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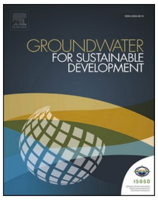

Research paper

Contamination of groundwater by potential harmful elements from gold mine tailings and the implications to human health: A case study in Welkom and Virginia, Free State Province, South Africa

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ABSTRACT

Mining of gold in the Welkom and Virginia areas of the Free State Province in South Africa has produced numerous gold mine tailings, which contain a variety of contaminants. The extent of contamination of groundwater in the area was studied by measuring several water quality indicators at eight sampling sites, and within three zones. The overall contamination of groundwater was quantified by computing a Drinking Water Quality Index (WQI). The results revealed that majority of the groundwater in the Welkom and Virginia areas is unsuitable for drinking, as confirmed by high WQIs. At only three sites was the water samples suitable for drinking. One site revealed water to be of very poor quality, while the remainder 40% of the sites indicated water to be of poor quality. The high indicator microbiological counts also affirmed the poor quality of the groundwater. Faecal coliform bacterial counts were 100% non-compliant to drinking water quality limits when compared to the World Health Organization and South African National Standard on Drinking Water 241, while *E. coli* counts exceeded both the drinking water quality limits at 50% of the sampling sites. Of the potential harmful elements analysed, Pb and Fe were found to be at toxic levels. For Pb, 40% of the water samples exceeded the drinking water quality limits while 63% of water samples were non-compliant for Fe. This result exposes the poor quality of the groundwater in the Welkom and Virginia areas, which poses a serious threat to the health of the local people, as groundwater is their primary source of drinking water. This research highlights the urgent need for mitigation measures to be introduced by the local authorities to improve the quality of the groundwater in the study area.

1. Introduction

Over the past century, mining has been the backbone of South Africa's economy. Gold mining brought about widespread employment, wealth, and contributed to the development of several sectors in the South African economy (Durand, 2012). These sectors include the development of infrastructure and the establishment of manufacturing and service industries (Durand, 2012). The rapid growing gold mining industry brought South Africa to the forefront as one of the most industrialised countries in Africa.

The mining of gold ore from the earth's crust and its processing produces large quantities of waste by-products (Lottermoser, 2010; Kossoff et al., 2014). In most instances, a larger proportion of the gold ores extracted end up as waste material (Kossoff et al., 2014). The mining waste by products are collected and accumulated in tailings on the surface of the earth in the vicinity of the gold mines. Gold mine tailings contain several different types of contaminants. Some of these contaminants originate from the gold containing ore, while others are added to the tailings during the chemical separation of gold from its ore (Lottermoser, 2010; Kossoff et al., 2014). Contaminants that originate from the gold containing ore include the mineral pyrite (iron disulfide), which is an acid producing rock, as well as chemicals, which are described as potentially harmful elements (PHEs), such as mercury (Hg), arsenic (As), cadmium (Cd) and lead (Pb) (Ngure et al., 2014). Mercury and cyanide (CN) can also be added to mine tailings during the chemical processing of gold ores (Nkuba et al., 2019). Gold containing ores also

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contain small quantities of other PHEs, described as micro-elements, which include cobalt (Co), copper (Cu), chromium (Cr), nickel (Ni), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se) and zinc (Zn) (Abdul-Wahab and Marikar, 2012). These contaminants from gold mine tailings, as well as mining activities have caused environmental pollution and impact the health of humans living in the vicinity of such mining activities (Wahl et al., 2013; Wu et al., 2014).

The contaminants in gold mine tailings are dispersed into the environment by wind, rainwater runoff and surface water flow. When rainwater percolates through gold mine tailings, sulfur-bearing pyrite reacts with water and air to form sulfuric acid and ferrous sulfate (Hansen, 2015; Kinna, 2016). The acid effluent further dissolves PHEs into ground or surface water bodies and soils in the area (Hansen, 2015; Kinna, 2016). Wind blows dust and particulate matter containing contaminants from gold mine tailings over long distances, which eventually settle on soil, water bodies and plant leaves within the vicinity of the gold mine tailings (Castillo et al., 2013; Stovern et al., 2016).

Humans and other living organisms at higher levels of the food chain are at risk if they consume contaminated water and plants contaminated with the non-biodegradable PHEs (Islam et al., 2015; Shaheen et al., 2016). Accumulation of PHEs in tissues of humans above tolerable upper intake levels may have severe health effects. In particular, Cd, Hg, Pb and As, have been described by the World Health Organization (WHO) as human carcinogens of major public health concern (Kamunda et al., 2016). Ingestion of these PHEs, even at trace levels, may be lethal (Tchounwou et al., 2012; Zhou et al., 2016).

Welkom and Virginia are the major gold mining towns in the Lejweleputswa District Municipality and of the Mathjabeng Local Municipality (MLM) area in the Free State Province of South Africa. Welkom and Virginia are surrounded by some of the largest gold fields in the Free State, with mining of gold being the dominant economic activity in the area. Gold mining in this area has produced numerous gold mine tailings, which may contain a variety of different contaminants (Kamunda et al., 2016). Such contaminants may cause extensive pollution to soils and surface water in the area (Orimoloye & Ololade. 2020a, 2020b). In addition, the contaminants from the gold mine tailings may also leach into groundwater (Keesstra et al., 2012), thereby causing the contamination of this water source, which is often used as a drinking water source in the area.

Extensive agricultural activities, such as food crop cultivation and livestock farming are also performed in the Welkom and Virginia area. Food crop farms in the area mainly grow commercial maize (corn) in extensive fields. The local people who work on these farms live in small farming communities in the area and they do not have any portable water supply. Groundwater abstraction from boreholes is the only source of water for drinking and domestic purposes in the area. Additionally, these groundwater sources do not receive any form of treatment before drinking, which makes it a source that may have been exposed to harmful contaminants.

The aim of this study was to investigate the extent of contamination of the groundwater by contaminants from gold mine tailings at eight sampling sites in and around the Welkom and Virginia area. Several indicators of contamination were used in this study to quantify the pollution condition of the groundwater sources. These indicators included physical, and microbiological water quality properties, as well as potential harmful elements (PHEs) in water. An overall level of the contamination of the different water samples was also determined by calculating a Drinking Water Quality Index (WQI) using the different water quality measurements.

2. Materials and methods

2.1. Study area

The study area is in and around the Welkom and Virginia area of Matjhabeng Local Municipality (MLM) in the Lejweleputswa District Municipality. The Welkom and Virginia areas are situated in the north eastern part of the Free State Province, about 250 km South of Johannesburg and 140 km north east of Bloemfontein, the province's capital. (Fig. 1). The study area is characterised by a warm temperate summer rainfall climate with an annual average precipitation of 530 mm, while the winters are dry (Green door Environmental, 2013). High summer temperatures are prevalent with average monthly temperatures of 17 ^{O}C in the summer and 5 ^{O}C in the winter.

2.2. Criteria for selection of zones and sampling sites

Three zones were selected in the Welkom and Virginia area to study the extent of pollution of groundwater, as well as to confirm if mine tailings were the dominant source of contamination in the area. Within these three zones, eight groundwater sampling sites were identified, from which groundwater contamination was examined. The three zones were selected based on distances from the mine tailings and mines, other anthropogenic activities, such as industries and agricultural activities in the area, and the prevailing wind direction in the area. Zone 1 contained sampling sites, F1 and F2 and the zone was positioned on the western side of Welkom, about 5 km from where mining is practiced in the Welkom and Virginia area. This mining area contains numerous gold mine tailings; therefore, the area was described as the highly dense mine tailing area. Zone 2 was positioned about 5–7 km beyond the highly dense mine tailing area, occupying the western side of Virginia, as well as the south-southwest border of the highly dense mine tailing area. The third zone, Zone 3, did not contain mine tailings or mining activities, but these sites were located approximately 7 km–10 km east of the highly dense mine tailing area. Sampling sites in Zone 1 and Zone 2, were situated in the downstream direction of the prevailing wind in the Welkom area, whereas the control sites in Zone 3 were positioned in the upstream direction of the prevailing wind in the area.

2.3. Collection of water samples

Water samples were collected according to the procedure in the sampling guide of the Water Research Commission of South Africa (WRC, 2017). Water samples were collected from the eight groundwater sampling sites that were identified in the three zones, in June of 2018, which is the winter season in the study area. At each sampling site, a water sample was collected from a borehole tap and then used for the measurement of turbidity, water pH, temperature, electrical conductivity (EC) and dissolved oxygen (DO). Water samples were also collected for the measurement of PHEs and the presence of indicator microorganisms in the water. In this study, the number of faecal coliform bacteria was counted to indicate the total bacterial load in the drinking water, as well as the number of *Escherichia coli* (*E. coli*) to determine the degree of pollution of water from faecal matter (WHO, 2018). For the measurement of the water quality properties on-site, water samples were collected in a 100 ml beaker from the borehole tap, while for the measurement of PHEs, water samples were collected in a 1-L bottle. Prior to the collection of a water sample destined for the measurement of the presence of the indicator microorganisms, the borehole tap was flamed, then opened, and allowed to run for at least 3 min, after which a water sample was collected in sterile 100 ml sampling bottle. All sample bottles destined for the measurement of PHEs and microorganisms were clearly labelled with site number, time and date of collection and then placed in a cooler box containing ice. These sample bottles were then transported to the Water Laboratory at the Central University of Technology, Bloemfontein, Free State (CUT), where the water samples were kept at 4 ^{O}C in the refrigerator until analysis.

3. Measurement of physical and microbial water quality properties

The water pH, temperature, EC and DO of the water samples were

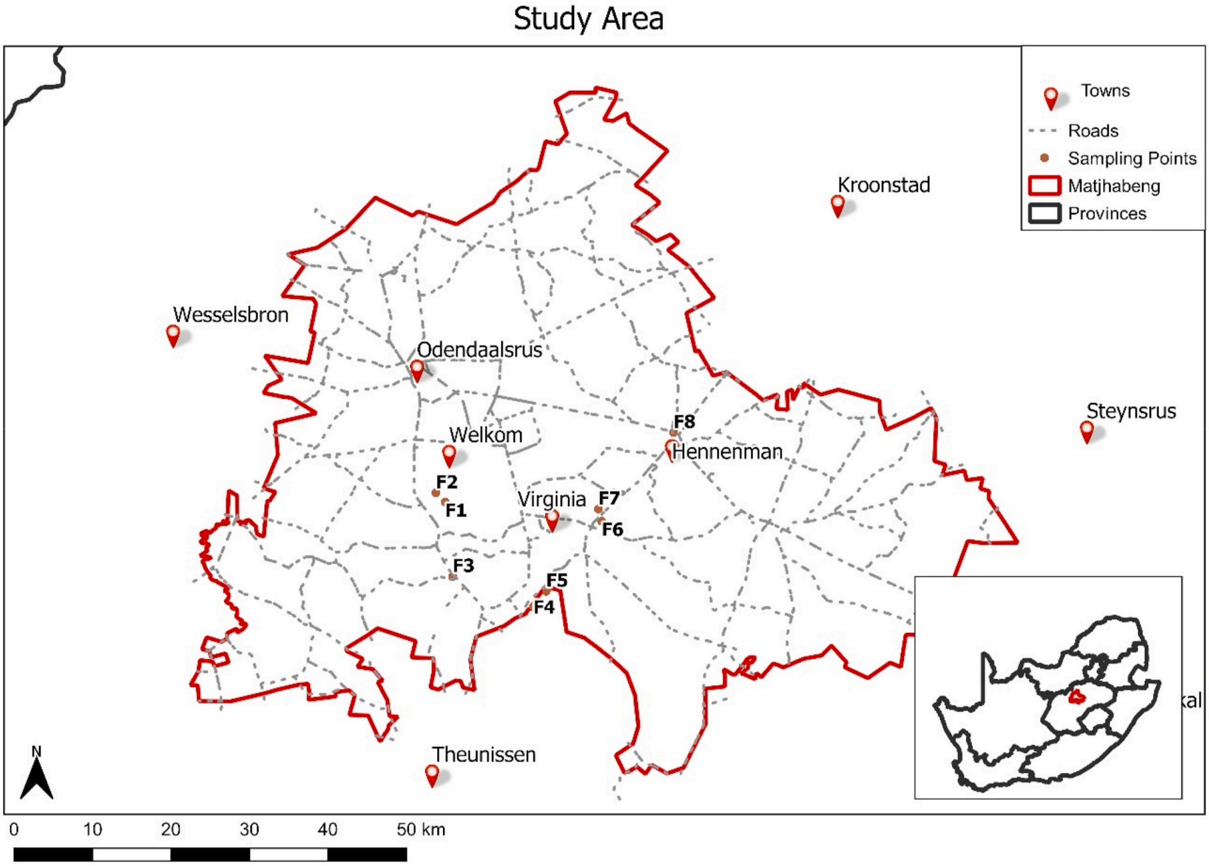

Fig. 1. Study area in Welkom and Virginia showing the eight groundwater sampling sites.

measured at each of the eight groundwater sampling sites, while the microbiological properties were measured in the laboratory. At a sampling site turbidity was measured with a calibrated, battery operated Hach 2100Q turbidity meter following the standard analytical procedures of the instrument. The water pH, temperature, EC and DO of the water samples were measured using a battery operated Hach HQd handheld meter, according to the analytical procedures of the instrument.

The number of faecal coliform bacteria and number of *E. coli* were counted using the Colilert 18/Quanti-Tray method (ISO 9308-2:2012) according to the manufacturer's specifications (COLILERT QUANTI-TRAY®, IDEXX Laboratories, Inc., United States). Colilert 18 powder was poured into each water sample in the bottle, which was then shaken for a few minutes until the powder had dissolved. Once the Colilert 18 powder had dissolved, the solution was poured into the 97-well Colilert 18 Quanti-TrayTM2000 tray, which was heat-sealed and incubated at 37 °C for 20 h. In natural light, the wells would appear yellow if faecal coliform bacteria were present. In contrast, if *E. coli* were present in the water sample, the wells would fluoresce blue when placed under UV light (Kinzelman et al., 2005). The number of colony forming units (cfu) of faecal coliform bacteria and *E. coli* present in 100 ml of water was determined using the Quanti-Tray®2000 Most Probable Number (MPN) table.

3.1. *Measurement of potential harmful elements*

The twelve PHEs As, Cd, Pb, Co, Cr, Cu, Fe, Ni, Se, Zn, Ca and Mg were measured using the inductively coupled plasma optical emission spectroscopy (ICP-OES). The measurements were performed at the School of Chemistry and Physics, University of Kwa-Zulu Natal, Westville campus. Prior to elemental analysis, the water samples were digested using open vessel digestion in nitric acid (HNO_3). The procedure that was followed for the measurements of the PHEs, as well as the digestion procedures for the water samples were according to Kisten et al. (2015). Digests were filtered through Whatman No. 1 filter papers into 25 ml volumetric flasks; diluted to the mark with double distilled water and then stored in polyethylene bottles for analysis. For quality control purposes, three digests were performed for each water sample to validate the digestion method. For each PHE measured in this study, a standard was also prepared to establish the accuracy and precision of the test method.

3.2. *Measurement of overall groundwater quality*

The drinking water quality of the groundwater samples was determined by computing a Water Quality Index (WQI) proposed by Rakotondrabe et al. (2017) using the physical and chemical measurements of the groundwater samples. The drinking WQI proposed by Rakotondrabe et al. (2017) was most appropriate for use to compute the WQI in this study based upon the fact that it only allowed for single set of measurement and it was also relatively easy to compute. A WQI integrates measurements of different water quality properties into a single value that describes the overall quality of the water at a particular sampling site (Kannel et al., 2007; Nikoo et al., 2011). To compute the WQI, three physical water quality properties and the measurements of five PHEs were selected based on their impact to water quality and human health (Rakotondrabe et al., 2017). The three physical water quality properties were turbidity, pH and EC. The five PHEs; Cu, Fe, Pb, Ca and Mg were selected because their concentrations were above the instrument detection limit at more than 50% of the sampling sites. Three main factors were computed in the determination of a WQI for a particular sampling site; relative weight (*Wi*), quality rating (*qi*) and sub-index of the ith property (*SIi*) according to the procedure of Rakotondrabe et al.

(2017).

For the calculation of W_i, weights ranging between 1 and 5, were assigned to each water quality property based on the impact of each property on water quality, as well as the harm that each of the water quality property may cause to human health. For example, a weight of two was assigned to a water quality property that may not have significant effect on water quality, as well as human health, but a weight of five was assigned when a water quality property can cause severe contamination to water and cause critical health implications to humans (Table 1).

W_i was computed according to the equation below.

$$W_i = w_i \Big/ \sum_{i=1}^{n} wi \tag{1}$$

where, W_i is the relative weight, w_i *is* weight of each property, n is the number of properties.

For the calculation of q_i, the concentration of each water quality property was divided by its limit according to the South African National Standard on drinking water (SANS 241, 2015), as the standard contained most of the water quality properties that were used in computing the WQI. But for Ca and Mg which did not have limits in SANS 241, the WHO (2018) drinking water limit was used. More so, where the limit in SANS 241 and WHO was a range, the middle number was used (SANS 241, 2015; WHO, 2018).

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{2}$$

where, q_i is quality rating, C_i is concentration of each water quality property and Si is the drinking water quality standard for each water quality property.

The product of the relative weights and the quality rating obtained for each water quality property is denoted by SI_i.

$$SI_i = W_i \times q_i. \tag{3}$$

where, SI_i is the sub-index of the ith property, W_i is the relative weights and q_i represents the quality rating.

With the three factors in place, the drinking WQI was then calculated in the following manner:

$$WQI = \sum_{i=1}^{n} SI \tag{4}$$

The calculated WQIs were interpreted according to five categories (Rakotondrabe et al., 2017). Water with a WQI value < 50 was classified as excellent; water with a value ranging from 50 to 100 as good; water with a value ranging from $>$100 to 200 as poor; water with a value ranging from $>$200 to 300 as very poor water; and water with a value $>$ 300 as extremely poor water.

3.3. Statistical analysis

The Statistical Package for Social Sciences (SPSS) Version 23 was used to analyse the data. Summary statistics were calculated for the physical water quality measurements, which included means and standard deviations. For all the physical properties and all the PHEs, the percentage compliance to the SANS 241 (2015) and the WHO (2018) standards were also calculated.

Table 1
Weights of water quality properties and standards.

Property	Weights	SANS 241 Drinking Water Standard
pH	3	$\geq$5 and $\leq$ 9.7
EC (mS/m)	2	170
Turbidity (NTU)	3	$\leq$5
Ca (mg/L)	2	(150–300)[a]
Mg (mg/L)	2	(150–300)[a]
Fe (mg/L)	3	0.3
Cu (mg/L)	3	2
Pb (mg/L)	5	0.01

[a] World Health Organisation drinking water standard (WHO, 2018).

3.4. Quality assurance and quality control

Quality assurance procedures were applied to ensure that the results were reliable. All instruments were calibrated before measurement. Double distilled water was used throughout the study to clean glassware and the reagents that were used were of analytical grade. Reagent blank determinations were used to correct the instrument readings. For validation of the analytical procedure, standard reference materials (CRMs), White Clover (BCR 402), obtained from the Community Bureau of Reference of the Commission of the European Communities was used. All samples were analysed in triplicate (n = 3) and to validate the digestion method, standards were also prepared.

4. Results

4.1. Physical and microbiological properties

Measurements were recorded for the five physical properties and the two microbiological properties of groundwater samples collected at the eight sampling sites during the winter season. Of the seven water quality properties, only pH and DO demonstrated 100% compliance when compared to the WHO (2018) and SANS 241 (2015) drinking water quality limits (Table 2). In contrast, the faecal coliform bacterial counts of the eight water samples were all non-compliant when compared to both the WHO (2018) and SANS 241 (2015) drinking water quality limits. On the other hand, the *E. coli* counts exceeded both the drinking water quality limits at half of the sampling sites, which is of great concern as the water is used for drinking purposes.

4.2. Potential harmful elements

Of the 12 PHEs studied, Cd, Co, Cr, Ni, Se and Zn were not detected in the water samples due to levels being below the instrument detection limit. Arsenic was only detected in the groundwater sample collected at site F5. The level of arsenic in this groundwater sample exceeded the limits of both the WHO (2018) and SANS 241 (2015) drinking water quality limits (Table 3). But for Cu and Mg, the concentrations of all the measurements, which were detected, were within the specified limits. In contrast, the groundwater measurements of Fe were non-compliant to both the WHO and the SANS 241 drinking water limits for 63% of the groundwater samples. On the other hand, for Pd, all the groundwater samples, in which Pb was detected, exceeded the specified limits. Calcium was detectable in all the groundwater samples, of which 63% of the samples exceeded the specified limits.

4.3. Overall groundwater quality

The WQI values for drinking water was computed for the groundwater samples collected at the eight sampling sites to evaluate the overall drinking water quality of the water at each of the sampling site. The WQI values indicated that the drinking water quality of the groundwater was classified as good at only three of the sampling sites (Table 4). The drinking water quality of the groundwater at the remainder of the sampling sites were poor or very poor. When the different zones were considered, no explicit pattern could be established. However, the groundwater of one of the sampling sites in Zone 1 had the worst quality water (F2). This site is located approximately 5 km from the highly dense mine tailing area. In contrast, the groundwater collected at sampling site F8, which lies the furthest from the mine tailing area at about 7 km–10 km, had the best quality water of all the groundwater samples.

Table 2
Results of the physical and microbiological properties of groundwater samples collected from the eight sampling sites.

Properties	Physical				DO (mg/L)	Microbiological	
Limits	pH	Temperature (°C)	EC (µs/cm)	Turbidity (NTU)		Faecal coliform/100 ml	*E. coli*/100 ml
WHO	**6.5–8.5**	**-**	**-**	**< 1**	**-**	**0**	**0**
SANS 241	**≥ 5 ≤ 9.7**	**-**	**≤ 1700**	**≤ 5**	**≤ 1200**	**0**	**0**
Sites							
F1	6.8	19.4	1496	0.62	9.3	> **2420**	**6**
F2	6.8	17.2	372	**2.3**	1.5	> **2420**	**1**
F3	7.2	15.0	537	0.8	7.1	> **2420**	0
F4	7.7	15.2	1244	0.6	4.6	**980**	0
F5	6.8	15.4	**8940**	0.8	8.1	> **2420**	0
F6	5.9	13.8	**1738**	0.3	7.7	**1300**	**1**
F7	6.3	15.6	232	0.2	7.6	**1203**	**1**
F8	6.7	17.2	952	0.2	6.6	**1046**	0
Minimum	5.95	13.8	232.00	0.27	1.59	980.00	0.00
Maximum	7.72	19.40	8940.00	2.33	9.38	2420.00	6.00
Mean	6.80	16.10	1938.88	0.76	6.62	1776.13	1.13
SD	0.53	1.75	2879.55	0.67	2,43	6,94.92	2.03
% compliance	100		75	88	100	0	50

Bold numbers represent measurements that exceeded the limit of the test; > 2420 = measurement exceeds the limit of the test.

Table 3
Mean concentrations (standard deviation) of potential harmful elements in groundwater samples collected at the eight sampling sites.

PHE	As	Cu	Fe	Pb	Ca	Mg
WHO limit (mg/L)	≤0.01	≤2.00	<1	≤0.01	150–300	150–300
SANS limit (mg/L)	≤0.01	≤2.00	≤2.00	≤0.01	–	–
Site						
F1	ND	0.03 (0.01)	**3.07** (0.16)	ND	**157.01** (1.85)	43.57 (0.30)
F2	ND	0.03 (0.01)	ND	ND	**305.23** (4.56)	127.14 (2.40)
F3	ND	0.06 (0.02)	**4.43** (0.04)	ND	66.65 (5.97)	16.80 (1.91)
F4	ND	ND	**2.33** (0.01)	**0.45** (0.01)	**152.53** (7.34)	22.16 (0.19)
F5	**0.02** (0.001)	0.22 (0.01)	**2.87** (0.15)	ND	87.99 (1.57)	16.12 (0.32)
F6	ND	ND	0.87 (0.10)	**2.04** (0.06)	**186.44** (3.89)	38.83 (0.13)
F7	ND	ND	0.25 (0.02)	**0.07** (0.01)	**268.26** (1.83)	51.17 (0.22)
F8	ND	ND	**11.29** (0.28)	**0.71** (0.02)	92.03 (3.71)	15.73 (0.49)

Bold numbers indicate numbers that exceeded the limits.

Table 4
Water quality indexes and water quality conditions of the groundwater samples collected at the different sampling sites.

Sites	Zones	Water source	WQI	Condition
F1	Z1	Borehole	107.40	Poor water
F2	Z1	Borehole	223.92	Very poor water
F3	Z2	Borehole	62.24	Good water
F4	Z2	Borehole	91.85	Good water
F5	Z2	Borehole	196.33	Poor water
F6	Z3	Borehole	106.88	Poor water
F7	Z3	Borehole	113.90	Poor water
F8	Z3	Borehole	56.70	Good water

The overall trend of the contamination of the different indicators of groundwater quality were assessed for the groundwater samples at the eight sampling sites, within the three zones. This assessment considered the quality of the various indicators of pollution that exceeded the limits in this study. Overall, there was no obvious trend that could be discerned for the level of contamination for the eight sampling sites, as well as for the three zones (Table 5).

5. Discussion

Several indicators were measured to ascertain the extent of groundwater contamination by gold mine tailings in the Welkom and Virginia area of the Matjabeng Local Municipality. The results revealed that several of the contaminants that were found in the groundwater samples could have originated from the gold mine tailings in the vicinity. When considering the quality of the groundwater samples from the different sampling sites for the different zones, the expectation that water samples from sampling sites beyond the mine tailings would present with lower levels of contamination, was not met. A possible explanation could be that mine tailings and the mining activities in the Welkom and Virginia area may not be the only source of contamination to the groundwater in the area. Other sources of contamination in the area may include natural sources, such as the weathering of parent materials, as well as anthropogenic sources, such as industries, motor vehicles, fossil fuel combustion, agricultural activities, and waste water treatment plant (WWTP) effluents (Masindi and Mued, 2018; Sun et al., 2019; Vareda et al., 2019).

The WQI, which describes the overall water quality as a single value,

Table 5
Overall trend of contamination of groundwater samples for the eight sampling sites, within the three zones.

Property exceeding limit	F1 Z1	F Z1	F3 Z2	F4 Z2	F5 Z2	F6 Z3	F7 Z3	F8 Z3	Number of exceeding properties
EC	–	–	–	–	X	X	–	–	2
Turbidity	–	X	–	–	–	–	–	–	1
Faecal coliform	X	X	X	X	X	X	X	X	8
E. coli	X	X	–	–	–	X	X	–	4
As	–	–	–	–	X	–	–	–	1
Fe	X	–	X	X	X	–	–	X	5
Pb	–	–	–	X	–	X	X	X	4
Ca	X	X	X	X	–	X	X	–	6
WQI	X	X	–	–	X	X	X	–	5

classified the groundwater quality as poor for majority of the sampling sites (Rakotondrabe et al., 2017). This is of major concern as the groundwater abstracted from the eight boreholes are used for domestic purposes, which includes drinking water. The poor water quality due to the high faecal coliform bacterial count, as well as the high *E. coli* count could impact on the health of the people since the groundwater is the only available domestic water source. The high faecal coliform bacterial count may cause diarrhoea, particularly in children, whilst abnormal levels of *E. coli* in the water may cause gastrointestinal diseases, such as, cholera, typhoid fever and dysentery (Fakhr et al., 2016; Mahmud et al., 2019).

Groundwater samples also presented with relatively high concentrations of PHEs. In particular, the concentrations of Fe, Pb and Ca in most of the water samples exceeded the prescribed limits, indicating the potential for metal toxicities due to these metals. These metals are typical contaminants associated with gold ores from mining activities and gold mine tailings, which could be the sources of contamination (Tutu et al., 2008; Jaishankar et al., 2014). When borehole water containing high levels of Fe, is used as drinking water, this could result in the production of hydrogen free radicals, which attack DNA, resulting in cellular damage, mutation and malignant transformations, which in turn, causes a series of diseases (Jaishankar et al., 2014). Lead, on the other hand, is known to cause brain, liver, and kidney damage in children, as well as nerve damage in adults (Khan, 2011; Jaishankar et al., 2014; AbuShady et al., 2017). Moreover, an increased intake of Pb can result in miscarriages in pregnant women, as well as damage of testis in males (Khan, 2011).

6. Conclusion

The findings indicate that the quality of the groundwater at majority of the sampling sites in the Welkom and Virginia areas were not suitable for drinking. This outcome was highlighted by the high levels of faecal coliform, *E. coli* and PHEs, particularly Fe and Pb in the groundwater and was confirmed by the WQI values that indicated the overall drinking water quality of the water. Therefore, remediation measures need to be implemented by local authorities to improve the quality of the groundwater in the area. This will prevent further deterioration to both the water quality and the potential effect that the water may have on human health. Based on the evidence and magnitude of contamination, these results laid the foundation for further research in which the extent of contamination of the groundwater in the Welkom and Virginia area could also be studied for the summer season, to be able to determine the seasonal variations in the level of contamination of the groundwater in the area.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2020.100507.

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