

# Hydrogeochemical Assessment and Groundwater Quality in Zebediela Sub-Region, Limpopo Province, South Africa

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## Abstract

Groundwater remains a critical resource for rural communities in South Africa, yet its quality is questionable due to geogenic processes and anthropogenic activities. This research evaluated groundwater quality through hydrochemical and microbial analysis of 20 borehole samples used domestically in the rural area of Zebediela subregion, Limpopo Province, South Africa. Parameters analysed included major ions, trace metals and faecal indicator bacteria, with data interpreted using multivariate analyses including co-occurrence matrices, Pearson correlation heatmaps and Principal Component Analysis. Nitrate, sulphate, phosphate, chloride and fluoride were within permissible limits, but COD and BOD were slightly above recommended levels, indicating moderate ion concentrations. Microbial contamination was detected in 80% of the samples (including Heterotrophic, *Escherichia coli*, coliform, *Salmonella* species, *Enterobacteriaceae*, *Bacillus cereus*, *Staphylococcus aureus* and *Enterococci*), with Heterotrophic bacteria present in most samples, indicating emerging contamination. PCA identified mineral dissolution, evaporative concentration, organic pollution and redox-mediated metal mobilization as the dominant processes shaping groundwater chemistry in Zebediela subregion. Therefore, regular monitoring, improved sanitation infrastructure and protection of borehole surroundings are recommended to manage water security in the Zebediela sub-region.

## Keywords

Water Quality, Borehole, Heavy Metals, Microbial Contamination,

## 1. Introduction

Access to safe, reliable drinking water is a major problem in Sub-Saharan Africa, particularly in rural and peri-urban regions [1]. A large population relies on untreated water sources from rivers, wells and boreholes, which are susceptible to contamination by organic matter, animal waste and surface pollutants. Waterborne diseases like cholera and typhoid fever, remain prevalent in some of these regions [2] [3]. This problem is worsened by aging infrastructure, leaking pipes, poor maintenance, delayed upgrades and mismanaged public funds, which disproportionately affect rural areas and increase reliance on groundwater [4].

Water drilling predates millennia and continues to provide a reliable, independent and inexpensive water source [5]. Although combination of natural and anthropogenic factors make up the quality of groundwater as well as natural processes like rock weathering, mineral dissolution, cation exchange and redox reactions. Additionally, soil properties, including mineral composition, permeability and organic matter content control the mobility of ions and trace metals [6] [7]. Anthropogenic activities such as agriculture, wastewater discharge, pit latrines, septic tanks and livestock farming introduce contaminants that can percolate into aquifers and compromise groundwater quality [8] [9].

Previous studies in Limpopo Province reported wide variation in physicochemical parameters like pH, salinity, electrical conductivity, total dissolved and microbial loads between boreholes, influenced by local geology, climate and land-use [10]. However, groundwater quality in many subregions, including Zebediela, remains poorly characterized, so communities often consume groundwater without knowing its safety or compliance with WHO and SANS drinking water [11]. The Zebediela subregion relies extensively on groundwater for domestic, agricultural and recreational use. The combination of semi-arid climatic conditions, diverse soil types, sedimentary geology and intensive agricultural activities creates complex hydrochemical interactions that influence groundwater quality [12] [13]. This study aimed to evaluate the hydrochemical composition, microbial contamination and heavy metal concentrations in borehole water from Zebediela subregion.

## 2. Study Area

### 2.1. Description of the Study Area

The study was conducted in Zebediela subregion (24.310°S, 29.270°E), located within the Capricorn District Municipality of Limpopo Province, South Africa. The area forms part of the Lowveld within the greater Limpopo River Basin and lies at an elevation of approximately 546 m above sea level [14]. It has a semi-arid and humid subtropical climate, predominantly covered by the savanna grassland biome. The mean summer temperature is around 33°C, and the mean winter tem-

perature is 14°C. Rainfall distribution is greatly influenced by the Soutpansberg Mountain. The catchment average annual precipitation is about 750 mm between November and March, and often varies between 340 mm and 2000 mm.

The area is underlined by sedimentary rocks which are good aquifers for underground water. The population is approximately 284,000 as per the 2022 census report and the local economy is primarily rural, characterised by cattle ranching and the cultivation of citrus. The soil composition is a mixture of red, structureless, freely-drained sandy clay loam solids from the Hutton form and the Olifants River catchment [15]. Borehole water is mainly used for domestic, recreational and agricultural purposes.

## **2.2. Sample Collection**

Twenty water samples were randomly collected from independent household boreholes in Zebediela subregion. Sampling was carried out in March 2025, during the peak dry season. Prior to collection, 500 mL polyethylene bottle containers were soaked in 70% ethanol and thoroughly rinsed with distilled water until they were free of the solvent. The tap was allowed to run freely for one minute, and the bottles were rinsed with borehole water prior to filling them. Samples were transported to the laboratory in an ice-filled cooler box for analysis.

## **3. Materials and Methods**

### **3.1. Laboratory Analysis of Physicochemical Parameters**

Total hardness was determined by complexometric titration using 0.01 M EDTA and Eriochrome Black T as the indicator; results were expressed in  $\text{mg}\cdot\text{L}^{-1}$  as  $\text{CaCO}_3$ . Chloride was analyzed using Mohr's argentometric titration method with 0.0141 N  $\text{AgNO}_3$  and potassium chromate as the indicator.

### **3.2. Nutrient and Anion Determination**

Nitrate concentrations were measured using a Shimadzu UV—1900 spectrophotometer (Shimadzu, Kyoto, Japan). Nitrate absorbance was read at 220 nm and corrected for organic matter interference at 275 nm. Sulphate was analyzed using the turbidimetric barium chloride method, with absorbance recorded at 420 nm. Phosphate was determined using the ascorbic acid (molybdenum blue) method at 880 nm. Fluoride concentrations were measured using the SPANDS spectrophotometric method at 570 nm. All nutrient analyses were validated using calibrated curves, reagent blanks, triplicate determinations and recovery rates within 95% - 105%.

### **3.3. Organic Pollution Indicator**

Biochemical Oxygen Demand ( $\text{BOD}_5$ ) was measured for borehole water samples over a period of five days ( $\text{BOD}_5$ ), using the Winkler iodometric titration method following the APHA standard procedure. Initial Dissolved Oxygen (DO) was measured immediately after collection, then samples were incubated for five days at a temperature of  $20^\circ\text{C} \pm 1^\circ\text{C}$  in the dark. Following incubation, the final DO was

measured and BOD<sub>5</sub> was calculated as the difference between the initial and final DO (DO<sub>0</sub> - DO<sub>5</sub>). All measurements were performed in triplicate for each site to ensure precision and reproducibility.

### 3.4. Trace and Heavy Metal Analysis

Trace and heavy metals (Fe, Mg, As, Cd, Zn and Pb) were quantified using Atomic Absorption Spectrophotometry (AAS). Prior to analysis, samples were digested according to APHA method 3030 E using a 3:1 (v/v) mixture of concentrated nitric acid (HNO<sub>3</sub>) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). Digestion was performed on a hotplate at 95 °C until the sample volume was reduced to approximately 20 mL. The digestates were filtered through a 0.45 µm membrane, diluted to 50 mL with deionised water and stored at 4 °C prior to analysis. Instrument calibration was performed using certified multi-element standard solution traceable to the National Institute of Standards and Technology (NIST). Quality control included the analysis of reagent blanks, duplicate samples and certified reference material for trace metals in water (NIST SRM 1643f).

### 3.5. Microbiological Analyses of Water Samples

Water samples were analysed for the presence of bacterial indicators for faecal contamination using Shimadzu CompactDry plates. Approximately 1 mL of filtered (0.45 µm paper filters) water samples were carefully pipetted on the CompactDry surface and allowed to diffuse evenly, followed by incubation in accordance with **Table 1**.

**Table 1.** Summary of the incubation conditions, duration of incubation and colony morphology characteristics of microbial species.

Bacterial Type	Incubation Temperature	Incubation Time	Colony Colour
Heterotrophic (AQ)	36 °C ± 2 °C	44 ± 4 hours	Red
<i>Escherichia coli</i> (ECO)	37 °C ± 1 °C	24 ± 2 hours	Blue/Blue purple
Coliform (CF)	37 °C ± 1 °C	24 ± 2 hours	Blue/Blue green
<i>Enterobacteriaceae</i> (ETB)	37 °C ± 1 °C	24 ± 2 hours	Red/Red purple
<i>Enterococci</i> (ETC)	37 °C ± 1 °C	22 ± 2 hours	Light blue/Blue
<i>Pseudomonas aeruginosa</i> (PA)	36 °C ± 1 °C	24 ± 48 hours	Red + Greenish yellow
<i>Salmonella</i> species (SL)	41 °C ± 43 °C	20 ± 24 hours	Yellow/Black/Green
<i>Bacillus cereus</i> (BC)	30 °C ± 1 °C	24 ± 2 hours	Green/Blue
<i>Staphylococcus aureus</i> (X-SA)	37 °C ± 1 °C	24 ± 2 hours	Light blue/Blue

### 3.6. Statistical Analysis

Mean values were calculated to evaluate parameter variability and multivariate analyses including co-occurrence matrices, Pearson correlation heatmaps and Principal Component Analysis (PCA) were utilized to identify contamination patterns, geochemical processes and relationship between parameters.

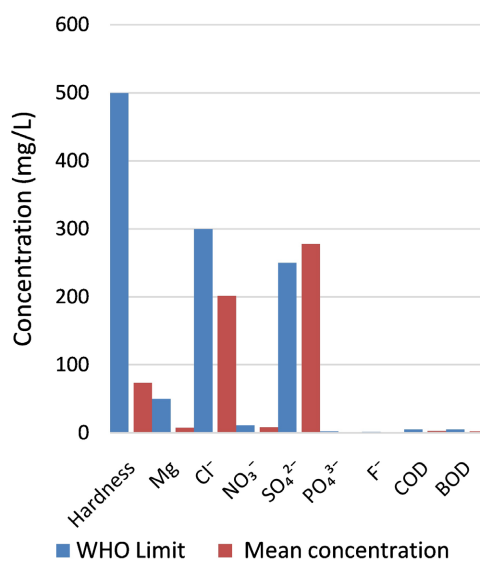
## 4. Results

### 4.1. Major Ion Chemistry

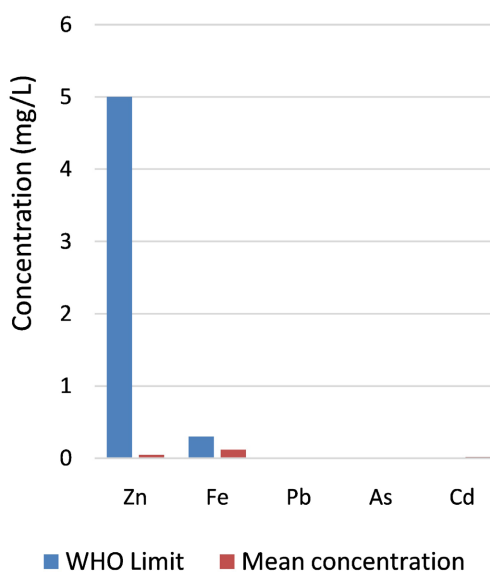
**Table 2** and **Figure 1(a)** show the composition of the major ions in the water samples. The groundwater from the study area showed hardness varied from 44 - 123 mg·L<sup>-1</sup> and a mean value of 73.90 mg·L<sup>-1</sup>. None of samples exceed the WHO permissible limit of 500 mg·L<sup>-1</sup>. Mg varied from 0.2 - 35.9 mg·L<sup>-1</sup> with an average value of 7.64 mg·L<sup>-1</sup>; all samples complied with WHO guideline of 50 mg·L<sup>-1</sup>. Cl<sup>-</sup> concentration ranged between 103 - 390 mg·L<sup>-1</sup> with an average of 201.85 mg·L<sup>-1</sup> below the WHO limit (300 mg·L<sup>-1</sup>), even though 15% of the samples were above the WHO permissible limit. NO<sub>3</sub><sup>-</sup> concentrations varied between 3 - 13.25 mg·L<sup>-1</sup>, with a mean value of 8.52 mg·L<sup>-1</sup> below WHO recommendation of 11 mg·L<sup>-1</sup>, despite 9 (45%) samples above the permissible limit. PO<sub>4</sub><sup>3-</sup> levels ranged from 0.01 to 0.61 mg·L<sup>-1</sup>, with an average of 0.63 mg·L<sup>-1</sup>. A total of 4 samples (20%) exceeded the WHO threshold limit of 1 mg·L<sup>-1</sup>. SO<sub>4</sub><sup>2-</sup> levels ranged between 100 to 633 mg·L<sup>-1</sup> with a mean value of 278.1 mg·L<sup>-1</sup>. None of the samples deviated from the WHO (250) guideline. F<sup>-</sup> concentration ranged from 0.01 to 0.65 mg·L<sup>-1</sup>, with a mean of 0.21 mg·L<sup>-1</sup>. All samples were below the WHO recommended limit (1.5 mg·L<sup>-1</sup>). BOD and COD were below threshold, ranging from 0.73 to 6.01 mg·L<sup>-1</sup> and 0.4 to 7.21 mg·L<sup>-1</sup>, with averages of 2.9 and 2.54 mg·L<sup>-1</sup>, respectively.

**Table 2.** Showing the results of the concentration of ions in groundwater from Zebediela subregion.

S/ID	Hardness	Mg	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	PO <sub>4</sub> <sup>3-</sup>	F <sup>-</sup>	COD	BOD
WHO Limit mg·L <sup>-1</sup> [16]	≤500	≤50	≤300	≤11	≤250	≤2.2	≤1.5	≤5	≤5
BH1	44	6.01	111	9.02	101	0.01	0.65	2.01	1.71
BH2	123	6.1	110	4.64	250	1.2	0.5	1.2	3.03
BH3	65	9.3	230	11.9	233	0.7	0.64	6.07	5.02
BH4	70	6.67	103	10.2	300	0.5	0.49	5.95	3.01
BH5	44	6.45	215	12.95	633	0.12	0.05	0.72	0.87
BH6	123	6.51	160	6.02	111	0.18	0.02	1.08	1.02
BH7	65	6.21	290	11.02	356	0.41	0.03	4.01	3.03
BH8	70	6.76	330	9.9	390	0.4	0.32	3.4	6.01
BH9	44	6.35	201	10.05	401	0.6	0.08	4.7	1.01
BH10	123	8.43	390	4.02	281	1.5	0.02	1.11	2.02
BH11	65	35.9	290	11.22	112	0.51	0.05	1.21	2.01
BH12	70	6.24	109	6.14	100	1.25	0.03	7.21	4.03
BH13	65	15.1	200	7.60	223	0.4	0.02	1.23	6.02
BH14	70	0.99	100	3.22	302	0.5	0.01	7.9	4.01
BH15	44	1.02	215	13.25	505	0.55	0.23	3.02	4.21
BH16	123	0.2	160	5.02	170	0.45	0.02	0.98	2.02
BH17	65	0.2	250	11.82	344	0.5	0.03	2.01	0.73
BH18	70	12.5	108	8.10	100	0.4	0.1	0.4	1.28
BH19	65	11.7	360	4.65	529	0.9	0.53	1.8	1.01
BH20	70	0.2	105	10.02	121	1.61	0.43	2.1	1.32



(a)



(b)

**Figure 1.** Major ion and trace metal average concentrations against WHO standard threshold.

#### 4.2. Trace and Heavy Metals

The concentration of selected metals (**Table 3** and **Figure 1(b)**) in the underground followed the order Fe > Zn > Cd > As > Pb. Fe ranged between 0.02 - 0.24 mg·L<sup>-1</sup>, an average of 0.12 mg·L<sup>-1</sup> lower than the WHO aesthetic limit of 0.3 mg·L<sup>-1</sup>. Zn varied from 0.02 - 0.09 mg·L<sup>-1</sup>, with a mean value of 0.05 mg·L<sup>-1</sup> well below WHO recommended threshold of 3.0. Cd ranged from non-detectable to 0.05 mg·L<sup>-1</sup>, with an average concentration of 0.018 mg·L<sup>-1</sup>. A total of 10 samples (50%) exceeded the WHO-recommended limit of 0.003 mg·L<sup>-1</sup>. Pb varied from

non-detectable to 0.019 mg·L<sup>-1</sup> with a mean of 0.006 mg·L<sup>-1</sup>. In spite of 3 samples (15%) exceeding the WHO permissible limits (0.01 mg·L<sup>-1</sup>). As levels ranged from non-detectable to 0.05 mg·L<sup>-1</sup> with a mean of 0.01 mg·L<sup>-1</sup>. 35% (7) of the samples deviated from the WHO threshold (0.01 mg·L<sup>-1</sup>), indicating potential contamination.

**Table 3.** Showing the results of the concentration of heavy metals in groundwater from Zebediela subregion.

S/ID	Pb	Fe	Cd	Zn	As
WHO Limit mg·L <sup>-1</sup> [16]	≤0.01	≤0.3	≤0.003	≤5.0	≤0.01
BH1	0.001	0.03	0.03	0.1	Undetected
BH2	0.001	0.081	Undetected	0.03	0.01
BH3	0.011	0.09	Undetected	0.02	Undetected
BH4	0.005	0.13	Undetected	0.05	0.05
BH5	0.006	0.11	0.001	0.07	0.01
BH6	0.001	0.16	0.03	0.05	0.04
BH7	0.005	0.14	0.03	0.09	Undetected
BH8	0.007	0.08	0.05	0.02	0.002
BH9	0.005	0.23	Undetected	0.04	Undetected
BH10	0.007	0.08	0.03	0.04	0.002
BH11	0.006	0.16	0.03	0.03	0.002
BH12	0.019	0.24	Undetected	0.05	Undetected
BH13	0.007	0.09	Undetected	0.05	Undetected
BH14	Undetected	0.07	Undetected	0.03	0.03
BH15	0.003	0.12	0.03	0.03	0.05
BH16	0.006	0.12	0.04	0.05	0.04
BH17	0.011	0.112	0.03	0.02	Undetected
BH18	0.009	0.11	Undetected	0.04	Undetected
BH19	0.005	0.02	0.002	0.05	Undetected
BH20	0.001	0.131	0.03	0.08	0.001

### 4.3. Microbial Assessment

The qualitative results of the microbial assessment are given in **Table 4**. The most common contaminants detected were Heterotrophic bacteria, *Escherichia coli* and general coliforms, with *Enterobacteriaceae* and *Enterococci* being slightly less common, which suggests that water is contaminated with faecal matter. Approximately 80% (**Figure 1(a)**) of Heterotopic bacteria were detected in 14 (**Figure 1(b)**) samples; *E. coli* and other coliforms were detected in 30% of the samples. *Salmonella spp.* were detected in 20% of the samples and *Enterobacteriaceae*, *Bacillus* and *Staphylococcus aureus* were detected sporadically in approximately 15%

of the samples (**Figure 1(a)**); *Enterococci* were detected at the lowest frequency and no *Pseudomonas aeruginosa* were detected in all samples.

**Table 4.** Quantitative analysis of bacteria based on the plate method.

S/ID	Di	AQ	EC	ETB	ETC	PA	SL	BC	X-SA
BH1	-	-	-	-	-	-	-	-	-
BH2	-	+	-	-	-	-	-	-	-
BH3	-	+	-	-	-	-	-	-	-
BH4	-	+	-	-	+	-	+	-	-
BH5	-	+	-	-	-	-	-	-	-
BH6	-	+	+	+	-	-	-	-	+
BH7	-	-	-	-	-	-	-	-	-
BH8	-	+	-	-	-	-	+	+	+
BH9	-	+	+	-	-	-	-	-	-
BH10	-	+	-	-	-	-	-	-	-
BH11	-	-	-	-	-	-	-	-	-
BH12	-	+	+	+	-	-	+	-	-
BH13	-	+	-	-	-	-	-	-	-
BH14	-	+	-	-	-	-	-	-	-
BH15	-	+	+	+	-	-	+	+	-
BH16	-	+	-	-	-	-	-	-	-
BH17	-	+	-	-	-	-	-	-	-
BH18	-	+	-	-	-	-	-	-	-
BH19	-	-	+	-	-	-	-	-	-
BH20	-	+	+	-	-	-	+	+	+

Distilled water (Di); Minus sign (-); - Absent; Plus sign (+); + Present.

#### 4.4. Correlation Coefficients

Pearson's correlation heatmap was generated to determine the relationships among the selected water quality parameters. A strong negative correlation was seen between Hardness and  $\text{NO}_3^-$  ( $r = -0.67$ ). A moderate positive correlation was found between  $\text{Cl}^-$  and Cd ( $r = 0.47$ ).  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  also showed a moderate positive correlation ( $r = 0.47$ ). Expectedly, BOD and COD were positively correlated ( $r = 0.45$ ). Pb and Fe showed a moderately positive correlation ( $r = 0.40$ ). Pb and As ( $r = -0.37$ ) and Mg and As ( $r = -0.33$ ), exhibited negative correlations. A moderate negative correlation was found between F- and Fe ( $r = -0.49$ ). Similarly, a negative correlation was identified between COD and Cd ( $r = -0.41$ ).

## 5. Discussion

Water quality assessment is imperative for public health and sustainable freshwa-

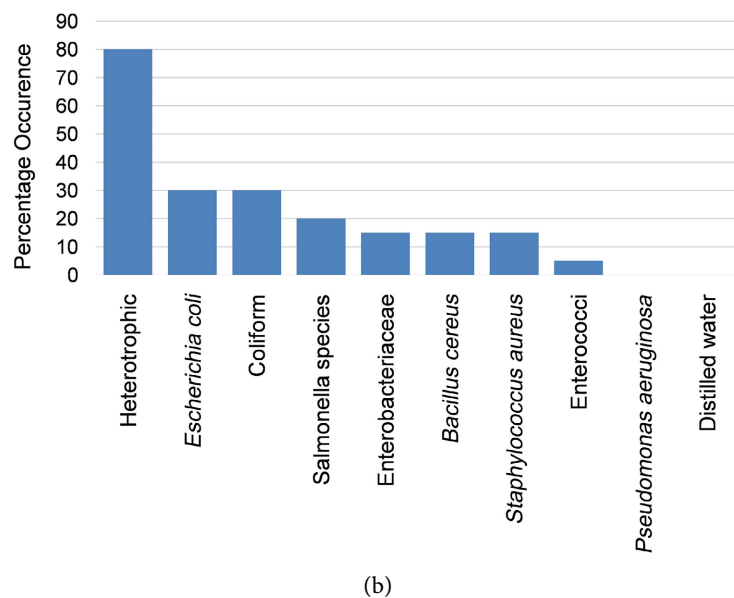
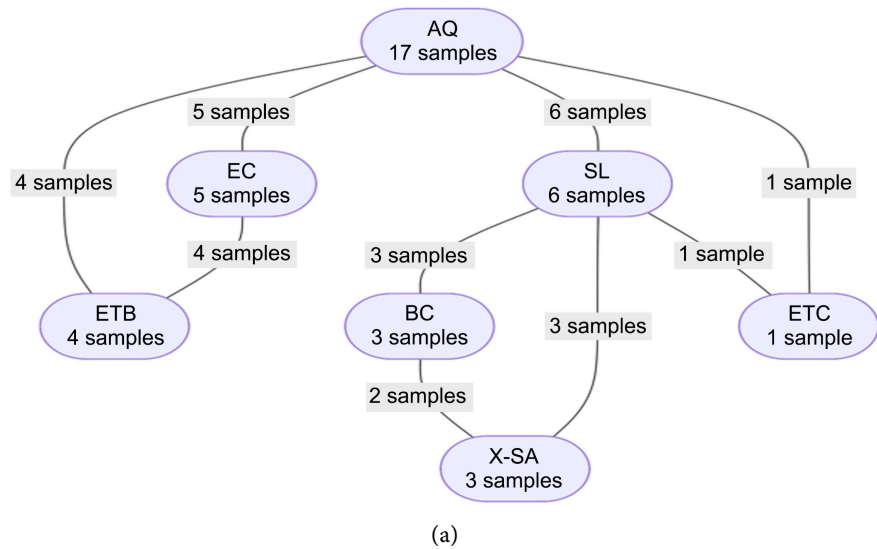
ter resources. Regular monitoring improves understanding of hydrochemical systems and supports resource management practices. This study investigated the chemical quality, heavy metal levels and microbial status of underground water collected from Zebediela subregion. The samples showed soft to moderately hard water (**Figure 1(a)**), like that reported by [17] in Ga-Matlala village in Limpopo, attributed to dissolution of calcium-magnesium carbonates and bicarbonates. Although not acutely toxic at this level, increased detergent and soap use can indirectly damage household infrastructure from chemical accumulation [18].

Sulphate evinced a greater spatial variation than hardness, most likely due to the dissolution of evaporite minerals or to lithological control rather than surface contamination. This contrasts with surface contamination, which typically manifests in primary aesthetic effects. Comparable sulphate enrichment has been reported in borehole water systems in the Vhembe district of Limpopo Province [19]. Adverse health effects related to exposure to sulphate at such low concentrations are generally confined to taste alteration and laxation effects in non-acclimated consumers [20]. Cumulative exposure to undesirable concentrations (above the recommended  $1.5 \text{ mg}\cdot\text{L}^{-1}$  by WHO) of  $\text{F}^{-}$  is concerning. Exposure to excessive  $\text{F}^{-}$  can lead to disturbances of bone homeostasis and enamel development [21]. The most likely cause of  $\text{F}^{-}$  enrichment is the geochemical weathering of fluoride-bearing minerals. This is further enhanced by low rainfall, high evaporation rates and elevated pH in Zebediela. The concurrent enrichment of  $\text{F}^{-}$  alongside elevated  $\text{SO}_4^{2-}$  concentrations and increased water hardness observed in several boreholes in Zebediela subregion may suggest prolonged water-rock interactions [22].

Elevated  $\text{NO}_3^{-}$  concentrations in regions characterized by intensive cropping are indicative of fertilizer-derived nitrate inputs. Accordingly, the occurrence of increased nitrate levels in Zebediela is plausible, given its designation as an area of high agricultural productivity. Similarly, comparable  $\text{NO}_3^{-}$  distributions in agriculturally impacted groundwater from Albert, Canada [23]. Chronic exposure to  $\text{NO}_3^{-}$  is associated with Methaemoglobinemia in infants and the *in vivo* conversion of  $\text{NO}_3^{-}$  to N-nitroso compounds has been associated with multiple systemic health effects, particularly through their mutagenic and carcinogenic potential [24]. Additionally, the presence of both nitrate and microbial contamination in some of the boreholes may lead to a greater incidence of gastrointestinal infections, due to microorganisms ability to facilitate the conversion of nitrate into nitrite [25] (**Figure 2**).

Moderate COD and BOD levels observed in Zebediela subregion groundwater (**Figure 1(a)**) suggested the presence of organic contaminants, potentially associated with surface activities and borehole exhibiting limited attenuation due to short subsurface travel. Although the COD and BOD measured in this study did not indicate severe organic pollution, they are indicative of sustained input of organic matter into the groundwater system [26]. Under such environmental conditions, the co-existence of a small amount of readily-biodegradable organic mat-

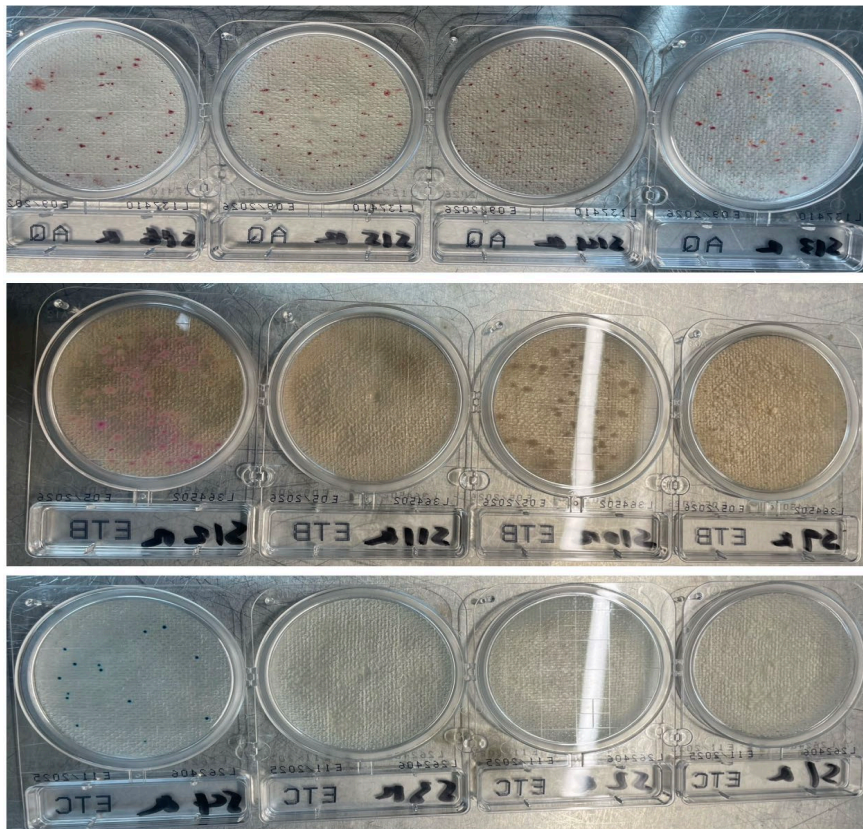
ter provides sufficient substrate to maintain viable population levels of heterotrophic bacteria and the potential proliferation of pathogenic organisms. This risk is particularly pronounced in rural borehole systems, where disinfection practices are either sporadic [27] or do not exist.



**Figure 2.** (a) Flow diagram showing the distribution and development of specific microorganisms in positive samples. Numbers indicate the count of samples positive for each microbial group or combination. (b) Bar chart showing the percentage occurrence of key microbial indicators and pathogens.

Heavy metals constitute one of the most widespread groups of groundwater contaminants, with their presence reflecting a combination of geogenic contributions and anthropogenic inputs. In the Zebediela subregion, intensive citrus cultivation, extensive limestone mining and unregulated waste disposal practices represent potential sources of metal contamination. Over time, these activities have

enhanced chemical loading in the subsurface environment and facilitated the infiltration of landfill derived leachates into local aquifers [28]. The hydrogeochemical quality system of the groundwater system (Table 2) was influenced by the metal speciation, transport and bioavailability, as suggested by the multivariate statistical analyses (Figure 3). Increased bicarbonate and sulphate concentrations enhance the mobility of metals such as lead and cadmium through the formation of carbonate and sulphato-complexes, respectively, while increased chloride levels promote metal solubility via the formation of thermodynamically stable chloro-complexes [29].

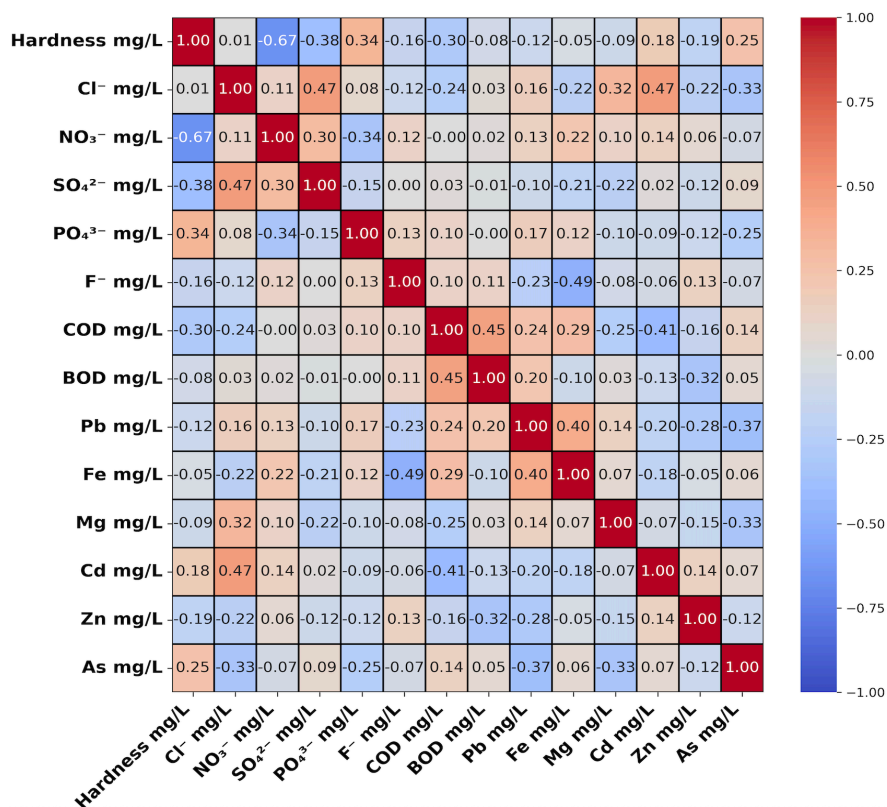


**Figure 3.** Present images depicting selected results from microbial detection in borehole water and colony development after incubation.

These associations are consistent with the observed correlations between major ions and trace metals and the PCA loadings (Figure 4), which suggest shared geochemical drivers and potential common sources. In addition, variations in pH also play a fundamental role in regulating metal behaviour, as acidic conditions can induce the desorption of metals from the solids phase of the aquifer and destabilize metal carbonate complexes, resulting in increased dissolved metals [30].

Elevated levels of iron and manganese have been recorded in a number of boreholes over an extended period of time (Figure 1(b)), which demonstrate the occurrence of redox conditions within different sections of the aquifer system. The reductive dissolution of iron and manganese oxides under these redox conditions

results in the release of dissolved ferrous ion ( $\text{Fe}^{2+}$ ) and dissolved manganese ion ( $\text{Mn}^{2+}$ ) into groundwater while also causing the mobilization of trace metals adsorbed to aquifer solids including Pb, Cd and As [31]. Elevated Mg and Fe are associated with other trace metals which suggests that redox-driven mobilization of trace metals is likely occurring at the sites of contamination, as opposed to independent or separate contamination events. Arsenic is one example where its mobility is directly related to the dissolution of iron oxyhydroxides [32].

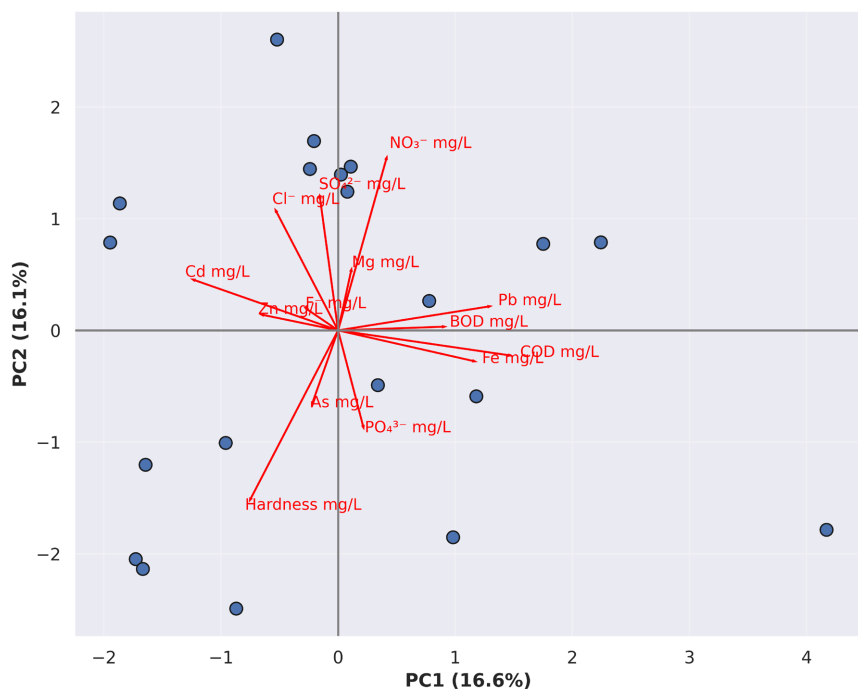


**Figure 4.** Correlation matrix of organic water quality parameters. The heatmap shows Pearson correlation coefficient ( $r$ ) from  $-1$  (dark blue, strong negative) to  $+1$  (dark red, strong positive), with significant relationships ( $r \geq 0.5$ ) highlighted.

The detection of faecal indicator bacteria such as *Escherichia coli* and enteric bacteria (Table 4) confirms faecal contamination of the groundwater system. Such contamination can probably be attributed to inadequately sited pit latrines, the concentration of shallow borehole and enhanced surface infiltration which make aquifers prone to microbial ingress [33]. Similar microbial contamination profiles of both total coliform and *E. coli* were detected in domestic borehole water from Vhembe District, Limpopo Province. The co-occurring patterns found in the microbiota (Figure 1(a), Figure 1(b)) imply shared contamination pathways rather than isolated events and a common source or transport mechanism consistent with network-based microbial ecology models [34]. When considered alongside elevated COD, BOD and nitrate levels, these indicate a sustained surface-derived contamination and limited natural attenuation within the aquifer system. These condi-

tions are an important public health issue, as faecal contamination of drinking water is strongly associated with increased risks of waterborne disease, including gastroenteritis, dysentery, cholera and typhoid fever [35] [36].

The results of the correlation analyses indicated a combination of weak, moderate and strong correlations among the major ions and physicochemical parameters in addition to indicating influence on the quality of groundwater by multiple controlling processes. The inverse association  $\text{NO}_3^-$  with  $\text{SO}_4^{2-}$  (Table 2) also suggests that nitrate and sulphate enrichment may be occurring through processes other than the dissolution of carbonates (*i.e.*, agricultural inputs or anthropogenic influences). These ions appear to be derived from either evaporative concentration of groundwater or anthropogenic contamination because of the presence of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  ( $r = 0.47$ ). moderate correlations were observed for Pb with both Fe ( $r = 0.40$ ) and COD ( $r = 0.24$ ); these correlations could indicate the occurrence of adsorption/desorption processes or co-mobility of Pb and Fe under similar geochemical conditions. Pb exhibits moderate correlations with both Fe  $r = 0.40$  and COD  $r = 0.24$ , which could indicate the occurrence of adsorption/desorption processes or co-mobility of Pb and Fe under similar geochemical conditions.



**Figure 5.** The plot shows variable loadings (vectors) for the first two principal components (PC1 and PC2), which explain 32.7% of the dataset variance. The length and direction of each vector indicate the strength and correlation of each parameter with the components.

As shown in Figure 5, PCA indicates that PC1 and PC2 explained 16.6% and 16.1% of the total variance, respectively, accounting for a cumulative variance of 32.7%. Although this cumulative variance is relatively low, such variance distribution is typical of complex hydrogeochemical systems influenced by multiple natural and anthropogenic processes, where no single factor dominates ground-

water chemistry [37] [38]. PC1 was primarily loaded with organic pollution and metal-related parameters including Pb, BOD, COD and Fe suggesting a possible pollution gradient exists due to local contamination sources, like agricultural runoff or domestic waste disposal. Conversely, variables that loaded negatively on PC1, such as hardness and As, suggest that these variables are largely controlled by geogenic processes (*i.e.*, mineral weathering) rather than anthropogenic activities. PC2 showed strong loading for nutrients and major ions ( $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , Cl<sup>-</sup> and Mg), suggesting geochemical and fertilizer applications and/or evaporative concentration effects. Additional variance was distributed across higher-order components, indicating the contribution of localized or site-specific hydrogeochemical controls.

## 6. Conclusion

In the present study, the quality of borehole water composition from Zebediela subregion, was utilized for the presence of major ions, trace metals and biological content compared to the drinking water standards. It is concluded that none of the major ions exceeded the permissible limits by WHO except for heavy metals Cd and As which were found fairly above for domestic use. Biological analysis revealed faecal indicator in 80% of the samples, demonstrating the ability of microorganism growth in groundwater due to external influence. Although groundwater in Zebediela subregion is essential for domestic, agricultural, and recreational use, microbial contamination and localized exceedances of some parameters mean it is not consistently safe for direct consumption. Regular monitoring, improved sanitation, borehole protection, and community education on safe water handling are needed to safeguard public health. The findings provide a critical baseline for sustainable groundwater quality management in Zebediela subregion.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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