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Human Health Risk Assessment of Physicochemical and Selected Trace Metal Contents of Borehole Water from Zebediela Sub-Region, Limpopo Province, South Africa

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Abstract: Access to safe drinking water remains a critical public health concern, particularly in rural communities. This study assessed borehole water quality from eight villages in Zebediela sub-region, Limpopo Province, South Africa. Twenty (20) borehole samples were collected and analyzed for physicochemical parameters (temperature, pH, total dissolved solids, electrical conductivity, dissolved oxygen, and salinity) and the concentration of selected trace metals (Boron, Magnesium, Iron, Copper, Manganese, Selenium and Molybdenum). The physicochemical water quality of some areas exceeded the WHO regulatory guidelines and trace metals such as Mn, Se Mo, Cu and Mg exceeded the threshold limit associated with aesthetic and long-term health exposure. Multivariate statistical analysis revealed that the hydrochemical parameters were enriched by natural geochemical processes including ion exchange, dissolution of silicate minerals from limestone and agricultural activities. The health risk assessment revealed that non-carcinogenic risks were higher for children than for adults, with long-term cumulative exposure identified as the key contributor to these risks. Se and Mo were the major contributors to non-carcinogenic risks in both age groups. Therefore, targeted monitoring and management of Se and Mo concentrations in groundwater are strongly recommended to reduce potential public health impacts.

Keywords: Borehole water, trace metals, physico-chemical properties, health risk assessment, Zebediela.

Introduction

Water is an indispensable resource that sustains life on earth (Randhir, 2012). Despite its abundance, availability of potable water remains a challenge, especially in developing nations (Elimelec, 2006; Nayebare et al., 2014). Recent estimation indicates that as of 2022, nearly 26% of the world's population lack access to safely managed drinking water (Rajapakse et al., 2023; WHO, 2023). In sub-Saharan Africa, this problem is profound, where approximately 39% of the people, or roughly 794 million individuals, remain without access to potable water (Onu et al., 2023; Isukuru et al., 2024). South Africa is one of the semi-arid countries with inadequate freshwater resources (Msweli et al., 2025). According to the Department of Water and Sanitation (DWS), an estimated 14.1 million South Africans are without access to clean water (Onu et al., 2023; Randhir, 2012). Drought caused by global warming and climate change continues to be a serious problem including population growth, infrastructure decay, industrial development and high living standards (Isukuru et al., 2024; Palamuleni and Akoth, 2015). As a results rural communities are compelled to rely on unsafe sources such as rivers, dams, lakes and boreholes to meet their daily water needs (Edokpayi et al., 2018; Mothetha et al., 2013).

Borehole water is the main source of drinking water in a sizable number of rural areas of South Africa. The DWS, supplies groundwater to around two thirds of the communities in the Limpopo province, especially those located in rural dwellings (Graham and Polizzotto, 2013; Guo et al., 2018). The quality of groundwater is primarily influenced by combination of natural and anthropogenic factors, including geology, soil composition, seasonal variations (Akhtar et al., 2021, 2015; Gauan et al., 2022), industrial discharges, agricultural runoff, and improper waste disposal (Madhav et al., 2020). Borehole water is generally considered safe for domestic purposes, including drinking, cooking, and bathing, because of its natural filtration through subsurface rock strata (Claasen, 2019; Madhav et al., 2020). However, contamination of water ecosystems has progressively emerged as a serious environmental concern (Singh et al., 2022; Maluleke et al., 2025). Underground water contamination including in boreholes, may result from the construction process itself, such as drilling fluids, chemical casings and other pollutants that might infiltrate the well, polluting the water (Graham and Polizzotto, 2013; Pietersen et al., 2016).

In the Zebediela sub-region of Limpopo Province, community members have long voiced concerns about the quality of borehole water, often describing it as salty in taste (Kulinkina et al., 2017). Groundwater conditions in the area are not uniform, some villages experience elevated nitrate levels and others reported high salinity, water hardness and microbial contaminations (Odiyo et al., 2012; Mutileni et al., 2023; Maliehe et al., 2024). These challenges are compounded by inadequate sanitation, as pit latrines and dug pits remain the most widely used systems (Hutton and Chase, 2017; Matthew, 2018).

The region is also situated within a triangle of intensive agricultural activity, bounded by the Marble Hall farming area, Zebediela Citrus Estate and Roedtan farming area, where extensive fertilizer and pesticide use may impact groundwater resources. Furthermore, industrial activities such as brick manufacturing and limestone mining introduce additional anthropogenic pressure on the environment. Despite these potential risks little is known about the quality of borehole water used by households across villages in the Zebediela sub-region.

Water sources in some villages are close to human settlements, thus there is an inherent risk of pollutants being introduced into the groundwater, potentially affecting quality of the aquifers (MacDonald and Davies, 2000). Mutikanga et al. (2011) have emphasized numerous health concerns linked to borehole water in rural South Africa, including dental fluorosis, skeletal and crippling fluorosis, mental retardation, and gastrointestinal issues like diarrhoea (Mutileni et al., 2023).

In addition, Edokpayi et al. (2016) suggested that chemical properties in groundwater pose potential non-carcinogenic health risks, especially for children. Among the most notorious water pollutants are microelements, which are a group of contaminants long detected as a threat to living organisms, even at trace concentrations (Chukwu Okeah et al., 2025; Kolarova et al., 2021). They are known for their toxicity and persistence in the environment (Miltra et al., 2022). They also have the tendency to bio-accumulate in living tissues to concentrations that can compromise the normal physiological processes in organisms (Edokpayi et al., 2016).

The World Health Organization (WHO) and South African National Standards (SANS 241) provide guidelines to ensure that water intended for human consumption meets acceptable quality thresholds. Exceeding these limits can result in aesthetic concerns as well as acute and chronic health risks (Mukwakungu et al., 2024).

In this context, the present study investigated the quality of borehole water in the Zebediela sub-region of Limpopo Province, with a focus on physico-chemical characteristics and potential trace metal contamination. The findings of this study are pertinent for guiding environmental approaches.

Materials and Methods

Study Area

Zebediela is a group of villages in Capricorn District municipality of Limpopo Province, South Africa. It is situated southeast of Polokwane and spans approximately 5962 km² between latitudes 24.310°S and longitudes 29.270°E. Zebediela is characterized by bushveld vegetation, with an average summer temperature of 28-31.5°C and mild winter average temperature of 12-17°C.

Rainy season typically ranges from November to April, with precipitation averaging around 469 mm annually with the highest rainfall occurring in November to March. Zebediela remains a predominantly rural economy, maintaining strong cultural traditions. However, the region faces significant challenges, including water scarcity, inadequate sanitation infrastructure, and unreliable water supplies, leaving many households dependent on borehole water.

Water Sampling

Eight villages were selected within the sub-district for borehole sampling using a stratified cluster (SCS) design to ensure spatial representativeness and capture land surface variability. The sub-district was stratified into homogeneous units based on land cover, elevation and soil type. Within each stratum, clusters were delineated by spatial proximity and villages were randomly selected to serve as sampling units. This approach reduces sampling bias, accommodates environmental heterogeneity,

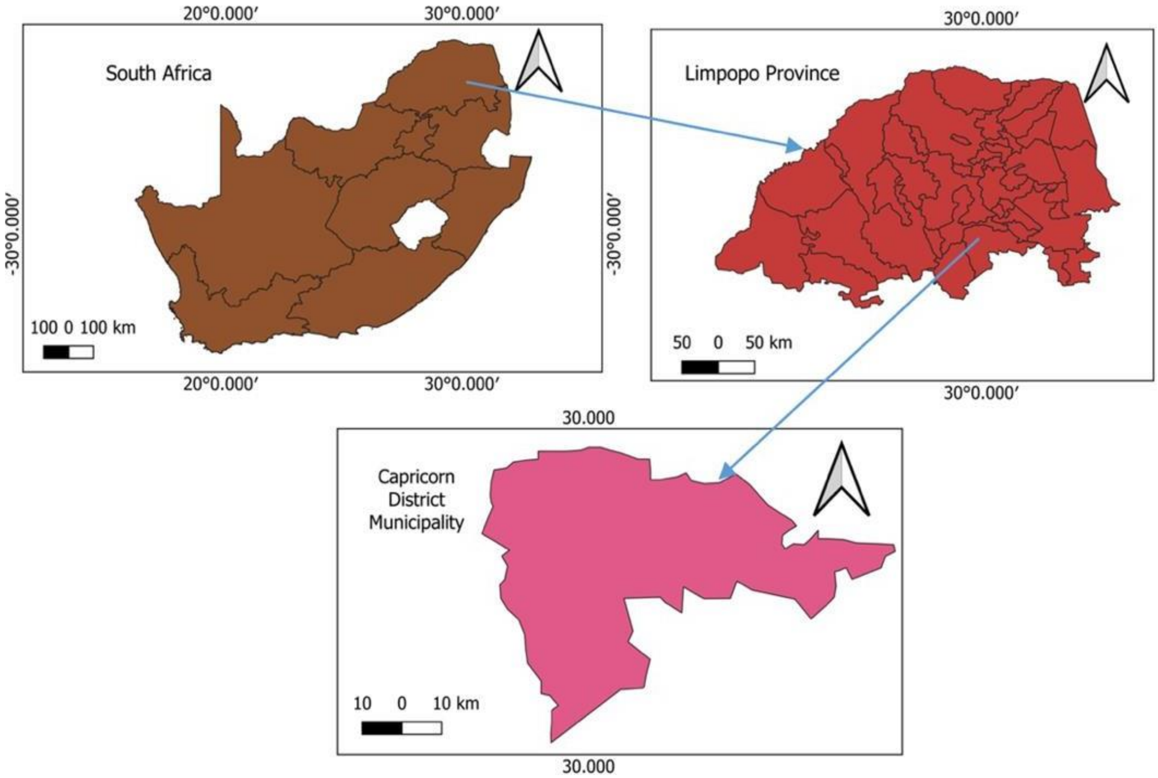

Fig. 1 Map of the study area under the Capricorn District municipality of the Limpopo Province, South Africa.

and also provides efficient coverage of large geographical areas. Subsequently, simple random sampling was employed to determine borehole locations within each selected village.

Approximately twenty borehole water samples were collected, with a minimum of two samples obtained from each village, using 500 mL high density polyethylene (HDPE) bottles. Prior to sampling, bottles were acid washed with 10% HN03 for 24 hours, rinsed thoroughly with deionized water (Milli-Q®Direct 8/16 system) and air dried under sterile conditions in a laminar flow cabinet (Lasec, Cape Town, South Africa). Sampling was conducted in March during the dry season. To minimize potential contamination from tap-piping, borehole faucet was flushed for several minutes before collection and sample bottles were pre-rinsed with the respective water prior to filling. A small headspace was left in each bottle to prevent pressurization or leakage. All samples were appropriately labelled (1-20) for subsequent analysis.

Physicochemical Properties

Physicochemical parameters including electrical conductivity (EC), turbidity, pH, temperature (T), dissolved oxygen (DO), total dissolved solids (TDS), resistivity, pressure, and salinity were measured on site with the Hanna multiparameter meter HI98194 tool (Masiye labs, 12 Quteniqua Alrode South, Alberton 1451, Johannesburg, South Africa). The multi-probe meter was calibrated with standard buffer solutions of pH 4.01, 7.01 and 10.01 on field temperature.

Trace Metals

Inductively coupled plasma optical emission spectrophotometer (ICP-OES) (Shimadzu Corporation, Nakagyo-ku, Kyoto, Japan) was used to analyse the trace metals [(Boron (B), Magnesium (Mg), Iron (Fe), Copper (C), Manganese (Mn), Selenium (Se), Molybdenum (Mo)] in the borehole samples. Appropriate portion of the collected groundwater samples were digested with concentrated HNO_3 for microelements analysis based on Moursy et al. (2020) previous study. The instrument was standardized with a multi-element calibration standard solution of ion. Calibration curves were plotted, and they were used to determine Boron (B), Magnesium (Mg), Iron (Fe), Copper (C), Manganese (Mn), Selenium (Se), Molybdenum (Mo) concentration from water samples collected from Zebediela sub-region.

Quantitative Health Risk Assessment

Human exposure to trace metal contamination can occur via three main routes: Inhalation through the nose and mouth, direct ingestion and dermal absorption through the skin. The chronic dose resulting from water ingestion (EXPing) and derma absorption (EXPderm) was calculated using established exposure assessment models, described in the literature. This calculation employs Equations (1) and (2), which are derived from the US EPA's Risk Assessment for Superfund (RAGS) methodology (US EPA 2009).

Ingestion exposure (EXPing) (in mg/kg/day), the exposure dose via ingestion was computed as:

$$EXPing = \frac{(\text{Cwater } x\ IR\ X\ ER\ XED)}{(\text{BW } X\ AT)} \quad (1)$$

Where:

- Cwater: Mean metal concentration in water (µg/L)
- IR: Daily intake rate (2.2 L/day for adults; 1.8 L/day for children)
- EF: Exposure frequency (365 days/year)
- ED: Exposure duration (70 years for adults; and 6 years for children)
- BW: Body weight (70 kg for adults; 15 kg for children)
- AT: Averaging time (365 days/year Å~ 70 years for an adult; 365 days/year Å~ 6 years for a child)
- CF: Unit conversion factor (0.001 L/cm^3)

Dermal exposure (EXPderm) (in mg/kg/day), the dermal absorption exposure dose was determined using the following expression.

$$EXPderm = \frac{(\text{Cwater } x\ SA\ x\ KP\ x\ ET\ x\ EF\ x\ ED\ x\ CF)}{(\text{BW } X\ AT)} \quad (2)$$

Where:

- ET: Daily exposure time (0.58 h/day for adults; 1 h/day for children)
- SA: Exposed skin area (18.000 cm^2 for adults; 6600 cm^2 for children)
- Kp: Chemical-specific dermal permeability coefficient (cm/h), with values of: (0.001 for B, Mn, Fe, Mg and Cu), while (0.0005 for Se and Mo)

Potential non-carcinogenic risks associated with exposure to metals were evaluated by comparing the estimated daily intake via ingestion (EXPing) and dermal absorption (EXPderm) to their respective reference doses (Rfd). This comparison was conducted using the Hazard quotient (HQ), which quantifies the toxicity potential of chronic exposure relative to established safety threshold.

Hazard quotient (HQ) for individual pathways:

$$HQing = \frac{\text{EXPing}}{\text{RfDing}} \quad (3)$$

$$HQderm = \frac{\text{EXPderm}}{\text{RfDderm}} \quad (4)$$

Where:

- HQ: Hazard quotient for exposure route (EXPing and EXPderm)
- EXPing/derm: Estimated exposure does (mg/kg/day)
- RfD: Reference does (mg/kg/day) for the corresponding pathway

HQ > 1 indicates a potential risk of adverse health effects, whereas HQ ≤ 1 suggest that exposure level is unlikely to pose significant harm.

To evaluate the total potential, non-carcinogenic effects arising from more than one metal and one metabolic pathway, the sum of the calculated HQs for all metals was expressed as a hazard index (HI) using Equation (5). A hazard index (HI) > 1 signifies a potential health risk associated with combined exposure.

$$HI = HQing + HQderm \quad (5)$$

Results and Discussion

Geographic Stratification of Sampling Area

The sampling areas characterization comprising different village names and their GPS coordinates are shown in Table 2. The sampling areas were classified into four clusters, namely Zebediela - North, West, Central and South. The bottles after sampling were numerically designated from 1 to 20.

Physicochemical Properties

The borehole water samples from the Zebediela sub-region were analysed for physicochemical properties (temperature, pH, DO, EC, salinity, TDS) and the results are given in Table 3. The temperatures of the water sample in Zebediela ranged between 23.58 ^{0}C and 31.94 ^{0}C in the different study-based area clusters. The samples located in the Zebediela- North, South and West clusters recorded average temperature surpassing the WHO standard limit of 25 ^{0}C, while samples from Zebediela - Central cluster recorded a slightly lower average temperature, falling below the WHO limits. Temperature plays a crucial role in water bodies regarding the variations of the chemical, physical and life forms of the water (Madilonga et al., 2021; Price and Sowers 2004). The temperature of the borehole water is dependent on the climatic conditions and the time of the year in which it is collected. In this study sampling was conducted in

Table 2. GPS coordinates and classification of the sampling village areas of Zebediela sub-region into four study clusters.

ZEBEDIELA SUB-REGION				
S/ID:	Area	Village name	Latitude	Longitude
1		Ga-Mogotlane	24.35507ºS	29.31482ºE
2	Zebediela- North	Ga-Mogotlane	24.35610ºS	29.31502ºE
3		Sekgweng	24.35415ºS	29.31121ºE
4		Sekgweng	24.51682ºS	29.41653ºS
5		Bolahlakgomo	24.44634ºS	29.31228ºE
6	Zebediela- West	Bolahlakgomo	24.43877ºS	29.32601ºE
7		Sekgophokgophong	24.43036ºS	29.32728ºE
8		Sekgophokgophong	24.42942ºS	29.32286ºE
9		Sekgophokgophong	24.42573ºS	29.32950ºE
10		Ga-Molapo	24.51798ºS	29.42203ºE
11		Ga-Molapo	24.50978ºS	29.42849ºE
12	Zebediela- South	Ga-Molapo	24.51391ºS	29.40879ºE
13		Mehlareng	24.41711ºS	29.31649ºE
14		Mehlareng	24.40978ºS	29.32849ºE
15		Mamogoasha	24.41107ºS	29.34309ºE
16		Mamogoasha	24.41385ºS	29.34405ºE
17	Zebediela-Central	Mamogoasha	24.41301ºS	29.34224ºE
18		Magatle	24.45168ºS	29.39162ºE
19		Magatle	24.44594ºS	29.38016ºE
20		Magatle	24.45053ºS	29.39135ºE

S/NO=Sample number

the dry season which may have contributed to the observed temperature (Mshelia et al., 2023; Evison and Sunna 2001).

The pH water is an important parameter, as numerous biological and chemical processes are influenced by its acidity or alkalinity. Deviations from the recommended range can disrupt these processes, potentially harming aquatic life and affecting human health (Palamuleni and Akoth, 2015).

In this study, the average pH of water in all sampling areas fell below the WHO recommended range of 6.5–8.5, indicating acidic conditions. Water with a pH below 6.5 is considered corrosive, which can accelerate the leaching of metals such as Cu, Fe, Mn and Zn from pipes and plumbing systems. Such conditions can also cause undesirable aesthetic effects, including metallic taste, staining and discoloration, and may cause skin or eye irritation at sufficient low pH levels (Maluleke et al., 2025).

EC and TDS measure the concentration of inorganic and organic substances dissolved in water, including minerals, salts and trace elements. This implies that EC and TDS are directly correlated to each other, and this correlation can be seen in Figure 3, which displays a positive linear relationship between salinity, EC and TDS. As expected, EC and resistivity were strongly inversely correlated ($r = -0.90$), as were TDS and salinity with resistivity ($r = -0.92$). Conversely, pH was weakly to moderate negatively correlated with EC, TDS and salinity ($r = -0.42$ to -0.49). This suggests that acidic conditions enhance ion dissolution and conductivity.

Dissolved oxygen (DO) is a key parameter influencing both the taste and quality of water. Concentration between 6 to 8 mg/L are generally considered optimal for aquatic life and overall water quality. Higher dissolved oxygen in water is often associated with a bitter taste and can also raise the risk of pipe corrosion. The current study found DO levels within the permissible threshold of < 6.0 mg/L, indicating that the water samples meet both physiological health and water quality standards.

The borehole water samples exhibited high TDS levels (702.67–1249.67 ppm), exceeding the WHO's recommended aesthetic limits of 600 ppm and approaching the upper tolerance threshold of 1200 ppm, but posing no direct risk at this range. Elevated TDS levels may indicate excessive dissolved ions like Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-} may stem from agricultural runoff (fertilizers like KCI and NH_4NO_3) and natural geological dissolution in Zebediela's farming intensive region (Maluleke et al., 2025). While TDS influences water taste, electrical conductivity and limescale formation (due to associated Ca^{2+}/Mg^{2+}), health risk such as kidney stones or cardiovascular stress are more closely tied to specific ions (calcium oxalate) rather than TDS alone (Davies et al., 2024).

Table 3. Physicochemical parameters for borehole water samples of Zebediela sub region.

Parameters	Zebediela North	Zebediela West	Zebediela South	Zebediela Central	WHO (2022,2023)	SANS (2015, Mukwakungu et al., 2024)
Temperature (^{0}C)	31.31±3.82	27.26±3.82	31.94±4.78	23.58±1.37	≤ 25	≤ 25
pH	6.31±0.14	6.44±0.23	6.04±0.57	6.27±0.54	≥ 6.5 - ≤ 8.5	≥ 5 - ≤ 9.7
DO (ppm)	0.63±0.39	1.44±1.11	2.62±0.35	1.03±0.26	≤ 6.0	-
EC (uS/cm)	1569.33±19.09	2634.83±1305.46	2706.6±1069.16	2279.67±1209.35	≥ 41.62 - ≤ 202.54	≤ 170
TDS (ppm)	702.67±55.29	1249.67±560.16	1209.2±491.81	1173.33±627.69	≤ 1200	≤ 1200
Salinity (ppt)	0.70±0.06	1.29±0.61	1.23±0.53	1.22±0.69	≤ 0.5	-
Pressure (psi)	13.28±0.04	13.43±0.04	13.5±0.0070	13.39±0.019	-	-

The salinity levels in the borehole samples varied from 0.70 to 1.29 ppt, as shown in Table 3. This measure is an important indication of water quality since it represents the overall concentration of dissolved inorganic ions and salts. Salinity is a major component of TDS and demonstrates a strong positive correlation with EC, as seen in Table 5.

Conversely, a negative correlation with salinity and DO concentrations was observed (Table 5). These could indicate a high concentration of dissolved solids such as sodium and chloride ion in the underground water, which could account for the salty taste of borehole water often complained about by residents of Zebediela sub-region concentration of trace metals.

Table 4 shows the concentrations (mg/L) of boron (B), magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn), selenium (Se), molybdenum (Mo) in borehole water measured by ICP-MS analysis. The concentration of boron (B) ranged from 0.0251 to 1.66 mg/L and correspond to the permissible limit of 2.4 mg/L set by WHO for potable water.

The average magnesium (Mg) concentration in the studied borehole water ranged from 75.51 to 136.1 ppb (0.075–0.136 mg/L), well below the WHO's taste-based guideline of 30 mg/L. These levels are unlikely to pose health risks. Magnesium carbonate dissolution in groundwater may contribute to Mg content, though higher concentrations typically arise from minerals like dolomite (John et al., 2024). While excessive Mg (> 250 mg/L) can cause diarrhea, the reported levels are far low for such effects (Sengupta, 2013).

The concentrations of iron (Fe) in the samples were below the detectable range of 0.01 to 0.032 mg/L, falling well within the WHO permissible limit of ≤ 0.3. Despite the high natural abundance of iron in the earth's crust, which often leads to elevated iron concentrations in groundwater due to dissolution from soil and rock layers (Briffa et al., 2020), the levels observed in this study pose no human health risk. However, it's worth noting that excessive iron accumulation has been linked to aesthetic issues, including a metallic taste and the discoloration and staining of clothes (Rahman et al., 2023)

The average copper (Cu) levels in this study, ranging from 6.74 to 34.7 ppb, exceeding the WHO guideline of ≤ 2.0 ppb for drinking water. The geological setting of the Zebediela subregion, which is rich in limestone, may contribute to the elevated copper concentrations. As groundwater flows through these formations, the dissolution of limestone can increase the water's pH, which in turn influences the solubility and mobility of copper. This elevated pH can enhance desorption of copper from mineral surfaces or facilitate the formation of soluble copper complexes, leading to higher concentrations in the water. Chronic exposure to these elevated copper levels has been associated with adverse health effects, including gastrointestinal distress, vomiting and irritation (Agrawal et al., 2021; Al-Tamimi et al., 2025).

The average manganese (Mn) concentrations in this study, which ranged from 6.78 to 54.73 mg/L, significantly exceeded the WHO guideline limit of ≤ 4.0 mg/L for household use. While Mn is a vital component for numerous biological functions, acting as a cofactor in many enzymes, elevated concentrations in drinking water are often noticeable due to a metallic taste and discoloration (Wu et al., 2022). Increased Mn levels have been linked to adverse neurological effects, particularly in children. Studies have associated Mn concentration between 0.24 and 0.335 mg/L with memory deficits (Edokpayi et al., 2017) and drinking water with elevated Mn has been linked to cognitive impairments, impulsive behavior, hyperactivity and attention problems (Schullehner et al., 2020). The elevated Mn content observed in the borehole samples from Zebediela subregion may be a result of the local citrus agriculture operations. Leaching from soil and additives, as well as irrigation practices associated with agriculture, are known to increase Mn levels in groundwater systems (Rashed

Table 4. Trace metal concentrations within borehole water samples for Zebediela.

Area	**Boron** (B)mg/L	**Magnesium** (Mg)mg/L	**Iron** (Fe)mg/L	**Copper** (Cu)ppb	**Manganese** (Mn)ppb	**Selenium** (82Se) ppb	**Molybdenum** (95Mo) ppb
ZB- North	0.074±0.01	119.0±6.00	0.010±0.00	13.14±6.43	7.357±1.71	4.573±1.90	2.503±0.25
ZB- West	0.471±0.60	100.8±85.9	0.028±0.02	13.98±8.36	6.785±0.83	17.17±6.95	4.525±2.08
ZB- South	0.237±0.03	136.1±67.2	0.032±0.00	6.736±5.73	11.85±4.62	17.98±14.3	2.535±1.79
ZB- Central	0.147±0.07	75.50±41.0	0.026±0.01	34.70±4.10	54.73±3.84	12.63±6.38	1.130±0.70
SANS(2015, Mukwakungu et al., 2024) (mg/L)	≤ 2.4	≤ 0.4	≤ 2.0	≤ 2.0	≤ 4.0	≤ 0.04	≤ 0.01
WHO (2022, 2023) (mg/L)	≤ 2.4	≤ 150	≤ 0.3	≤ 2.0	≤ 4.0	≤ 0.04	≤ 0.07

ZB: Zebediel.

Table 5. Correlations of physicochemical parameters and trace metals for borehole water of Zebedia.

	T	pH	DO	EC	Res	TDS	Sal	Pre	B	Mg	Fe	Cu	Mn	Se	Mo
T	1.00														
pH	0.14	1.00													
DO	0.58	-0.22	1.00												
EC	0.09	-0.42	0.35	1.00											
Res	0.17	0.52	-0.24	-0.90	1.00										
TDS	-0.11	-0.49	0.23	0.98	-0.92	1.00									
Sal	-0.12	-0.49	0.22	0.97	-0.92	1.00	1.00								
Pre	0.27	-0.23	0.84	0.41	-0.39	0.34	0.33	1.00							
B	0.13	-0.08	0.47	0.25	-0.30	0.21	0.20	0.35	1.00						
Mg	0.31	-0.18	0.03	0.40	-0.28	0.31	0.30	0.08	-0.21	1.00					
Iron	-0.12	-0.28	0.02	0.24	-0.29	0.22	0.22	0.22	-0.01	0.67	1.00				
Cu	-0.15	-0.37	-0.06	0.08	-0.10	0.14	0.14	-0.11	0.32	-0.02	0.18	1.00			
Mn	-0.18	-0.31	-0.01	-0.14	0.03	-0.12	-0.12	0.01	-0.04	0.07	0.38	0.53	1.00		
Se	0.14	-0.26	0.38	0.69	-0.66	0.62	0.61	0.49	0.21	0.67	0.60	0.02	0.09	1.00	
Mo	0.06	0.24	-0.10	-0.13	0.01	-0.15	-0.15	0.08	0.13	0.10	0.08	0.08	-0.17	-0.11	1.00

et al., 2019; Hou et al., 2020).

The mean concentration of Se in the borehole water ranged from 4.57 to 17.97 ppb, exceeding the WHO permissible limit of ≤ 10 ppb for Se in drinking water. Se is commonly associated with sulphide minerals and mining activities; therefore, nickel sulphide mining in the Zebediela region may be one of the contributing factors to the elevated Se levels in groundwater. This suggests that both natural geochemical processes and anthropogenic activities play a role in Se enrichment (Graham and Polizzotto, 2013). Although Se is an essential trace element, it must be consumed in appropriate amounts. Deficiency can result in fatigue, muscle soreness, thyroid dysfunction and Keshan disease (Shreenath et al., 2023) and gastrointestinal irritation (MacFarquhar et al., 2010).

The mean concentration of molybdenum (Mo) in the borehole water ranged from 1.30 to 4.54, which is well below the WHO permissible limit of ≤ 70 ppb for drinking water. Although the measured levels do not pose an immediate health risk, monitoring remains important due to the potential adverse effects of excessive Mo intake. High Mo exposure has been linked to copper deficiency and elevated blood uric acid levels, as it can interfere with copper absorption and influence purine metabolism (Solaiman et al., 2024).

While Mo is an essential trace required for the function of several enzymes, including xanthene oxidase, aldehyde oxidase and sulfite oxidase, it should be consumed in limited amounts to prevent negative health outcomes. (Bursakov et al., 2023; Solaiman et al., 2024).

Hydrochemical Relationship and Geochemical Influence in Groundwater

The interrelationships among hydrochemical parameters were evaluated using Pearson correlation analysis (Table 5). The results revealed a strong positive correlation (r ≥ 0.97) between EC, TDS and salinity. This strong association is expected given their fundamental interdependence. EC measures water's electrical current conductivity, which is governed by dissolved ion concentration, ionic strength, and temperature. TDS is the total concentration of dissolved substances and is often derived from EC measurements (Rusydi, 2018). These parameters collectively serve as robust indicator of saline conditions in water. DO demonstrated a moderate positive correlation with pressure (r = 0.84), consistent with the known dependence of oxygen saturation on hydrostatic pressure (Ludwig and Macdonald, 2005).

Se exhibited moderate to strong correlations with EC, Mg, Fe, TDS and salinity (r = 0.60–0.69). Notably, pH showed weak to moderate negative correlations with EC, TDS and salinity (r = -0.42 to -0.49), indicating that acidic conditions may promote enhanced ion dissolution and consequently increase conductivity. As expected, EC and resistivity displayed a strong inverse relationship (r = -0.90), as did TDS and salinity with resistivity (r = -0.92). These consistent patterns strong suggest that natural geochemical processes constitute the dominant control on groundwater composition in the Zebediela sub-region.

Multivariate Statistical Analysis

Classifying groundwater samples using PCA and HCA techniques: A multivariate statistical analysis was conducted on the hydrochemical data to elucidate the sources and governing factors affecting the constituents of groundwater. For this analysis, IBM SPSS (version 29.0.2.0) and Microsoft Excel were employed.

Among the most robust and widely applied approaches in hydro-geochemical studies are factor analysis, with Principal Component Analysis (PCA) as the extraction method and Hierarchical Cluster Analysis (HCA). In this study, both the PCA and HCA we applied to the hydrochemical dataset, these methods were chosen for their effectiveness in reducing data complexity, revealing correlations among variables and grouping sampling sites with similar water quality characteristics, thereby enabling a clearer interpretation of geochemical processes and contamination sources.

PCA extracted two components (PC1: 36.46%; PC2: 15.12%) shown in fig 2, with PC1 presenting mineralization (TDS, EC, Mg) and PC2 reflecting redox-sensitive elements (Mn, Se, Mo). Although cumulative variance (51.58%) was moderate, the biplot identified three groups: (1) low-mineralization, high-DO waters; (2) high TDS, metal-rich water and (3) intermediate compositions. HCA (fig 3) corroborated these patterns, with cluster I (high Mn-Se-Mo) suggesting redox or industrial impacts, Cluster II (moderate ions) representing near-background conditions and Cluster III (high EC/pH) indicating saline/alkaline processes. Discrepancies (e.g Mg distribution across clusters) imply mixed contamination sources

Human Health Risk Assessment

Health risk assessment is crucial for assessing the health risks of extended environmental chemical exposure (Dewa et al., 2025). Tables 6 and 7 provide an overview of the estimated health hazards associated with both ingestion and dermal exposure to metals for adults and children in the Zebediela sub-region. The CDIs for the identified metals in both adults and children were ranked as follows: Mg > Mn > Se > Cu > Mo > B > Fe for consumption in both demographics. Mg, Cu, Mn, Se, and Mo all exceeded the RfD levels used in this study, indicating a severe health risk for groundwater users in the Zebediela area.

This highlights the community reliance on borehole water for domestic needs, particularly drinking and cooking, strongly indicating that this is the most likely route of exposure. Children are substantially more vulnerable than adults, as indicated by their higher CDIs, which can be attributed to their higher water consumption relative to body weight (Brown and Foo, 2009). Notably, the CDIs for dermal exposure in both adults and children fell below the RfDs, suggesting negligible non-carcinogenic health risks from transient dermal contact.

HQ analysis reveals that Se poses the highest non-carcinogenic risk to both children (HQ = 40.47) and adults (HQ = 10.60), exceeding the acceptable threshold (HQ > 1). Mo also presents elevated risk levels, with HQ of 4.638 in children and 1.215 in adults, suggesting potential adverse effects from chronic exposure to these elements. In contrast, dermal exposure contributes minimally to cumulative risk, as all HI values remained below 1. The aggregate HI further underscore the heightened vulnerability of children (Se: 40.62; Mo: 4.655) compared to adults (Se: 10.60; Mo: 1.22), consistent with established literature on children's increased susceptibility to metal toxicity (Birgül, 2024; Cao et al., 2016).

The elevated Se and Mo concentrations detected in Zebediela's groundwater likely derive from both geogenic and anthropogenic sources. Geogenic contributions may arise from the weathering of mineralized rocks, particularly the region's prevalent limestone formations, which are known to host these elements (Edward, 2012; Oyeku and Eludoyin, 2010). Anthropogenic inputs could stem from intensive agricultural activities, notably

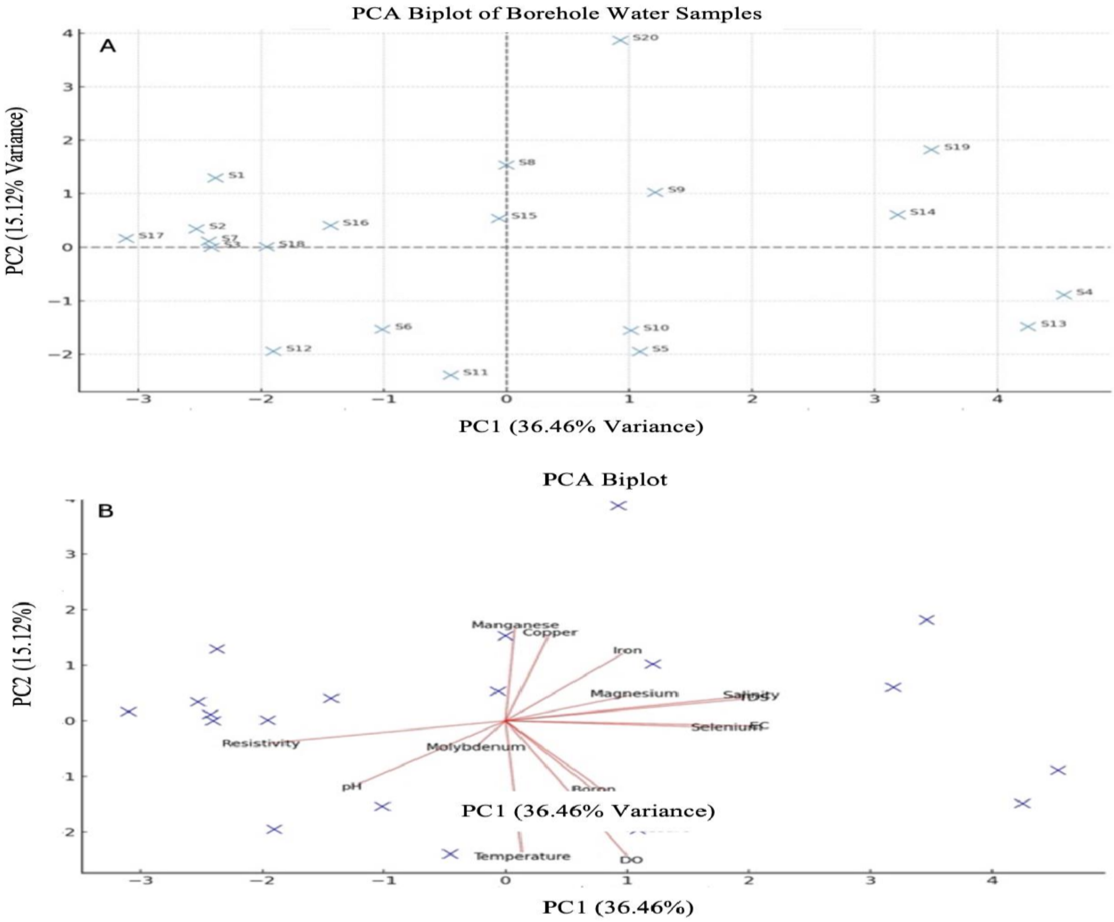

Fig 2. Principal component analysis (PCA). (a) Correlation circle represented by the Planes 1–2 and (b) projection of individuals onto the Planes 1–2.

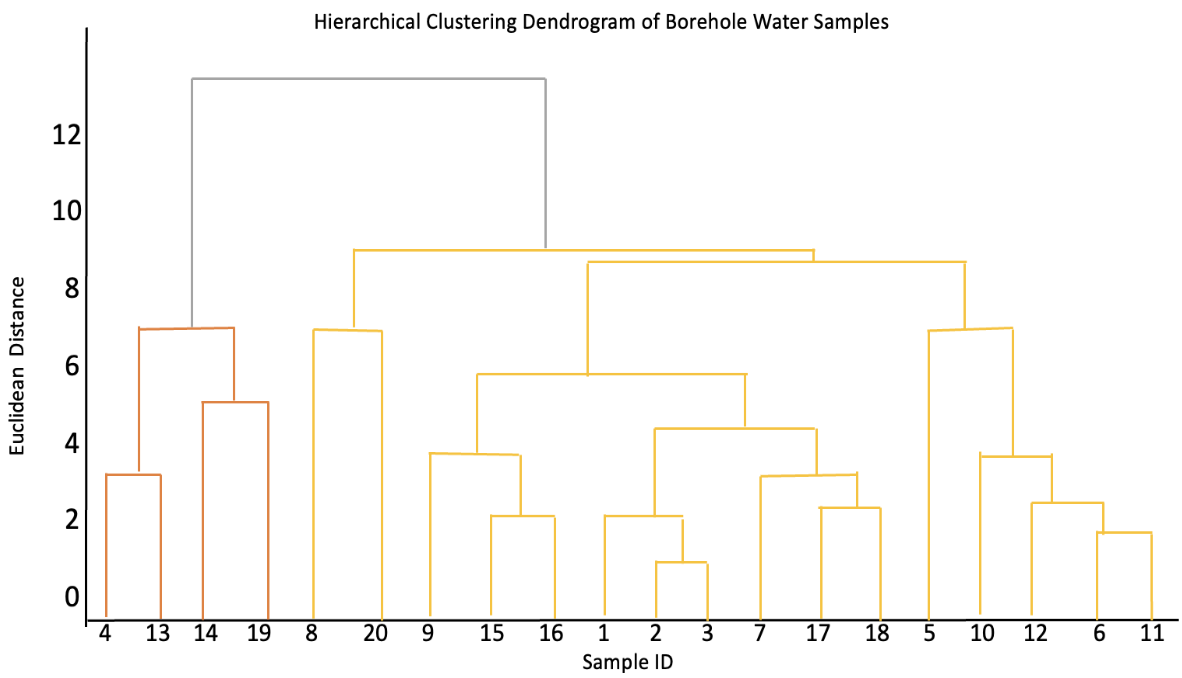

Fig 3. Hierarchical clustering dendrogram of trace elements in borehole water from Zebediela sub-region, Limpopo province of South Africa.

Table 6. Non-carcinogenic health risks from trace metals in Zebediela borehole water (Adults).

INGESTION ADULT										DERMAL AUDIT			
Trace metal	CDI (mg/kg/day)			Hazard Quotient (HQ)			CDI (mg/kg/day)			Hazard quotient (HQ)			HI
	Mean	Min	Max	Mean	Min	Maxi	Mean	Min	Maxi	Mean	Mini	Maxi	
B	0.01	0.00	0.05	0.003	0.001	0.007	3.82E-05	1.07E-05	9.86E-06	1.6E-05	1.0E-04	8.1E-06	0.003
Mg	3.29	1.25	6.41	0.022	0.000	0.053	1.56E-02	1.11E-02	8.95E-03	1.0E-04	1.0E-04	1.9E-06	0.022
Fe	0.00	0.00	0.00	0.002	0.001	0.004	2.57E-06	1.49E-06	5.61E-03	8.6E-04	1.5E-05	9.9E-06	0.002
Cu	0.36	0.02	1.18	0.180	0.009	0.591	1.71E-03	1.14E-03	8.95E-05	8.5E-04	1.2E-03	8.5E-04	0.181
Mn	0.45	0.01	4.40	0.113	0.003	1.100	2.14E-03	1.01E-03	9.95E-04	5.4E-04	1.3E-03	5.4E-02	0.113
Se	0.42	0.00	1.30	10.60	0.055	32.60	2.01E-03	1.01E-03	8.74E-04	5.0E-02	1.1E-01	8.3E-02	10.60
Mo	0.09	0.01	0.27	1.215	0.243	3.834	4.04E-04	1.27E-03	8.87E-05	5.8E-03	1.0E-02	9.1E-03	1.221

Table 7. Non-carcinogenic health risks from trace metals in Zebediela borehole water (Children).

INGESTION CHILDREN							DERMAL CHILDREN						
Trace Metal	CDI (mg/kg/day)			Hazard Quotient (HQ)			CDI (mg/kg/day)			Hazard quotient (HQ)			HI
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Mini	Maxi	
B	0.03	0.01	0.20	0.013	0.001	0.082	1.13E-04	1.01E-04	9.55E-05	4.7E-05	1.2E-05	9.3E-05	0.013
Mg	12.57	0.23	30.1	0.084	0.003	0.201	4.61E-02	1.10E-02	8.98E-02	3.1E-04	1.2E-04	5.5E-06	0.000
Fe	0.00	0.00	0.01	0.007	0.004	0.017	7.58E-06	1.32E-05	8.80E-06	2.5E.05	1.5E-05	5.5E-05	0.007
Cu	1.37	0.07	4.51	0.686	0.036	2.256	5.03E-03	1.13E-03	9.81E-03	2.5E-03	1.3E--03	8.3E-03	0.687
Mn	1.72	0.05	16.8	0.431	0.012	4.200	6.32E-03	1.58E-02	6.64E-03	1.6E-03	1.0E-03	9.3E-04	0.433
Se	1.62	0.01	4.98	40.472	0.210	124.500	5.94E-03	1.35E-02	9.81E-03	1.5E-01	1.2E-01	8.5E-02	40.62
Mo	0.32	0.07	1.02	4.638	0.729	14.640	1.19E-03	1.05E-03	9.46E-04	1.7E-02	1.4E-02	7.1E-03	4.655

Zebediela's large scale citrus farming, as well as backyard dumping and mining discharges found their way into the underground water.

While Se is essential for antioxidant function and thyroid hormone metabolism, chronic overexposure can induce selenosis, characterized by gastrointestinal distress (nausea, vomiting, diarrhea), and dermatological issues. Similarly, excessive Mo intake is associated with joint pain, gout-like symptoms and hyperuricemia. These findings align with prior studies documenting elevated Se and Mo in borehole water dependent communities (Ndwiga, 2014; Smedley et al., 2014).

Conclusion

The study findings suggest that borehole water from the sampled villages in the Zebediela sub-region of the Limpopo province contains high levels of some selected trace metals that include selenium and molybdenum which exceed the WHO permissible levels. Therefore, purification interventions or treatments are recommended on the borehole water from the area prior to household usage, including human consumption.

Limitations and Recommendations

This research was conducted only for some trace metals Boron, Magnesium, Iron, Copper, Manganese, Selenium and Molybdenum in a range of borehole samples. Additional research may be undertaken regarding the concentration of various trace metals across different seasons. Furthermore, factors such as borehole characteristics, including depth, proximity to pit and backyard dumping, should be considered during sampling, given their potential impact on contamination. The absence of microbial testing in this study for coliforms or E. coli further constrains the health risk assessment. Nevertheless, the findings provide critical baseline data on trace metal concentrations, highlighting the need for the community of Zebediela region to be educated of the possible risks associated with the use of borehole water for human consumption.

Education should encompass potential methods for water treatment, including boiling and the application of chlorination tablets, to mitigate possible adverse health effects. Furthermore, it is essential to implement remedial measures such as filtration, ion exchange techniques, and systematic monitoring to enhance the water situation in the area. The government ought to oversee activities in the region, particularly concerning the siting of pit latrines, the implementation of best management practices in agriculture, general hygiene standards.

Conflicts of Interest

The authors declare no conflicts of interest in this research.

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