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# Assessment of Carcinogenic and Non-Carcinogenic Health Risks from Heavy and trace metals in Groundwater Wells in Sabha City

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# تقييم المخاطر الصحية المسرطِنة وغير المسرطِنة للمعادن الثقيلة والمعادن النزرة في آبار المياه الجوفية في مدينة سبها

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**Abstract**
This study aimed to evaluate the non-carcinogenic and carcinogenic health risks associated with heavy and trace metals (HMs and TMs) in groundwater wells in Sabha City, Libya. Thirty-six samples were collected from nine wells, coded S1–S9. The results showed that the concentrations of Ni, Mn, Zn, Cr, and Cu were within the permissible limits established by the USEPA and WHO. In contrast, Fe concentrations exceeded the permissible limit in wells S2, S3, S7, S8, and S9, with average concentrations of 3.502, 1.210, .410, .405, and 1.948 mg/L, respectively. Pb concentrations exceeded the WHO permissible limit in samples S1, S2, S6, S7, S8, and S9, with average values of .0437, .0362, .0302, .0590, .0242, and .0200 mg/L, respectively. Cd concentrations exceeded the permissible limit in samples S2, S3, S4, S5, S6, S7, S8, and S9, with average concentrations of .0055, .0157, .0230, .0088, .0058, .0045, .0150, and .0150 mg/L, respectively.

Mathematical models were used to calculate the Average Daily Dose (ADD). The results indicated that the ADD values for HMs and TMs through ingestion and dermal exposure pathways for both adults and children were within the acceptable limits. The Total Hazard Quotient (THQ) and Hazard Index (HI) values for all detected metals were less than 1, indicating no significant non-carcinogenic health risks to adults or children. However, the Target Cancer Risk (TCR) values ranged from low to moderate carcinogenic risk levels. The sources of metals in groundwater were evaluated using correlation analysis, Principal Component Analysis (PCA), and Cluster Analysis (CA). The results revealed strong correlations among the studied metals, suggesting that they originate from common sources and follow similar geochemical pathways.

**Keywords:** Heavy metals, trace metals, groundwater, average daily dose (ADD), target hazard quotient (THQ), hazard index (HI), target cancer risk (TCR), non-carcinogenic risk, carcinogenic risk.

## الملخص

هدفت هذه الدراسة إلى تقييم المخاطر الصحية غير المسرطنة والمسرطنة المرتبطة بالمعادن الثقيلة والمعادن النزرة في آبار المياه الجوفية بمدينة سبها، ليبيا. حيث تم جمع ستة وثلاثين عينة من تسعة آبار مياه جوفية، ورُمز للإبار (س1 الي س9). أ ظهرت النتائج أن تراكيز النيكل والكروم والزنك والمنغنيز كانت ضمن الحدود المسموح بيها وفقا لمعايير منظمه الصحة العالمية ووكالة حماية البيئة الأمريكية. في المقابل تجاوزت تراكيز عنصر الحديد (س2, س3,س7.س8.س9) حيث بلغت متوسطات التراكيز ( 3.502, 1.210, 410. ,405. ، 1.948 ملغم\لتر. كما تجاوزت تراكيز عنصر الرصاص الحدود المسموح بها لمنظمه الصحة العالمية في الابار (س1 ,س2,س6 ,س7,س8,س9) بمتوسطات بلغت (0437. ,0362. , 0203. , 0590. ,0242. , 0200.ملغم \لتر) علي التوالي . كذألك تجاوزت تراكيز عنصر الكادميوم الحدود المسموح بيها ف الابار (س2, س3,س4,س5,س6,س7,س8, س9) بمتوسطات تراكيز بلغت 0055. , 0157. ,0230. , 0088. ,0045. , 0150. , 0150. ,ملغم \لتر) على التوالي. تم استخدام نماذج رياضية لحساب متوسط الجرعة اليومية المتناولة، وأظهرت النتائج أن قيم متوسط الجرعة اليومية للمعادن الثقيلة والمعادن النزرة عبر طريقي الابتلاع والتلامس الجلدي لدى البالغين والأطفال كانت ضمن الحدود المقبولة. كما بينت نتائج معامل الخطر الكلي ومؤشر الخطر لجميع المعادن المكتشفة أن قيمها كانت أقل من الواحد الصحيح، مما يدل على عدم وجود مخاطر صحية غير مسرطنة ذات أهمية لدى البالغين والأطفال. ومع ذلك، أظهرت نتائج خطر الإصابة بالسرطان مستويات تراوحت بين المخاطر المنخفضة والمتوسطة. كما تم تقييم مصادر المعادن في المياه الجوفية باستخدام تحليل الارتباط الإحصائي، وتحليل المكونات الرئيسية، والتحليل العنقودي. وأظهرت النتائج وجود علاقات ارتباط قوية بين المعادن المدروسة، مما يشير إلى أنها تنحدر من مصادر مشتركة وتخضع لعمليات ومسارات جيو كيميائية متشابهة.

**الكلمات المفتاحية:** المعادن الثقيلة، العناصر النزرة، المياه الجوفية، الجرعة اليومية المتوسط، حاصل الخطر، مؤشر الخطر، مخاطر الإصابة بالسرطان المستهدفة، المخاطر غير المسرطنة، المخاطر المسرطنة.

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## Introduction

Groundwater is considered an essential source of water for human use. A third of the world's population depends on it, also the demand for water has increased due to global population growth [8] and increased human activities. This has led to water resources being unable to meet these demands [2]. Consequently, the phenomenon of water scarcity has emerged in some countries, along with the problem of water pollution. Groundwater is one of the most important natural resources globally and especially in Libya [25]. Libya suffers from limited surface water resources, such as springs and rivers, as it is located within a desert region characterized by an arid climate. Groundwater in Libya is the primary source, meeting more than 90% of human, agricultural, economic, and industrial needs. It is also a crucial factor in the development of arid and semi-arid regions [26]. An individual's daily need for drinking and cooking water is estimated at about five litters for a person. Additionally, a person needs about 40 to 50 litters of water to maintain personal health and hygiene [3]. In Libya, the use of groundwater for agriculture was estimated at about 4,865 million m³ (Mm³) in 2010 and about 6,395 million m³ (Mm³) in 2015. For domestic uses, it was estimated at about 731 million m³ (Mm³) in the same year [5]. Despite its great importance, there are significant concerns about groundwater pollution [7]. Water pollution poses a serious threat every year about 15 million children die due to contaminated water, and approximately 180,000 animal species and 10,000 plant species are endangered by water pollution [4]. Various natural and human activities have affected groundwater quality, particularly pollution from heavy metals and btrace metals (HMs and TMs) [9]. The most important natural sources of HMs and TMs are the erosion of underlying rocks and natural geological processes, such as rock weathering and water-rock interactions. In contrast, anthropogenic sources result from atmospheric deposition and the release of metals from plants, especially btrace metals [11]. Industrial wastewater, mineral processing, mining, the excessive use of fertilizers in agriculture, industrialization, rapid unplanned urbanization, and the disposal of municipal, industrial, and medical waste are among the primary causes of groundwater pollution [23]. Furthermore, the extensive extraction of groundwater contributes to the deterioration of its quality [22]. Metals enter groundwater through the hydrological cycle, as well as through various reactions, including absorption, sedimentation, leaching, runoff, and the leaching of soil layers. These interactions influence their mobility and bioavailability [21]. Heavy and btrace metals (HMs, TMs) such as zinc (Zn), lead (Pb), manganese (Mn), iron (Fe), copper (Cu), nickel (Ni), cadmium (Cd), and chromium (Cr) are released into groundwater sources are negatively affecting human health [6]. They can cause numerous diseases, including cancer, peripheral vascular disease, impaired kidney and liver function, lung disease, high blood pressure, nervous system disorders [10]. The aim of this study was to determine the concentration levels of heavy metals and btrace elements in groundwater wells in the city of Sabha and to evaluate the associated carcinogenic and non-carcinogenic health risks.

## 1. Study Area and sampling

This study was conducted in Sabha, a city situated in south-western Libya. Geographically, it lies between latitudes 26°10′ and 27°04′ N and longitudes 13°58′ and 15°59′ E, approximately 640 km south of the capital, Tripoli. The city is bounded by Wadi Al-Shati to the north, Al-Jufra to the east, Murzuq to the south, and Wadi Al-Hayat to the west. The climate is predominantly desert, characterized by average surface temperatures ranging from 20°C to 40°C, with monthly minimums in November and maximums in May. The region receives minimal average annual rainfall of 64 mm. Despite the absence of rivers and springs, the area possesses substantial aquifer systems[47].

Water samples were collected from nine distinct wells in Sebha, as illustrated in Figure 1. The sampling campaign was conducted between May and June 2024 in accordance with WHO guidelines [15], and the geographical coordinates of all wells were recorded using a GPS device [48]. The wells were designated as S1 through S9, with their locations detailed in Table 1. Before sampling**,** the water taps were flame-sterilized for a specified period. Each well was then activated and pumped for 15 minutes to ensure system purging before a representative sample was collected from the feed outlet. A volume of 200 ml was gathered from each well, and this process was repeated four times per well to ensure statistical reliability. All samples were stored in pre-treated glass bottles**.** As a preparatory step**,** these bottles had been thoroughly washed with a 10% nitric acid solution and subsequently rinsed multiple times with distilled water to guarantee sample purity and prevent any potential contamination [1, 44].

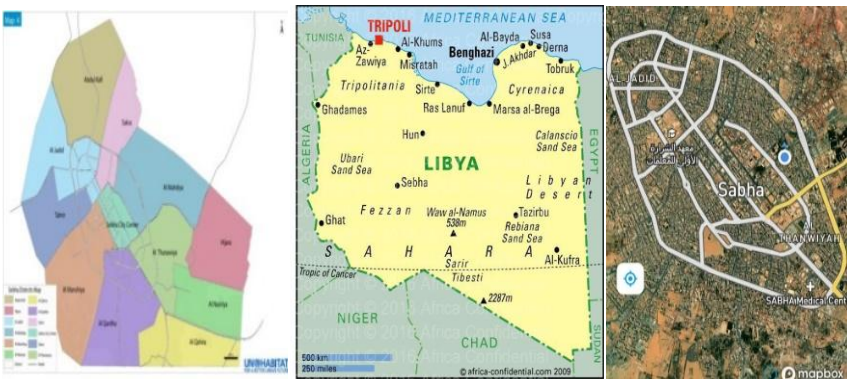

**Figure 1**: Map showing the locations of groundwater wells in Sabha city.

**Table 1**. Specifications locations and geographical coordinates of groundwater wells in the city of Sabha

| Region | Well No | Productivity m3/hour | Well depth(m) | Packaging diameter (mm) | Pump landing depth (m) | The researched wells' geographic coordinates |
|---|---|---|---|---|---|---|
| Al-Jadid | S1 | 30 | 139 | 300 | 66 | N 27°05′25″ and E 14°41′76″ |
| Abd Kafi | S2 | 30 | 90 | 300 | 89 | N 27°06′16″ and E 14°41′75″ |
| Al-Mahdia | S3 | 50 | 154 | 400 | 84 | N 27°04′41″ and E 14°43′16″ |
| Al-Karama | S4 | 50 | 135 | 350 | 66 | N 27°02′36″ and E 14°44′15″ |
| Sokra | S5 | 50 | 154 | 400 | 81 | N 27°04′97″ and E 14°42′57″ |
| Al-Manshiya | S6 | 40 | 90 | 300 | 90 | N 27°04′05″ and E 14°42′04″ |
| Al-Qarada | S7 | 50 | 117 | 300 | - | N 27°04′04″ and E 14°43′52″ |
| Al-Thaniya | S8 | 40 | 150 | 300 | 72 | N 27°03′84″ and E 14°44′31″ |
| Al-Nasiriyah | S9 | 40 | 147 | 300 | 72 | N 27°02′05″ and E 14°45′18″ |

## Material and methods

### 1. Preparation of Groundwater Samples for Heavy and trace Metal

Following the procedures outlined in [29] and [41], Water samples were collected in sterile 500 mL polyethylene bottles, washed with 10% nitric acid and deionized water to prevent contamination. The samples were immediately filtered in the laboratory using 0.45 µm filter membranes to remove suspended solids, then preserved by adding ultrapure nitric acid until pH < 2.0 was achieved according to the EPA standard method.

Fifty mL of each filtered sample was digested by adding 2 mL of concentrated $HNO_3$ and heated on a hot plate at 85°C until it evaporated to approximately 20 mL. The solution was then cooled and the volume was topped up to 50 mL with deionized water. The concentrations of Fe, Zn, Cr, Cu, Pb, Ni, Mn, and Cd were measured using a NovAA400 atomic absorption spectrometer at the Scientific Research and Consulting Laboratory, Sebha University. Recovery rates ranged from 93% to 105%, and the relative standard deviation (RSD) was less than 5%. The limit of detection (LOD) and limit of quantification (LOQ) for each element were set at 3 and 10 times the standard deviation of the blank samples, respectively.

### 2. Preparation of Standard Solution

Standard solutions were prepared at concentrations of 0.1, 0.3, 0.5, 1.0, and 2.0 mg/L for each element by sequential dilution of a 1000 mg/L standard solution from the Italian company Carlo Erba Reagents, and the coefficient of determination $R^2 \geq 0.999$.

### 3. Evaluation of risks to human health caused by TMs and HMs in groundwater

Non-carcinogenic risks and carcinogenic risks were assessed through oral ingestion of groundwater (drinking) and direct skin contact with water during washing, rinsing, and bathing by calculating the average daily dose (ADD), risk quotient (THQ), hazard index (HI), and target cancer risk (TCR) for life [40].

**Average daily dose (ADD):** ADD was calculated for **HMs and TMs** for children and adults by ingestion (oral) and skin contact [30].

$$ADD_{\mathrm{ingestion}} = C \times \frac{\mathrm{IngR} \times EF \times ED}{BW \times AT} \times 10^{-6} \qquad (1)$$

$$ADD_{\mathrm{dermal}} = C \times \frac{SA \times AF \times ABF \times EF \times ED}{BW \times AT} \times 10^{-6} \qquad (2)$$

**Where:** C is the concentration of HMs and TMs in mg/L day−1, while IngR, the average water intake, is 2.2 L day−1 for adults and 1.5 L day−1 for children. EF is 365-day year$^{-1}$, and ED is the duration of exposure, 6 years for children and 24 years for adults. BW is the average body weight (child = 15 kg, adult = 70 kg). AT is the average time (365×ED). SA is the surface area of exposed skin, 5700 cm$^{2}$. ABF percutaneous absorption factor 0.001, AF skin adhesion factor in milligrams cm$^{-1}$ (0.2 for adults and 0.07 for children) [12].

**Hazard Quotient (THQ):** ADD is the ratio of exposure routes (oral and skin), and RfD is the reference dose for each metal in mg/kg/day, which is usually used to estimate its non-carcinogenic probability [39].

$$TGQ = \frac{ADD_{dem,i}}{RfD_{dem,i}}, \frac{ADD_{ing}}{RfD_{ing}} \qquad (3)$$

RfD mg/kg$^{-1}$/day for HMs and TMs are shown in Tables 9 and 10. While THQ < 1 is considered, HMs and TMs in water do not pose a significant health risk [36].

Hazard index (HI): It is the sum of all HMs and TMs expected non-carcinogenic risks through oral and skin routes to calculate the total non-carcinogenic risks through exposure routes according to the following equation [43].

$$\mathrm{ingestion} + \left(\frac{ADD_{ing}}{\mathrm{RfD}}\right) \ \mathrm{dermaHI} = \left(\frac{ADD_{dem,i}}{\mathrm{RfD}}\right) \qquad (4)$$

**Where:** ADD and RfD are daily and reference doses for the element. If HI<1, it indicates no adverse health effects, while HI>1 indicates potential non-carcinogenic adverse health effects, and the probability increases with higher values [32].

**Target cancer risk TCR:** It is the risk resulting from exposure to an average dose over a lifetime, such that a person may develop cancer over 70 years of age after exposure to a potentially carcinogenic substance for adults, while children have the possibility of developing cancer over 15 years of age. Cancer risk was calculated as follows.

$$TCR = \mathrm{LADD}_{\mathrm{ingestion},\ ADD_{\mathrm{dermal}}} \times CSF \qquad (5)$$

**Where**: ADD and CSF are daily doses multiplied by the cancer regression factor for chromium, l5ead, zinc, cadmium, and nickel listed in Tables 11 and 12, while the rest of the elements have not been determined as cancer regression factors according to the United States Environmental Protection Agency guidelines [20,42].

### 4. Statistical Analysis

Statistical analysis data were analyzed using SPSS to determine statistical significance. The metal concentrations of HMs and TMs in groundwater were evaluated, and the mean, standard deviation, and one-way analysis of variance (ANOVA) were calculated to determine significant differences for each metal in groundwater.

In addition, multivariate multiple range tests were performed following Duncan's test and Pearson's correlation coefficient, where p-values less than 0.05 were considered statistically significant.

All statistical analyses were conducted SPSS 26. Metal concentrations are presented as mean ± standard deviation. One-way analysis of variance (ANOVA) was applied to compare mean concentrations among sites. When ANOVA indicated significant differences ($p < 0.05$), Duncan’s multiple range test was used for pairwise comparisons. Pearson’s correlation coefficient was calculated to evaluate inter-element relationships. A p-value $< 0.05$ was considered statistically significant.

## 5 Result and decoctions

### Concentration of HMs and TMs in Groundwater Wells

The results showed a clear variation in the concentrations of heavy and trace metals among the groundwater wells in the city of Sabha.

Table 2 shows the concentrations of the HMs and TMs studied, namely Ni, Mn, Fe, Zn, Cr, Cu, Pb, and Cd. In nine groundwater wells in the city of Sabha. The highest average of HMs and TMs was in groundwater wells: Fe (3.50 ± 0.017) > Cu (0.26 ± 0.052) > Ni (0.14 ± 0.0469) > Mn (0.155 ± 0.0129) > Pb (0.059 ± 0.0046) > Zn (0.044 ± 0.0009) > Cd (0.023 ± 0.0008) > Cr (0.006 ± 0.0009) mg/L$^{-1}$. At sites S2, S6, S5, S8, S7, S3, S4, and S1, respectively.

Iron (Fe) was the most concentrated mineral in the wells, averaging in S2, S3, S7, S8, and S9, with an average of 3.5025±.01707, 1.2100±.02000, .410±.0082, 1.2100±.02000, .410±.0082, and .405±.00577 mg/L$^{-1}$ respectively. according to the World Health Organization (WHO), which estimated it at 0.3 mg/L$^{-1}$ ppm [16]. The high iron concentrations can be attributed to two main sources: natural geological sources. The city of Sabha is located on the Fezzan aquifer, and the aquifer rocks are characterized by high iron content. Prolonged interaction of groundwater with these rocks leads to the dissolution and increase of iron in the groundwater [49,53,54]. The second source is human-induced, such as leakage of sewage and industrial wastewater, and corrosion of old iron pipes in the distribution network [25,38,48].

Lead (Pb) levels exceeded the WHO limit of 0.01 mg/L in 6 out of 9 wells [16]. The highest value was recorded in well S7, with an average of 059±.005 mg/L$^{-1}$. Lead is naturally rare in groundwater, so its presence indicates human-caused contamination [28,38]. This contamination can be caused by the use of leaded water pipes, emissions from vehicle exhaust accumulating in the soil and battery and paint waste [55]. Lead is a cumulative metal, and there is no safe level for it in drinking water. Chronic exposure, even at low concentrations, causes neurological damage, memory impairment, and high blood pressure. It is particularly dangerous for children due to its impact on brain development [48].

Cadmium (Cd) levels were above the permissible limit of 0.003 mg/L in all wells except S1. These results are consistent with study [26]. The most likely source is industrial activities such as battery and paint production, as well as phosphate fertilizers used in agriculture around Sabha [43]. Cadmium's classification as a Group 1 carcinogen by the IARC makes this elevation a serious health concern [28].

In contrast, the concentrations of copper (Cu), zinc (Zn), chromium (Cr), manganese (Mn), and nickel (Ni) were within internationally permitted limits, indicating no significant contamination with these elements in the study area [16] These findings are in agreement with previous studies [38, 27].

**Table 2.** Average Conc of HMs and TMs (mg/L −1), and Duncan analysis in groundwater wells in the city of Sabha.

| Location | Water (n = 4) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | cd | Pb | Cu | Cr | Zn | Fe | Mn | Ni |
| S1 | $^{f}$.002±0E-7 | $^{b}$.044±.006 | $^{a, b}$.210±.103 | $^{a}$.006±.001 | $^{b}$.044±.001 | $^{g}$.180±0E-7 | $^{d}$.04±0E-7 | $^{c}$.012±0E-7 |
| S2 | .005±0.001 $_{e.d}$ | $^{c}$.036±.007 | $^{b}$.182±.009 | .004±.000 $^{c}$ | $^{a}$.135±.010 | $^{a}$ 3.50±.017 | $^{f}$ 020±0E-7 | .0152±.006 $^{c}$ |
| S3 | $^{b}$.015±0.000 | $^{e, f}$.019±.001 | .148±.005 $^{b}$ | .003±.000 $^{d}$ | $^{b}$.045±.001 | $^{c}$ 1.21±.02 | $^{b}$.127±.009 | .023±.0038 $^{c}$ |
| S4 | $^{a}$.023±0.000 | $^{f}$.014±.004 | $^{b}$.1675±.015 | $^{a, b}$.006±.001 | $^{c}$.021±.001 | $^{e}$.340±.008 | $^{d}$.035±.01 | $^{b}$.080±.0116 |
| S5 | $^{c}$.008±0.000 | $^{f}$.013±.001 | $^{b}$ .185±.010 | $^{d}$.003±.000 | $^{c, d}$.017±.000 | $^{f}$.28±.012 | $^{f}$.017±.005 | $^{a}$.140±.046 |
| S6 | $^{d}$.005±0.000 | $^{c, d}$.030±.000 | $^{a}$.260±.052 | $^{c, d}$.004±.000 | $^{d}$.016±.001 | $^{e}$.35±.024 | $^{c}$.100±0E-7 | $^{b}$.078±.0047 |
| S7 | $^{e}$.004±0.000 | $^{a}$.059±.005 | $^{a, b}$.207±.075 | $^{c, d}$.004±.000 | $^{d}$.014±0E-7 | $^{d}$.410±.008 | $^{e f}$.023±.00 | $^{c}$.013±.0048 |
| S8 | $^{b}$.015±0.001 | $^{e, d}$.024±.005 | $^{a, b}$.190±0E-7 | $^{a, b}$.005±.0003 | $^{d}$.015±.0001 | $^{d}$.405±.005 | $^{a}$.155±.012 | $^{c}$.022±.003 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| S9 | $^{b}$.015±0E-7 | $^{e,f}$.020±.004 | $^{b}$.175±.005 | $^{a,b}$.005±.000 | $^{d}$.012±.000 | $^{b}$1.94±.043 | $^{d,e}$.032±.002 | $^{c}$.020±.000 |
| WHO | 0.003 | 0.01 | 2.0 | 0.1 | 3.0 | 0.3 | 0.5 | 0.1 |
| USEPA | 0.01 | 5.0 | 2.0 | 0.1 | 2.0 | 5.0 | 0.2 | 0.2 |

WHO, 2004; WHO, 2011; USEPA; 200

**ANOVA:** To determine the differences between HMs and TMs in groundwater wells. The results of the ANOVA analysis shown in Table 3 showed that there were no significant differences for the Cu element at a significance level of 0.106, where P>0.05. While there are statistically significant differences at the level (P < 0.05) for Cd, Pb, Cr, Zn, Fe, Mn, and Ni. These differences can be attributed to the different sources of HMs and TMs in groundwater wells and to the diversity and differences in sources of pollution.

**Table 3.** One-way variance of analysis ANOVA showing variation HMs and TMs in groundwater wells in the city of Sabha.

| Metal | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Cd | Between Groups | .002 | 8 | .000 | 320.9 | .000 |
| | Within Groups | .000 | 27 | .000 | | |
| | Total | .002 | 35 | | | |
| Pb | Between Groups | .007 | 8 | .001 | 42.9 | .000 |
| | Within Groups | .001 | 27 | .000 | | |
| | Total | .008 | 35 | | | |
| Cu | Between Groups | .033 | 8 | .004 | 1.9 | .106 |
| | Within Groups | .060 | 27 | .002 | | |
| | Total | .093 | 35 | | | |
| Cr | Between Groups | .000 | 8 | .000 | 21.2 | .000 |
| | Within Groups | .000 | 27 | .000 | | |
| | Total | .000 | 35 | | | |
| Zn | Between Groups | .050 | 8 | .006 | 542.8 | .000 |
| | Within Groups | .000 | 27 | .000 | | |
| | Total | 0.050 | 35 | | | |
| Fe | Between Groups | 39.8 | 8 | 4.968 | 12992.3 | .000 |
| | Within Groups | .010 | 27 | .000 | | |
| | Total | 39.8 | 35 | | | |
| Mn | Between Groups | 0.087 | 8 | .011 | 302.3 | .000 |
| | Within Groups | 0.001 | 27 | .000 | | |
| | Total | 0.088 | 35 | | | |
| Ni | Between Groups | 0.064 | 8 | .008 | 29.4 | .000 |
| | Within Groups | 0.007 | 27 | .000 | | |
| | Total | 0.071 | 35 | | | |

Pearson's Correlation Matrix: The Pearson correlation coefficient between HMs and TMs is presented in Table 4. Where there is a statistically significant negative relationship ($p < 0.05$) between Cd and Pb at ($r = 0.707$-), between Cd and Cu at ($r = 0.389$-), between Ni and Pb at ($r = 0.53$), between Ni and Cr at ($r = 0.33$-), and between Ni and Fe at ($r = 0.371$-), and there is a positive relationship at a significance level ($p < 0.05$) between Cu and Pb at ($r = 0.335$-) and between Fe and Zn at ($r = 0.80$).

**Table 4**. Pearson’s coefficient correlation matrix analysis between HMs and TMs in groundwater wells in the city of Sebha.

| Metal | Cd | Correlation coefficient | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Pb | Cu | Cr | Zn | Fe | Mn | Ni |
| cd | 1 | | | | | | | |
| Pb | -.707-** | 1 | | | | | | |
| Cu | -.389-* | .335* | 1 | | | | | |
| Cr | .182 | .068 | .106 | 1 | | | | |
| Zn | -.291- | .185 | -.119- | -.089- | 1 | | | |
| Fe | -.052- | .006 | -.199- | -.061- | .800** | 1 | | |
| Mn | .277 | -.225- | .015 | -.136- | -.223- | -.235- | 1 | |
| Fe | .152 | -.530-** | .094 | -.330-* | -.315- | -.371-* | -.185- | 1 |

*. Correlation is significant at the 0.05 level (2-tailed)

**. Correlation is significant at the 0.01 level (2-tailed).

## Principal component analysis (PCA) and factor analysis (FA)

Principal component analysis, yielding a Kaiser-Meier value of 0.31 with a total contribution of 84.422%, was performed to identify potential sources of heavy and trace metals in groundwater wells in Sabha. Eigenvalues are used to measure the variance each component reveals. Higher eigenvalues indicate greater variance explained or revealed by the factor. Bartlett's test of sphericity yielded a statistically significant result (Sig. = 0.000), indicating a correlation between variables that justifies the analysis. A correlation greater than 0.30 is considered a strong indicator of the quality of the variables.

Table 5. shows the main components and their variations. Four main components with Eigenvalues greater than 1 were extracted: 13.503%, 17.025%, 22.961%, and 30.934%. These four components explain 84.422% of the total variance in the data, a high percentage indicating that the model represents the data well despite the low KMO value.

After rotation (Table 6), strong relationships between variables and components became evident as follows: The first factor, 13.503%, which has strong relationships with iron and zinc, explains a common source for these two elements, most likely a natural geological source from the iron- and zinc-bearing rocks of the Fezzan Basin [49]. The second factor is Fe concentration was the highest among all elements, averaging 3.502 mg/L in well S2. The second factor, 17.025%, has strong relationships with cadmium, lead, and copper. This group of heavy metals is known to have an anthropogenic origin. Their presence together indicates Pollution originating from human activities such as phosphate fertilizers, batteries, pipes, and industrial waste is a contributing factor [43,55]. This explains the exceeding of permissible limits for Pb and Cd in most wells.

The third component, 22.961%, was strongly correlated with Ni and Cr. The correlation between Ni and Cr may reflect an industrial source or corrosion in the water network, especially since Cr appeared at low but varying concentrations across the wells [40]. The fourth component, Mn, explains 30.934% of the variance. The independent manganese factor, 0.907, represents a very strong loading, as shown in Table 6. It is interpreted as an independent geochemical factor related to manganese dynamics, indicating that its concentration in the water is controlled by oxidation-reduction processes within the aquifer [50].

**Table 5**. Principal component analysis (PCA) of HMs and TMs in groundwater wells in the city of Sabha.

| Total Variance Explained | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Component | Initial Eigenvalues | | | Extraction Sums of Squared Loadings | | | Rotation Sums of Squared Loadings | | |
| | Total | % of Variance | Cumulative % | Total | % of Variance | Cumulative % | Total | % of Variance | Cumulative % |
| 1 | 2.475 | 30.934 | 30.934 | 2.475 | 30.934 | 30.934 | 2.151 | 26.891 | 26.891 |
| 2 | 1.837 | 22.961 | 53.895 | 1.837 | 22.961 | 53.895 | 2.110 | 26.370 | 53.260 |
| 3 | 1.362 | 17.025 | 70.920 | 1.362 | 17.025 | 70.920 | 1.313 | 16.413 | 69.673 |
| 4 | 1.080 | 13.503 | 84.422 | 1.080 | 13.503 | 84.422 | 1.180 | 14.749 | 84.422 |
| 5 | .730 | 9.124 | 93.546 | | | | | | |
| 6 | .288 | 3.596 | 97.142 | | | | | | |
| 7 | .164 | 2.054 | 99.196 | | | | | | |
| 8 | .064 | .804 | 100.000 | | | | | | |

Extraction Method: Principal Component Analysis.

**Table 6**. Principal Component Matrix. The rotation is used to illustrate the correlation coefficients between heavy and trace metals in groundwater wells in the city of Sabha.

Rotated Component Matrix$^a$

| | Component | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| cd | -.165- | -.880- | .201 | .152 |
| Pb | .159 | .886 | .213 | .066 |
| Cu | -.372- | .632 | .013 | -.080- |
| Cr | -.111- | -.044- | .945 | -.127- |
| Zn | .898 | .139 | -.078- | -.104- |
| Fe | .921 | -.082- | .011 | -.090- |
| Mn | -.221- | -.170- | -.135- | .907 |
| Ni | -.495- | -.306- | -.556- | -.537- |

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 6 iterations.

Cluster analysis using the Average Linkage method showed that heavy and trace minerals in Sabha city well water clustered into three main groups based on their concentration similarity and chemical behavior, as shown in Figure. The first group comprised iron and zinc. The clustering of these two elements at a close similarity distance indicates a common geological source. This is consistent with the iron-rich geological nature of the Fezzan Basin and with the results of the principal component analysis (PCA), which grouped Fe and Zn together in the first component, suggesting a natural geological explanation. The high Fe concentration in well S2, reaching 3.5 mg/L, supports this interpretation. The second group comprised lead, copper, and chromium. The clustering of these elements suggests a common human- and industrial-source pollution. Lead and copper are often associated with water pipes, batteries, and phosphate fertilizers, while chromium is associated with industrial activities. This grouping aligns with the second component in PCA. The third group comprised nickel, manganese, and cadmium. The fact that this group remained separate until the final stages of clustering indicates independent geochemical behavior and a different source of pollution. Cadmium, in particular, showed a strong inverse correlation with lead in the correlation matrix, which explains its delayed integration with the second group. Overall, the cluster distribution is consistent with the PCA results.

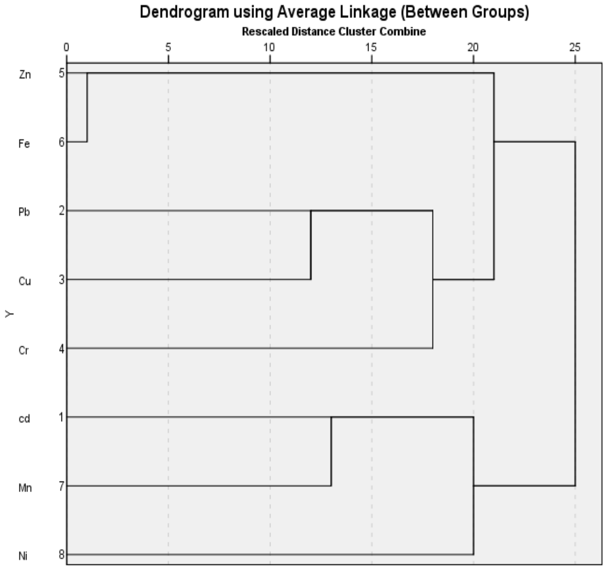

**Fig 2.** The dendrogram of clustering of TMs and HMs in groundwater wells in the city of Sabha.

## Evaluate the potential health risks of HMs and TMs

Average daily dose (ADD) for adults and children via ingestion route: MN, Fe, Cu, Ni, Pb, Cd, Zn, and Cr for nine groundwater wells are consumed for drinking and daily uses by an adult weighing 70 kg ,and the average water intake is 2.2 liter/ day, while the average consumption for children with a body weight of about 15 kg is 1.5 litre/ day [41]. Table 7. shows the results for adults ADD values ranged from $2.67\times10^{-6}$ to $8.17\times10^{-6}$ mg/kg/day for Cu,$6.30\times10^{-7}$ to $4.10\times10^{-6}$ mg/kg/day for Mn, and $5.60\times10^{-6}$ to $1.10\times10^{-4}$mg/kg/day for Fe. The highest ADD for children was observed for Fein S2 ($3.50\times10^{-4}$ mg/kg/day) and Pb in S8 ($1.00\times10^{-4}$ mg/kg/day).

The highest ADD values observed in children relative to adults for most metals are attributed to lower body weight and higher water intake per unit body weight, rather than longer exposure duration. This is consistent with findings reported by [29]. The elevated Pb and Fe concentrations inS2 and S8 likely reflect localized contamination sources, such as corrosion of distribution pipes or orogenic inputs, and warrant further investigation and monitoring [39].

**Table 7.** Calculated ADD values for HMs and TMs for groundwater samples via the ingestion exposure route for adults and children

| **ADD$_{ing}$ (Adults)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Cu** | **Mn** | **Cr** | **Pb** | **Fe** | **Cd** | **Zn** | **Ni** |
| S1 | 6.60E-06 | 1.30E-06 | 1.98E-07 | 1.38E-06 | 5.60E-06 | 6.29E-08 | 1.40E-06 | 3.70E-07 |
| S2 | 5.65E-06 | 6.30E-07 | 1.26E-07 | 1.26E-06 | 1.10E-04 | 1.57E-07 | 1.70E-05 | 4.70E-07 |
| S3 | 2.67E-06 | 4.10E-06 | 9.43E-08 | 6.29E-07 | 3.80E-05 | 8.17E-07 | 1.40E-05 | 7.20E-07 |
| S4 | 5.03E-06 | 1.10E-06 | 1.76E-07 | 4.40E-07 | 1.00E-05 | 7.23E-07 | 6.60E-07 | 2.50E-06 |
| S5 | 5.81E-06 | 6.30E-07 | 1.01E-07 | 4.24E-07 | 8.80E-06 | 2.83E-07 | 5.34E-07 | 4.40E-06 |
| S6 | 8.17E-06 | 3.10E-06 | 1.10E-06 | 9.43E-07 | 1.10E-05 | 1.89E-07 | 5.02E-07 | 2.50E-06 |
| S7 | 6.60E-06 | 6.30E-07 | 1.26E-07 | 1.88E-06 | 1.30E-05 | 1.57E-07 | 4.40E-07 | 4.10E-07 |
| S8 | 5.97E-06 | 4.70E-06 | 1.63E-07 | 9.11E-07 | 1.30E-05 | 4.71E-07 | 4.40E-07 | 6.90E-07 |
| S9 | 5.34E-06 | 9.70E-07 | 1.76E-07 | 6.29E-07 | 6.10E-05 | 4.71E-07 | 3.70E-07 | 6.60E-07 |
| ADD$_{ing}$ (Children) | | | | | | | | |
| S1 | 2.10E-05 | 4.00E-06 | 6.30E-07 | 4.40E-06 | 1.80E-05 | 2.00E-07 | 4.40E-06 | 1.20E-06 |
| S2 | 1.80E-05 | 2.00E-06 | 4.00E-07 | 4.00E-06 | 3.50E-04 | 5.00E-07 | 5.40E-05 | 1.50E-06 |
| S3 | 8.50E-03 | 1.30E-05 | 3.00E-07 | 2.00E-06 | 1.21E-04 | 2.60E-06 | 4.50E-06 | 2.30E-06 |
| S4 | 1.60E-06 | 3.50E-06 | 5.60E-07 | 1.40E-06 | 3.40E-05 | 2.30E-06 | 2.10E-06 | 8.00E-06 |
| S5 | 1.85E-05 | 2.00E-06 | 3.20E-07 | 1.35E-06 | 2.80E-05 | 9.00E-07 | 1.70E-06 | 1.40E-05 |
| S6 | 2.60E-05 | 1.00E-05 | 3.50E-07 | 3.00E-06 | 3.50E-05 | 6.00E-07 | 1.60E-06 | 8.00E-06 |
| S7 | 2.10E-05 | 2.00E-06 | 4.00E-07 | 6.00E-06 | 4.10E-05 | 5.00E-07 | 1.40E-06 | 1.30E-06 |
| S8 | 1.90E-05 | 1.50E-05 | 5.20E-07 | 1.00E-04 | 4.00E-05 | 1.50E-06 | 1.40E-06 | 2.20E-06 |
| S9 | 1.70E-05 | 3.10E-06 | 5.70E-07 | 2.00E-06 | 1.94E-04 | 1.50E-06 | 1.20E-06 | 2.10E-06 |

### Average daily dose (ADD) for adults and children via the transdermal route

Calculated average daily dose of HMs and TMs by skin contact in adults Calculated ADD derma values for adults and children are presented in Table 8. For adults, the highest dermal ADD was observed for Fe in S2 ($5.70\times10^{-5}$ mg/kg/day) and for children in S2 ($9.30\times10^{-5}$ mg/kg/day). Across all metals, dermal ADD values for children were generally higher than those for adults primarily due to higher skin surface area per unit body weight and greater exposure frequency during daily activities.

Hazard quotients (HQ derma ) were calculated using dermal reference doses (RfDderm) derived from oral RfD values adjusted by gastrointestinal absorption factors, following USEPA guidelines [13]. All HQderm values for both adults and children were below 1.0, indicating that dermal exposure to the studied metals does not pose a significant non-carcinogenic health risk. .The highest HQ derma was observed for Fe in S2 for children (HQ = 0.26), which remains below the threshold of concern These results are consistent with study at reference [37] and [14]. who reported that dermal exposure typically contributes less than 5% to total exposure compared to ingestion. However, the elevated Fe and Zn concentrations in S2 and S5 suggest that localized sources, such as pipe corrosion, may increase dermal exposure and should be monitored. The assumption that dermal exposure is negligible cannot be generalized without site-specific verification [19].

**Table 8.** Calculated ADD values for TMs and HMs for groundwater samples via the dermal exposure route for adults and children.

| **$\text{ADD}_{\text{derm}}$ (Adults)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Cu** | **Mn** | **Cr** | **Pb** | **Fe** | **Cd** | **Zn** | **Ni** |
| S1 | 3.42E-06 | 6.51E-07 | 1.03E-07 | 7.16E-07 | 2.93E-06 | 3.26E-08 | 7.16E-07 | 1.90E-07 |
| S2 | 2.93E-06 | 3.25E-07 | 6.51E-08 | 6.51E-07 | 5.70E-05 | 8.14E-08 | 8.80E-06 | 2.40E-07 |
| S3 | 1.38E-06 | 2.12E-06 | 4.88E-08 | 3.25E-07 | 1.97E-05 | 4.23E-07 | 7.32E-07 | 3.70E-07 |
| S4 | 2.60E-07 | 5.60E-07 | 9.12E-08 | 2.28E-07 | 5.54E-06 | 3.74E-07 | 3.42E-07 | 1.30E-06 |
| S5 | 3.01E-06 | 3.25E-07 | 5.21E-08 | 2.19E-07 | 4.56E-06 | 1.46E-07 | 2.77E-07 | 2.28E-06 |
| S6 | 4.23E-06 | 1.63E-06 | 5.69E-08 | 4.88E-07 | 5.70E-06 | 9.77E-08 | 2.60E-07 | 1.30E-06 |
| S7 | 3.42E-06 | 3.25E-07 | 6.51E-08 | 9.77E-07 | 6.68E-06 | 8.14E-08 | 2.27E-07 | 2.11E-07 |
| S8 | 3.09E-06 | 2.44E-06 | 8.46E-08 | 4.72E-07 | 6.51E-06 | 2.44E-07 | 2.27E-07 | 3.50E-07 |
| S9 | 2.76E-06 | 5.05E-07 | 9.28E-08 | 3.25E-07 | 2.43E-05 | 2.44E-07 | 1.95E-07 | 3.40E-07 |
| $\text{ADD}_{\text{derm}}$ (Children) | | | | | | | | |
| S1 | 5.50E-06 | 1.00E-06 | 1.60E-07 | 1.10E-06 | 4.70E-06 | 5.59E-06 | 1.10E-06 | 3.10E-07 |
| S2 | 4.70E-06 | 5.30E-07 | 1.00E-07 | 1.00E-06 | 9.30E-05 | 4.70E-06 | 1.40E-05 | 3.90E-07 |
| S3 | 2.20E-06 | 3.40E-06 | 7.90E-08 | 5.30E-07 | 3.20E-05 | 2.26E-06 | 1.10E-06 | 6.10E-07 |
| S4 | 4.20E-07 | 9.30E-07 | 1.40E-07 | 3.70E-07 | 9.00E-06 | 4.25E-07 | 5.50E-07 | 2.10E-06 |
| S5 | 4.90E-06 | 1.00E-06 | 8.50E-08 | 3.50E-07 | 7.40E-06 | 4.92E-06 | 4.52E-07 | 3.70E-06 |
| S6 | 6.90E-06 | 2.60E-06 | 9.30E-09 | 7.90E-07 | 9.30E-06 | 6.90E-06 | 4.20E-07 | 2.10E-06 |
| S7 | 5.50E-06 | 1.00E-06 | 1.00E-07 | 1.50E-06 | 1.00E-05 | 5.59E-06 | 3.70E-07 | 3.40E-07 |
| S8 | 5.00E-06 | 3.90E-06 | 1.30E-07 | 7.70E-07 | 1.00E-05 | 5.00E-06 | 3.70E-07 | 5.80E-07 |
| S9 | 4.50E-06 | 3.40E-07 | 1.50E-07 | 5.30E-07 | 5.10E-05 | 4.52E-06 | 3.10E-07 | 5.50E-07 |

## Target Risk Quotient (THQ) and Risk Index (HI)

Table 9 and 10 displays the target hazard quotient (THQ) and hazard index (HI) were calculated to evaluate the non-carcinogenic health risks associated with ingestion and dermal exposure to heavy metals and trace metals in groundwater, following USEPA guidelines. Ingestion Pathway: For adults, THQ values for all metals were < 1 across the nine wells, indicating that exposure to individual metals through drinking water does not pose a significant non-carcinogenic risk (Table 9). The corresponding HI values ranged from $8.22\times10^{-4}$ to $2.14\times10^{-3}$, all well below the threshold of 1.

The THQ and HI for children patterns differed notably. While most metals showed THQ < 1, two critical exceedances were observed: Cu in S3 (THQ = $2.12\times10^{-1}$) and Pb in S8 (THQ = $2.86\times10^{-2}$). The HI for children ranged from $2.59\times10^{-3}$ to $2.18\times10^{-1}$. Importantly, none of the HI values exceeded 1, with the highest value recorded in S3 (HI = $2.18\times10^{-1}$). This indicates that the cumulative non-carcinogenic risk from ingestion of the studied metals remains within acceptable limits for children under the assumed exposure scenario. Cd and Pb contributed most to the total HI in children, accounting for 45–68% of the cumulative risk in wells S3, S4, S8, and S9. The elevated risk in S3 is primarily driven by Cu, likely reflecting localized contamination, and these results are consistent with [51].

## Dermal Pathway

Dermal exposure resulted in substantially lower risks compared to ingestion. For adults, THQ derma values were < 1 for all metals, with HI ranging from $3.18\times10^{-3}$ to $4.76\times10^{-3}$. For children, HI values ranged from $4.16\times10^{-3}$ to $3.93\times10^{-2}$, also below the threshold of 1. The highest dermal HI for children was observed in S3 ($3.93\times10^{-2}$), driven mainly by Mn and Pb. Overall, dermal exposure contributed < 15% of the total HI when combined with ingestion, consistent with findings by [29], confirming that ingestion is the dominant exposure route. All calculated HI values for both ingestion and dermal pathways were < 1 for adults and children, suggesting no significant cumulative non-carcinogenic risk at the population level. However, the elevated THQ values for Cu and Pb in specific wells (S3, S8) highlight site-specific concerns that warrant targeted monitoring and mitigation [33].

**Table 9**. Calculated HQ values for TMs and HMs for groundwater samples via ingestion exposure route for adults and children

| **Locations** | **THQ$_{Ing}$ (Adults)** | | | | | | | | **Hi = ∑ THQing** |
|---|---|---|---|---|---|---|---|---|---|
| | **Cu** | **Mn** | **Cr** | **Pb** | **Fe** | **Cd** | **Zn** | **Ni** | |
| S1 | 1.60E-04 | 8.90E-06 | 6.60E-05 | 3.95E-04 | 8.00E-06 | 1.26E-04 | 4.60E-06 | 1.80E-05 | 8.22E-04 |
| S2 | 1.40E-04 | 4.50E-06 | 3.14E-05 | 3.59E-04 | 1.60E-04 | 3.14E-04 | 5.60E-05 | 2.40E-05 | 1.13E-03 |
| S3 | 6.60E-05 | 2.90E-05 | 3.14E-05 | 1.79E-04 | 5.40E-05 | 1.63E-03 | 4.70E-05 | 4.00E-05 | 2.14E-03 |
| S4 | 1.25E-06 | 8.00E-06 | 5.86E-05 | 1.26E-04 | 1.50E-05 | 1.45E-03 | 2.20E-06 | 1.30E-04 | 1.84E-03 |
| S5 | 1.50E-04 | 4.50E-06 | 3.35E-05 | 1.21E-04 | 1.30E-05 | 5.66E-04 | 1.80E-06 | 2.20E-04 | 1.18E-03 |
| S6 | 2.00E-04 | 2.20E-05 | 3.66E-04 | 2.70E-04 | 1.60E-05 | 3.77E-04 | 1.70E-06 | 1.30E-04 | 1.45E-03 |
| S7 | 1.60E-04 | 4.50E-06 | 4.20E-05 | 5.40E-04 | 1.80E-05 | 3.14E-04 | 1.50E-06 | 2.00E-05 | 1.16E-03 |
| S8 | 1.50E-04 | 3.40E-05 | 5.40E-05 | 2.60E-04 | 1.70E-05 | 9.43E-04 | 1.50E-06 | 3.40E-05 | 1.51E-03 |
| S9 | 1.30E-04 | 6.90E-06 | 5.80E-05 | 1.70E-04 | 8.70E-05 | 9.43E-04 | 1.30E-06 | 3.30E-05 | 1.48E-03 |
| THQ$_{Ing}$ (Children) | | | | | | | | | |
| S1 | 5.25E-04 | 2.85E-05 | 2.10E-04 | 1.26E-03 | 2.57E-05 | 4.00E-04 | 1.46E-05 | 6.00E-05 | 2.63E-03 |
| S2 | 4.50E-04 | 1.42E-05 | 1.33E-04 | 1.10E-04 | 5.00E-04 | 1.00E-03 | 1.80E-04 | 7.50E-05 | 2.59E-03 |
| S3 | 2.12E-01 | 9.28E-05 | 1.00E-04 | 5.70E-04 | 1.73E-04 | 5.20E-03 | 1.50E-05 | 1.15E-04 | 2.18E-01 |
| S4 | 4.00E-05 | 2.50E-05 | 1.86E-04 | 4.00E-04 | 4.85E-05 | 4.60E-03 | 7.00E-06 | 4.00E-04 | 5.85E-03 |
| S5 | 4.60E-04 | 1.42E-05 | 1.07E-04 | 3.80E-04 | 4.00E-05 | 1.80E-03 | 5.66E-06 | 7.00E-04 | 3.72E-03 |
| S6 | 6.50E-04 | 7.14E-05 | 1.17E-04 | 8.50E-04 | 5.00E-05 | 1.20E-03 | 5.33E-06 | 4.00E-04 | 3.54E-03 |
| S7 | 5.25E-04 | 1.42E-05 | 1.33E-04 | 1.70E-03 | 5.85E-05 | 1.00E-03 | 4.67E-06 | 6.50E-05 | 3.70E-03 |
| S8 | 4.70E-04 | 1.07E-04 | 1.73E-04 | 2.86E-02 | 5.71E-05 | 3.00E-03 | 4.67E-06 | 1.10E-04 | 3.26E-02 |
| S9 | 4.20E-04 | 2.21E-05 | 1.90E-04 | 5.71E-04 | 2.77E-04 | 3.00E-03 | 4.00E-06 | 1.05E-04 | 4.73E-03 |
| RFD$_{Ing}$ | 0.04 | 0.14 | 0.003 | 0.0035 | 0.7 | 0.0005 | 0.3 | 0.02 | |

**Table 10.** Calculated HQ values for TMs and HMs for groundwater samples via the dermal exposure route for adults and children.

| **Locations** | **THQ$_{derm}$ (Adults)** | | | | | | | | **Hi = ∑THQderm** |
|---|---|---|---|---|---|---|---|---|---|
| | **Cu** | **Mn** | **Cr** | **Pb** | **Fe** | **Cd** | **Zn** | **Ni** | |
| S1 | 1.43E-07 | 3.61E-04 | 1.71E-05 | 1.36E-03 | 4.19E-06 | 6.51E-05 | 2.38E-06 | 3.48E-05 | 3.03E-03 |
| S2 | 1.22E-04 | 1.80E-04 | 1.08E-05 | 1.24E-03 | 8.14E-05 | 1.62E-04 | 2.93E-05 | 4.36E-05 | 3.23E-03 |
| S3 | 5.76E-05 | 1.18E-03 | 8.14E-06 | 6.20E-04 | 2.82E-05 | 8.46E-04 | 2.44E-06 | 6.60E-05 | 4.76E-03 |
| S4 | 1.08E-05 | 3.17E-04 | 1.52E-05 | 4.34E-04 | 7.91E-06 | 7.49E-04 | 1.14E-06 | 2.32E-04 | 3.34E-03 |
| S5 | 1.26E-04 | 1.80E-04 | 8.68E-06 | 4.18E-04 | 6.51E-06 | 2.93E-04 | 9.23E-07 | 4.07E-04 | 3.71E-03 |
| S6 | 1.76E-04 | 9.04E-04 | 9.50E-06 | 9.31E-04 | 8.14E-06 | 1.95E-04 | 8.69E-07 | 2.32E-04 | 4.74E-03 |
| S7 | 1.45E-04 | 1.80E-04 | 1.08E-05 | 1.86E-03 | 9.53E-06 | 1.62E-04 | 7.59E-07 | 3.70E-05 | 4.69E-03 |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| S8 | 1.28E-04 | 1.35E-03 | 1.41E-05 | 8.99E-04 | 9.30E-06 | 4.88E-04 | 7.59E-07 | 6.30E-05 | 3.49E-03 |
| S9 | 1.15E-04 | 2.80E-04 | 1.55E-05 | 6.20E-04 | 3.47E-05 | 4.88E-04 | 6.51E-07 | 6.10E-05 | 3.18E-03 |
| THQ$_{derm}$ (Children) |  |  |  |  |  |  |  |  |  |
| S1 | 2.30E-04 | 5.90E-04 | 2.70E-05 | 2.20E-03 | 6.80E-06 | 2.32E-04 | 3.90E-06 | 5.70E-05 | 5.25E-03 |
| S2 | 1.90E-04 | 2.90E-04 | 1.70E-05 | 2.00E-03 | 1.30E-04 | 1.99E-04 | 4.70E-05 | 7.10E-05 | 5.14E-03 |
| S3 | 9.40E-05 | 1.90E-03 | 1.30E-05 | 1.00E-03 | 4.50E-05 | 9.42E-05 | 3.90E-06 | 1.00E-04 | 3.93E-02 |
| S4 | 1.70E-05 | 5.10E-04 | 2.40E-05 | 7.00E-04 | 1.20E-05 | 1.77E-05 | 1.80E-06 | 3.80E-04 | 4.16E-03 |
| S5 | 2.00E-04 | 2.90E-04 | 1.40E-05 | 6.80E-04 | 1.00E-05 | 2.05E-04 | 1.50E-06 | 6.60E-04 | 5.76E-03 |
| S6 | 2.80E-04 | 1.40E-03 | 1.50E-05 | 1.50E-03 | 1.30E-05 | 2.88E-04 | 1.40E-06 | 3.80E-04 | 7.38E-03 |
| S7 | 2.30E-04 | 2.90E-04 | 1.70E-05 | 3.00E-03 | 1.50E-05 | 2.32E-04 | 1.20E-06 | 6.10E-05 | 7.35E-03 |
| S8 | 2.10E-04 | 2.20E-03 | 2.30E-05 | 1.40E-03 | 1.50E-05 | 2.10E-04 | 1.20E-06 | 1.00E-04 | 5.04E-03 |
| S9 | 1.80E-04 | 1.90E-04 | 2.50E-05 | 1.00E-03 | 7.00E-5 | 1.80E-04 | 1.00E-06 | 9.90E-05 | 4.25E-03 |
| RFD$_{derm}$ | 0.024 | 0.0018 | 0.006 | 0.000525 | 0.7 | 0.0005 | 0.3 | 0.0056 |  |

**Targeted Cancer Risk (TCR)**

The cancer risk was calculated for each mineral and he target cancer risk (TCR) was calculated for Cr, Pb, Cd, Zn, and Ni via ingestion and dermal exposure Ingestion Pathway: For adults, cumulative TCR values ranged from $2.31\times10^{-6}$ to $1.90\times10^{-5}$ (Table 11). All values fell within the $10^{-6}$–$10^{-4}$ range, indicating a low carcinogenic risk. The highest contribution came from Zn and Ni in S2 and S3, respectively. For children, cumulative TCR values ranged from $1.62\times10^{-6}$ to $1.24\times10^{-5}$, also within the low risk category. Ni and Cd were the primary contributors, accounting for 60–85% of the total TCR in most wells. Notably, S5 for children showed the highest TCR ($1.24\times10^{-5}$), driven by Ni exposure [52].None of the wells exceeded the USEPA acceptable risk threshold of $10^{-4}$. However, several wells approached the upper bound of the low-risk category, suggesting that long-term consumption could elevate risk if exposure conditions worsen.

**Dermal Pathway**

Dermal exposure resulted in higher TCR values compared to ingestion due to the larger CSF values used for dermal absorption (Table 12). For adults, cumulative TCR ranged from $1.17\times10^{-5}$ to $9.49\times10^{-5}$, corresponding to low risk across all wells. For children, TCR values ranged from $4.21\times10^{-5}$ to $1.84\times10^{-4}$. Wells S5 and S6 exceeded $10^{-4}$, indicating moderate carcinogenic risk via dermal contact. The elevated risk in S5 and S6 is primarily attributed to Ni and Cd, which have high dermal CSF values of 40.25 and 6.3 $(mg/kg/day)^{-1}$, respectively, according to [35]. This suggests that dermal exposure, often overlooked, can contribute significantly to cumulative cancer risk in children due to higher skin surface area per body weight and longer contact duration during daily activities. wells pose a low carcinogenic risk via ingestion, the moderate risk identified for children via dermal exposure in S5 and S6 warrants attention. Long-term exposure to Cr, Cd, and Ni—classified as Group 1 carcinogens by IARC is of particular concern due to their bio accumulative nature and lack of biological function [28]. These findings are partially consistent with [52,35]. but highlight that risk varies significantly by well and exposure route. Continuous monitoring and mitigation measures, such as pipe replacement and source control, are recommended for wells S2, S3, S5, and S6.

**Table 11.** Calculated TCR values for TMs and HMs for groundwater samples via the ingestion exposure route for adults and children.

| **Locations** | **$TCR_{ingr}$ (Adults)** | | | | | **$\sum CSFing$** |
|---|---|---|---|---|---|---|
| | **Cr= ADD x 0.5** | **Pb= ADD x 0.0085** | **Cd= ADD x 0.38** | **Zn= ADD x 0.06** | **Ni= ADD x 0.84** | |
| S1 | 1.98E-07 | 1.38E-06 | 6.29E-08 | 1.40E-06 | 3.70E-07 | 3.41E-06 |
| S2 | 1.26E-07 | 1.26E-06 | 1.57E-07 | 1.70E-05 | 4.70E-07 | 1.90E-05 |
| S3 | 9.43E-08 | 6.29E-07 | 8.17E-07 | 1.40E-05 | 7.20E-07 | 1.63E-05 |
| S4 | 1.76E-07 | 4.40E-07 | 7.23E-07 | 6.60E-07 | 2.50E-06 | 4.50E-06 |
| S5 | 1.01E-07 | 4.24E-07 | 2.83E-07 | 5.34E-07 | 4.40E-06 | 5.74E-06 |
| S6 | 1.10E-06 | 9.43E-07 | 1.89E-07 | 5.02E-07 | 2.50E-06 | 5.23E-06 |
| S7 | 1.26E-07 | 1.88E-06 | 1.57E-07 | 4.40E-07 | 4.10E-07 | 3.01E-06 |
| S8 | 1.63E-07 | 9.11E-07 | 4.71E-07 | 4.40E-07 | 6.90E-07 | 2.68E-06 |
| S9 | 1.76E-07 | 6.29E-07 | 4.71E-07 | 3.70E-07 | 6.60E-07 | 2.31E-06 |
| $TCR_{ing}$ (Children) | | | | | | |
| S1 | 3.15E-07 | 3.74E-08 | 7.60E-08 | 2.64E-07 | 1.01E-06 | 1.70E-06 |
| S2 | 2.00E-07 | 3.40E-08 | 1.90E-07 | 3.24E-06 | 1.26E-06 | 4.92E-06 |
| S3 | 1.50E-07 | 1.70E-08 | 9.88E-07 | 2.70E-07 | 1.93E-06 | 3.36E-06 |
| S4 | 2.80E-07 | 1.19E-08 | 8.74E-07 | 1.26E-07 | 6.72E-06 | 8.01E-06 |
| S5 | 1.60E-07 | 1.15E-08 | 3.42E-07 | 1.02E-07 | 1.18E-05 | 1.24E-05 |
| S6 | 1.75E-07 | 2.55E-08 | 2.28E-07 | 9.60E-08 | 6.72E-06 | 7.24E-06 |
| S7 | 2.00E-07 | 5.10E-08 | 1.90E-07 | 8.40E-08 | 1.09E-06 | 1.62E-06 |
| S8 | 2.60E-07 | 8.50E-07 | 5.70E-07 | 8.40E-08 | 1.85E-06 | 3.61E-06 |
| S9 | 2.85E-07 | 1.70E-08 | 5.70E-07 | 7.20E-08 | 1.76E-06 | 2.70E-06 |

**Table 12.** Calculated TCR values for TMs and HMs for groundwater samples via dermal exposure route for adults and children.

| **Locations** | **$TCR_{derm}$ (Adults)** | | | | **$\sum CSFderm$** |
|---|---|---|---|---|---|
| | **Cr= ADD x 41** | **Pb= ADDx 0.042** | **Cd= ADD x 6.3** | **Ni= ADD x 40.25** | |
| S1 | 4.22E-06 | 3.01E-08 | 2.05E-07 | 7.65E-06 | 1.21E-05 |
| S2 | 2.67E-06 | 2.73E-08 | 5.13E-07 | 9.66E-06 | 1.29E-05 |
| S3 | 2.00E-06 | 1.37E-08 | 2.66E-06 | 1.49E-05 | 1.96E-05 |
| S4 | 3.74E-06 | 9.58E-09 | 2.36E-06 | 5.23E-05 | 5.84E-05 |
| S5 | 2.14E-06 | 9.20E-09 | 9.20E-07 | 9.18E-05 | 9.49E-05 |
| S6 | 2.33E-06 | 2.05E-08 | 6.16E-07 | 5.23E-05 | 5.53E-05 |
| S7 | 2.67E-06 | 4.10E-08 | 5.13E-07 | 8.49E-06 | 1.17E-05 |
| S8 | 3.47E-06 | 1.98E-08 | 1.54E-06 | 1.41E-05 | 1.91E-05 |
| S9 | 3.80E-06 | 1.37E-08 | 1.54E-06 | 1.37E-05 | 1.91E-05 |
| $TCR_{derm}$ (Children) | | | | | |
| S1 | 6.56E-06 | 4.62E-08 | 3.52E-05 | 1.25E-05 | 5.43E-05 |
| S2 | 4.10E-06 | 4.20E-08 | 2.96E-05 | 1.57E-05 | 4.94E-05 |
| S3 | 3.24E-06 | 2.23E-08 | 1.42E-05 | 2.46E-05 | 4.21E-05 |
| S4 | 5.74E-06 | 1.55E-08 | 2.68E-06 | 8.45E-05 | 9.29E-05 |
| S5 | 3.49E-06 | 1.47E-08 | 3.10E-05 | 1.49E-04 | 1.84E-04 |
| S6 | 3.81E-07 | 3.32E-08 | 4.35E-05 | 8.45E-05 | 1.28E-04 |
| S7 | 4.10E-06 | 6.30E-08 | 3.52E-05 | 1.37E-05 | 5.31E-05 |
| S8 | 5.33E-06 | 3.23E-08 | 3.15E-05 | 2.33E-05 | 6.02E-05 |
| S9 | 6.15E-06 | 2.23E-08 | 2.85E-05 | 2.21E-05 | 5.68E-05 |

USEPA2013, USEPA,(2007), USEPA,(2020), Health Canada, 2016.

## Conclusions

From the results we obtained in this study, the following was concluded: The results showed the presence of eight heavy and trace metals in groundwater wells, which are Ni, Mn, Fe, Zn, Cr, Cu, Pb, and Cd.The consequences of the chemical analysis showed that the concentration of Ni, Mn, Zn, Cr, and Cu was within the permissible limit according to USEP and WHO. While Fe was higher than the permissible limit in wells S2, S3, S7, S8, and S9, lead was higher than the permissible limit in wells S1, S2, S6, S7, S8, and S9. Cadmium was higher than the permissible limit in the water of wells S2, S3, S4, S5, S6, S7, S8, and S9.

The outcomes of the health risk assessment of groundwater wells using some mathematical models to calculate the average daily dose (ADD) of metals, HMs, and TMs through ingestion and skin contact for adults and children showed that it is less than the limit permitted by international organizations. Also all hazard quotients (HQ) and hazard indices (HI)For adults, via ingestion and dermal routes were $< 1$, indicating no significant non-carcinogenic risk. For children, HI values for both pathways ranged from $2.59\times10^{-3}$ to $2.18\times10^{-1}$ and were also $< 1$. However, individual metal risks exceeded thresholds in specific wells: Pb in S8 via ingestion (HQ = 2.86) and Cu in S3 (THQ = $2.12\times10^{-1}$), indicating potential health concern for children consuming water from these sources.

The carcinogenic risks range from low to moderate, depending on pathway and well. Ingestion TCR values for adults and children were $2.31\times10^{-6}$ to $1.90\times10^{-5}$ and $1.62\times10^{-6}$ to $1.24\times10^{-5}$, respectively, falling within the USEPA low-risk range ($10^{-6}$–$10^{-4}$). Dermal TCR for children in S5 and S6 reached $1.84\times10^{-4}$ and $1.28\times10^{-4}$, classified as moderate risk per NYSDOH criteria. Ni and Cd were the main contributors to cancer risk due to their high slope factors. Risk is well-specific not even across Sabha groundwater. It appears that wells S2, S3, S5, S6, and S8 showed elevated risks for Pb, Cu, Ni, and Cd. This pattern suggests localized contamination, likely from inorganic sources and distribution system corrosion, rather than regional pollution.

## Recommendations

To ensure the long-term protection of groundwater resources and safeguard public health, an integrated management approach is strongly recommended. First, a systematic groundwater quality monitoring program should be established by the relevant authorities to continuously assess the concentrations of heavy and trace metals, identify potential pollution sources, and detect temporal and spatial variations in contamination levels. Particular attention should be given to carcinogenic elements such as chromium (Cr), cadmium (Cd), and nickel (Ni), due to their bio accumulative properties and classification as human carcinogens (IARC Group 1/2), even at low concentrations.

In parallel, effective mitigation strategies must be developed and implemented to reduce the influx of contaminants into groundwater systems, ensuring the provision of safe and reliable drinking water for domestic use. This should include pollution source control, environmental regulation enforcement, and sustainable water management practices.Furthermore, public awareness programs are essential to educate local communities about the potential health risks associated with exposure to heavy and trace metals in groundwater, as well as to promote safe water consumption practices.

Finally, further research is required to better understand the long-term health effects of chronic low-level exposure to these elements and to improve analytical and risk assessment methodologies for more accurate evaluation of groundwater contamination.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

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