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Research article

Evaluating Water Quality and Health Risks from Heavy Metals Contamination in Dug Well Water in Ramkot Area of Nagarjun Municipality, Kathmandu, Nepal

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Abstract

Groundwater is an important drinking water source in Kathmandu Valley, Nepal. With the increasing extraction and utilization of the groundwater source, the quality and impact on health of groundwater consumption remain significant issues. Hence, the study was aimed at evaluating the quality of water from dug-wells in the Ramkot area of the Nagarjun Municipality of the Valley, and the assessment was based on water quality index (WQI), heavy metal evaluation index (HEI), and health risks associated with heavy metals (HMs). Thirty-one water samples were collected during winter (December-January, 2023/2024) and analyzed for eleven physicochemical parameters. Inductively coupled plasma-mass spectrometry (ICP-MS) was used to analyze Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn, while pH, electrical conductivity (EC), and total dissolved solids (TDS) were recorded in situ. The results showed concentrations of heavy metals in the order of Fe > Mn > Zn > Cu > Cr > Ni > Pb > Cd. The Fe and Mn concentrations exceeded the safe limits as per the USEPA, NDWQS, and WHO guidelines. Pearson's correlation analysis showed strong and significant positive correlations between EC and TDS, and Cr and Ni. The WQI of 59.74 classified the water quality as of good category and grade B, indicating that the water was suitable for agricultural, commercial, and domestic purposes but not for drinking. The HEI value of 8.479 implied low heavy metal contamination. The health risk assessment indicated that children had a higher non-carcinogenic risk (HI_{total} = 1.39) compared to adults. Moreover, both children and adults may experience a potential carcinogenic risk from Cr exposure, based on TLCR values. This study provides critical insights into the extent of heavy metal pollution in dug-well water, supplying essential information that can

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shape public health policies and assist in effective groundwater management strategies to mitigate health risks in the Ramkot area.

Keywords: health risk assessment; heavy metal evaluation index; heavy metals; Kathmandu; water quality index; dug well water; physicochemical parameters

1. Introduction

Water is essential for all forms of life and plays a vital role in our day-to-day lives. Water covers over 71% of the surface of the earth. However, freshwater makes up just around 3% of the water on Earth, with the majority being sea water, which is unfit for human consumption. A very small portion of the earth's surface is covered with fresh water, and of that, nearly 69% is found in a frozen form that makes it inaccessible for human use, with the remaining 30% being covered by groundwater (Chitonge et al., 2020). Surface water accounts for less than 2%. Access to proper sanitation and safe drinking water has become a significant challenge in the 21st century. A population of 663 million worldwide lacks water that is safe. In developing countries, over 2.6 billion people do not have access to sanitation, and over 750 million people to better water sources (Khanal et al., 2023). It has been reported that 80% of all diseases in the world may be attributed to pollution, unavailability of water, and poor sanitation (WHO, 2024). Hence, both the quality and quantity of safe drinking water have become a major problem.

Globally, one-third of freshwater used for industrial, agricultural, and domestic purposes is extracted through groundwater, particularly in arid and semi-arid regions where water sources are limited and unequally distributed (Zhang et al., 2018). Over 1.5 billion population throughout the world rely on groundwater for their essential needs (Adimalla & Wu, 2019). However, the quality of groundwater is deteriorating as a result of various anthropogenic activities like rapid growth of population, urbanization, and industrial and agricultural activities leading to groundwater contamination in various parts globally (Adimalla et al., 2018). Groundwater can be polluted by several pollutants such as toxic heavy metals, inorganic salts, cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, etc.), and anions (Cl^{-}, NO_3^{-}, SO_4^{2-}, CO_3^{2-}, HCO_3^{-}, etc.) (Zhang et al., 2018).

Heavy metals are defined as elements with a density of 5 g/cm^3 or higher. They are of essential and nonessential types and their toxicity to living organisms are affected by various factors such as chemical nature, speciation, and concentration level (Napit et al., 2020). They are persistent environmental contaminants and very harmful to living organisms because of their non-biodegradable nature, extended half-life periods, and ability to accumulate in plants and various human body parts (Bhandari et al., 2021). Although certain heavy metals such as Fe, Ni, Zn, Cu, Co, etc., are vital for living organisms and exist in natural waters, high concentrations can be extremely detrimental (Niroula et al., 2022).

Groundwater quality issues with heavy metal contamination have become a burning issue in many parts of the world and Nepal is no exception. Such toxic contaminants not only degrade groundwater leaving it unfit for drinking; they also have negative health impacts because of their non-carcinogenic and carcinogenic behaviors. Carcinogenic heavy metals like As, Cd, Pb, and Cr cause malfunction of the immune, nervous and blood circulation systems in the human body. These heavy metals can damage human organs like the kidneys, liver, and brain. Besides, negative health conditions like skin and lung cancer, neurological disease, hypertension, cardiovascular diseases, infertility, and irregular pregnancy in women have also been reported (WHO, 2011). Health issues from the oral ingestion of contaminated groundwater have become a significant concern over the last few decades. Therefore, the evaluation of groundwater quality concerning health issues associated with heavy metals has largely been studied worldwide including in the South Asian countries and the USA (Jehan et al., 2020).

Assessment of heavy metal contamination in groundwater and its health risks has widely been carried out globally. Islam and Mustafa (2021) investigated the potential health risks of Cd, Cr, Co, Cu, Fe, Mn, Pb, and Zn in 40 groundwater samples collected from different areas of the middle west part of Bangladesh. Their findings indicated low, medium, and high risks from the heavy metals in an average of 32.6, 15.6, and 51.8% of the total water samples, respectively. Similarly, Ganguli et al. (2024) examined carcinogenic and non-carcinogenic health risks of As, Cd, Co, Cr, Fe, and Mn in groundwater collected from Feni, a southeastern district of Bangladesh. Aswal et al. (2023) evaluated the health risks of As, Al, Cd, Cr, Cu, Mn, Pb, Se, and Zn in groundwater collected from the region of the Garhwal Himalaya, India. Their study indicated no non-carcinogenic risks from exposure to the metals and low cancer risk associated with As, Cd, Cr, and Pb from groundwater use. Latif et al. (2025) evaluated the water quality and health risks of As, Cd, and Pb in groundwater collected from the Kasur rural area of Pakistan. Their study indicated a high non-carcinogenic risk from the heavy metals for infants, children, and adults through drinking water. Among the heavy metals, Pb posed a higher carcinogenic risk to adults than infants and children. Loganathan and Rajkumar (2025) assessed the toxicity of five heavy metals (Cd, Cr, Fe, Pb, and Co) and health risks in groundwater from 42 open and bore wells located in three industrial corridors of the Vellore district of Tamil Nadu, India. They reported that the groundwater in the study area was unsuitable for drinking and other domestic uses and over 75 % of infants and children were found at high carcinogenic risk from Cr and Cd while more than 65% of adults and children were at non-carcinogenic risk from the heavy metal contaminated groundwater. Besides, many studies have shown that the groundwater sources of Kathmandu Valley are unsafe for drinking without proper treatment (Bhandari et al., 2020; Maharjan et al. 2020; Shrestha et al., 2023). The groundwater of the Valley contained elevated levels of iron, arsenic, lead, manganese, and ammonia that exceeded the allowable limits set by the WHO and NDWQS guidelines (Bhandari et al., 2020; Gwachha et al., 2020; Maharjan et al., 2020). Due to limited water availability and a significant gap between increasing water demand and supply imbalance, groundwater continues to be a reliable drinking water source for several communities in Nepal, and the Ramkot area of Nagarjun Municipality, Kathmandu Valley is no exception. Hence, the study area is particularly vulnerable to contamination of dug well water by potentially toxic heavy metals due to heavy dependence on the water source for drinking and other household purposes. Besides, the study area also faces a lack of proper water treatment facilities. A number of factors such as potential contamination from agricultural runoff, traffic emissions, industrial activities, and nearby organic manure and household waste facilities increase the risk of heavy metal contamination in groundwater sources; threats which pose serious health threats to local communities. Prolonged exposure to dug well water polluted by heavy metals can increase risk levels, particularly for vulnerable groups such as elderly people and children, pregnant women, and individuals with pre-existing health issues in the Ramkot area.

Groundwater has become a vital source, particularly for those who have no choice other than the source for their daily consumption. Despite the importance of groundwater quality, there are limited studies on groundwater contamination in the Ramkot area of Nagarjun Municipality. Earlier studies in the relevant field predominantly concentrated more on river water than groundwater in the Kathmandu Valley (Shakya et al., 2019). Thus, this study aimed at evaluating the quality of dug well water for drinking purposes in the Ramkot area of Nagarjun Municipality, using the indices of water quality, heavy metal evaluation, and associated health risks. This study attempts to address a significant research gap by focusing on the water quality of dug wells in the Ramkot area where previous studies on heavy metal contamination in groundwater sources and their associated health risks are limited so far. While similar studies have been carried out earlier in other parts of Kathmandu Valley, this study provides the first comprehensive assessment of water quality, heavy metal pollution, and associated health risks in this particular area. Conducting such a study could help educate the local community about the importance of water quality and public health issues related to contaminated groundwater. Besides, it provides baseline information for the planners to develop public health policies and water management strategies in the study area and other similar regions in Nepal.

2. Materials and Methods

2.1 Study area

Nagarjun municipality (Figure 1) lies within Kathmandu district, Bagmati province. The municipality was formally established in December 2014 through the combination of five former VDCs *viz*., Sitapaila, Ramkot, Syuchatar, Bhimdhunga, and Ichangu Narayan. Currently, the municipality consists of 10 wards covering a total area of 29.8 km^2. Geographically, it lies between 27° 40” to 27° 44” N latitude and 85° 12” to 85° 17” E longitude with an average altitude ranging between 1300 to 2500 m above sea level. Nagarjun municipality is surrounded by Kathmandu Metropolitan City in the east, Dhading Municipality in the west, Tarakeshwar Municipality in the north, and Chandragiri Municipality in the south. The municipality has a population of approximately 115,000, comprising 57,596 males (49.89%) and 57,841 females (50.11%) (CBS, 2023). It has 31301 households with a population density of 3,867 people per sq. km. with an annual population growth of 5.1% and a settlement density of 536.4 per sq. km.

The village of Ramkot is part of the Nagarjuna Municipality and has a population of 21,240 (CBS, 2023), accommodated about 2500 independent households. It includes 6 and 7 ward numbers inhabited by Newar, Brahmin, Chhetri, and Tamang as a demographic population with a majority engaged in an agricultural occupation. Currently, this area has turned into a focal point for new residents due to its natural beauty and tranquility. Since the residents of the Ramkot area are out of reach to the KUKL pipelines, groundwater sources like dug wells, bore tube wells and spring water have become their primary water supplies. According to the ward officials, most households (~70 %) have privately owned dug wells in the study area.

2.2 Sampling and analysis of dug-well water

Initially, a preliminary survey was undertaken in the study area to ascertain the detailed number of households with privately owned dug wells. All households facilitated with dug wells were numbered consecutively to avoid bias during sampling. From the list of households with dug wells, 31 households were selected for water sample collection using a lottery method. The positions of sampling points were also traced with a GPS tool (Figure 1). The water samples were collected during the winter season in the months of December and January (2023/2024). In hilly regions like the Ramkot area of Nagarjun municipality, the winter season presents distinct environmental challenges such as less precipitation

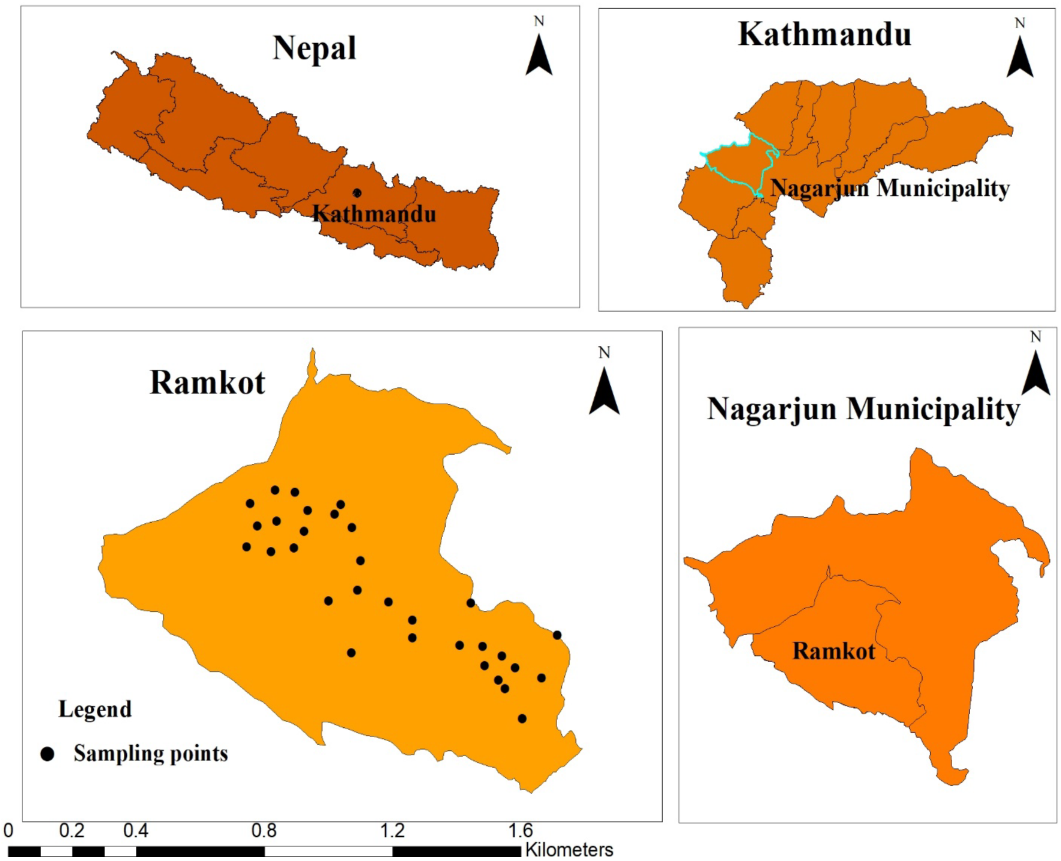

Figure 1. Location map of the study area showing sampling points at Ramkot area, Nagarjun Municipality, Kathmandu, Nepal

Summary caption: The figure depicts a geographical map of the Ramkot area, marking specific sampling points showing their spatial distribution. The selection of sampling points for water sample collection was based on a lottery method from the list of households with privately owned dug wells in the study area.

and reduced groundwater replenishment. This makes the dug wells more susceptible to contamination from surrounding environments, including surface runoff, domestic waste, and pollutants. Hence, winter sample collection would help assess the water quality in the study area during a time when the groundwater is not being replenished, potentially highlighting issues that could remain unnoticed in wetter periods. These samples would represent the water quality status of dug wells in the Ramkot area of Nagarjun Municipality. The depth of the sampled dug wells ranged from 8 to 18 m. Figure 2 depicts a flow chart summarizing the steps for water sampling, physicochemical analysis of drinking suitability, heavy metal evaluation, and health risk assessment.

The sample collection was carried out using acid-treated (5% HNO_3) and deionized water-washed sampling bottles of high-density polyethylene (HDPE). The samples were collected from the sampling sites following standard procedure (APHA, 2017). The pH,

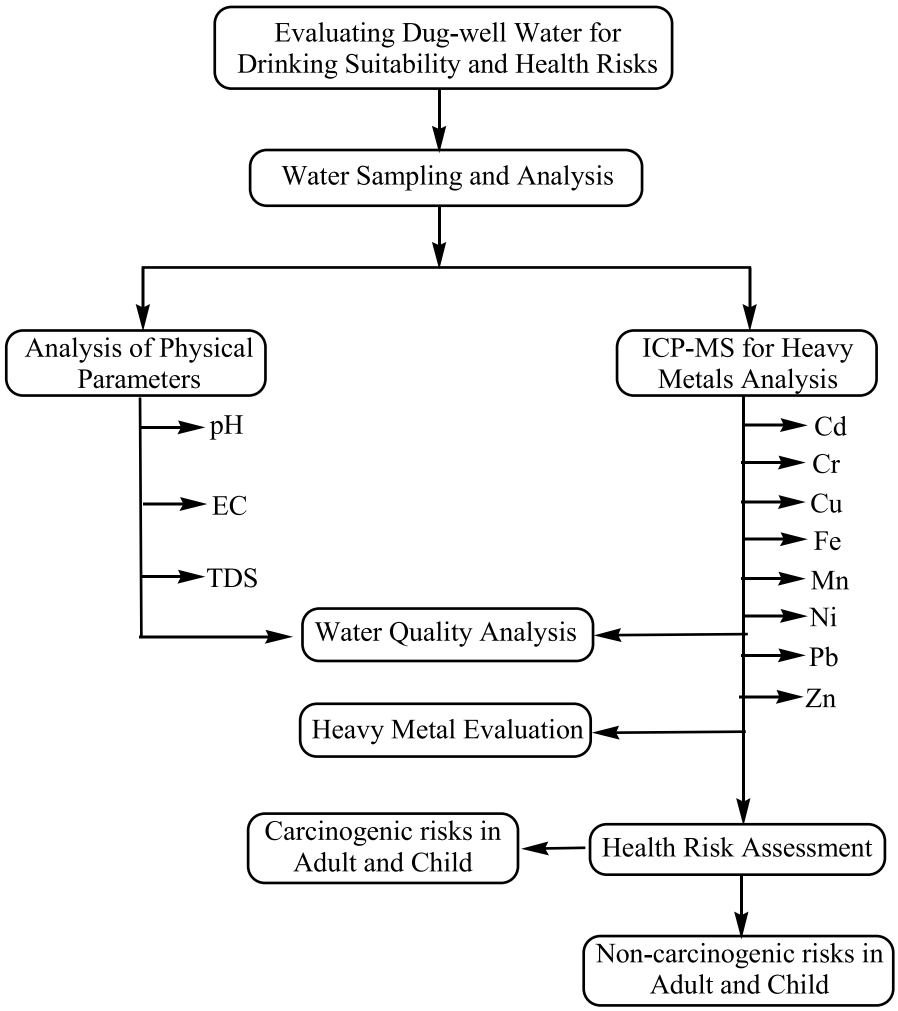

Figure 2. Flowchart summarizing steps for dug-well water analyses involved in the study

electrical conductivity (EC), and total dissolved solids (TDS) of the samples were recorded in situ using a calibrated pH meter (Hanna AD 100), a conductivity meter (Hanna DiST3 Tester-HI98303), and a TDS meter (EI Electronics-651), respectively. All the bottles were thoroughly labeled and brought to the lab of Environmental Science, Padmakanya Multiple Campus, Bagbazar. In the lab, all samples were filtered through a 0.45 μm membrane filter made of polypropylene and then acidified with pure conc. HNO_3 to maintain the pH < 2. This was intended to prevent the inner walls of the bottles from HM adsorption as well as metal precipitation (APHA, 2017). All the samples were stored in a refrigerator at 4°C until further chemical investigation. The targeted heavy metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) were determined by inductively coupled plasma-mass spectrometry (PerkinElmer, NexION 2200 ICP-MS). The calibration curves were prepared using multi-element standard solutions (SPEX CertiPrep USA) designed especially for ICP or ICP-MS. The analysis was conducted at the Indian Institute of Technology of Banaras Hindu University (IIT-BHU), Varanasi, India.

2.3 Quality assurance/control

Before heavy metal analysis was performed, nitric acid (10%, v/v) was used to clean all the glassware and usable equipment. The precision and accuracy of the analytical protocol of the ICP-MS were accomplished by the measurements of NIST traceable certified standard reference materials in triplicate. These were measured using the same procedure as the water samples analyzed in this study. The certified and determined values were observed to be in good agreement with percentage recovery ranging from 87-102%. As a result, the heavy metals Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn exhibited better recovery rates of 97.5, 99.0, 96.8, 97.2, 87.2, 102.1, 100.3, and 98.8%, respectively, showing relative standard deviation (RSD) below ±5%. Blank solutions were also analyzed in a similar way as the samples. The water samples detected a very negligible quantity of metals or even nil. The detection limit (LOD) for each metal was calculated to be between 0.5 and 10 ng/L for water samples.

2.4 Water quality index (WQI)

According to Nepal standards, there are twenty-six physicochemical parameters for drinking water quality including health-based and non-health-based guideline values (NDWQS, 2022). In this research, the water quality index (WQI) was determined based on water quality standards in compliance with the World Health Organization (WHO, 2011) to analyze the groundwater quality of the area under investigation. The index, first suggested by Horton (1965) and subsequently extended by Brown et al. (1972), is often considered an important mathematical tool. The key advantage of using this tool lies in its ease of synthesizing huge quantities of data into a simple and single integer value. Hence, it is often used to represent the overall quality of water sources in a specific study area and time relying on heavy metal concentration (Wu et al., 2015).

In this study, the WQI was determined following equation (1):

$$WQI = \sum_{i=1}^{n} Wi \, . \, qi \tag{1}$$

Where n refers to the number of water quality parameters or variables; Wi is the relative weight for the ith variable, and qi is the quality rating scale of the ith variable.

In this investigation, the assessment of drinking water suitability involved calculating the WQI based on eleven water quality parameters, which consisted of pH, electrical conductivity (EC), and total dissolved solids (TDS) as physical parameters, alongside eight heavy metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) as chemical parameters. The selection of pH, EC, and TDS in this study is based on the fact that these parameters significantly influence the behavior, toxicity, and mobility of the heavy metals in groundwater.

The relative weight (Wi) for each water quality parameter was determined following equation (2):

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \tag{2}$$

Where wi refers to the unit weight for the ith water quality variable, and $\sum wi$ is the sum of unit weights of the nth variables.

In the present investigation, the standard values for each selected variable were obtained from WHO (2011) guidelines while their unit weights (*wi*) were referenced from Tripathee et al. (2016). Accordingly, the weights (*wi*) of 1, 2, 3, 4, and 5 for physical parameters (pH, EC, and TDS) were allotted respectively for the ranges of 81-100, 61-80, 41-60, 21-40, and 0-20% of the tested samples that meet the acceptable limits as per the WHO standards (Raychaudhuri et al., 2014; Tripathee et al., 2016; Singh et al., 2021). In the case of heavy metals (HMs), the allotted values for the unit weightings (wi) were, however, based on the relative significance of each HM under investigation (Li & Zhang, 2010; Pant et al., 2021). Accordingly, the weight (wi) of 1 was assigned to Fe, Ni, and Zn since they possess insignificant human health effects, whereas the highest rank of 5 was assigned to Cd, Cr, Mn, and Pb owing to their significant health risk (Xiao et al., 2014). Copper, however, was assigned a weight (wi) of 2.

The quality rating (*qi*) was estimated by taking the mean concentration of each variable dividing it by its recommended WHO standard and subsequently multiplying the quotient by 100, as shown in equation (3) below.

$$qi = \left(\frac{Ci}{Si}\right) x\ 100 \quad (3)$$

Where, *Ci* is the mean concentration of each variable, and *Si* is the recommended value for each water quality variable prescribed by the WHO (2011) standards.

To assess the appropriateness of groundwater for drinking, the current study calculated the WQI for eleven water quality variables, which encompass pH, electrical conductivity (EC), and total dissolved solids (TDS) as physical criteria, along with eight heavy metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) as chemical criteria. Finally, the quality of groundwater in the area was categorized into five groups (Table 1) designated with grade A to E, based on the computed WQI values (Raychaudhuri et al., 2014; Patil et al., 2020).

Table 1. Classification of water quality and grade according to WQI

WQI Value	Water Quality Rating	Grade
< 50	Excellent	A
50 – 100	Good	B
100 – 200	Poor	C
200 – 300	Very poor	D
>300	Unsuitable for drinking purposes	E

2.5 Heavy metal evaluation index (HEI)

The heavy metal evaluation index (HEI) serves as a tool to evaluate the contamination level of heavy metals in drinking water. It helps evaluate the degree of pollution by heavy metals and their potential effect on the health of humans (Ghaderpoori et al., 2018). The index was determined following equation (4):

$$HEI = \sum_{i=1}^{n} \frac{H_c}{H_{mac}} \quad (4)$$

Where, H_c = observed concentration of the ith parameter, H_{mac} = maximum permissible concentration of the ith parameter, and n = total number of heavy metals as water quality variables. To estimate the index, the H_{mac} of the ith parameter was determined following the WHO (2011) guideline values. The index categorizes the groundwater into three levels of contamination: low (HEI <10), moderate (HEI = 10-20), and high (HEI >20) heavy metals (Edet & Offiong, 2002).

2.6 Health risk assessment (HRA)

Health risk assessment models (USEPA, 1989; 2010) designate the potential health risks that heavy metals pose to humans. These established USEPA models are widely accepted and are the most often used tools for evaluating the risks (Adimalla & Wu, 2019). The health risks comprising non-carcinogenic and carcinogenic risks of the toxic pollutants can be quantified through three potential routes *viz.*, direct ingestion, inhalation, and dermal absorption (skin contact). Nevertheless, human exposure to the heavy metals in water through oral ingestion and dermal contact are the two potential routes for groundwater (Pant et al., 2021). This study assessed the health risks of the measured heavy metals in children and adults through these two routes. For this, average daily doses (ADDs), hazard quotient (HQ), hazard index (HI), lifetime carcinogenic risk (LCR), and total lifetime carcinogenic risk (TLCR) for the separate routes were estimated.

2.6.1 Average daily doses (ADDs) of heavy metals (HMs)

Estimating the ADDs involves identifying the number of pollutants (e.g., HMs) consumed through sources like water, food, soil, and so on (Vrhovnik et al., 2013). The estimated values refer to the proportionating concentrations of potentially toxic pollutants in the sources. In this evaluation, human body weight according to the receptor group has a significant effect particularly on the degree of tolerance to such toxic pollutants (Vrhovnik et al., 2013).

The average daily doses (ADDs) for two separate pathways were examined using equations (5) and (6) (USEPA, 1989; 2010):

$$ADD_{ing} = C_w \times \frac{IR_{ing} \times EF \times ED}{BW \times AT} \tag{5}$$

$$ADD_{derm} = C_w \times \frac{SA \times Kp \times ET \times EF \times ED}{BW \times AT} \times CF \tag{6}$$

Where ADD_{ing} and ADD_{derm} are the average daily doses (mg/kg/day) through the ingestion and dermal absorption pathways, respectively. The receptor parameters for estimating average daily doses of HMs in water samples by the two receptor groups are presented in Table 2.

2.6.2 Non-carcinogenic risk

Non-carcinogenic health risks of the heavy metals in the receptor groups were evaluated using hazard quotient (HQ) and hazard index (HI) according to the USEPA (2010) deterministic model.

Table 2. Receptor parameters for computing health risks of heavy metals in dug-well water in the study area through ingestion and dermal pathways (Hashmi et al., 2014; Tripathee et al., 2016).

Parameter	Unit	Children	Adult
Concentration of HMs in water (*Cw*)	mg/L	-	-
Water ingestion rate (*IRing*)	L/day	0.64	2.0
Exposure frequency (*EF*)	days/year	350	350
Exposure duration (*ED*)	year	6	30
Average body weight (*BW*)	kg	15	70
Average time (*AT*)	days	ED ×365 days/year	ED ×365 days/year
Exposed skin area (*SA*)	cm^2	6,600	18,000
Exposure time spent in bathing/shower (*ET*)	h/day	1.0	0.58
Unit conversion factor (*CF*)	L/cm^3	1×10^{-3}	
Dermal permeability coefficient in water (*Kp*)	cm/h	-	-
Cadmium (Cd)		1×10^{-3}	
Chromium (Cr)		2×10^{-3}	
Copper (Cu)		1×10^{-3}	
Iron (Fe)		1×10^{-3}	
Manganese (Mn)		1×10^{-3}	
Nickel (Ni)		2×10^{-4}	
Lead (Pb)		4×10^{-3}	
Zinc (Zn)		6×10^{-4}	

1) Hazard quotient (HQ)

The hazard quotient (HQ) index evaluates non-carcinogenic risk associated with the toxicity imposed by a single metal in the human body through different pathways. The index is characterized as the proportion of the mean daily dose of a single heavy metal to a reference dose (RfD) for that metal estimated over a defined exposure duration (Li et al., 2017). The index for each exposure route was estimated following equation (7):

$$HQ_{ing/derm} = \frac{ADD_{ing/derm}}{RfD_{ing/derm}} \quad (7)$$

Where, HQ is the hazard quotient through ingestion/dermal absorption, and R*f*D is the reference dose of heavy metal (mg/kg/day). Table 3 shows the R*f*D values for both pathways. The R*f*D values were obtained from the reference of Zheng et al. (2015) and USEPA IRIS (2011).

Table 3. Reference doses (R*f*D) of heavy metals for computing health risks through ingestion and dermal pathways, and oral cancer slope factors (CSFo)

Heavy metals	*R*f*D$_{ing}$ (mg/kg/day)	*R*f*D$_{derm}$ (mg/kg/day)	**CSFo (mg/kg/day)$^{-1}$
Cd	5.0×10^{-4}	2.5×10^{-5}	0.5
Cr	3.0×10^{-3}	7.5×10^{-5}	0.5
Cu	4.0×10^{-2}	8.0×10^{-3}	-
Fe	7.0×10^{-1}	1.4×10^{-1}	-
Mn	2.4×10^{-2}	9.6×10^{-4}	-
Ni	2.0×10^{-2}	8.0×10^{-4}	-
Pb	1.4×10^{-3}	4.2×10^{-4}	8.5×10^{-3}
Zn	3.0×10^{-1}	6.0×10^{-2}	-

* Zheng et al. (2015); **USEPA IRIS (2011)

2) Hazard index (HI)

This index evaluates the total non-carcinogenic risk presented by multiple heavy metal contaminants in water (Li & Zhang, 2010). The index was estimated by equation (8), which includes the total of HQs for each HM through both pathways. Then, the overall non-carcinogenic risk was examined by equation (9), which includes the sum of HQs of all contaminants through the pathways.

$$HI_j = HQ_{ing} + HQ_{derm} \quad (8)$$

$$HI_{total} = \sum_{i=1}^{n} HI_j \quad (9)$$

The receptor groups (children and adults) would suffer less from non-carcinogenic risk if HI ≤ 1; however, a negative health risk arises upon exceeding the threshold limit of 1.0 (Li & Zhang, 2010).

2.6.3 Lifetime carcinogenic risk (LCR)

Lifetime cancer risk (LCR) involves the possibility of a receptor group suffering from cancer over a lifetime upon exposure to carcinogens (USEPA, 2010). This risk parameter was calculated using equation (10):

$$LCR_{ing/derm} = ADD_{ing/derm} \times CSFo \quad (10)$$

Where LCR_{ing} and LCR_{derm} refer to the lifetime cancer risks caused by the ingestion and dermal absorption respectively; and CSFo is the oral carcinogenic slope factor. In this work, only three heavy metals (Cd, Cr, and Pb) were assessed for carcinogenic risk since they are carcinogens and their CSFo values are available in the literature (USEPA IRIS, 2011). The CSFo values (Table 3) obtained from the USEPA IRIS (2011) database were computed in the LCR estimation of these heavy metals.

Total lifetime cancer risk (TLCR) was measured by summing up the LCR values through both pathways using equation (11) as follows:

$$TLCR = LCR_{ing} + LCR_{derm} \quad (11)$$

A TLCR value in the $1\times10^{-6} – 1\times10^{-4}$ range is considered an acceptable and safe limit (Wu et al., 2015). The value exceeding 10^{-4} would pose a carcinogenic health risk to the receptor groups.

2.7 Statistical analysis

This study processed and analyzed data using Excel spreadsheets on an IBM PC and IBM SPSS 19. Descriptive statistical metrics such as mean, median, range, frequency, percentage, and standard deviation were employed for data presentation. The correlation matrices for the selected physicochemical parameters were determined using Pearson's correlation coefficient along with significance tests ($P<0.05$).

3. Results and Discussion

3.1 Overall physicochemical characteristics of dug well water

In this section, the overall physicochemical characteristics of dug-well water in the study area are discussed. Altogether 11 physicochemical parameters were measured to evaluate the water quality status of the wells in the area under investigation. The statistical summary of the parameters measured in the water samples is presented in Table 4. In this study, the guidelines of the United States Environmental Protection Agency (USEPA, 2009a), National Drinking Water Quality Standards (NDWQS, 2022), and World Health Organization (WHO, 2011) were considered as references for comparing safe limits. The number and percentage of the water samples within the safe limits as per the guidelines are presented in Table 5.

The results revealed that the median values of pH, EC, and TDS in the dug well water of the area were 7.1, 605 μScm^{-1}, and 317 mgL^{-1}, respectively. The median and mean concentrations of eight HMs in dug wells were found in the decreasing order of Fe > Mn > Zn > Cu > Cr > Ni > Pb > Cd (Table 4). The overall HMs level ranged from 115-8504 μgL^{-1} (median 1864 and mean 2615 μgL^{-1}). Of the studied eight HMs, Fe was the most abundant metal in dug wells accounting for 78% of $\sum_8$HM while Cd was the least abundant accounting for less than 1%. It was found that only the mean levels of Fe and Mn crossed the maximum permissible safe limits of all three standard guidelines (Tables 4 and 5). Earlier studies also showed the presence of high levels of Fe and Mn in the groundwater of Kathmandu Valley (Shrestha et al., 2016; Sarkar et al., 2022). The elevated concentration of these elements in the groundwater may result from the release of Fe(II) and Mn(II) from Fe/Mn oxyhydroxides (Hem, 1985). Besides, Fe_2O_3 and MnO being the major chemical components of the sediments may be attributed to the occurrence of the metals at higher concentration levels in the Kathmandu Valley (Dill et al., 2003).

3.2 General hydrochemistry of physicochemical parameters of dug well water

The pH level of water represents the acidity or alkalinity of water. It is among the most often used physical parameters for water quality testing since it influences biological and chemical reactions (Rahman et al., 2020). In this investigation, the pH of the tested dug well water varied between 6.2 and 8.2, with an overall mean of 7.2 (Table 4). Thirty (97%)

Table 4. Statistical summary of water quality parameters analyzed in water samples of dug wells in the study area

Parameters	Units	Minimum	Maximum	Mean	Median	SD
pH	-	6.2	8.2	7.2	7.1	0.48
Electrical conductivity (EC)	μScm^{-1}	264	922	608	605	188
Total dissolved solids (TDS)	mgL^{-1}	142	442	302	317	88.5
Cadmium (Cd)	μgL^{-1}	0.00	1.05	0.39	0.38	0.38
Chromium (Cr)	μgL^{-1}	3.67	14.79	7.68	7.55	2.73
Copper (Cu)	μgL^{-1}	15.87	54.41	31.29	29.09	9.96
Iron (Fe)	μgL^{-1}	60.0	6520	2041	1560	1778
Manganese (Mn)	μgL^{-1}	20.0	1470	428	210	424
Nickel (Ni)	μgL^{-1}	2.59	11.07	6.51	6.24	2.36
Lead (Pb)	μgL^{-1}	0.27	3.49	1.78	1.57	1.00
Zinc (Zn)	μgL^{-1}	12.84	430	97.69	49.43	112
$\sum_8$HM	μgL^{-1}	115	8504	2615	1864	2330

Summary caption: The Table shows the statistical summary of three physical parameters (pH, EC, and TDS) and eight heavy metals in water samples collected from the Ramkot area. The results revealed a slightly alkaline nature of dug well water in the study area with high concentrations of Fe and Mn indicating a potential health concern.

Table 5. Number and percentage of water samples collected from dug wells in the study area within safe limits according to different standard guidelines.

Parameters (units)	Drinking Water Quality Guidelines			Samples within USEPA Safe Limits		Samples within NDWQS Safe Limits		Samples within WHO Safe Limits	
	USEPA (2009a)	NDWQS (2022)	WHO (2011)	No.	%	No.	%	No.	%
pH	6.5 – 8.5	6.5 – 8.5	6.5 – 8.5	30	97	30	97	30	97
EC (μScm^{-1})	-	1500	1000	-	-	31	100	31	100
TDS (mgL^{-1})	-	1000	500	-	-	31	100	31	100
Cd (μgL^{-1})	5	3	3	31	100	31	100	31	100
Cr (μgL^{-1})	100	50	50	31	100	31	100	31	100
Cu (μgL^{-1})	1300	1000	2000	31	100	31	100	31	100
Fe (μgL^{-1})	300	300	300	07	23	07	23	07	23
Mn (μgL^{-1})	50	200	400	05	16	15	48	19	61
Ni (μgL^{-1})	100	-	70	31	100	-	-	31	100
Pb (μgL^{-1})	15	10	10	31	100	31	100	31	100
Zn (μgL^{-1})	5000	3000	3000	31	100	31	100	31	100

Summary caption: The Table presents the number and percentage of dug-well water collected from the Ramkot area compared to the drinking water quality guidelines prescribed by USEPA, NDWQS and WHO. The results showed that almost all selected parameters for the water samples except pH, Fe and Mn were found within safe limits of all the three standard guidelines.

of the total dug wells complied with the 6.5-8.5 permissible range of USEPA, NDWQS, and WHO standards (Table 5). The remaining 3% of the samples were found below the allowable range which is in line with the results of Koju et al. (2014) and Shrestha et al. (2023) who similarly observed 3% and 4.3% of the well water of Kathmandu falling out of the permissible range. Although the pH of water is no longer associated with human health risks, it is crucial in the chlorination process. Particularly, disinfection remains less effective in water with a pH exceeding 8.0 due to sufficient carbonates (Tadesse et al., 2018). pH is not static and hence keeps changing over time. This physical parameter influences the rocks, organic matter, and leaching of soils (Koju et al., 2014).

Electrical conductivity (EC) measures the ability of water to carry electricity and is an important physical parameter in evaluating groundwater quality (Pant et al., 2021). The present study indicated that the parameter of the water samples ranged from 264 to 922 µS/cm in the area studied. The mean EC of all water samples was determined to be 608 µS/cm. All analyzed samples of water fell within the safe limits prescribed by the NDWQS and WHO standards. Ghartimagar et al. (2020) found that 2% of well water in Kathmandu Valley crossed the NDWQS standard for the same parameter. Shrestha et al. (2016) and Shrestha et al. (2023) also reported EC values between 92 and 1729 µS/cm in deep groundwater wells and between 92 and 1375 µS/cm in the well water of Kathmandu Valley, respectively. An elevated EC value signifies the presence of pollutants in groundwater such as dissolved solids and inorganic elements like phosphate, nitrate, chloride, sulfate, calcium, sodium, magnesium, iron, and manganese (Shrestha et al., 2023).

Total dissolved solids (TDS) is a non-health-related water quality measure that directly affects electrical conductivity (EC) (Singh et al., 2021). A high level of TDS is due to inorganic species such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, and HCO_3^{-} at higher levels in the water (Boyd, 2000). In the present study, the average TDS of water samples of the dug wells was 302 mg/L, varying between 142 and 442 mg/L. The results revealed that none of the tested samples of dug well water crossed the safe limits of 500 and 1000 mg/L suggested by WHO and NDWQS guidelines, respectively. The findings of this research align with Mandal et al. (2023), who similarly indicated that most well water samples from Bhaktapur Municipality fell within the allowable safe limits of WHO and NDWQS standards. Moreover, seasonal variations like pre-monsoon and post-monsoon showed no considerable differences in TDS values in their research. Although health risks are not directly associated with TDS, its presence at a high level may reduce water transparency, and impart an undesirable taste. In addition, elevated levels of TDS can influence the physicochemical characteristics and aesthetic value, restricting their utilities for industrial, domestic, and agricultural applications (Gurung et al., 2019).

The average level of Cd in dug well water samples was 0.39 µg/L, varying between 0.00 µg/L and 1.05 µg/L. All tested samples complied with the allowable limit of 5 µg/L suggested by USEPA and 3 µg/L by NDWQS and WHO guidelines. Our results were consistent with Sarkar et al. (2022) who also found a low concentration of Cd (<1.00 µg/L) in the groundwater samples from the Kathmandu Valley. Chapagain et al. (2010) in their studies, however, revealed higher Cd levels (5.0 µg/L) in deep well groundwater of Kathmandu Valley both in pre-monsoon and monsoon seasons. Cadmium is an element that is intrinsic to the Earth's crust and, once discharged into the environment, remains in sediments and soils. Over time, Cd accumulates in plant tissues through absorption and then eventually humans suffer from the food chain (Kumar et al., 2024).

In this investigation, the average level of Cr in dug wells was 7.68 µg/L, with the lowest level of 3.67 µg/L and the highest level of 14.79 µg/L. The levels of Cr in the dug wells examined were within the acceptable limits established by all three standard guidelines. Similar results were also obtained by Chapagain et al. (2010) and Sarkar et al.

(2022), who reported less than 10.0 μg/L of Cr in groundwater from the Kathmandu Valley. Chromium is a naturally occurring element that exists mainly in two oxidation states in the environment, *viz.*, trivalent [Cr(III)] and hexavalent [Cr(VI)]. Cr(III) is an essential trace element for human beings, which is involved in glucose metabolism, with deficiencies linked to some diabetic cases. In contrast, Cr(VI) is highly soluble in groundwater under alkaline conditions and poses a significant public health concern due to its toxicity and mobility. Exposure to Cr(VI) through inhalation, ingestion, or dermal pathways can cause skin irritation, increased cancer risks, organ damage, and respiratory issues (Rahman et al., 2020).

Copper is a naturally occurring element that is required in small quantities for all forms of life. It is found in relatively small amounts in groundwater, soils, rocks, plants, and animals. Groundwater gets contaminated with Cu through agricultural practices, mining operations, manufacturing activities, and domestic or industrial effluents (Kumar et al., 2024). In the present investigation, Cu concentration in dug wells ranged from 15.87 - 54.41 μg/L with an average concentration of 31.29 μg/L. The tested water samples fell within the safe limits of standard guidelines (1300 μg/L, 1000 μg/L, and 2000 μg/L as per USEPA, NDWQS, and WHO guidelines, respectively). Sarkar et al. (2022) noted Cu levels between < 20 and 50 μg/L in groundwater from the Valley, which were in line with the present study. Similarly, Ram et al. (2021) also reported Cu levels between 0.00 and 8.00 μg/L in the groundwater from District Mahoba, UP, India.

The weathering of iron-bearing minerals and rocks is the primary source of iron in groundwater. The ferrous state (Fe^{2+}) of iron is water soluble and less health-hazardous. In groundwater systems, the Fe^{2+} state is the naturally occurring form of iron and gets readily oxidized to Fe^{3+} (insoluble hydroxides) in contact with atmospheric air (Ghosh et al., 2008). So, groundwater usually has a higher concentration of Fe than surface water. The present study indicated a significant level of Fe in dug wells that was between 60 and 6520 μg/L. The level of Fe was 2041 μg/L, showing the highest among the heavy metals examined in this research. Iron in the dug wells of the study area at elevated levels was possibly from the reductive dissolution of Fe/Mn oxides in the reduced redox conditions of groundwater (Laing et al., 2009). Out of all the samples analyzed, merely 7 (23%) fell within the acceptable limit established by these three standard guidelines, while the other 24 (77%) samples surpassed the limit. The findings of the present study are in agreement with several research works carried out by Shrestha et al. (2016), Ghartimagar et al. (2020), Sarkar et al. (2022), Gaihre et al. (2022), and Paudel and Basi-Chipalu (2022), all of which indicated higher concentrations of Fe in the groundwater from the Kathmandu Valley that surpassed both the NDWQS and WHO threshold limits.

Manganese is naturally found in both freshwater and groundwater, and it is particularly abundant in anaerobic environments. The primary way that Mn enters into groundwater is by leaching minerals from the underlying rocks and the overlying soils (Adhikari et al., 2023). In this study, the levels of Mn in dug wells varied significantly between 20 and 1470 μg/L. The average level of Mn (428 μg/L) was observed to be higher after Fe in the dug wells of the area under investigation. The results align with Shrestha et al. (2016) and Sarkar et al. (2022), who also found 440 μg/L and 350 μg/L of Mn in groundwater wells within Kathmandu Valley. Of the total analyzed samples, 5 (16%) and 15 (48%) were found within the permissible limits of 50 μg/L and 200 μg/L for Mn set by USEPA and NDWQS guidelines, respectively, whereas the remaining samples exceeded the limits. Similarly, 19 (61%) of the total samples complied with the WHO limit of 400 μg/L for Mn. Similar to this study, Ganguli et al. (2024) also found the levels of Fe and Mn in groundwater from Feni, Bangladesh that exceeded the safe limits of WHO guidelines. Despite both the elements being required in trace amounts, their concentrations exceeding safe limits in water may cause serious health issues through ingestion and to a lesser degree, dermal absorption. Elevated Fe in drinking water may lead to gastrointestinal discomfort, including diarrhea, nausea, and vomiting. Long-term exposure can damage the liver and heart (Fraga & Oteiza, 2002). Chronic exposure to high Mn levels can damage the liver and kidneys and can also result in neurological effects, including symptoms similar to Parkinson's disease such as tremors, muscle rigidity, and cognitive difficulties (Iregren, 1999). Both elements are generally not absorbed through the skin in significant quantities. However, elevated concentrations in water may cause staining of the skin including irritation or dermatitis in sensitive people, although this is less commonly observed (Moss & McNeill, 2001). Some effective methods for reducing Fe and Mn levels include oxidation, ion exchange, aeration, reverse osmosis, and chemical precipitation (USEPA, 2009b). However, the choice of the appropriate method depends on the level of these metals in the water, the pH level, and various other water quality variables.

Nickel-bearing minerals and ores are the primary sources of metal contamination in groundwater (Wuana & Okieimen, 2011). Besides, corrosion of water supply pipes and fitting activities in the water distribution system is also considered a source of Ni contamination in groundwater. In the current investigation, the average concentration of Ni in dug wells was determined to be 6.51 μg/L, with minimum and maximum levels ranging from 2.59 to 11.07 μg/L. The findings showed that all analyzed water samples met the acceptable limits of 100 μg/L and 70 μg/L established by USEPA and WHO standard guidelines, respectively. In research conducted by Sarkar et al. (2022), elevated levels of 10 μg/L Ni were detected in groundwater wells of the Kathmandu Valley, corresponding with the results of the present study. In contrast, Ram et al. (2021) found a higher Ni concentration of 41 μg/L in the groundwater of the Mahoba District, Uttar Pradesh, India. Nickel is an essential trace element but toxic to human health at elevated concentrations. As an immunotoxin and carcinogen agent, Ni can cause contact dermatitis, respiratory tract cancer, cardiovascular illness, lung fibrous, and asthma, depending on the amount and period of exposure (Genchi et al., 2020).

In this study, the Pb content detected in dug wells varied between 0.27 and 3.49 μg/L. The concentration of Pb was determined to be 1.78 μg/L. All tested dug wells of the study area complied with the permissible limit of 15 μg/L for Pb set by USEPA and 10 μg/L by NDWQS and WHO standard guidelines. Lead is a non-essential and very toxic element even at low concentrations that causes widespread damage to ecosystems and human health in various regions worldwide. In addition to teratogenic effects and impaired hemoglobin synthesis, lead poisoning can cause cardiovascular dysfunctions, reproductive issues, joint problems, gastrointestinal problems, neurological issues, and permanent brain damage. It can also cause significant harm to both the central and peripheral nervous systems (Kumar et al., 2024).

In the present study, the Zn levels in the area's dug wells ranged from 12.84 to 430 μg/L (mean 97.69 μg/L). The range was, however, lower compared to Fe and Mn. All examined water samples displayed Zn levels comfortably below the permissible limits of 5000 μg/L established by USEPA and 3000 μg/L according to NDWQS and WHO guidelines. Many studies also showed a wide range of Zn in similar water sources in the Kathmandu Valley. Shrestha et al. (2016) reported Zn concentrations of <3 to 951 μg/L (mean 65 μg/L) in their research. Sarkar et al. (2022) found Zn levels at 20 μg/L, varying from < 20 to 450 μg/L. Likewise, Ram et al. (2021) indicated a Zn concentration of 14 μg/L in the groundwater of Mahoba District, Uttar Pradesh, India. Although rocks contain substantial amounts of Zn, groundwater seldom exhibits Zn levels exceeding those of Fe and Mn (Ram et al., 2021). The mobility of Zn is very high in groundwater since the compounds of the metal are readily soluble at pH between the neutral and acidic range.

However, the solubility of Zn is controlled at higher pH values due to its complexation as metal carbonates and hydroxides (Smith et al., 1995). Although Zn is an essential element required for the growth of living beings, prolonged exposure to the metal can bring several human health disorders (Bertholf, 1988).

3.3 Correlation matrices

The correlation analysis of water quality parameters substantially reveals statistically significant relationships among various metrics. Strong positive correlations between pairs of parameters normally imply a common source, whereas weak or negative correlations suggest they originate from different sources (Egbueri & Unigwe, 2019).

The Pearson's correlation coefficient (Table 6) showed that the pH of dug well water was positively correlated ($p<0.05$) with Cr ($r = 0.749$) and Ni ($r = 0.770$) and negatively correlated with Fe ($r = -0.781$) and Mn ($r = -0.700$), consistent with the findings of Shrestha et al. (2016) and Ghartimagar et al. (2020), who also observed pH having negative correlation with Fe and Mn in their studies. The strong negative correlation of pH with Fe and Mn may be attributed to the dissolution of the metals in acidic media (Shrestha et al., 2016). The pH also negatively correlated with Zn ($r = -0.518$).

3.4 Water quality index (WQI)

The WQI of the dug well water in the Ramkot area, Nagarjun Municipality, based on the eleven measured physicochemical parameters, is presented in Table 7. In this study, the WHO (2011) standard guidelines were employed to calculate the WQI for evaluating the water source's suitability for drinking. The WQI of dug well water in the study area was found to be 59.74, classifying it as good water quality (WQI: 50-100; Table 1), thereby placing it in grade B. The dug well water classified as grade B quality is appropriate for agricultural, commercial, and domestic uses, but not for consumption (Shrestha et al., 2023). While analyzing 159 groundwater samples from the Kathmandu Valley for water quality testing, Shrestha et al. (2023) found the WQI index ranging from 5 to 581. Adhikari et al. (2023) similarly found low water quality in dug wells (WQI=124.8) while examining water samples from certain squatter settlements along the Bagmati River corridors in Kathmandu. Mandal et al. (2023) indicated that the majority of well water samples from Bhaktapur municipality were unsuitable for drinking based on the WQI. They noted that the water quality of wells was better during the pre-monsoon than the post-monsoon. Ganguli et al. (2024) found that only 18% of the groundwater samples were rated as grade B (good water quality) according to the computed WQI during their studies in Feni, Bangladesh. Yadav et al. (2025) also reported that water from most of the traditional stone spouts (swallow groundwater) in the Kathmandu metropolitan area of Kathmandu Valley, Nepal was unfit for drinking based on WQI values. Nonetheless, the differences in the results of the WQI and water quality ratings might arise from the inclusion of various water quality parameters in the earlier studies. Poor groundwater quality may be linked to anthropogenic activities such as excessive use of chemical fertilizers and groundwater, agricultural runoff, sewage system and septic tank leakages, inadequate cleanliness of groundwater sources and nearby areas, organic matter effluent, etc. (Thakur et al., 2015).

Table 6. Correlation matrices of the water quality parameters of the dug wells (n=31)

	pH	**EC**	**TDS**	**Cd**	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
pH	1.000										
EC	-0.211	1.000									
TDS	-0.194	**0.982***	1.000								
Cd	0.298	0.141	0.178	1.000							
Cr	**0.749***	-0.113	-0.132	0.212	1.000						
Cu	0.328	0.136	0.192	**0.881***	0.021	1.000					
Fe	**-0.781***	0.039	0.029	-0.391	**-0.854***	-0.327	1.000				
Mn	**-0.700***	0.185	0.168	-0.359	**-0.736***	-0.268	**0.886***	1.000			
Ni	**0.770***	-0.132	-0.133	0.170	**0.937***	0.073	**-0.917***	**-0.800***	1.000		
Pb	0.324	0.163	0.212	**0.745***	0.215	**0.700***	-0.467	**-0.599***	0.264	1.000	
Zn	-0.518	0.169	0.148	-0.483	-0.444	-0.454	**0.655***	**0.798***	-0.487	**-0.798***	1.000

*Correlation is significant at $p<0.05$

Table 7. Unit weight (wi), relative weight (Wi), concentration of each variable (Ci), standard value of each variable (Si), and quality rating (qi) used for computing the water quality index (WQI) and classification of water quality and grade of water samples collected from dug wells in the study area.

Parameters	*wi*	*Wi*	*Ci*	*Si*	*qi*	*Wi.qi*	Water Quality	Grade
pH	1.000	0.036	7.2	8.5	84.70	3.05	Good	B
EC	1.000	0.036	608	1000	60.82	2.19		
TDS	1.000	0.036	302	500	60.40	2.17		
Cd	5.000	0.178	0.39	3	13.00	2.31		
Cr	5.000	0.178	7.68	50	15.36	2.73		
Cu	2.000	0.071	31.29	2000	1.57	0.11		
Fe	1.000	0.036	2041	300	680.33	24.50		
Mn	5.000	0.178	428	400	107.00	19.05		
Ni	1.000	0.036	6.51	70	9.30	0.34		
Pb	5.000	0.178	1.78	10	17.80	3.17		
Zn	1.000	0.036	97.69	3000	3.26	0.12		
Total	28.000	1.000	-	-	-	WQI = 59.74		

Summary caption: The Table shows the evaluation of the water quality of dug wells in the Ramkot area expressed as water quality index (WQI), with computation of different essential components for each parameter. The study revealed a WQI value of 59.74, classifying the dug wells of the study area as having good water quality and a B grade. The results highlight the public concerns for water safety as well as future water management strategies.

Similarly, a highly significant and strong positive correlation ($p<0.05$) was observed between EC and TDS ($r = 0.982$) and Cr and Ni ($r = 0.937$), as illustrated in Figures 3a and 3b). In contrast, Cr and Mn ($r = -0.736$) demonstrated a negative correlation between them. The positive relationship between EC and TDS suggests that the EC readily increases with TDS in water and hence TDS itself is a good indicator of EC (Singh et al., 2021). Likewise, Cd revealed a significant and positive correlation with Cu ($r = 0.881$) and Pb ($r = 0.745$) indicating the natural origin of these elements in groundwater. Copper showed a positive correlation with Pb ($r = 0.700$) while Fe was associated positively with Mn ($r = 0.886$) and Zn ($r = 0.655$). Iron (Fe) and Mn have common natural sources of origin in various soil, sediments, and water environments and hence always co-exist with mutual interaction (Bhandari & Nayal, 2008). Conversely, a highly significant and strong negative correlation ($p<0.05$) was observed between Fe and Ni ($r = -0.917$) as well as between Fe and Cr ($r = -0.854$), also illustrated in Figures 3c and 3d. Manganese (Mn) was found to be positively correlated with Zn ($r = 0.798$) and negatively correlated with Ni ($r = -0.800$) and Pb ($r = -0.599$). Moreover, Pb was negatively correlated with Zn ($r = -0.798$) indicating the parameters from different sources of origin in dug wells. According to the correlation matrices (Table 6), the contamination of heavy metals in dug wells in the study area may be associated with natural geogenic, pedogenic, and anthropogenic origins.

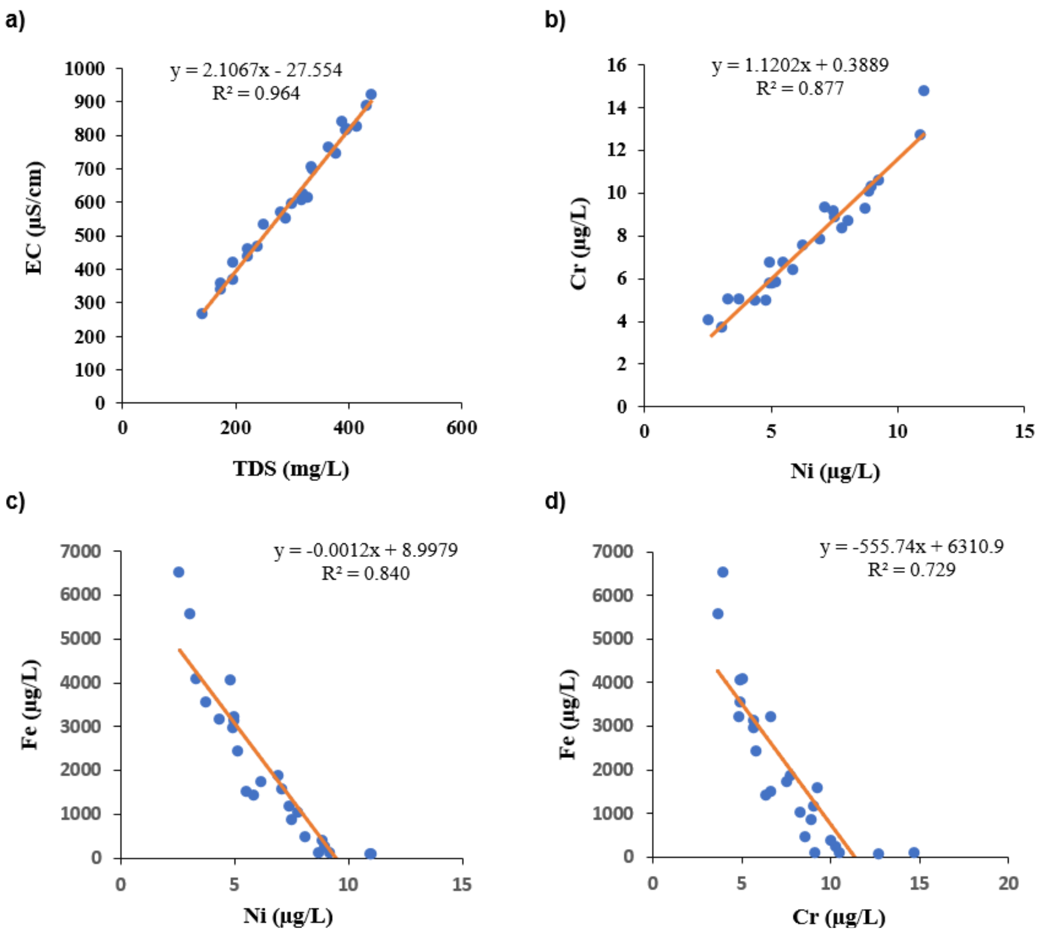

Figure 3. Correlation between (a) EC and TDS (b) Cr and Ni (c) Fe and Ni, and (d) Fe and Cr

3.5 Heavy metal evaluation index (HEI)

The heavy metal evaluation index (HEI) is an important measure that evaluates water quality by considering the level of heavy metal contamination. In the present investigation, this index was adopted to assess the water quality of selected dug wells concerning eight heavy metals, and the results are shown in Table 8.

The total HEI value of 8.477 suggested that the dug well water quality in the Ramkot area fell under the low HEI category (low heavy metals). Similar studies on groundwater in Haridwar, India (Khan & Rai, 2022), and Kaduna State in Northern Nigeria (Pukuma & Enock, 2024) revealed HEI values exceeding 20, indicating a high level of heavy metal pollution. In contrast, the study by Dheeraj et al. (2024) in Chhattisgarh, India, indicated that 70% of the overall samples exhibited low HEI values, indicating low heavy metal contamination. In a similar study by Kada et al. (2022) on the groundwater in North-East Algeria, most samples exhibited elevated HEI values indicating that the groundwater was significantly contaminated and unsafe for human consumption. Comparing these studies, the HEI value determined in the current study was quite low.

Table 8. Monitored concentrations of heavy metals (H_c) and standard permissible limits of each heavy metal (H_{mac}) used for computing the heavy metal evaluation index (HEI) of dug well water in the study area.

Heavy Metals	H_c	H_{mac}	H_c/H_{mac}	HEI	HEI Classification
Cd	0.39	3	0.130	8.479	Low heavy metals
Cr	7.68	50	0.154		
Cu	31.29	2000	0.016		
Fe	2041	300	6.803		
Mn	428	400	1.070		
Ni	6.51	70	0.093		
Pb	1.78	10	0.178		
Zn	97.69	3000	0.033		
Total	-	-	8.477		

Summary caption: The Table presents the evaluation of heavy metal contamination in dug wells of the Ramkot area using a heavy metal evaluation index (HEI). The study identified the dug well water quality in the study area with the degree of low heavy metal contamination, based on the HEI value of 8.479, and provided valuable information about the potential health risks.

3.6 Health risk assessment (HRA)

The assessment of health risks is an effective method for examining the potential dangers of exposure to heavy metals. It provides crucial information to safeguard human well-being. In this study, health risk was assessed through oral ingestion and dermal absorption pathways. This helped in identifying whether the well water in the research area was safe for consumption.

3.6.1 Non-carcinogenic risk

In the present investigation, the hazard quotient (HQ) and hazard index (HI) were used to estimate the non-carcinogenic risk from heavy metals. The estimated HQ and HI values of the examined HMs via ingestion and dermal pathways for both children and adults are presented in Table 9.

Our results revealed that the estimated HQ values for both the ingestion and dermal absorption pathways were less than 1.0. This indicated negligible risk due to a single metal exposure to both the receptor groups through intake of dug well water. However, it was found that the HQ values of all analyzed HMs through oral ingestion were higher than the dermal route for both receptor groups, which was in line with the findings of Zhang et al. (2020). Moreover, the HQ values for both pathways were higher in children than adults, indicating children as a vulnerable group, consistent with the findings of Li and Zhang (2010).

Table 9. Non-carcinogenic risk of the heavy metals in water samples of dug wells in the study area through ingestion and dermal pathways for children and adults

Heavy Metals	Children			Adult		
	HQ_{ing}	HQ_{derm}	HI_j	HQ_{ing}	HQ_{derm}	HI_j
Cd	3.20×10^{-2}	6.60×10^{-3}	3.86×10^{-2}	2.14×10^{-2}	2.23×10^{-3}	2.36×10^{-2}
Cr	1.05×10^{-1}	8.64×10^{-2}	1.91×10^{-1}	7.00×10^{-2}	2.93×10^{-2}	9.93×10^{-2}
Cu	3.20×10^{-2}	1.65×10^{-3}	3.37×10^{-2}	2.14×10^{-2}	5.60×10^{-4}	2.20×10^{-2}
Fe	1.19×10^{-1}	6.15×10^{-3}	1.25×10^{-1}	7.98×10^{-2}	2.09×10^{-3}	8.19×10^{-2}
Mn	7.29×10^{-1}	1.89×10^{-1}	9.18×10^{-1}	4.88×10^{-1}	6.38×10^{-2}	5.51×10^{-1}
Ni	1.33×10^{-2}	6.86×10^{-4}	1.37×10^{-2}	8.90×10^{-3}	2.33×10^{-4}	9.13×10^{-3}
Pb	5.20×10^{-2}	7.14×10^{-3}	5.91×10^{-2}	3.48×10^{-2}	2.43×10^{-3}	3.72×10^{-2}
Zn	1.33×10^{-2}	4.12×10^{-4}	1.34×10^{-2}	8.90×10^{-3}	1.40×10^{-4}	9.04×10^{-3}
Total	-	-	1.39	-	-	0.83

Summary caption: This Table shows the estimated non-carcinogenic risks of the heavy metals in the dug well water in the Ramkot area through ingestion and dermal absorption for children and adults. The results revealed higher hazard quotient (HQ) and hazard index (HI) for the ingestion pathway for both receptor groups. The total hazard index (HI_{total}) of 1.39 for children indicated potential non-carcinogenic risks to them.

In this study, the hazard index (HI) was calculated for the cumulative risk of eight heavy metals indicating the overall potential for non-carcinogenic effects (Table 9). The results showed that the HI values were in the descending order of Mn > Cr > Fe > Pb > Cd > Cu > Ni > Zn for both receptor groups. The highest HI values of 9.18×10^{-1} and 5.51×10^{-1} were noted for Mn in children and adults, respectively. As a result, exposure to Mn could present a potential risk to the local community in the Ramkot area, even though it is less toxic than other metals. Furthermore, the HI values for all HMs through the combined pathways were relatively higher in children than in adults. These findings were similar to the studies carried out by Pant et al. (2021), and Anyanwu and Nwachukwu (2020). Moreover, the estimated HI_{total} value was 1.39 for children and 0.83 for adults. Since the HI_{total} for children surpassed the safe limit of 1.0, the non-carcinogenic health risk in the receptor group cannot be ignored. On the contrary, adults did not face such risks based on their HI_{total} value. Similar to this study, the findings of Eziz et al. (2023) also showed oral ingestion as the primary route for the non-carcinogenic risk in children while Cd posed the most significant risk in groundwater samples from the Baghrash Lake Basin, China. Ganguli et al. (2024) found non-carcinogenic risks from As, Co, and Mn through oral ingestion when they examined groundwater quality in Feni, Bangladesh. Loganathan & Rajkumar (2025), however, found that more than 65% of adults and children were at non-carcinogenic risk from heavy metal-contaminated groundwater in the Vellore district of Tamil Nadu, India.

3.6.2 Carcinogenic risk

Exposure to carcinogenic elements for a prolonged time may increase cancer risk in humans. This risk evaluation helps estimate the expected cancer in an individual and the chances of developing risk in the future. The estimated LCR and TLCR values for carcinogenic elements (Cd, Cr, and Pb) for children and adults via oral ingestion and dermal routes are presented in Table 10.

Table 10. Carcinogenic risk of the heavy metals in water samples of dug wells in the study area through ingestion and dermal pathways for children and adults

Heavy Metals	Children			Adult		
	LCR_{ing}	LCR_{derm}	TLCR	LCR_{ing}	LCR_{derm}	TLCR
Cd	8.00×10^{-6}	8.25×10^{-8}	8.08×10^{-6}	5.35×10^{-6}	2.79×10^{-8}	5.38×10^{-6}
Cr	1.57×10^{-4}	3.24×10^{-6}	1.60×10^{-4}	1.05×10^{-4}	1.10×10^{-6}	1.06×10^{-4}
Pb	6.19×10^{-7}	2.55×10^{-8}	6.45×10^{-7}	4.15×10^{-7}	8.67×10^{-9}	4.24×10^{-7}

Summary caption: This Table presents the estimated carcinogenic risks of the heavy metals in the dug well water in the Ramkot area via ingestion and dermal absorption for children and adults. The results showed higher LCR values for the ingestion route for both receptor groups. The TLCR values indicated a potential carcinogenic risk of chromium for both receptor groups prompting the need for immediate measure for remediation.

The results showed that the LCR values were comparatively higher in children than in adults across both pathways. Likewise, LCR values for the ingestion pathway were notably higher than those for the dermal pathway for both receptor groups. They exhibited LCR values in the descending order of Cr > Cd > Pb via both exposure pathways. The LCR_{ing} values of Cr of children and adults were 1.57×10^{-4} and 1.05×10^{-4}, respectively. The LCR_{ing} values for Cr indicated that children were at a higher carcinogenic risk from the element than adults. Additionally, TLCR values of 1.60×10^{-4} and 1.06×10^{-4} for Cr were noted in children and adults, respectively. The TLCR values between 1×10^{-6} and 1×10^{-4} are considered safe limits (Wu et al., 2015). A value greater than 10^{-4} presents a carcinogenic health threat to the receptors. Therefore, it can be inferred from the findings that both receptor groups in the study area might suffer from carcinogenic risks due to Cr. On the other hand, Cd and Pb could not pose any carcinogenic risk to the receptors considering their LCR and TLCR values. A research work by Aendo et al. (2022) also demonstrated similar results consistent with those of the present study. Lan et al. (2024) also indicated that Cr in the groundwater of a Karst basin in SW China was the primary source of carcinogenic risk for the local community, which was similar to the findings of this study. They also reported children as the vulnerable group and ingestion as the main pathway for the risk. Zhou et al. (2024), however, reported high carcinogenic risks from Cd and Cr in groundwater from the Daxin area of Chongzuo, Southern China. They also indicated ingestion as the main route for the risk and identified children as being more vulnerable group than adults for the risks similar to the present study. Ganguli et al. (2024) also found lifetime cancer risks in children and adults from As, Cd, and Cr through ingestion of groundwater in Feni, Bangladesh. Moreover, Loganthan and Vignesh (2025) also found over 75 % of infants and children at high carcinogenic risks from Cr and Cd when they assessed the health risks of Cd, Cr, Fe, Pb, and Co in the groundwater in the industrial corridors of the Vellore district of Tamil Nadu, India.

4. Conclusions

The present study evaluated the water quality and health risks from heavy metal (HM) contaminants in dug well water in the Ramkot area of Nagarjun Municipality, Kathmandu district. Altogether eleven physicochemical parameters were analyzed in thirty-one water samples collected from the area studied. Most parameters were found within the allowable limits prescribed by USEPA, NDWQS, and WHO guidelines, with exceptions for Fe and Mn. The mean levels of HMs were in the order of Fe > Mn > Zn > Cu > Cr > Ni > Pb > Cd, with Fe accounting for 78% of the total heavy metals. Strong positive correlations were noted between EC and TDS, as well as between Cr and Ni. The results indicated that the dug well water in the area studied was rated as good quality and fell under grade B according to the computed WQI, making it suitable for agricultural, commercial, and domestic uses, but unsafe for consumption. The health evaluation index (HEI) indicated a class of low heavy metal contamination in the water of studied dug wells. Health risk assessment revealed a non-carcinogenic risk less likely to occur in both receptor groups through exposure to a single element according to the HQ values. However, the total hazard index (HI_{total}) for children could pose a potential non-carcinogenic risk to their health. Moreover, the total lifetime carcinogenic risk (TLCR) for Cr suggested a possible cancer risk to both the receptors from the elemental exposure.

The contamination risk of the heavy metals is high as nearly 70% of the local communities in the Ramkot area of Nagarjun municipality depends on dug-well water as the main source of drinking water. Numerous cases of health disorders from the consumption of heavy metal-contaminated water have been reported across the globe. Iron and Mn at elevated levels in drinking water can cause adverse health effects such as diabetes and heart disease. Children can be at high risk due to Pb poisoning from the contaminated water, leading to developmental issues such as cognitive impairments and behavioral problems. It can also cause hypertension and kidney damage in adults. Besides, Cd, Cr, and Pb are known carcinogens associated with lung, bladder, and kidney cancers, and skin lesions. Long-term exposure can cause neurotoxicity and cardiovascular diseases. Chronic exposure to Cu and Zn also has negative impacts on human health. Besides, pregnant women and children are vulnerable groups to the harmful impacts of heavy metals and can suffer from developmental effects such as low birth weight, and other health difficulties. Elderly individuals can also suffer more due to weak immunity systems. With heavy dependency on dug-well water in the Ramkot area, the local population may be at a high risk of exposure to the metals, particularly when the dug-wells are not regularly monitored or treated.

Hence, this study suggests the need for regular monitoring and testing of dug-well water to ensure that the concentrations of heavy metals in dug-well water are maintained within the safe limits. Since heavy metals in dug-well water pose a great threat and health risks, proper attention must be paid to reducing all possible sources of metal contamination in the groundwater sources across the area to ensure public health safety. Besides, the local government should incorporate into its plans to safeguard public health by supplying clean water to the local populations of the Ramkot area. This can be achieved through the implementation of affordable or cost-effective water purification or filtration systems. Some effective methods for reducing heavy metals include oxidation, ion exchange, aeration, reverse osmosis, and chemical precipitation. The present study also points to the value of the use of appropriate remediation technologies such as phytoremediation, phytoextraction, phytofiltration, and phytostabilization at site-specific contaminated groundwater sources. Similarly, this study suggests that the local ward offices should take the initiative to raise voices on public awareness plans and programs about the risks of heavy metal exposure. This could be done through training local communities to identify contaminated water sources and be aware of the public health implications of heavy metal exposure. Further, this study may also provide baseline information to researchers, local NGOs, and health inspectors to develop mitigation strategies and to ensure that the policies are implemented effectively according to the local needs. Moreover, a comprehensive analysis of the probability of risks posed by non-carcinogenic and carcinogenic metals in the dug wells in the long term and through seasonal variations will be the emphasis of our future work.

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6. Authors' Contribution

Supriya Kandel: Methodology, Investigation, Formal analysis, Data curation, Writing-original draft preparation; Bijaya Adhikary: Methodology, Investigation, Formal analysis, Data curation, Writing-review and editing; Jasana Maharjan: Methodology, Investigation, Formal analysis, Data curation, Writing-review and editing; Bindra Devi Shakya: Methodology, Investigation, Formal analysis, Data curation, Writing-review and editing; Mahesh Shrestha: Formal analysis, Writing-review and editing; Deepak Chhetry Karki: Formal analysis, Writing-review and editing; Dipesh Raj Pant: Formal analysis, Writing-review and editing; Pawan Raj Shakya: Conceptualization, Resources, Funding acquisition, Writing-review and editing, supervision.

7. Conflicts of Interest

The authors declare no conflict of interest.

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