Variable water quality of domestic wells emphasizes the need for groundwater quality monitoring and protection: Stinkwater, Hammanskraal, Gauteng

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ABSTRACT

Groundwater is a critical water resource in many peri-urban areas without municipal water supply, a common situation globally, but especially in Africa. These areas contain multiple water pollution risks from various human activities, including small industry, dumping, stock and pet animals, and pit latrines. Stinkwater village, 40 km north of Pretoria in Gauteng Province, that has only partial municipal water supply, was sampled for water quality from municipal taps, boreholes and open hand-dug wells. The water quality varied greatly, with few obvious geographic or geochemical correlations, other than high bacterial counts in the open wells. The key health concerns were nitrate, fluoride and coliform bacteria (including *E. coli*), some at dangerous levels. Relatively subtle variations in land use, including water use and pollution sources, as well as vadose zone character, including depth to water table, permeability and recharge pathways, could account for much of the variation in water quality. The study reveals the risk of relying upon a single water quality analysis to determine groundwater conditions for an area. In areas with multiple possible pollution sources, thorough groundwater monitoring is needed to determine the usability of water resources.

Keywords: groundwater, domestic wells, pit latrines, contamination, urban areas

INTRODUCTION

Use of groundwater as a water supply, for agricultural, industrial and domestic use, has been on the rise globally (Villholth and Giordano, 2007). This is due to the overuse and declining quality of surface water resources, as well as improvements in understanding and engineering methods to access groundwater resources. However, with increased use of groundwater and the increase in human population and activities, groundwater is now also subject to declining levels and quality in areas as far afield as Korea (Lee et al., 2005) and India (Naik et al., 2008). The situation in Africa is similar, and subject to even more intense pressures. Population growth, as a percentage, is the highest of all the continents, and urbanization was predicted to double between 2000 and 2030 in sub-Saharan Africa, which currently has an urban population of around 250 million (Lapworth et al., 2017). Needless to say, the stress on water resources can only increase and as stated over 10 years ago: The challenges of achieving sustainable development will be particularly formidable in Africa.' (Cohen, 2006 p. 63).

Studies of groundwater quality across Africa are numerous, and include rural (Grimason et al., 2013), urban (Mangore and Taigbenu, 2004) and peri-urban (Mokuolu et al., 2017), as well as agricultural (Esterhuizen et al., 2014), industrial (Takem et al., 2015) and domestic (Vala et al., 2011) studies. Most of these studies reveal decreases in groundwater quality related to human activities at the surface. In most cases, even though baseline data is not available from prior to the commencement of the activity, the source of the contamination is obvious, as it carries the signature of heavy metals, synthetic nitrate fertilizers and other contaminants that do not occur naturally, or are orders of magnitude less abundant in natural groundwater. In particular, rural, industrial and agricultural settings have relatively clear sources of pollutants, whereas domestic or urban settings are more challenging, with multiple possible sources of pollutants.

The need for groundwater monitoring is self-evident where groundwater is being used as a water resource. Without information on the quantity and quality of groundwater, both spatially and temporally, planning and management of the groundwater resource, to ensure its sustainable use, is not possible. The state of groundwater quality assessment across Africa varies, from non-existent to fair. Much of the work done is either focused on a particular location at one site, such as a mine or heavy industry (e.g. Gomo and Vermeulen, 2014; El Khalil et al., 2008) or is of a broad, regional or continental scale using aggregated data and much statistical processing (e.g. Ouedraogo and Vanclooster, 2016; Lapworth et al., 2017). The former information is often not available, being corporate and classified (Coetser et al., 2007), and the value of the latter depends totally on the quality of the input data. Some governments (at local, regional or national scales) do perform regular groundwater monitoring, but the accessibility of this data is not always easy, and experts may be needed to interpret the data. All in all, understanding groundwater quality is a task beset by many difficulties, not the least of which are the lack of monitoring, the buried nature of much of the data and the complex mix of information available.

This paper aims to highlight the need for regular monitoring and simple, accessible reporting, by showing the great variations in groundwater quality in a small, peri-urban area where residents are dependent upon groundwater for water supply.

STUDY AREA

Stinkwater is about 40 km north of Pretoria and 13 km west of the N1 freeway as it runs through Hammanskraal, with access off Lucas Mangope Drive (M21) (see Fig. 1). It forms part of the

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City of Tshwane Metropolitan Municipality, within Gauteng Province of South Africa. The Stinkwater settlement is part of the broader Hammanskraal-Shoshanguve area, a wide area of rural, low-density urban and industrial development within remnants of natural vegetation.

The area has a mean elevation of 1 100 m amsl and the landscape is flat to very gently sloping, except for the notable rim of the 220 000-year-old Tswaing meteorite impact crater, about 5 km west of Stinkwater.

As shown in Fig. 2, the geology of the area comprises basement of the Nebo Granite of the Lebowa Granite Suite, part of the Bushveld Igneous Complex, nonconformably overlain by Ecca Group in the Springbok Flats basin of the Karoo Supergroup. The Nebo Granite is coarse-grained rock, bearing

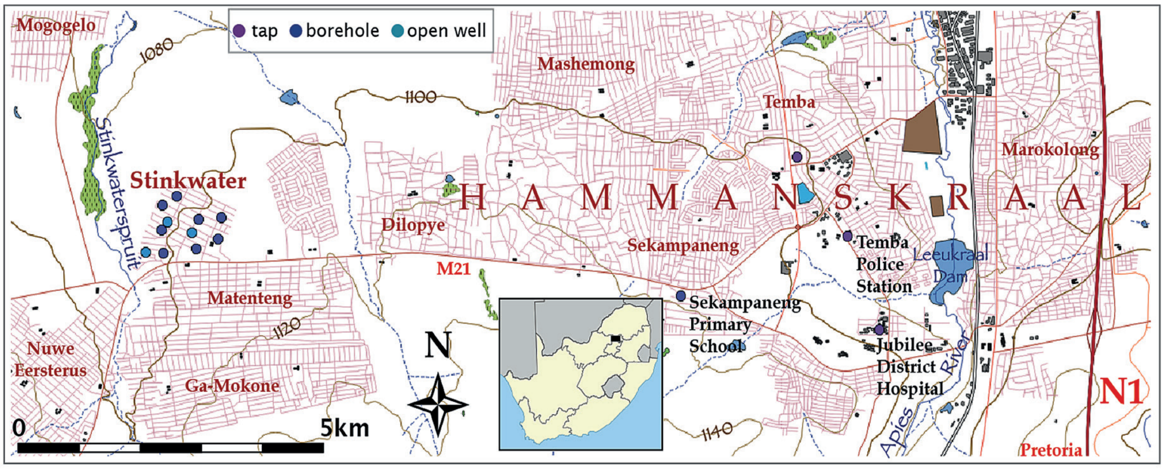

Figure 1
Location map (raw data courtesy of Surveys and Mapping, RSA Government)

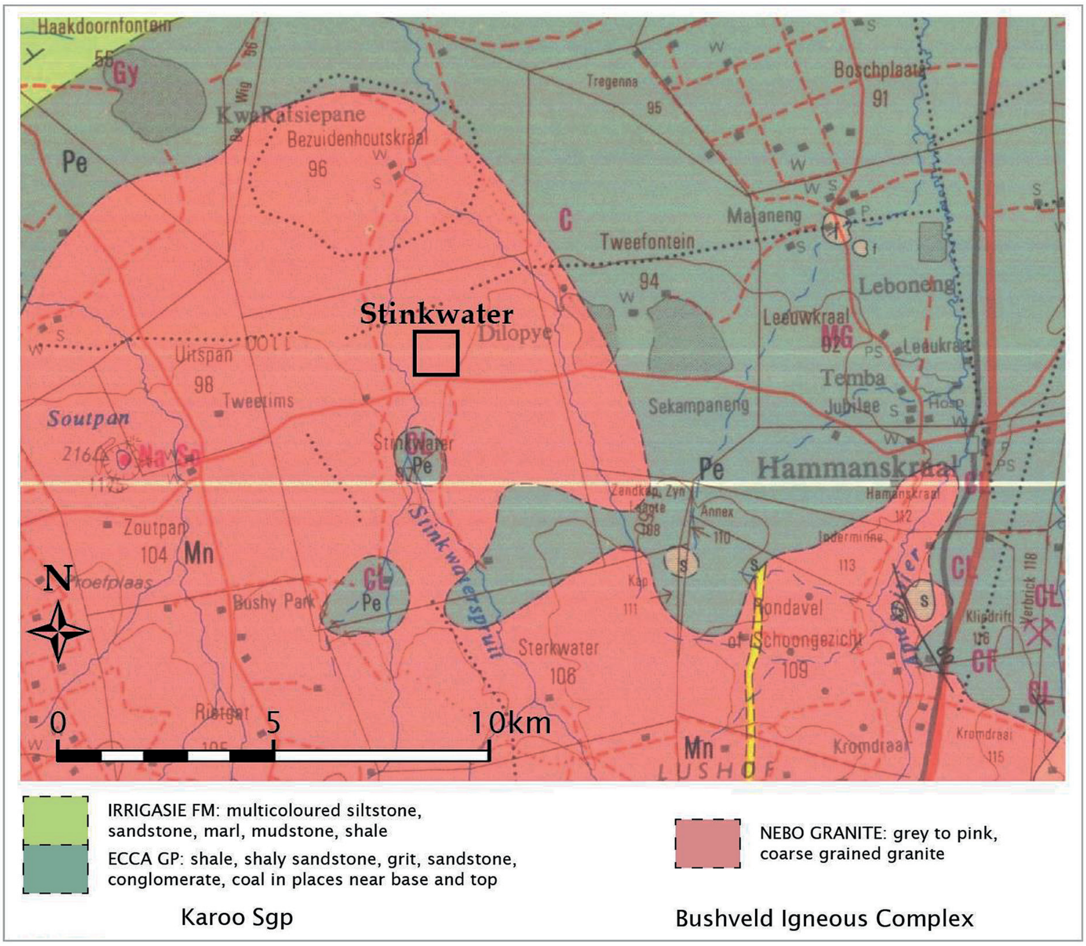

Figure 2
Geological map of the area (Geological Survey, 1978)

alkali feldspar, quartz, minor mafic minerals and accessory minerals, with rare primary plagioclase (Cawthorn et al., 2006). The Ecca Group is represented here by the Hammanskraal Formation, which normally overlies the basal unit of the Karoo Supergroup, the Dwyka Group, not present in this locality. The Hammanskraal Formation is a horizontal sequence of clastic sedimentary rocks, at the base mainly sandy with minor shaly coal, overlain by mudrock dominated layers that transition to micaceous sandstones, and finally a coal-rich zone where major carbonaceous mudrock alternates with minor, but potentially economic bright coal seams. Significant uranium is also present in the Springbok Flats Basin (Johnson et al., 2006).

Cenozoic cover is generally thin, as the area is erosive, but weathered profiles can be many metres thick. The transported Cenozoic sediments found at the surface are predominantly sandy, as the other components are either weathered, in the case of feldspars and mafic minerals in the granite, or are transported by wind and water in the case of clays and silts in the Karoo rocks. Stinkwater village itself lies above the weathered Nebo Granite and thin Cenozoic cover.

The Nebo Granite has no primary porosity, so groundwater movement at depth is limited to fractures, which themselves diminish in frequency and aperture with depth. The Hammanskraal Formation has minimal primary porosity and groundwater flow is mainly through fractures associated with sandstones and coal seams (Fourie, 2016). Weathered profiles of both the granite and the sedimentary rocks generally result in improved permeability as the porosity of the residual material increases with increasing quartz sand fraction (Dippenaar, 2014a).

The area has a dry subtropical climate with cool, dry winters and hot, moist summers. Mean annual precipitation is about 600 mm, with most of this falling as thundershowers from October to March. Temperatures vary from daily maximums of 31°C and 21°C for summer and winter, to minimums of 21°C and 3°C, similarly (Meteoblue, 2017).

Stinkwater village has municipal water supply to some properties, from Magalies Water. It is generally not drunk due to taste, odour or colour concerns. Water is obtained from Rand Water tanker deliveries or from private boreholes. Sanitation is by pit latrine (‘long drop’ toilet) and grey-water is discarded or irrigated on surface.

METHODS

A walk around Stinkwater village was done to locate possible water sampling points. In the end, 8 boreholes and 3 hand-dug wells were sampled in Stinkwater. In addition, in the lead-up to selecting Stinkwater as a detailed investigation location, 3 samples of tap water and 1 borehole water sample were taken in Hammanskraal. For details of the sampling locations, see Figs 1 and 3 and Table 1.

No Magalies scheme water was available from the taps in Stinkwater village, so the 3 samples from Hammanskraal were used. Boreholes were connected to pumps and samples were taken from a tap connected to the borehole water supply system. Hand-dug wells were sampled by means of a bailer attached to a rope. Water samples were placed in plastic bottles supplied by WaterLab and placed on ice until delivery to the laboratory on the same day.

Samples were analysed at Waterlab (Pty) Ltd in Pretoria. The main analysis methods were inductively-coupled plasma mass spectrometry (ICP-MS) according to South African National Standard 11885:1996 (SABS, 1996) for most cations, including major and trace elements, and spectrophotometry

Figure 3
Satellite image of Stinkwater showing sample locations (Google Earth, 2018)

TABLE 1
Sample site information. Elevation is in metres above mean sea level.

ID	Site	Source	Location		Elevation
			South	East	m amsl
HMS 01	Jubilee District Hospital	Tap	25° 24′ 09.16″	28° 15′ 54.16″	1 101 m
HMS 02	Hammanskraal household	Tap	25° 22′ 38.78″	28° 15′ 08.67″	1 106 m
HMS 03	Temba Police Station	Tap	25° 23′ 20.29″	28° 15′ 36.83″	1 104 m
HMS 04	Sekampaneng Primary School	Borehole	25° 23′ 51.83″	28° 14′ 04.60″	1 124 m
HMS 05	Stinkwater household	Borehole	25° 23′ 10.42″	28° 09′ 50.23″	1 107 m
HMS 06	Stinkwater household	Borehole	25° 23′ 21.63″	28° 09′ 48.10″	1 109 m
HMS 07	Stinkwater household	Borehole	25° 23′ 11.44″	28° 09′ 37.34″	1 105 m
HMS 08	Stinkwater household	Borehole	25° 22′ 59.48″	28° 09′ 25.62″	1 101 m
HMS 09	Stinkwater household	Borehole	25° 23′ 03.96″	28° 09′ 17.60″	1 101 m
HMS 10	Stinkwater household	Borehole	25° 23′ 16.88″	28° 09′ 16.84″	1 104 m
HMS 11	Stinkwater household	Well	25° 23′ 12.92″	28° 09′ 20.35″	1 104 m
HMS 12	Stinkwater household	Well	25° 23′ 18.66″	28° 09′ 33.58″	1 106 m
HMS 13	Stinkwater household	Well	25° 23′ 25.87″	28° 09′ 08.34″	1 099 m
HMS 14	Stinkwater household	Borehole	25° 23′ 29.29″	28° 09′ 17.91″	1 103 m
HMS 15	Stinkwater household	Borehole	25° 23′ 26.65″	28° 09′ 36.11″	1 107 m

using a discrete analyser for most anions. Various other methods were employed for determination of pH, organics, micro-organisms, colour and other specific parameters, according to Waterlab's methods list.

RESULTS

Fifteen water samples were analysed for a range of 43 different parameters, including EC, pH, TDS, colour, major ions, trace elements, nutrients, organics and bacteria. Table 2 contains the results from this study. The waters are low in salinity, with all concentrations falling well below 1 000 mg/L TDS (mean 537 mg/L, standard deviation 147 mg/L). The pH ranges from slightly acidic to slightly alkaline (mean 7.3, range 6.2–8.3).

The water chemistry is summarised in the Piper plot in Fig. 4. It shows a wide range of ratios of the major dissolved ions. The Mg^{2+} concentration varies the least, staying below 20% of the cations, whereas Ca^{2+}, and Na$^+$ + K$^+$, both have ranges of around 80%. Variation amongst the anions is more even, with SO$_4^{2-}$ the lowest at 40% and HCO$_3^-$ + CO$_3^{2-}$ the most, at about 80%.

Tap water is seen to have a very consistent major ion composition and the shallow hand-dug wells moderately consistent, although this is probably related to the low number of samples (3). The boreholes display a wide range of major ion composition. The TDS and Cl$^-$ are well correlated, with a Pearson's *r* value of 0.74, whereas TDS and alkalinity (as CaCO$_3$) have $r = 0.31$, but with only one outlying point (HMS13) removed, the *r* value becomes 0.66. TDS and Na$^+$ also show a good correlation, with $r = 0.74$, however, SO$_4^{2-}$ and K$^+$, Mg^{2+} and Ca^{2+} show weak or non-existent correlations with TDS. The major ion water chemistry is clearly complex.

Figure 5 shows several scatter plots of the more interesting or important analytes, in terms of pollution or health studies. In these graphs it becomes apparent that there is a lot of variation in critical parameters that have environmental or human health consequences, yet there is little real correlation. In Fig. 5.1, TDS and NO$_3^-$ show a very weak correlation, with a Pearson's *r* value equal to 0.45, which is not considered significant. The best correlation is seen in Fig. 5.2, where Cl$^-$ and NO$_3^-$ record an *r* value of 0.63, which is a moderate positive correlation. Coliforms and NO$_3^-$, shown in Fig. 5.3, show a barely significant correlation with *r* of 0.55. Lastly, in Fig. 5.4, F$^-$ and Cl$^-$ show no correlation, with *r* equal to −0.24.

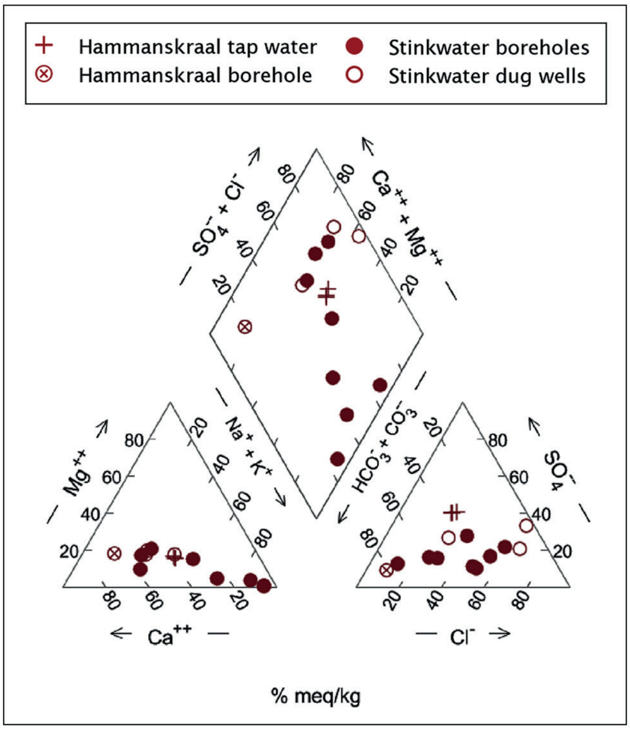

Figure 4
Piper plot of all samples

TABLE 2
Water quality results

mg/L (unless specified)	SANS 241:2015 Limits	Sample ID – HMS														
		1	2	3	4	5	6	7	8	9	10	14	15	11	12	13
pH @ 25°C	≥ 5 to ≤ 9.7	7.6	7.5	7.4	7.6	7.4	7.6	8.3	7.8	6.2	7.9	6.6	7.1	7.5	6.2	6.6
EC, mS/m @ 25°C	≤ 170	78.2	79.9	79.7	33.6	94.3	119	104	93.2	45.6	95.1	45.6	63.8	77.7	66.0	122
TDS @ 180°C	≤ 1 200	500	490	482	230	622	788	670	588	406	572	354	560	524	502	774
Colour, PtCo Units	≤ 15	23	23	27	13	7	6	5	3	2	93	2	1	15	4	11
Turbidity, N.T.U	≤ 1 / ≤ 5	0.6	0.5	2.0	5.0	16	1.0	1.4	0.2	0.6	39	6.9	0.6	5.5	1.5	2.3
Total alkalinity $CaCO_3$	---	200	204	180	152	200	244	460	272	40	348	48	108	224	44	20
Chloride, Cl	≤ 300	87	85	91	11	161	166	49	92	46	95	88	80	93	136	204
Sulphate, SO_4	≤ 500 / ≤ 250	69	69	68	5	16	60	24	24	7	29	16	9	41	21	53
Fluoride, F	≤ 1.5	0.4	0.4	0.3	1.6	1.0	1.6	14	10	< 0.2	11	0.3	0.4	0.8	< 0.2	0.2
Nitrate, N	≤ 11	8.8	8.3	9.6	0.1	15	25	0.1	7.0	29	0.1	11	28	7.7	19	53
Nitrite, N	≤ 0.9	0.1	0.09	1.2	< 0.05	0.4	0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.08	< 0.05	< 0.05	< 0.05	< 0.05
Nitrate & Nitrite	≤ 1	0.9	0.9	2.3	< 0.1	1.8	2.3	< 0.1	0.7	2.7	< 0.1	1.1	2.6	0.7	1.7	4.9
Free cyanide (µg/L)	≤ 200	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Total organic carbon, C	≤ 10	7.6	7.6	5.7	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	<1.0	< 1.0	1.2
Phenols (µg/L)	≤ 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Chloroform (µg/L)	≤ 300	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Bromoform (µg/L)	≤ 100	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Dibromochloromethane(µg/L)	≤ 100	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Bromodichloromethane (µg/L)	≤ 60	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Combined trihalomethanes	≤ 1	0.18	0.19	0.15	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	<0.10	< 0.10	< 0.10
Total colifom bacteria/(100 mL)	≤ 10	0	0	3	2	2	33	35	3 300	460	1	0	45	7200	9 600	13 000
E. coli/(100mL)	Not detected	0	0	0	0	0	2	0	1	0	0	0	0	19	78	17
Free & saline ammonia, N	≤ 1.5	6.4	7.7	2.7	0.1	0.4	< 0.1	< 0.1	< 0.1	< 0.1	0.2	0.1	< 0.1	0.1	0.1	0.1
Sodium, Na	≤ 200	81	82	81	15	116	244	238	170	25	200	24	53	58	28	99
Potassium, K	---	14.8	14.8	14.2	3.1	12.6	2.4	2.3	7.7	11.0	4.1	14.8	7.5	14.1	25	24
Calcium, Ca	---	43	42	43	40	38	7	7	32	35	12	30	56	62	46	55
Magnesium, Mg	---	17	17	18	11	18	1	1	6	11	4	13	9	21	18	25
Aluminium, Al (µg/L)	≤ 300	< 100	< 100	128	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	268	< 100	< 100
Antimony, Sb (µg/L)	≤ 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	<20	< 20	< 20
Arsenic, As (µg/L)	≤ 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	18	< 10	< 10	<10	< 10	< 10
Barium, Ba (µg/L)	≤ 700	< 25	< 25	< 25	499	319	261	140	332	581	123	532	613	534	533	92
Boron, B (µg/L)	≤ 2 400	114	116	114	43	57	51	361	207	25	256	31	27	55	< 25	< 25
Cadmium, Cd (µg/L)	≤ 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	<3	< 3	< 3
Chromium, Cr (µg/L)	≤ 50	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	<25	< 25	< 25
Copper, Cu (µg/L)	≤ 2 000	184	< 10	711	< 10	< 10	< 10	< 10	< 10	12	< 10	< 10	< 10	<10	< 10	< 10
Iron, Fe (µg/L)	≤ 2 000 / ≤300	67	97	117	441	693	88	71	56	59	4 281	454	80	169	44	66
Lead, Pb (µg/L)	≤ 10	< 10	< 10	< 10	< 10	17	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Manganese, Mn (µg/L)	≤ 400 / ≤ 100	59	90	117	72	52	70	< 25	< 25	< 25	66	84	< 25	<25	< 25	< 25
Mercury, Hg (µg/L)	≤ 6	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1	1	< 1	< 1	<1	< 1	< 1
Nickel, Ni (µg/L)	≤ 70	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	< 25	<25	< 25	< 25
Selenium, Se (µg/L)	≤ 40	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	<10	< 10	< 10
Uranium, U (µg/L)	≤ 30	< 1	< 1	< 1	< 1	1	1	< 1	2	< 1	1	< 1	< 1	3	< 1	< 1
Zinc, Zn	≤ 5	< 0.025	0.114	0.268	0.029	1.12	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	0.067	0.038	0.051	0.115
% Balancing	---	96.1	96.8	96.4	98.7	93.5	93.4	95.7	99.3	96.5	94.7	93.3	95.3	94.9	92.8	93.6

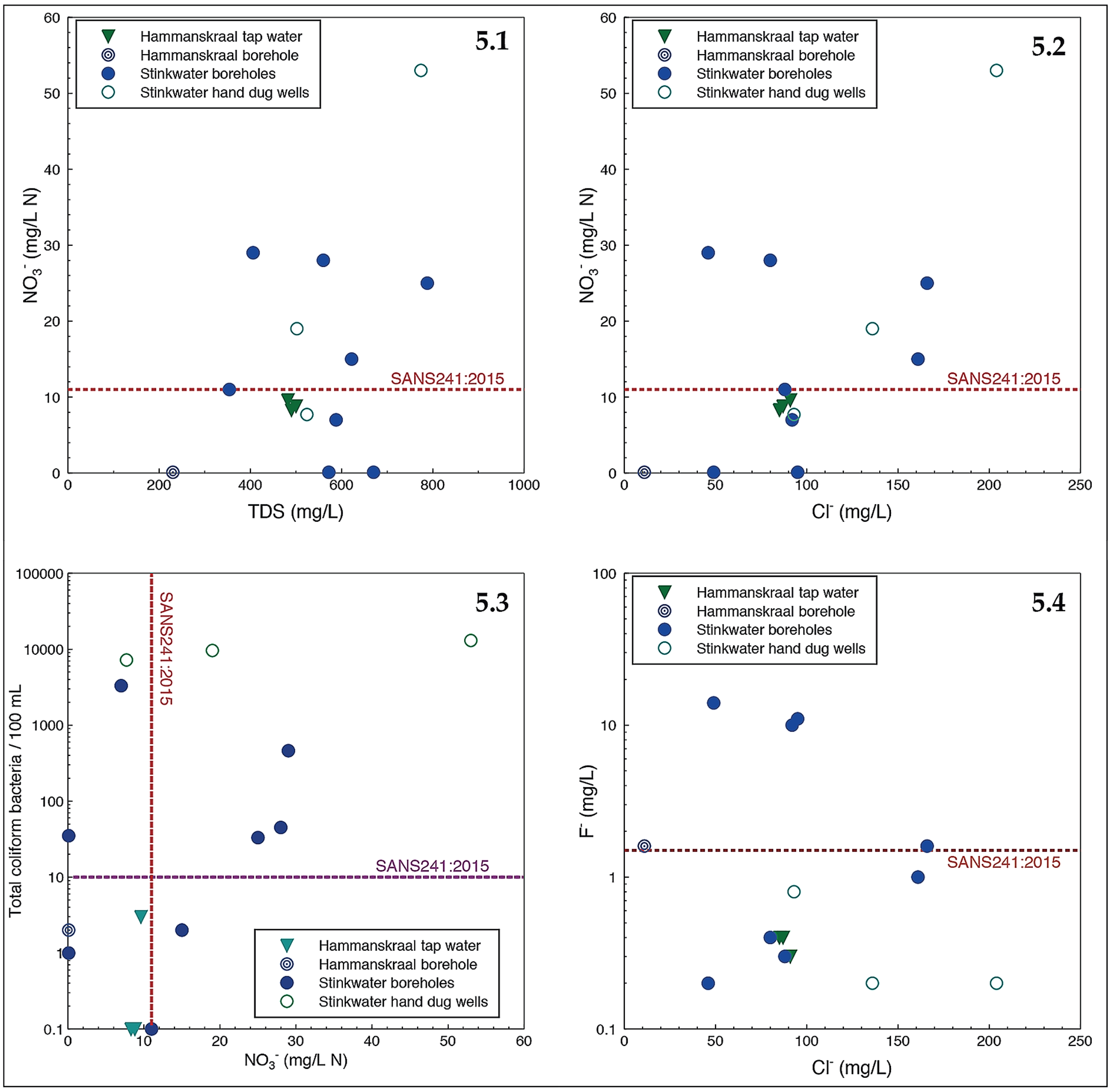

Figure 5

Scatter plots of several water quality parameters of environmental and health interest, including water quality guideline limits

Figure 5 also shows the South African National Standard 241-1:2015 (SABS, 2015) for drinking water limits. For NO$_3^-$, the limit is exceeded in 4 of the boreholes and 2 of the hand-dug wells. For the total coliform bacteria, the limit is exceeded in 5 of the boreholes and all 3 of the hand-dug wells. For *E. coli* (not plotted), the standard (which is any detection at all) is exceeded in 5 of the samples, 3 of which are the hand-dug wells. Levels of bacteria in the 3 hand-dug wells are extremely high, constituting an acute health risk. For F$^-$, the limit is exceeded in 5 of the boreholes, one of which is the Hammanskraal borehole. The water clearly has some significant health risks associated with drinking it, both for short- and long-term consumption.

DISCUSSION

Figure 6 shows the water quality of 7 parameters at the boreholes and hand-dug wells in Stinkfontein. The most obvious thing about this image is the lack of geographic pattern in the distribution of any one of these seven water quality parameters. In fact, the degree of variation is remarkable given the similarity in geology beneath the site: it is all underlain by Nebo Granite. Furthermore, there are no strong co-variations between the parameters, as was partly outlined above in the results section by analysing the correlations using the Pearson's *r* coefficient.

Land use across the site is mainly residential, but, as seen in Fig. 3, there are a few other land uses, such as cemeteries and schools. There are also other operations, such as animal feedlots and open dump sites that may be potential sources of groundwater contamination, or at least have the ability to influence the groundwater hydrochemistry.

Unfortunately, information on borehole depth and construction was not available, and similarly for age of the borehole, historical and current usage of the groundwater, or even water levels, as boreholes were sampled from taps connected directly to the pump. Geological logs were also not available, so a detailed examination of the water quality data cannot be done in the context of the geology or hydrogeology. One can therefore only speculate on possible causes of the

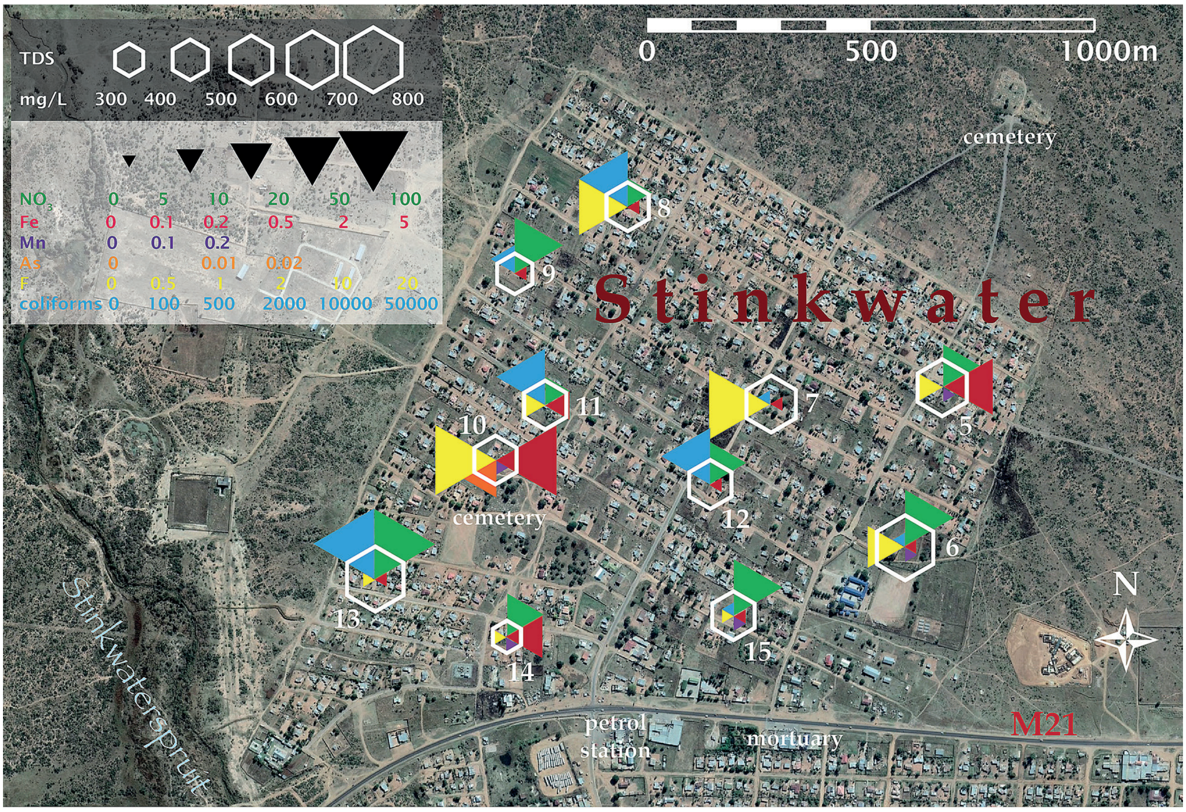

Figure 6
Map of Stinkwater with selected hydrochemistry depicted. The lack of spatial patterns in the data should be apparent. Results below detection limits are not shown.

variation in water quality. As an example, the only borehole (HMS10) with detectable As (above 0.01 mg/L), which, at 0.18 mg/L, was also above the SANS limit of 0.01 mg/L, is adjacent to a small cemetery. Cemeteries are not known to produce much groundwater pollution (Dippenaar, 2014b) although enrichments in certain trace elements, including As, have been reported (Amuno and Amuno, 2014).

The most serious water quality issues revealed in this study are, in order of increasing severity: iron, nitrate, fluoride and coliform bacteria. Iron levels are of real concern only in the arsenic-bearing borehole and of minor concern at a few other sites, and are largely at the level of aesthetic concern regarding water taste. Nitrate is not an accumulative toxin and its danger to infants, pregnant mothers or normally healthy people is not well proven. Manassaram et al. (2006 p. 320) state: 'The epidemiological evidence of a direct exposure-response relationship between drinking water nitrate level and adverse reproductive effect is still not clear.' However, other studies have implicated nitrate, such as for colon cancer (Van Grinsen et al., 2010). The topic is still very much open for further research and debate (Powlson et al., 2008).

Fluoride has very specific health effects in bones and teeth, with optimal levels ensuring strength and flexibility, whereas fluoride concentrations that are too low or too high cause different forms of fluorosis, resulting in discoloured, weak and brittle teeth and bones. The optimal level varies according to the individual and their total fluoride exposure through diet and topical applications, such as toothpaste usage. Studies in South Africa (Chikte et al., 2001) and elsewhere (McGrady et al., 2012) indicate levels of around 0.5 mg/L in drinking water are suitable, whereas levels from 0.9 mg/L upwards are not ideal, suggesting that the SANS 241 limit of 1.5 mg/L is perhaps a bit high. Fluoride levels in 5 of the samples are too high for optimal health, 3 of which are at the level which will likely cause debilitating effects.

The *Escherichia coli* bacterium was detected in 5 of the 8 samples in which the coliform bacterial counts exceeded the SANS 241 guidelines. Note that any detection at all for *E. coli* is considered an exceedance, whereas for total coliforms, the limit is 10 per 100 mL. There are 4 samples where coliforms were detected, but at an amount below 10 per 100 ml. There are only 3 samples (2 of which are tap water) where no coliforms were detected. The real concern, however, is the 4 samples which have total coliforms well above 1 000 per 100 mL, one of which is above 10 000 per 100 mL. The health effects of drinking such water are potentially fatal.

The most obvious correlation is that the 3 hand-dug wells contain the worst water quality in terms of bacterial properties. This is easily explained by their open nature, in which surface runoff, or soil interflow containing animal (including human) faecal matter is able to recharge the well water. Animals, including dogs, cats, goats and cattle, roam freely and humans use pit latrines for sanitation. These provide abundant sources of bacterial contamination.

The common occurrence of high nitrate in the groundwater is also easily explained by the above array of possible sources; however, the lack of correlation between the bacterial and nitrate contamination demands another explanation. Katz et al. (2010), when researching groundwater in an area of abundant septic tanks, found highly variable depth profiles of NO_3^- and

Cl^-, and concluded that water use and minor lithological differences in the unsaturated zone were probably causes of differences in hydrochemistry. They calculated that about 25–40% of nitrate was denitrified during movement through the unsaturated zone. More specifically, Gill et al. (2008) found that differences in permeability controlled the denitrification rate, with more permeable soils resulting in less denitrification. It is possible that minor differences in water table depth, water usage and vadose zone permeability could give rise to the large range of nitrate concentrations measured. Greater depth to the water table, lower water usage and infiltration at surface, and lower vadose zone permeability, may all contribute to increasing the residence time in the vadose zone, and therefore the denitrification potential.

CONCLUSIONS

In an area underlain by sandy soils derived from the Nebo Granite, large differences in water quality, specifically those with health implications, were detected in several nearby boreholes and open wells. The main health concerns are related to high levels of nitrate, fluoride and coliform bacteria, in concentrations such that chronic, acute and potentially fatal effects could occur. Correlations, both geographic and geochemical, were few, suggesting a complex range of hydrochemical processes taking place in this small area. Likely causes of the complexity include the spatial distribution of pollution sources, the variety of possible sources, the quantity of water use at each sample location, permeability differences and variations in interflow and recharge pathways in the unsaturated zone, resulting in variation in potential for denitrification, adsorption and other processes to attenuate or mix the pollutants.

The study revealed that, within a single village, groundwater quality can vary from drinkable to very dangerous, almost on a house-by-house basis. Reliance on a water quality analysis from a single borehole to determine the general state of groundwater would be inadequate. Without strict control of land use (dumping, stock animals, pit latrines, etc.), thorough and detailed groundwater monitoring is essential to ensure safe usage of the water resource. Considering the expense and expert input required for such monitoring, analysis and interpretation, water source protection measures, including land use and water use regulation, offer the best solution to protecting human and environmental wellbeing.

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