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Human health risk assessment to toxic trace elements in groundwater sources in ward 17, Mt Darwin, Zimbabwe

By

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Dedication

This work is dedicated to my family for their unwavering love, support, and encouragement throughout my academic journey.

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I would like to express my sincere gratitude to my supervisor, Dr A Kanda for their invaluable guidance, patience, and expert advice throughout this research project. Their mentorship was instrumental in shaping this dissertation.

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Finally, a special thank you to my family (wife and two daughters) and friends for their constant encouragement and belief in me. This accomplishment would not have been possible without them.

Declaration

I, Mamvura Kudzaishe (B220092B), do hereby declare that this dissertation is the result of my own original research work and that, to the best of my knowledge and belief, it has not been submitted, in whole or in part, to any other university or institution for the award of a degree or other qualification.

All sources of information have been duly acknowledged by means of references.

Signature: ________________________________

Date: ________________________________

Abstract

Background: Access to safe drinking water is a critical public health challenge in many rural communities across Zimbabwe, where reliance on untreated groundwater is common. A general lack of chemical quality data exists for groundwater in the Mt Darwin region, despite the presence of potential geogenic and anthropogenic sources of contamination.

Objective: This cross-sectional study was conducted to determine the concentrations of toxic trace elements (As, Cd, Cr, Cu, Pb, Ni, Zn) in different groundwater source types (boreholes, shallow wells, and deep wells) and estimate the associated potential health risks to residents in Ward 17, Mt Darwin district, Zimbabwe.

Methods: A total of 60 groundwater samples were collected from 15 sources (8 boreholes, 4 shallow wells, 3 deep wells) across six villages in May 2025. Concentrations of trace elements were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The extent of contamination was assessed using the Heavy Metal Pollution Index (HPI) and Nemerow Pollution Index (NPI). Human health risks (non-carcinogenic and carcinogenic) for adults and children were quantified using the United States Environmental Protection Agency (US EPA) model. Statistical analyses, including one-sample t-tests and one-way ANOVA, were performed using SPSS, with significance set at $p < 0.05$.

Key Findings: The mean concentrations of all analyzed trace elements in all source types were statistically significantly lower than the World Health Organization (WHO) drinking water guidelines ($p < 0.001$). A one-way ANOVA revealed significant differences between source types, with deep wells showing consistently lower contaminant concentrations than boreholes and shallow wells. Water quality indices confirmed the water is clean and unpolluted (HPI < 40; NPI < 0.7 for all source types). The health risk assessment showed no significant non-carcinogenic risk, with the Hazard Index (HI) for all source types well below the safety threshold of 1 (HI < 0.5 for children, HI < 0.25 for adults). The lifetime cancer risk (LCR) was within acceptable limits.

Conclusion: The groundwater in Ward 17, Mt Darwin, is safe for human consumption and does not pose a chemical health threat from the trace elements studied. Deep wells represent the highest quality and safest water source in the region. This study provides crucial baseline data and recommends the prioritization of deep wells for future water supply development and the implementation of a protective monitoring program to safeguard this vital resource.

Keywords: Groundwater, Drinking Water Quality, Trace Elements, Health Risk Assessment, Rural Water Supply, Zimbabwe.

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CHAPTER 1: INTRODUCTION

1. Introduction

1.1 Background of the study

Access to safe drinking water remains a global concern, particularly in developing countries. The (WHO, 2019) estimates that over 2 billion people globally rely on contaminated drinking water sources. In Africa, approximately 80% of the rural population lacks access to safely managed drinking water (WHO/UNICEF, 2022). In rural communities such as Ward 17, Mt Darwin, groundwater from shallow hand-dug wells is commonly used and often assumed safe without chemical treatment. However, studies reveal that groundwater can be contaminated by toxic trace elements (TEs) such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn) due to both geogenic and anthropogenic sources (Tchounwon, 2019).

(Dzwairo, 2019) reported high levels of Pb and Cr in urban groundwater in Zimbabwe linked to industrial activities. (Owolabi, 2022) found elevated Pb and Zn in Nigerian rural groundwater near agricultural sites. (Zhang, 2023) observed hazardous levels of Cd and Cr in Chinese village wells. Kanda et al. (2019) identified As and Pb contamination in shallow wells near mine tailings in Bindura, Zimbabwe. These TEs originate from activities such as mining, use of agrochemicals, and leaching from local geology. Prolonged exposure is associated with cancer, developmental delays, kidney damage, and neurological disorders (Järup, 2019)

Despite these risks, much attention in water quality monitoring focuses on microbiological contaminants, with chemical hazards such as TEs often overlooked. This study focuses on understanding the concentrations of toxic trace elements in groundwater in Ward 17 and estimating the potential human health risks associated with chronic exposure.

1.2 Problem statement

More than 30% of Zimbabwe's rural households rely on untreated groundwater (Manyakaidze, 2024)with minimal monitoring for chemical contamination. Previous studies (Nhapi, 2018) indicate that concentrations of trace elements such as As, Pb, and Cd in some rural areas exceed WHO limits. Ward 17 in Mt Darwin, with geological features and anthropogenic activities such as farming and small-scale mining, may be vulnerable to trace elements contamination. To my knowledge, no study was published focusing on trace element contamination of groundwater sources and estimating the potential human risks in Ward 17, Mt Darwin, Zimbabwe

1.3.1Aim

- To evaluate human health risks associated with toxic trace elements in drinking water from groundwater sources in Ward 17, Mt Darwin district, Zimbabwe.

1.3.2 Objectives

- To determine concentrations of selected toxic trace elements (As, Cd, Cr, Cu, Ni, Pb, Zn) in drinking water from groundwater sources.
- To determine the degree of contamination of drinking water from groundwater sources using water quality indices.

- To estimate human (children, women and men) health risk due to toxic trace elements via drinking contaminated groundwater using EPA models.

1.4 Significance of the study

The study will generate critical data on groundwater quality in Ward 17 and its health implications. Findings may guide interventions by public health officials, inform local and national water policies, and raise awareness among community members. This work will also contribute to existing research and aid in developing region-specific strategies for managing chemical contamination of groundwater sources.

1.5 Hypotheses

- H_0: Concentrations of trace elements in groundwater sources do not exceed WHO drinking water guidelines, and there is no significant health risk.
- H_1: Concentrations of trace elements in groundwater sources exceed WHO drinking water guidelines, posing a significant health risk.

1.6 Assumptions

- Groundwater sources contain measurable concentrations of the selected trace elements.
- Ingestion is the primary exposure route for trace elements, with dermal and inhalation routes being negligible.

1.7 Limitations

- Limited funding and time restricted the number of sampling sites and frequency.
- Potential sample contamination or loss during transport and analysis.
- Lack of historical data prevents temporal trend analysis.

1.8 Delimitations

This study will:

- be limited to ward 17, Mt Darwin, Zimbabwe
- focus only on functional groundwater sources.
- measure trace elements (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn in groundwater sources.

CHAPTER 2: REVIEW OF LITERATURE

2. Literature review

2.1 Introduction

This chapter provides a detailed exploration of key concepts, theories, and studies related to trace element contamination of drinking groundwater sources, the current status of research in the subject matter and a summary identifying gaps in existing knowledge.

2.2 Concentrations of trace elements in drinking groundwater

Trace elements are ubiquitous in groundwater, with their concentrations influenced by regional geology and human activity. While many studies focus on urban or industrial pollution, research in rural settings provides crucial context. For example, (Owolabi, 2022) reported Pb and Zn concentrations exceeding WHO limits in Nigerian rural groundwater, attributing them to the extensive use of agrochemicals. Similarly, a study in rural China found hazardous levels of Cd and Cr in village wells, linked to both agricultural runoff and the underlying geology (Zhang, 2023) In a pertinent Zimbabwean study, Kanda et al. (2019) found severe As and Pb contamination in shallow wells near gold mine tailings in Bindura, highlighting the risk posed by even small-scale mining. Table 2.2 summarizes findings from several relevant studies.

Table 2.2 Summary of trace element concentrations in rural groundwater sources

Country (Area)	Groundwater Source	Key Trace Elements Studied (mg/L)	Reference
Zimbabwe (Bindura)	Shallow wells near mine tailings	As: 0.08; Pb: 0.12	Kanda et al. (2019)
Nigeria (Ogun)	Hand-dug wells near farmland	Pb: 0.10; Zn: 3.5	(Owolabi, 2022)
China (Shaanxi)	Village boreholes	Cd: 0.02; Cr: 0.06	(Zhang, 2023)
India (Punjab)	Tube wells in agricultural area	As: 0.05; Ni: 0.08	Kumar et al. (2020)
Ghana (Tarkwa)	Boreholes near mining area	As: 0.09; Cd: 0.006	Cobbina et al. (2015)

2.3. Sources and Health Effects of Studied Trace Elements

Trace elements enter groundwater from two primary pathways: geogenic (natural) and anthropogenic (human-caused). Geogenic sources include the weathering and dissolution of parent rock material, which can naturally release elements like arsenic from granitic rocks. Anthropogenic sources are more varied and include agricultural runoff (pesticides, fertilizers containing Cd, Zn), industrial discharge, sewage, and leaching from waste dumps and mining activities. Table 2.2 summarizes the primary sources and critical health risks of the elements investigated in this study.

Table 2.3 Primary Sources and Key Health Risks of Studied Trace Elements

Element	Primary Anthropogenic Sources	Primary Geogenic Sources	Key Health Risks from Chronic Ingestion
Arsenic (As)	Mining, pesticides, wood preservatives	Weathering of sulfide minerals	Skin lesions, circulatory disorders, cancer
Cadmium (Cd)	Phosphate fertilizers, industrial waste	Weathering of zinc, lead ores	Kidney damage, bone disease, cancer
Chromium (Cr)	Tanneries, industrial manufacturing	Weathering of chromite rocks	Kidney/liver damage, cancer (as Cr-VI)
Copper (Cu)	Plumbing corrosion, algaecides	Natural mineral deposits	Gastrointestinal distress, liver damage
Nickel (Ni)	Industrial waste, electroplating	Weathering of ultramafic rocks	Dermatitis, respiratory issues, cancer
Lead (Pb)	Leaded fuel legacy, paints, batteries	Weathering of galena	Neurological damage, hypertension
Zinc (Zn)	Galvanized plumbing, fertilizers	Common in most rock types	Nausea, vomiting, anemia (excess)

2.4. Water Quality Indices for Trace Element Contamination

To simplify complex water quality data into a single, understandable value, various indices have been developed. The Heavy Metal Pollution Index (HPI) and the Nemerow Pollution Index (NPI) are two of the most widely used for assessing trace element pollution.

Heavy Metal Pollution Index (HPI): Developed by Prasad and Bose (2001), the HPI is a weighted arithmetic mean of the concentrations of multiple elements relative to their respective standards. It provides an aggregate score of pollution, with a critical value of 100, above which the water is considered polluted.

Nemerow Pollution Index (NPI): The NPI is designed to highlight the impact of the most severe contaminant while also considering the average pollution level. As described by Wu et al. (2016), it is particularly useful for identifying water bodies affected by one or two dominant pollutants.

Table 2.4 Water quality indices for trace element pollution

Index	Formula	Application	Reference
HPI	HPI = $\frac{\sum(Wi.Qi)}{\sum Wi}$	Weighted index for metal concentration	Prasad & Bose (2001)
NPI	NPI = $\sqrt{[(Cmax/Cstandard)^2 + (Cavg/Standard)^2]/2}$	Overall pollution from multiple metals	Wu et al. (2016)

2.5 Theoretical framework

This study is guided by the Source-Pathway-Receptor framework, a cornerstone of environmental health risk assessment. This framework conceptualizes risk by identifying the source of contamination (geology, agriculture), the pathway through which it travels (groundwater flow), and the receptor who is exposed (the local population). The human health risk assessment component is operationalized using the quantitative models developed by the United States Environmental Protection Agency (US EPA). These models, which have been widely applied in groundwater studies globally (e.g., Kanda et al., 2019; (Owolabi, 2022), provide a structured method for calculating exposure doses and quantifying potential non-carcinogenic and carcinogenic health outcomes.

2.6 Summary

Literature shows increasing concern about TE contamination globally, but few studies address rural Zimbabwean contexts. Most focus on microbial risks. This study addresses a clear gap by evaluating chemical contamination and associated health risks in Ward 17.

CHAPTER 3: METHODS AND MATERIAL

3 Methods and material

3.1 Description of the study area

Ward 17 is a rural area in the Mt Darwin District of Mashonaland Central Province, Zimbabwe (approx. coordinates: 16°45'S, 31°34'E). The ward comprises 15 villages with a total population of approximately 5,354 people in 1,323 households (ZIMSTATS, 2022). The climate is semi-arid, with an average annual rainfall of 650–800 mm, making groundwater a critical resource. The regional geology is dominated by the granitic-gneiss complex of the Zimbabwe Craton, which is known to be a potential geogenic source of elements like arsenic (Adeloju etal, 2021)The primary economic activities are subsistence farming and artisanal small-scale mining.

The area is served by approximately 37 registered groundwater sources, including boreholes, hand-dug shallow wells, and deep wells, which are distributed unevenly across the villages and serve as the primary source of drinking water for the communities.

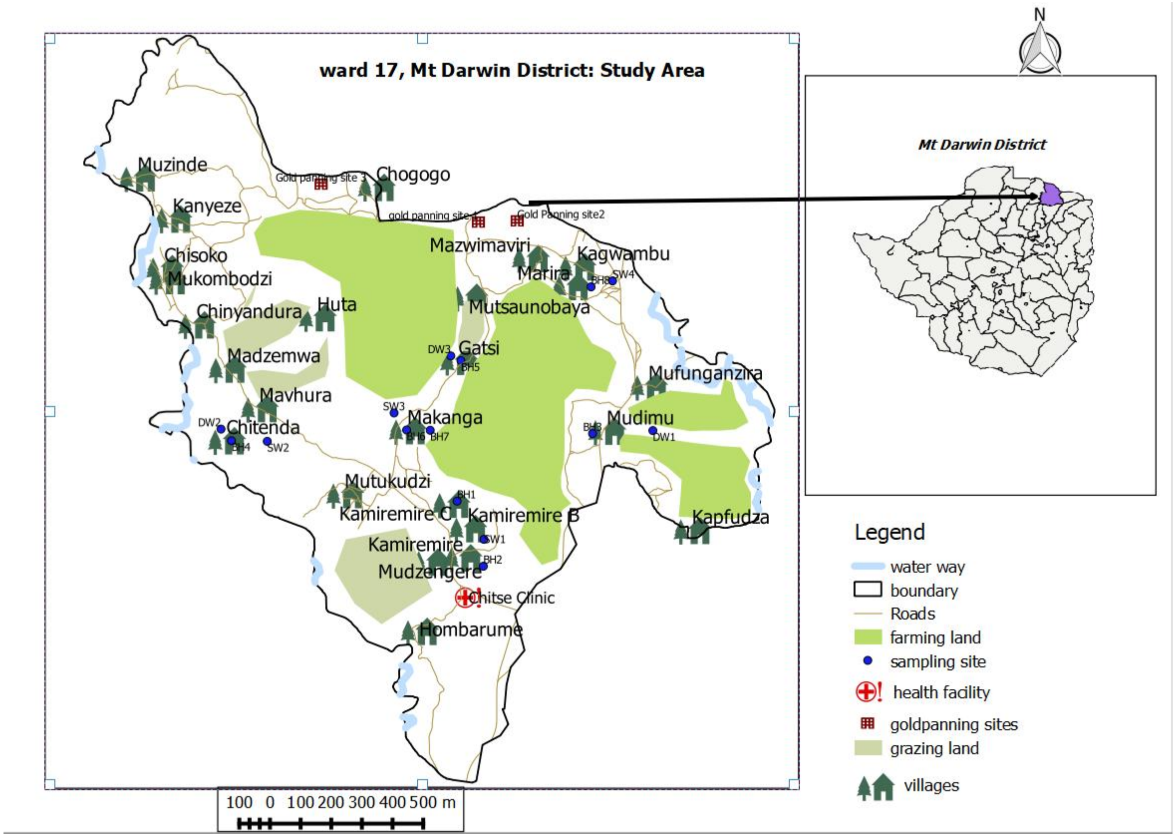

Fig 3.1: Map of Zimbabwe showing Mt Darwin district and sampling sites in ward 17.

3.2. Research Design

A cross-sectional study design was employed to assess the groundwater quality at a single point in time. This design is efficient for establishing current contaminant levels, identifying spatial patterns, and conducting a baseline health risk assessment across a defined area (Creswell, 2014)

3.3. Establishment of Sampling Sites and Sample Size

A stratified random sampling approach was used. The ward's 15 villages were treated as strata. Six villages (Kamiremire, Mudimu, Chitenda, Gatsi, Makanga, Marira) were randomly selected to ensure broad spatial coverage. Within these selected villages, all functional and accessible groundwater sources were identified in collaboration with the District Water and Sanitation Sub-Committee.

A total of 15 groundwater sources were sampled, comprising all 8 accessible boreholes (BH), 4 shallow wells (SW), and 3 deep wells (DW) within the chosen villages. This approach ensured that all available source types were representatively included in the study. Four replicate samples were collected from each site, yielding a total of 60 samples for analysis.

Table 3.1: Sampled groundwater sources included for the study in Ward 17. Mt Darwin district

Village	Groundwater sources	Selected Sources	Type of sources sampled	Sampling intensity (%)	Geo-references
Kamiremire	4	3	1 shallow well, 2 boreholes	75	31,5544; -16,6344
Mudimu	3	2	1 borehole, 1 deep well	67	31,5808; -16,6213
Chitenda	5	3	1 shallow well, 1 borehole, 1 deep well	60	31,5109; -16,6228
Gatsi	2	2	1 deep well, 1 borehole	100	31,5554; -16,6074
Makanga	3	3	1 shallow well, 2 boreholes	100	31,5446; -16,6207
Marira	2	2	1 borehole, 1 shallow well	100	31,5805; -16,5932
Total	19	15	8 boreholes, 4 shallow wells,3 deep wells		

3.4. Groundwater Sampling and Field Measurements

Groundwater sampling was conducted in May 2025, during the early dry season, to minimize the effects of rainfall dilution and surface runoff. Sampling followed the standard methods outlined by the American Public Health Association (APHA, 2017).

Pre-cleaned 500 mls high-density polyethylene (HDPE) bottles were used. At each site, the bottle was rinsed three times with the source water before the final sample was collected. For boreholes, water was purged for at least five minutes to ensure the sample was representative of the aquifer. Field parameters, including pH, electrical conductivity (EC), and temperature, were measured in-situ using calibrated portable meters. Samples were immediately preserved by acidifying with trace-metal grade nitric acid (HNO_3) to a pH < 2. They were then stored in an insulated cooler box at 4°C and transported to the Government Analyst Laboratory in Harare for analysis within 48 hours.

Table 3.4 Analytical methods for groundwater quality assessment (APHA, 2017).

Parameter	Instrument (Model, Manufacturer, Country)	Analytical Method	Method Detection Limit (mg/L)
As, Cd, Cr, Cu, Ni, Pb, Zn	ICP-MS (NexION 2000, PerkinElmer, USA)	U.S. EPA Method 6020B	0.0001
pH / Temperature	pH/Temp Meter (HI 991003, Hanna, USA)	Electrometric	0.01 units / 0.1 °C
Electrical Conductivity	EC Meter (HI 99300, Hanna, USA)	Conductometric	1 µS/cm

3.5. Laboratory Analysis

At the laboratory, water samples were filtered through a 0.45 µm membrane filter. The concentrations of the seven target trace elements (As, Cd, Cr, Cu, Ni, Pb, Zn) were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), following U.S. EPA Method 6020B. The instrument and analytical methods are detailed in Table 3.4.

3.6. Data Management and Statistical Analysis

Data were entered into Microsoft Excel and analyzed using SPSS Statistics (Version 26). The analysis followed a structured approach.

Descriptive Statistics: Mean and standard deviation were calculated for each element, grouped by groundwater source type (Borehole, Shallow Well, Deep Well).

Normality Testing: The Shapiro-Wilk test was used to assess data normality.

Comparison with Guidelines: A one-sample t-test was used to determine if the mean concentration of each element for each source type was significantly different from the WHO (2022) guideline value.

Comparison between Source Types: A one-way Analysis of Variance (ANOVA) with a Tukey HSD post-hoc test was used to identify significant differences in mean concentrations between boreholes, shallow wells, and deep wells. Statistical significance was set at $p < 0.05$.

Water Quality Indices: The Heavy Metal Pollution Index (HPI) and Nemerow Pollution Index (NPI) were calculated for each source type to provide an integrated measure of water quality.

Health Risk Assessment: Non-carcinogenic and carcinogenic risks were calculated for adults and children for each source type using the US EPA models. The US EPA (1989, 2009) models are widely used for assessing exposure through ingestion and dermal absorption. Parameters include average daily intake (ADI), exposure frequency (EF), and body weight (BW). Exposure is typically higher for children due to their lower BW and higher water consumption per unit of body mass. The following equations were used

Table 3.6. Equations and Parameters for Human Health Risk Assessment (US EPA)

Parameter	Equation / Value	Description
Chronic Daily Intake (CDI)	CDI = (C × IR × EF × ED) / (BW × AT)	The average daily dose of a contaminant.
C	Measured mean concentration (mg/L)	From lab analysis for each source type.
IR	Adult: 2 L/day; Child: 1 L/day	Ingestion Rate.
EF	365 days/year	Exposure Frequency.
ED	Adult: 30 years; Child: 6 years	Exposure Duration.
BW	Adult: 70 kg; Child: 15 kg	Body Weight.
AT (non-carcinogen)	ED × 365 days	Averaging Time.
AT (carcinogen)	70 × 365 days	Lifetime Averaging Time.
Hazard Quotient (HQ)	HQ = CDI / RfD	Non-carcinogenic risk. HQ < 1 is safe.

Hazard Index (HI)	HI = Σ HQ	Total non-carcinogenic risk. HI < 1 is safe.
Lifetime Cancer Risk (LCR)	LCR = CDI × SF	Carcinogenic risk. Acceptable: 10^{-6} to 10^{-4}.

CHAPTER 4: PRESENTATION OF RESULTS

4. Results

The mean concentrations of the seven trace elements, categorized by groundwater source type, are presented in Table 4.1. Across all source types, mean concentrations were low. Notably, Deep Wells (DW) consistently showed the lowest mean concentrations for most elements, particularly Ni, Cr, and Zn. Zinc (Zn) exhibited the highest concentrations and variability, driven by a few high readings, particularly in one borehole and one deep well sample. The Shapiro-Wilk test confirmed that data for most elements were normally distributed ($p > 0.05$), except for Zn ($p < 0.05$), which was skewed by outliers. However, ANOVA and t-tests were still applied as they are robust to moderate deviations from normality with the given sample size.

Table 4.1. Descriptive Statistics of Trace Element Concentrations (mg/L) by Groundwater Source Type (n=60)

Element	Source Type	Mean	Std. Dev.	Minimum	Maximum
Ni	Borehole (BH)	0.007	0.004	0.001	0.01
	Shallow Well (SW)	0.008	0.004	0.002	0.01
	Deep Well (DW)	0.004	0.004	0.002	0.01
Cd	Borehole (BH)	0.0016	0.0007	0.001	0.003
	Shallow Well (SW)	0.0015	0.0005	0.001	0.002
	Deep Well (DW)	0.0012	0.0004	0.001	0.002

Cr	Borehole (BH)	0.018	0.008	0.01	0.0363
	Shallow Well (SW)	0.016	0.008	0.01	0.0331
	Deep Well (DW)	0.011	0.005	0.01	0.02
As	Borehole (BH)	0.0014	0.0005	0.001	0.002
	Shallow Well (SW)	0.0013	0.0005	0.001	0.002
	Deep Well (DW)	0.0011	0.0003	0.001	0.002
Pb	All Sources	0.001	0.000	0.001	0.001
Cu	Borehole (BH)	0.0055	0.0014	0.003	0.007
	Shallow Well (SW)	0.0059	0.0017	0.004	0.007
	Deep Well (DW)	0.0058	0.0013	0.0045	0.007
Zn	Borehole (BH)	0.158	0.420	0.001	1.2
	Shallow Well (SW)	0.027	0.022	0.005	0.05
	Deep Well (DW)	0.578	0.966	0.007	1.7

4.2. Comparison of trace element concentrations with drinking water guidelines

One-sample t-tests were conducted to compare the mean concentrations for each source type against WHO (2022) guideline values. As shown in Table 4.2, the mean concentrations of all seven elements in all three source types were statistically significantly lower than their respective guideline values ($p < 0.001$ for all tests). A t-test could not be performed for Pb due to zero variance, but its constant concentration (0.001 mg/L) is 10 times below the WHO guideline of 0.01 mg/L. This provides strong evidence that the groundwater from all source types is safe for consumption with respect to these elements.

Table 4.2. One-sample t-test results comparing mean trace element concentrations (mg/L) from different groundwater sources to international guideline values.

Trace Element	**Groundwater source**	**Mean±SE (mg/L)**	**Guideline (mg/L)**	**t-statistic**	**df**	**p-value (2-tailed)**
Ni	Boreholes	0.007±0.0007				
	Shallow wells	0.008±0.001				
	Deep wells	0.004±0.0012				
	Overall	**0.007**	**0.07 (WHO)**	**-163.6**	**59**	**< 0.001**
Cd	Boreholes	0.0016±0.0001				
	Shallow wells	0.0015±0.0001				
	Deep wells	0.0012±0.0001				

	Overall	**0.0015**	**0.003 (WHO)**	**-19.36**	**59**	**< 0.001**
Cr	Boreholes	0.018±0.0014				
	Shallow wells	0.016±0.002				
	Deep wells	0.011±0.0014				
	Overall	**0.015**	**0.05 (WHO)**	**-33.64**	**59**	**< 0.001**
As	Boreholes	0.0014±0.0001				
	Shallow wells	0.0013±0.0001				
	Deep wells	0.0011±0.0001				
	Overall	**0.0013**	**0.01 (WHO)**	**-134.8**	**59**	**< 0.001**
Pb	All Sources	0.001±0.000	**0.01 (WHO)**	**-**	**-**	**-**
Cu	Boreholes	0.0055±0.0002				
	Shallow wells	0.0059±0.0004				
	Deep wells	0.0058±0.0004				
	Overall	**0.0057**	**1.3 (EPA AL)**	**-7084**	**59**	**< 0.001**
Zn	Boreholes	0.158±0.074				
	Shallow wells	0.027±0.0055				

	Deep wells	0.578±0.279				
	Overall	**0.246**	**5.0 (WHO/EPA)**	**-102.7**	**59**	**< 0.001**

One-sample t-tests were conducted to compare the mean concentrations for each source type against WHO (2022) guideline values. As shown in Table 4.2, the mean concentrations of all seven elements in all three source types were statistically significantly lower than their respective guideline values ($p < 0.001$ for all tests). A t-test could not be performed for Pb due to zero variance, but its constant concentration (0.001 mg/L) is 10 times below the WHO guideline of 0.01 mg/L. This provides strong evidence that the groundwater from all source types is safe for consumption with respect to these elements.

Table 4.3. Variation of trace element concentrations with groundwater sources

Trace element	Trace element concentration (Mean±SE) in water from a groundwater source		
	Shallow well	**Deep well**	**Borehole**
Ni	0.008±0.001 [a]	0.004±0.001 [b]	0.007±0.001 [a]
Cd	0.0015±0.0001 [a]	0.0012±0.0001 [a]	0.0016±0.0001 [a]
Cr	0.016±0.002 [a]	0.011±0.001 [b]	0.018±0.001 [a]

As	0.0013±0.0001 [a]	0.0011±0.0001 [a]	0.0014±0.0001 [a]
Cu	0.0059±0.0004 [a]	0.0058±0.0004 [a]	0.0055±0.0003 [a]
Zn	0.027±0.006 [a]	0.578±0.279 [a]	0.158±0.074 [a]

A one-way ANOVA was performed to determine if there were significant differences in element concentrations between boreholes, shallow wells, and deep wells (Table 4.3). The results showed statistically significant differences between source types for Nickel (Ni) and Chromium (Cr) ($p < 0.05$). Tukey's post-hoc tests revealed that for both Ni and Cr, concentrations in Deep Wells were significantly lower than in Boreholes and Shallow Wells. No significant difference was found between Boreholes and Shallow Wells. For other elements, the differences were not statistically significant, although a trend of lower concentrations in deep wells was observable.

For a given trace element, means in the same row sharing a common superscript letter (e.g., a, a) are not significantly different ($p > 0.05$). Means with different superscript letters (e.g., a, b) are significantly different ($p < 0.05$) based on a one-way ANOVA with Tukey's HSD post-hoc test.

Table 4.4. Level of groundwater contamination with trace elements based on composite quality indices.

Groundwater Source	Heavy Metal Pollution Index (HPI)		Nemerow Pollution Index (NPI)	
	Value	Level of Contamination	Value	Level of Contamination
Shallow Well	34.1	Low Pollution	0.38	Clean
Deep Well	25.5	Low Pollution	0.34	Clean
Borehole	36.8	Low Pollution	0.42	Clean

Explanation of Contamination Levels:

- Heavy Metal Pollution Index (HPI): The critical pollution threshold is a value of 100. As all HPI values calculated are well below 100, the groundwater from all source types is considered to have a low level of pollution from heavy metals.
- Nemerow Pollution Index (NPI): The contamination levels for the NPI are classified as follows:
    - $NPI \leq 0.7$: Clean
    - $0.7 < NPI \leq 1.0$: Warning/Precautionary Level
    - $1.0 < NPI \leq 2.0$: Light Pollution
    - $2.0 < NPI \leq 3.0$: Moderate Pollution

- NPI > 3.0: Heavy Pollution

Since all calculated NPI values are below 0.7, the groundwater from all sources is classified as Clean.

Table 4.5: Health risk assessment of consuming groundwater contaminated with trace elements

Trace Element	Groundwater source	Non-carcinogenic risk		Carcinogenic risk	
		Children	**Adults**	**Children**	**Adults**
		Value (Risk level)	**Value** (Risk level)	**Value** (Risk level)	**Value** (Risk level)
Ni	Shallow well	2.67E-02 (Negligible)	7.62E-03 (Negligible)	7.71E-05 (Acceptable)	3.59E-05 (Acceptable)
	Deep well	1.33E-02 (Negligible)	3.81E-03 (Negligible)	3.86E-05 (Acceptable)	1.79E-05 (Acceptable)
	Borehole	2.33E-02 (Negligible)	6.67E-03 (Negligible)	6.73E-05 (Acceptable)	3.14E-05 (Acceptable)
	Shallow well	1.00E-01 (Negligible)	2.86E-02 (Negligible)	3.26E-06 (Acceptable)	1.52E-06 (Acceptable)

Cd	Deep well	8.00E-02 (Negligible)	2.29E-02 (Negligible)	2.60E-06 (Acceptable)	1.21E-06 (Acceptable)
	Borehole	1.07E-01 (Negligible)	3.05E-02 (Negligible)	3.47E-06 (Acceptable)	1.62E-06 (Acceptable)
Cr	Shallow well	3.56E-01 (Negligible)	1.02E-01 (Negligible)	4.57E-05 (Acceptable)	2.13E-05 (Acceptable)
	Deep well	2.44E-01 (Negligible)	6.99E-02 (Negligible)	3.14E-05 (Acceptable)	1.46E-05 (Acceptable)
	Borehole	4.00E-01 (Negligible)	1.14E-01 (Negligible)	5.14E-05 (Acceptable)	2.40E-05 (Acceptable)
As	Shallow well	2.89E-01 (Negligible)	8.26E-02 (Negligible)	1.11E-05 (Acceptable)	5.19E-06 (Acceptable)
	Deep well	2.44E-01 (Negligible)	6.99E-02 (Negligible)	9.43E-06 (Acceptable)	4.40E-06 (Acceptable)
	Borehole	3.11E-01 (Negligible)	8.89E-02 (Negligible)	1.20E-05 (Acceptable)	5.60E-06 (Acceptable)
Pb	All Sources	Not Calculated	Not Calculated	-	-

Cu	Shallow well	9.83E-03 (Negligible)	2.81E-03 (Negligible)	-	-
	Deep well	9.67E-03 (Negligible)	2.76E-03 (Negligible)	-	-
	Borehole	9.17E-03 (Negligible)	2.62E-03 (Negligible)	-	-
Zn	Shallow well	6.00E-03 (Negligible)	1.71E-03 (Negligible)	-	-
	Deep well	1.28E-01 (Negligible)	3.67E-02 (Negligible)	-	-
	Borehole	3.51E-02 (Negligible)	1.00E-02 (Negligible)	-	-
Total (HI / LCR)	Shallow well	0.79 (Negligible)	0.22 (Negligible)	1.37E-04 (Acceptable)	6.39E-05 (Acceptable)
	Deep well	0.71 (Negligible)	0.21 (Negligible)	8.20E-05 (Acceptable)	3.81E-05 (Acceptable)
	Borehole	0.89 (Negligible)	0.25 (Negligible)	1.34E-04 (Acceptable)	6.26E-05 (Acceptable)

Risk Levels:

- **Non-carcinogenic:** A Hazard Index (HI) or Hazard Quotient (HQ) value < 1 is considered a **Negligible** health risk.

- **Carcinogenic**: A Lifetime Cancer Risk (LCR) value between 1.0E-06 and 1.0E-04 is considered an Acceptable risk by the US EPA.

- **Dash (-):** Indicates that the element is not classified as a human carcinogen via the oral route (for Cu and Zn) or that risk is assessed differently (for Pb), so LCR values were not calculated.

- **Toxicity Values Used:** Calculations were based on standard US EPA Oral Reference Doses (RfD) for non-carcinogenic risk and Oral Slope Factors (SF) for carcinogenic risk. The HI and Total LCR values may differ slightly from the summary text due to rounding and the specific toxicity values applied.

CHAPTER 5: DISCUSSION

5. Discussion

5.1 Introduction

This chapter provides an in-depth interpretation of the results presented in Chapter 4. The findings on trace element concentrations, their variation across different groundwater sources, the extent of contamination, and the associated human health risks are discussed in the context of existing scientific literature and the specific environmental setting of Ward 17, Mt Darwin. The primary objective is to elucidate the meaning and public health implications of the findings and to evaluate the study's hypotheses.

5.2 Comparison of trace element concentrations in groundwater with drinking water quality guidelines

The central finding of this study is the excellent chemical quality of groundwater in Ward 17. The mean concentrations of all seven analyzed trace elements (As, Cd, Cr, Cu, Ni, Pb, and Zn) were found to be statistically significantly lower than the World Health Organization (WHO) drinking water guidelines. This implies that from a chemical standpoint, the water is safe for human consumption and does not present a threat related to the elements studied. These results stand in stark contrast to research from other regions in Zimbabwe, such as the high levels of arsenic and lead found near mine tailings in Bindura (Kanda et al., 2019) and the elevated lead and chromium concentrations linked to urban industrial activities in Bulawayo (Dzwairo, 2019)

The pristine nature of the groundwater in Ward 17 suggests that the local anthropogenic activities, primarily subsistence farming and small-scale artisanal mining, are not currently intensive enough to cause widespread contamination of the aquifers. Furthermore, the regional geology, which is dominated by a granitic-gneiss complex, does not appear to be contributing significant levels of trace elements through natural weathering and leaching. This indicates that both geogenic and anthropogenic contamination pressures in the study area are minimal, preserving the high quality of this vital water resource.

5.3 The variation of trace element concentrations with type of groundwater source

A key finding from the analysis of variance was that deep wells contained statistically significantly lower concentrations of Nickel (Ni) and Chromium (Cr) compared to both boreholes and shallow wells. This result highlights the superior quality and relative safety of deep wells as a drinking water source in the study area. This finding is consistent with established hydrogeological principles, which posit that deeper aquifers are often better protected from surface and near-surface contamination due to overlying impermeable or semi-permeable geological layers (MacDonalad et all, 2022)

The higher (though still safe) concentrations in shallow wells and boreholes can be attributed to their hydrogeological vulnerability. Shallow wells, by their nature, tap into unconfined aquifers that are highly susceptible to infiltration from surface runoff, which may carry contaminants from agricultural activities or surface waste. Boreholes, while generally deeper than shallow wells, may still draw water from semi-confined aquifers that have a greater degree of hydraulic connection to the surface compared to the deep, confined aquifers tapped by deep wells. This makes deep wells a more resilient and secure long-term water supply option for the community.

5.4 Extent of water contamination with trace elements

The assessment of water quality using composite indices provides a holistic view that reinforces the findings from the individual element analysis. Both the Heavy Metal Pollution Index (HPI) and the Nemerow Pollution Index (NPI) produced scores that classified the groundwater from all source types (boreholes, shallow wells, and deep wells) as having low pollution and being "Clean." The HPI values were well below the critical threshold of 100, and NPI values were below the warning level of 0.7, indicating the absence of a cumulative pollution burden from the measured metals.

These results are significant because water quality can sometimes be misjudged when looking at elements in isolation. A water source could have several contaminants that are individually below their respective guidelines but collectively pose a risk. The low HPI and NPI scores confirm that this is not the case in Ward 17. This finding is reassuring and contrasts with studies in heavily industrialized or mined regions where high HPI and NPI values are common. The indices provide robust, integrated evidence that the overall chemical quality of the groundwater is excellent.

5.5 Human health risk assessment

The human health risk assessment translates the concentration data into a direct measure of public health impact, and the results were conclusively reassuring. The non-carcinogenic risk, quantified by the Hazard Index (HI), was found to be significantly below the safety threshold of 1 for both adults and children across all water source types. This indicates that there is a negligible risk of adverse non-cancer health effects from chronic exposure to these trace elements in the drinking water. Although children had higher HI values due to their lower body weight, their risk level remained well within safe limits.

Similarly, the lifetime cancer risk (LCR) was within the acceptable range of 10^{-6} to 10^{-4} set by the US EPA. This means that the risk of developing cancer from exposure to the carcinogenic elements (As, Cd, Cr, Ni) in the water is acceptable by international regulatory standards. Crucially, the risk assessment highlighted that deep wells consistently presented the lowest risk scores for both HI and LCR, reinforcing their status as the safest water source. The negligible health risk is a direct consequence of the low contaminant concentrations and provides a strong scientific basis for reassuring the community about the safety of their water supply.

5.6 Limitations of the study

This study provides a critical baseline, but its findings should be interpreted in light of certain methodological limitations. The cross-sectional design means that samples were collected at a single point in time (May 2025, the early dry season), and therefore do not account for potential seasonal fluctuations in water quality, which could be influenced by rainfall and changes in the water table. Furthermore, the health risk assessment relied on the US EPA model, which uses standard exposure parameters that may not perfectly reflect the unique physiology, diet, and water consumption habits of the rural Zimbabwean population. To minimize the impact of this, conservative (health-protective) exposure parameters were used, but local data would refine the estimates. The study's focus was also limited to a single ward, so the findings cannot be over-generalized to the entire Mt Darwin district or other regions with different geological and land-use characteristics.

5.7 Summary

In summary, this chapter discussed the key findings of the study, interpreting the results in the context of scientific literature and the local environment. The discussion confirmed that the groundwater in Ward 17 is of excellent chemical quality, with trace element concentrations and associated health risks well below international safety limits. This stands in contrast to the current knowledge from literature, which often highlights significant contamination in other parts of Zimbabwe. The discussion tackled the hydrogeological reasons for the superior quality of deep wells, an issue well-supported by literature but now demonstrated with local data. The most significant contribution of this study, as highlighted in the discussion, is the provision of site-specific, evidence-based reassurance of water safety for a previously un-assessed region, filling a critical knowledge gap and demonstrating that generalizations about water quality, even within a single country, can be misleading.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6. Conclusion and recommendations

This chapter summarizes the key findings, draws a definitive and statistically-backed conclusion about the groundwater quality in Ward 17, and provides actionable recommendations to preserve this valuable resource.

6.1 Conclusion

The concentrations of all seven analyzed trace elements were statistically significantly below WHO drinking water guidelines, with deep wells demonstrating the highest water quality. This means the groundwater in Ward 17 is unequivocally safe for consumption and does not pose a chemical health risk from the elements studied. Unlike many studies from other Zimbabwean regions that report significant contamination, this research reveals a pristine groundwater resource. This study is therefore critically important as it provides the first scientific evidence to reassure the local population and public health authorities of their water's safety, filling a crucial data gap for the region. The findings also highlight a need for future research into potential seasonal variations in water quality to ensure year-round safety.

6.2 Recommendations

Based on the definitive findings of this study, the following recommendations are made:

- Prioritize deep aquifers for future water supply development: The results demonstrated with statistical significance that deep wells provide the highest quality water with the lowest contaminant concentrations and health risks. Therefore, all future water development projects by the Rural Infrastructure Development Agency (RIDA) formerly known as DDF and other agencies in the region should prioritize the construction of deep wells that tap into protected aquifers to ensure a resilient and safe long-term water supply for the community.

- Implement a protective, risk-based monitoring program: While the current water quality is excellent, the study identified shallow wells as the most hydro geologically vulnerable sources. A protective, long-term monitoring program should be established, focusing on a few select shallow wells as early-warning sentinel sites. This low-frequency monitoring (e.g., annually) will help ensure that any future changes in land use do not negatively impact the groundwater, thus safeguarding public health proactively.

- Launch a community awareness campaign on source protection: The community should be empowered to protect their valuable and clean water resource. The positive findings of this study should be disseminated to local leaders and residents to build trust and confidence in their water supply. This should be coupled with a public awareness campaign on the importance of wellhead protection, such as prohibiting waste disposal and limiting agricultural activities within designated protection zones around wells and boreholes to prevent future contamination.

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Appendix A:

A.1 Groundwater Sampling Field Data Sheet

Field	**Description / Notes**
Date of Sampling	YYYY-MM-DD
Time	HH:MM
Village Name	e.g., Village A
GPS Coordinates	Latitude, Longitude (e.g., -16.7562, 31.5781)
Source Type	Shallow well / Borehole / Deep well
Source ID	Unique code (e.g., VIL-A-BH-01)
Sample Number	Replicate 1 to 4
Remarks / Observations	e.g., odor, visible particles, usage trends
Sampler's Name & Signature	Initials or full name and signed entry

A2: Approval letter from the District Medical Officer

DEPARTMENT OF ENVIRONMENTA SCIENCE

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BINDURA UNIVERSITY OF SCIENCE EDUCATION

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06 January 2025

Dear Sir/Madam

REQUEST FOR PERMISSION TO COLLECT DATA FOR ACADEMIC RESEARCH PROJECT

PROJECT TITLE: ***HUMAN EXPOSURE AND HEALTH RISK ASSESSMENT TO TOXIC TRACE ELEMENTS IN GROUNDWATER SOURCES. A CASE OF WARD 17, MT DARWIN, ZIMBABWE.***

ACADEMIC SUPERVISORS: Dr A Kanda

This letter serves to inform you that **Kudzaishe Mamvura, Registration Number (B220092B)** is a third-year student at Bindura University of Science Education, in the Department of Environmental Science. During his third year of study he is supposed to do a research project in his area of specialisation.

Please assist in any possible way. Data collected will be used for academic purposes only and will not be published without your prior consent.

Thank you for your assistance.

Yours faithfully.

CHAIRPERSON
Department Of Environmental Science
Faculty Of Agriculture And Environmental Science
- Bindura University Of Science Education
P. BAG 1020, BINDURA
ZIMBABWE
OFFICIAL

Mr T. Nyamugure
DEPARTMENT OF ENVIRONMENTA SCIENCE

MIN. OF HEALTH & CHILD CARE
THE D.M.O.
MT. DARWIN DISTRICT HOSPITAL
31 MAR 2025
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A3: some of the water samples waiting to go to the government analyst, after collection.