [78]. This means that if the dose is lower than (or equal to) the reference level, then the water is suitable for drinking purposes and no further action is necessary. On the other hand, if the dose exceeds the reference level of the annual effective dose, then remedial measures are required to reduce it. In the current study, the estimated average of the total annual effective dose due to radon inhalation and ingestion is 0.056.3 mSv/y, which is well below the reference level of the WHO and hence does not pose any health problem from the radon dose received from drinking water in the study area. In the current study, the values of the mean annual effective dose from ingestion and inhalation of water-borne radon were 4.3 and 52.03 µSv/y, respectively. It is clear that the inhalation dose contribution is higher than the ingestion part of the radiological hazard. The annual effective doses estimated in this work were found to be in good agreement with the work reported in the literature (Table 1). For instance, the annual mean effective dose from inhalation and ingestion of radon was estimated at 17 µSv in the central part [27] and 28.99 ± 2.12 µSv in the southern part [40] of Saudi Arabia and 22.7 µSv in the United Arab Emirates [39]. Moreover, the total annual mean effective dose range from a study in Bangladesh was reported at 1.00–42.87 µSv.

The main limitation encountered while conducting the study could be attributed to the inaccessibility of some groundwater wells, which limited our access. This limitation was overcome by selecting another sampling location within a 5 km diameter circle in order to substitute the inaccessible sampling locations.

Table 6. Radon levels of the studied groundwater wells in addition to the radiation risk through inhalation and ingestion.

Well Code	Radon (Bq/L)	Annual Mean Effective Dose (µSv/y)		
		Ingestion	Inhalation	Total
592	5.57	1.17	14.04	15.21
661	16.50	3.47	41.58	45.05
677	5.16	1.08	13.00	14.09
819	41.90	8.80	105.59	114.39
903	2.71	0.57	6.83	7.40
1224	52.40	11.00	132.05	143.05
1272	12.40	2.60	31.25	33.85
1574	28.90	6.07	72.83	78.90

Table 6. *Cont.*

Well Code	Radon (Bq/L)	Annual Mean Effective Dose (μSv/y)		
		Ingestion	Inhalation	Total
1762	45.30	9.51	114.16	123.67
1803	11.90	2.50	29.99	32.49
1891	58.80	12.35	148.18	160.52
1993	49.40	10.37	124.49	134.86
2049	60.70	12.75	152.96	165.71
2121	9.87	2.07	24.87	26.95
2217	6.90	1.45	17.39	18.84
2242	14.40	3.02	36.29	39.31
2357	10.50	2.21	26.46	28.67
2534	11.00	2.31	27.72	30.03
2537	10.50	2.21	26.46	28.67
2626	4.87	1.02	12.27	13.30
2709	10.80	2.27	27.22	29.48
2874	37.20	7.81	93.74	101.56
2940	44.00	9.24	110.88	120.12
2990	27.20	5.71	68.54	74.26
3001	55.50	11.66	139.86	151.52
3189	7.55	1.59	19.03	20.61
3233	11.00	2.31	27.72	30.03
3266	21.20	4.45	53.42	57.88
3279	20.90	4.39	52.67	57.06
3327	8.55	1.80	21.55	23.34
3518	12.60	2.65	31.75	34.40
3800	14.50	3.05	36.54	39.59
3890	16.10	3.38	40.57	43.95
4083	18.30	3.84	46.12	49.96
4290	17.40	3.65	43.85	47.50
4473	18.50	3.89	46.62	50.51
4549	9.00	1.89	22.68	24.57
5146	17.70	3.72	44.60	48.32
5162	15.60	3.28	39.31	42.59
5551	39.10	8.21	98.53	106.74
5754	15.30	3.21	38.56	41.77
5799	14.50	3.05	36.54	39.59
6055	15.60	3.28	39.31	42.59
6191	18.90	3.97	47.63	51.60
6199	17.20	3.61	43.34	46.96
6555	7.50	1.58	18.90	20.48
7418	8.59	1.80	21.65	23.45
8019	11.10	2.33	27.97	30.30
Statistical Analysis				
Min		0.57	6.83	7.40
Max		12.75	152.96	165.71
Mean		4.34	52.03	56.37
Standard Deviation		3.30	39.62	42.93

4. Conclusions

Summary of the main findings:

- Forty-eight groundwater samples were collected from different parts of Qatar and analyzed for their physical parameters and radon level.
- The radon levels observed ranged between 2.710 ± 0.205 and 60.700 ± 13.400 Bq/L.
- The mean value calculated at 20.647 Bq/L is higher than the EPA's maximum contaminant level (MCL) for radon in public drinking water of 11.1 Bq/L.
- The radon radiological hazard through inhalation is higher than the ingestion dose.

- The estimated average of the total annual effective dose due to radon inhalation and ingestion was 0.056.3 mSv/y which is well below the reference level of the WHO (0.1 mSv/y).

Future studies could focus on evaluating the radiation levels in vegetation irrigated by groundwater. A thorough investigation should be carried out on Ra-226 uptake by plants as well as differences in plant species uptake.

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