



Continuous assessment of drinking and surface water quality: Addressing the key challenges to sustainable water access in Makhanda, Eastern Cape, South Africa

Siphumze Bani¹, Sandile M. M. Khamanga¹, Roman Tandlich^{1*}, Brendan Wilhelmi²

*r.tandlich@ru.ac.za; roman.tandlich@gmail.com

¹Rhodes University, Faculty of Pharmacy, Artillery Road, P.O. Box 94, Makhanda, 6140, South Africa

²Rhodes University, Department of Biochemistry and Microbiology Artillery Road, P.O. Box 94, Makhanda, 6140, South Africa

ORCID:

S. Bani <https://orcid.org/0000-0002-4255-7451>

S. M. M. Khamanga <https://orcid.org/0000-0003-2374-8460>

R. Tandlich <https://orcid.org/0000-0002-9696-0473>

B. S. Wilhelmi <https://orcid.org/0000-0002-7854-891X>

Authors' Contributions:

BS: Sample collection and analysis; Data processing; Statistical analysis; Writing — original draft.

KSM: Expertise on the electronic tongue analysis of the water samples.

TR: Data analysis; Writing — original draft, review & editing.

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The small city of Makhanda has been facing issues of limited water access over the years, which badly affect public health, well-being, and socioeconomic functioning. This observational study encourages the continuous assessment of drinking and surface water quality as an approach to communicating and finding solutions to these challenges. Water samples from site 3 had no fecal coliforms, however, 0.42 ± 0.09 CFU/100 ml of total bacteria was observed to be resistant to ampicillin, chloramphenicol, doxycycline, penicillin G and sulfamethoxazole, and susceptible to ciprofloxacin, kanamycin, and rifampicin. The Gram-staining and potassium hydroxide test techniques revealed the bacteria to be *Staphylococcus aureus*. In addition to the conventional physicochemical quality parameters, the potentiometric electronic tongue instrument was employed to analyse the aesthetic quality (taste). The drinking water samples from sites 3 and 4 were bitter and sour, respectively, while water samples from sites 1, 2 and 6 were sweet, and sites 5, 7, and 8 had an umami taste. The taste profiles correlate with drinking water's microbial and physicochemical quality and can be used to predict long-term health risk conditions such as nephrolithiasis. Continuous microbiome and antibiotic resistance profiling are essential to predict and quantify public health risks in drinking and surface water.

Keywords: electronic tongue, water quality, fecal coliforms, continuous assessment

Introduction

Over the years, many South African communities have faced serious challenges in maintaining consistent and sustainable access to water, sanitation, and hygiene (WASH) [66, 74, 84, 99]. According to the Department of Water and Sanitation (DWS) 2024 intranet database, the Eastern Cape Province has lowest (44 %) reliability to water access and is where the city of Makhanda is located. These challenges badly affect the local community's health, well-being and socioeconomic functioning, for instance during the week of 2nd to 8th February 2025, there

was a municipal water cut-off which badly affected orientation of first year students at Rhodes University, while on the 26th February 2025 the residents and Rhodes University students organised a march to the Municipality to complain about water access and sanitation services.

The significant triggers to these challenges include the ageing and incapacitating water infrastructure that leads to wasting and microbiological contamination of potable water due to bursting freshwater distributing and sewage pipes [20, 25, 95]. The students and local residence have normalized buying water from local vendors. The bursting of sewage pipes is not only causing contamination of

drinking and surface water, it also creates serious health risks to humans and the environment. For instance, ponding sewage can result in dermatological infection, accidental inhalation, mosquito breeding, and offensive smell. The contamination of potable water from municipal taps or vendors and surface water from rivers is making local communities vulnerable and prone to waterborne diseases such as cholera and diarrhoea [13, 22, 34, 81, 99].

Other pressing issues include the improper solid waste management and limited availability of public toilets in key areas like the town centre and taxi ranks; this leads to open defecation and further contamination of surface water and the environment. Additionally, the inconsistent water supply and climate change (drought) are causing communities to be subjected to food insecurity and malnutrition because many residents rely on community gardens and subsistence agriculture to source healthy and affordable vegetables [76].

The preliminary efforts on awareness of climate change impacts (*i.e.*, prolonged drought and unpredicted floods) have been put to encourage sustainable water resource management [24, 53, 55]. For instance, studies by [36], [54], [72], and [79] conducted an assessment of climate change resilience strategies from small farmers and commercial sugar producers while [10] suggested a framework for sustainable water management in the agricultural sector for climate stressed regions. Particularly in Makhanda, the study conducted by [82] reported awareness and resilience of the communities towards climate change effects. However, the local municipality retards in communicating and formulating water management strategies and supply challenges respectively. The findings from [44], [62], [82], and [93] indicate the need for ongoing assessment of water availability, quality and reuse perceptions in South African communities.

Apart from the climate change impacts, predictions and solutions, the most critical indicators of WASH are the availability and quality of drinking and surface water [110]. Continuous updates on the availability and quality of water ensure sustainable public health and confidence, stress relief, and preparedness, especially during disasters such as COVID-19 [101]. Different approaches and targets are used in microbial and physicochemical analysis depending on the type of water; for instance, [81] suggested consistent observation of cholera causing pathogens in surface waters while [46] and [92] reported presence of antibiotic resistance *E. coli* strains and high concentration levels of metals in rainwater respectively. Rainwater is the main source of drinking water in local communities, hence continuous surveillance of health risks using advanced techniques is recommended [65].

The addressed challenges require the government and municipalities to renovate and ensure a capacitating water distribution infrastructure [71, 108]. The local Municipality needs to engage firmly with private institute(s) to educate and encourage communities to be aware and resilient to the climate change impacts; this needs to be conducted concurrently with the implementation of water

conservation, treatment and reuse technologies [30, 70, 78, 104]. There is a need for accredited and active water quality testing laboratory that can be supported through the engagement and partnering of the Municipality and private institute(s) [35]. Additionally, implementing sanitation services and adequate solid waste management can significantly reduce microbial and physicochemical pollution of surface and ground waters [91]. Overall, continuous expansion of previous studies [69, 46, 75, 78, 82, 100, 101] is recommended.

Therefore, the aim(s) and objectives of this study are based on communication of the challenges affecting reliable and sustainable WASH in local Makhanda. The implementable and previously suggested solutions to the addressed WASH challenges are reviewed. The contributing components include microbiological and physicochemical analysis of drinking water from local sources (*i.e.*, vendors, communal spring, and private household sources). The taste analysis of drinking water using electronic tongue instrument is noted to be aesthetic while informing potential health risks overtime. The analysis of surface water quality is also conducted to substantiate the challenges of bursting sewage networks, insufficient sanitation services, and improper solid waste management. The severe contamination of surface water is observed to have potential health risks to the downstream local communities (*i.e.*, farmers) that are likely reusing for irrigation, toilet flushing, and livestock drinking. Overall, this study encourages ongoing implementation of reliable water access and quality surveillance approaches across the South African communities.

Materials and Methods

Literature review

The literature review of this research paper was conducted by exploring studies that focus on communicating WASH challenges, resilience and perceptions about climate change impacts, and sustainable availability and quality of drinking water in local and other South African communities. The Introduction section is composed of 40 sources while in the Materials and Methods, and Results and Discussion sections there 4 and 74 cited sources respectively.

Aseptic sampling of the water samples

Drinking water sampling was conducted using sterile bottles in the same manner as a typical local citizen at all the sites (fig. 1), including local drinking water vendors (**sites 1–4**), a local spring (**site 5**), and private household sources (**site 6**: reverse osmosis system, **site 7**: tank, **site 8**: tap). The sites 1–4 were selected because they are at the centre in Makhanda and are accessible and popular to students and local residents. The local/communal spring (site 5) was sampled because some and sometimes most community members source free drinking water due to municipal

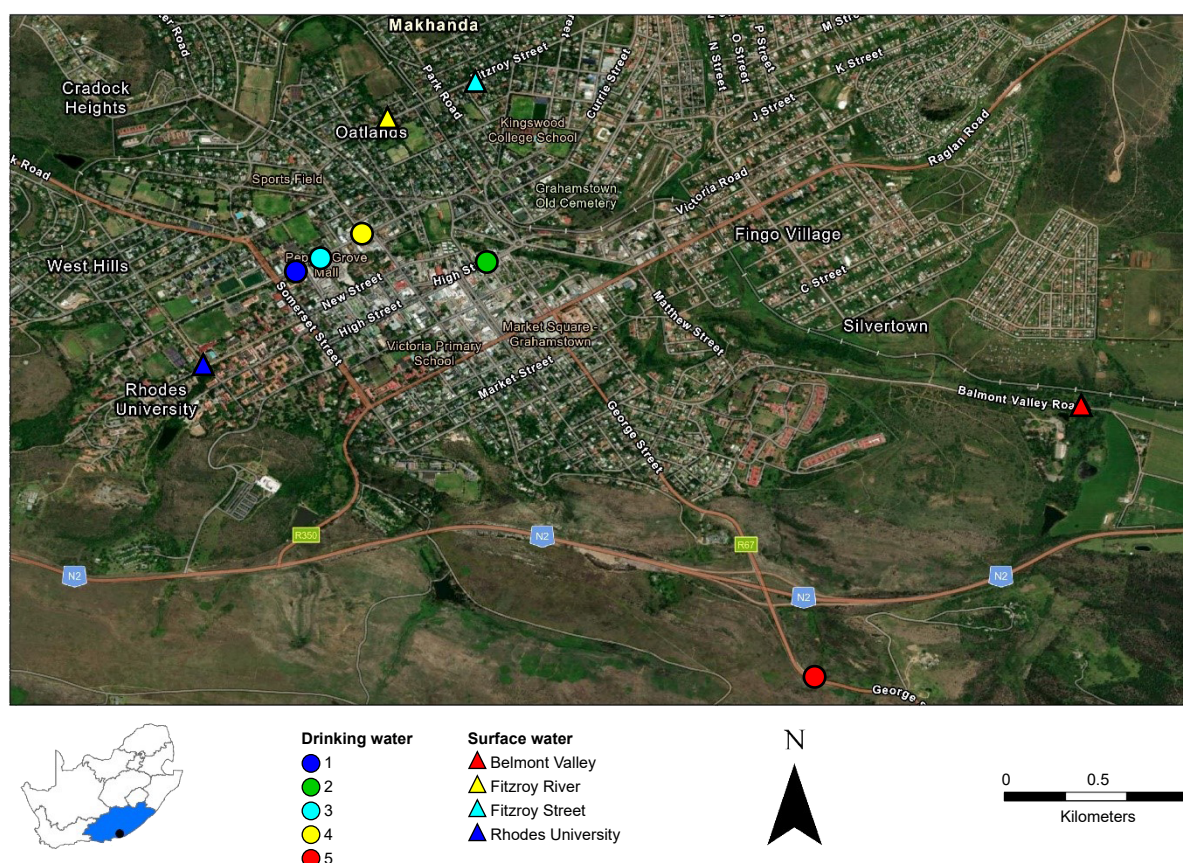


Fig. 1. Map of drinking and surface water sampling sites in Makhanda, Eastern Cape, South Africa.

This map was formulated using Garmin (GPSMAP 62 Series) and ArcGIS Pro software (Geography Department, Rhodes University).

Nota bene: The sites 6, 7 and 8 are not shown on the map because they are private household water sources

water outages, taste preferences, and cultural beliefs. The sites 6, 7, and 8 were voluntary selection as the private household owner allowed sampling and analysis of their drinking water. The sites (6, 7 and 8) are important because they represent typical drinking water from Makhanda resident.

As such, there was no need for formal Ethical clearance, commonly required for Scientific sampling. We took the opportunity to sample as local citizens to reflect the community's everyday practices. The time spent at each sampling site was recorded; this was necessary to predict the over-crowding, demonstrating the demand for drinking water and the potential for contamination due to compromised hygiene practices. Once collected, the samples were quickly transported to the laboratory for immediate microbial and physicochemical analysis.

Surface water sampling was conducted during the heavy rainy days between October and December 2024. Concurrently, temperature measurements were taken at each sampling site. The sampling sites (fig. 1) included Fitzroy Street, road drain gully (cyan triangle), Fitzroy River (yellow triangle), Belmont Valley River (red triangle) and Rhodes University, road drain gully (blue triangle). As visible in fig. 1, the sampling sites (Fitzroy Street and Fitzroy River) are representing the environment and infrastructure in the upstream communities while Rhodes

University represents the impact of surface pavement and sewage leaks on campus. The downstream communities (i.e., farmers) are represented by Belmont Valley River. Overall, the conducted sampling and analysis of both drinking water and surface water is related to the guidance of the International Organisation for Standardization (ISO) standards listed in [109].

Quality analysis of the water samples

Microbiological analysis. The microbial quality included total bacteria and fecal coliform analysis, which were performed using standard protocols as described in previous studies [6, 77, 114]. The analysis of total bacteria was conducted aseptically by spread plating 100 μ l of the water samples (after necessary serial dilution using 1x Phosphate Buffer Saline) onto Nutrient Agar plates (Sigma-Aldrich) followed by incubation at 37 °C. Enumeration of colonies was performed after 24 hours followed by calculation of colony forming units (CFU/100ml) using the standard equation. The analysis of fecal coliforms was conducted by aseptically filtering 100 ml of the water samples. The filter paper (Pall-GN-6 Metrical membrane, diameter 47 mm, pore size 0.45 μ m, Pall Corporation) was then placed in membrane-Faecal Coliform agar plate (m-FC agar) (Biolabs) followed by incubation at 44.5 $\pm$ 0.5 °C for 24 hours. Enumeration of blue colonies

was performed and colony forming units (CFU/100ml) were calculated. The antibiotic resistance screening in drinking water samples was carried out by aseptic spread plating 100 µl onto nutrient agar plates followed by placing of the antibiotic discs (*Oxoid™*) (3 discs per sample). After incubation at 37 °C for 24 hours, zone of clearance or microbial growth around the antibiotic discs was observed [46]. Further evaluation of the cell wall characteristics of the antibiotic resistant Total bacterial colonies that were observed in site 3 drinking water sample was conducted by standard gram-staining technique and further confirmed using the potassium hydroxide (KOH 3 %) test, which was performed as described in the video from <https://youtu.be/Ldm-UE5aFRI?si=8dzd5dmr5dq40NYq>.

Physicochemical analysis. The analysed physicochemical quality parameters included electrical conductivity (EC) (mS/cm), pH, total suspended solids (TSS) (mg/L), turbidity (NTU) and surface tension (mN/m). Except for the surface tension and electronic tongue tasting, all the analysed physicochemical parameters were conducted using the protocols described by Bani et al. [6]. The surface tension was analysed using a KRUSS tensiometer at room temperature, using distilled water and sodium lauryl sulphate (0.05 M) as standards.

Electronic tasting of drinking water samples from sites 1–8 was conducted using the *Alpha MOS (Astree)* instrument. Prior to the tasting, the instrument sensors were calibrated using deionised water, HCl (0.01 M), NaCl (0.01 M) and monosodium glutamate (MSG) (0.01 M). The calibration occurred over 4 hours according to the standard operating procedure. It was important to ensure that the instrument sensors were conditioned (hydrated), sensitive (able to test and reproduce) and diagnostic (able to differentiate different ions) to the taste of the water samples using the respective taste sensors, which are sourness (AHS), saltiness (CTS), umami (NMS), sweetness (ANS), bitterness (SCS) and complex (PKS and CPS). With the aid of the instrument, the blank/reference sample (type 1 MilliQ water) and water samples (site 1–8) were labelled and colour coded as site 0 (blue), site 1 (red), site 2 (lemon), site 3 (pink), site 4 (yellow), site 5 (cyan blue), site 6 (green), site 7 (light red), and site 8 (light purple). The analysis/tasting of the water samples occurred over 5 hours.

Data analysis and presentation

The microbial quality parameters (total bacteria (TB) and fecal coliform (FC)) counts are presented as geometric mean $\pm$ standard deviation, while the physicochemical parameters are presented as mean $\pm$ standard deviation. The statistical analysis was performed using ONE-WAY ANOVA at a 5 % significance level to evaluate differences between sampling sites regarding microbial and physicochemical parameters. Calculations and statistical analysis were all conducted using *Excel (Microsoft Office Professional Plus 2019)*.

The results of the electronic tasting of drinking water are presented sequentially; the Principal Component

Table 1. Distance table across the water samples

Sample (Site)	Compared samples	Distances	Pattern discrimination index, %
Site 0	Site 1	1562.24	93.92
Site 0	Site 2	1977.50	96.68
Site 0	Site 3	2239.25	97.56
Site 0	Site 4	455.08	53.52
Site 0	Site 5	1999.29	98.68
Site 0	Site 6	1744.00	95.89
Site 0	Site 7	2457.23	98.22
Site 0	Site 8	2311.28	97.86
Site 1	Site 2	678.49	83.74
Site 1	Site 3	742.82	87.29
Site 1	Site 4	1199.30	91.41
Site 1	Site 5	1152.14	93.48
Site 1	Site 6	478.59	72.78
Site 1	Site 7	1221.02	95.86
Site 1	Site 8	1223.57	95.41
Site 2	Site 3	549.44	84.23
Site 2	Site 4	1570.05	95.68
Site 2	Site 5	658.97	86.33
Site 2	Site 6	538.08	82.40
Site 2	Site 7	602.00	89.49
Site 2	Site 8	589.95	87.84
Site 3	Site 4	1871.11	97.16
Site 3	Site 5	1161.12	95.76
Site 3	Site 6	607.14	87.47
Site 3	Site 7	732.66	94.45
Site 3	Site 8	958.34	95.91
Site 4	Site 5	1612.10	95.78
Site 4	Site 6	1363.16	94.53
Site 4	Site 7	2074.86	98.04
Site 4	Site 8	1922.07	97.52
Site 5	Site 6	1093.59	94.84
Site 5	Site 7	803.44	93.65
Site 5	Site 8	433.63	78.53
Site 6	Site 7	983.14	96.33
Site 6	Site 8	1082.95	96.35
Site 7	Site 8	417.18	88.25

Analysis (PCA)/Discrimination index graph (fig. 2) is presented along with the distance table (table 1) to show the relationship between the reference sample (site 0) and the water samples (site 1–8) in terms of their overall taste. The mean sensor graph and the radar plot (fig. 3AB) show the intensity of taste parameters across the reference and water samples. The sensor graph for individual water samples and taste screening radar plot (fig. 4AB) indicates the dominant taste parameter for each water sample. The numerical data for the taste composition of the individual water samples is shown in table 2 as mean $\pm$ standard deviation (SD) (n=3); the presentation of the relative standard deviation (%) is omitted because it confirms the precision of the data points and is calculated from the SD. The ranking of the taste screening is shown in table 3, which shows the taste score of the water samples.

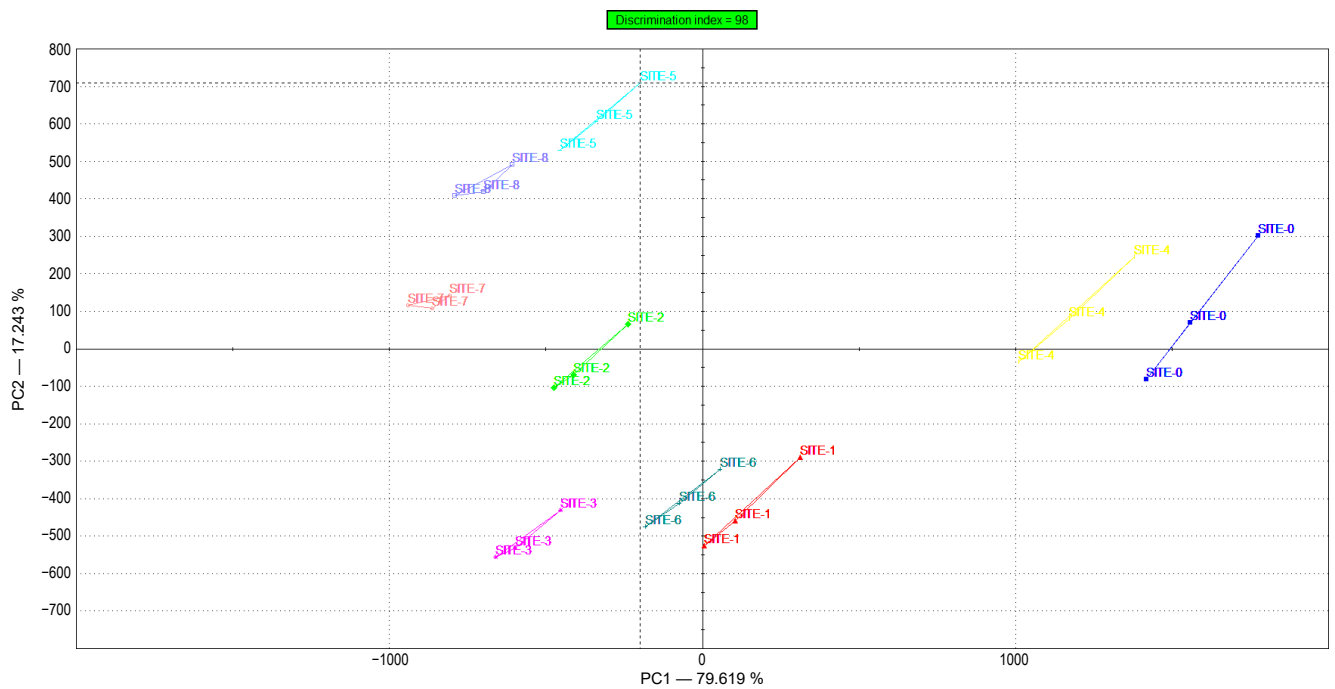


Fig. 2. Principal component analysis of the water samples

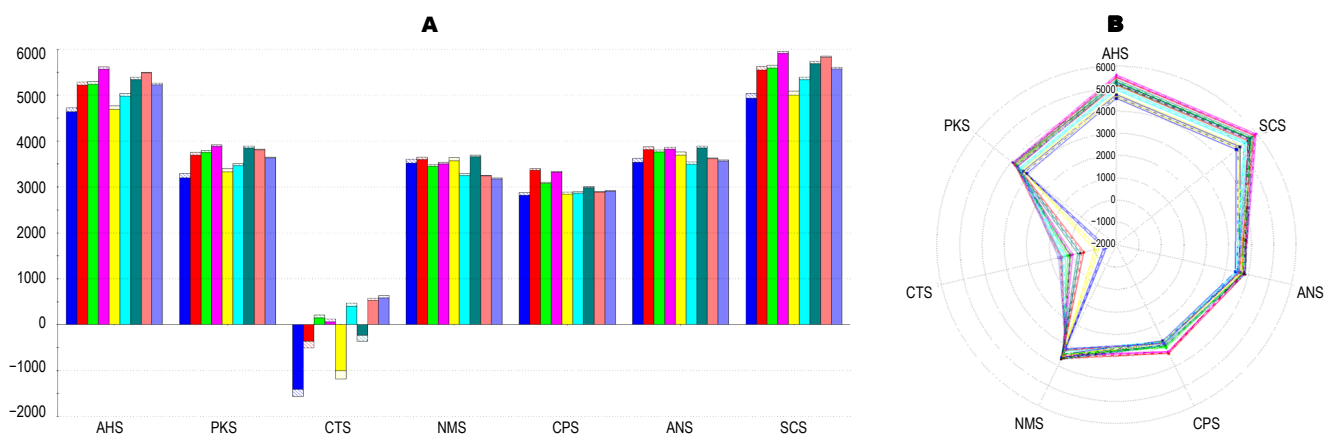


Fig. 3. A — average intensity of taste parameters of the reference and water samples; B — radar plot showing shifting of the water samples towards dominant taste parameters (AHS and SCS). Amongst the water samples, site 3 water sample had highest intensity of AHS and SCS

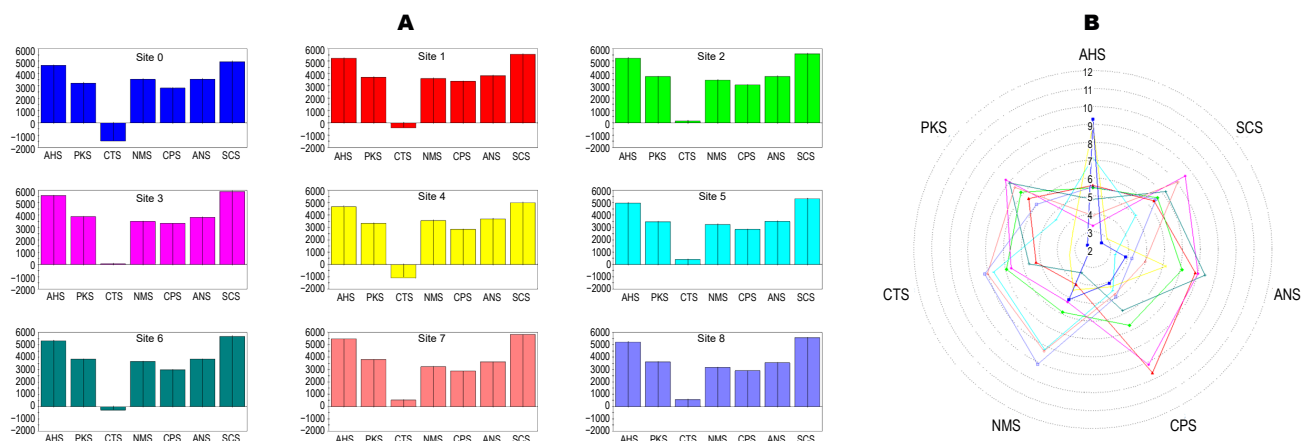


Fig. 4. A — sensor bar graph showing taste screening for individual water samples; B — radar plot showing taste screening for individual water samples

Table 2. Intensity of taste parameters in individual water samples

Sample (Site)	Parameters (Mean±SD)						
	AHS	PKS	CTS	NMS	CPS	ANS	SCS
Site 0	4640.32±87.29	3204.00±89.50	-1489.13±74.28	3619.04±85.73	2822.20±56.77	3536.62±91.15	4938.04±103.27
Site 1	5217.52±75.79	3693.39±58.13	-434.59±75.77	3600.09±54.75	3368.72±35.00	3813.69±60.50	5549.49±74.57
Site 2	5238.77±55.36	3757.63±39.29	152.50±61.64	3451.19±39.28	3078.54±28.97	3761.31±45.14	5593.89±59.68
Site 3	5570.60±43.81	3884.72±34.88	60.95±60.52	3505.17±35.36	3318.41±21.646	3824.09±40.64	5914.57±41.36
Site 4	4689.13±83.25	3328.63±67.13	-1093.73±94.24	3570.93±67.33	2843.60±45.92	3697.24±66.90	5000.43±88.32
Site 5	4977.98±58.35	3468.47±42.68	401.95±68.01	3250.75±42.21	2866.23±29.07	3495.67±48.12	5339.78±56.57
Site 6	5339.60±51.29	3853.05±38.75	-295.58±65.02	3662.09±34.67	2987.45±26.14	3851.84±40.10	5686.11±51.73
Site 7	5484.75±16.32	3811.26±11.89	529.00±49.38	3241.41±14.79	2889.22±5.40	3614.23±21.13	5830.08±18.36
Site 8	5230.98±31.14	3629.53±22.53	579.93±56.32	3171.47±25.44	2903.93±17.56	3562.07±27.72	5572.80±36.49

Ethical approval statement

According to the current South African legislation, no ethical clearance was required for the current study. This is the case, as not live animals nor any human participants' data were used in the current research. All samples of water were taken in public areas and no access restrictions applied to them. The study contributes to the ongoing data collection on the water quality in Makana Local Municipality.

Data availability statement

The data presented in this article originated from the raw data that is available from the authors upon request. An email can be sent to the corresponding author.

Results and Discussion

As briefly stated in the introduction, this study aims to build on previous studies by offering ongoing assessments of drinking and surface water quality. The current assessment is based on microbiological and physicochemical quality analysis. The analysed quality parameters are evaluated according to the South African National Standard (SANS) 241 [94] Drinking Water Specifications and the South African Water Quality Guideline for Agricultural use [18, 19, 20, 30]. The water quality observations from previous studies are compared with the current observations to predict and detect public health risks over time.

Drinking water

Microbiological quality. Continuous assessment of the microbial quality of water is important because polluted water can cause world-noted diseases such as gastroenteritis, giardiasis, hepatitis, typhoid fever, cholera, salmonellosis, dysentery, and organ/dermatological infections [18, 19, 111]. The risk, exposure, and causes of these diseases are drinking polluted water, making contact during irrigation, and consuming raw vegetables that were irrigated with polluted water. Microbial contamination of water is mainly assessed through quantifying indicator microorganisms such as Total coliform bacteria, Fecal coliform bacteria, *E. coli*, *Enterococci* and bacteriophages [18, 19]. In this present study, total coliform bacteria/total

Table 3. Individual ranking for taste composition of the water samples

Sample (Site)	Parameter ranking, score						
	AHS	PKS	CTS	NMS	CPS	ANS	SCS
Site 0	9.3	2.4	2.2	5.1	4.1	3.9	2.6
Site 1	5.6	6.6	5.2	4.2	9.7	7.9	6.4
Site 2	5.5	7.1	7.0	5.9	6.7	7.1	6.6
Site 3	3.3	8.2	6.7	5.3	9.1	8.0	8.6
Site 4	9.0	3.5	3.3	4.5	4.3	6.2	3.0
Site 5	7.1	4.7	7.7	8.2	4.6	3.3	5.1
Site 6	4.8	8.0	5.7	3.5	5.8	8.4	7.2
Site 7	3.9	7.6	8.1	8.3	4.8	5.0	8.1
Site 8	5.5	6.0	8.2	9.1	4.9	4.2	6.5

Table 4. Microbiological quality of drinking water from Makhanda

Site	Parameters	
	Total bacteria, CFU/100 ml	Fecal coliforms, CFU/100 ml
1	0	0
2	0	0
3	1.0±0.1	0
4	0	0
5	0	0
6	0	0
7	1.0±0.1	1.12±0.1
8	2.0±0.1	1.25±0.1
ANOVA (P-value)	1.20×10 ⁻²	1.70×10 ⁻¹
Quality guidelines		
[94]	0	0
[109, 110, 111]	0	0

bacteria and fecal coliform bacteria are used as indicator organisms to evaluate microbial contamination in drinking and surface waters, for instance, to indicate the presence of *E. coli* which is regarded an acute human health risk [18, 19, 97, 111].

Over the days of sampling, the sampling sites (site 1, 2, 4, 5 and 6) (table 4) had no microbial contamination, while in site 3, 7 and 8, total bacteria of 0.42±0.09, 1.31±0.11, and 1.63±0.11 CFU/100ml was observed respectively. Particularly in site 5, unfavourable microbial growth conditions (consistent water flow) and natural disinfection through sunlight are suspected to be the case.

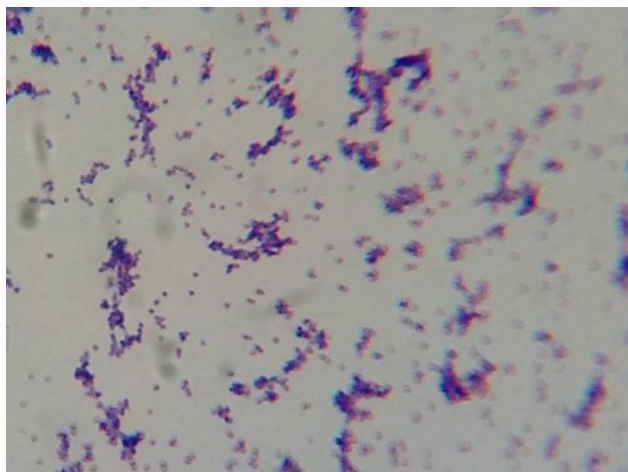


Fig. 5. Gram-staining results of the total bacterial colonies from sites 3. Round morphology is related to *S. aureus*.

The absence of microbial contamination in the water samples from these sites (1, 2, 4, 5 and 6) confirms the safety of the drinking water and adequate maintenance of hygiene practices [97, 111] this has been observed in previous studies [75]. The total bacterial colonies observed in site 3 were analysed using the KOH (3 %) test and Gram staining technique, and they were found to be gram-positive bacteria (fig. 5). Judging by the cell wall characteristics (gram-positive) and circular morphology, the observed bacterial colonies were suspected to be *S. aureus* (fig. 5). The assumption of *S. aureus* presence in drinking water from site 3 is motivated by the observations from previous studies; for instance, [7] and [40] reported drinking water faucet aerator screens to have a potential for *S. aureus* and other bacterial biofilm development while [11] and [89] observed trace concentrations of *S. aureus* in drinking water fountains and bottled water producers. Additionally, the antibiotic resistance studies showed that the Total bacterial colonies from site 3 drinking water samples were resistant to ampicillin (10 µg), chloramphenicol (30 µg), doxycycline (30 µg), penicillin G (10 µg) and sulphamethoxazole (25 µg). In comparison, they were susceptible to ciprofloxacin (10 µg), kanamycin

(5 µg), and rifampicin (30 µg) with 0.1, 3, 1 and 2 cm zone of clearances respectively. However, according to the [94], the observed concentration of the total bacteria (table 4) does not pose a threat to human health. Besides, there is a need for further investigation of the observed colonies, which can be done by re-culturing in *S. aureus* selective media or using the genomic sequencing technique.

According to the [94] and [109, 110, 111], the observed concentrations of fecal coliforms in sites 7 and 8 (table 4) are posing a threat to human health because they are supposed to be not present, while total bacterial concentration is within the acceptable limit because is less than 10 CFU/100ml. The presence of total bacteria and fecal coliforms have been observed in drinking water sources such as rainwater tanks (site 7) and municipal taps (site 8) due to microbial contamination and proliferation during storage and distribution [46, 75, 78, 101]. The statistically insignificant difference across the sampling sites (table 4) is mainly between sites 7 and 8, which indicated significant total bacterial and fecal coliform contamination. Further investigation, such as antibiotic resistance, genomic analysis, and scanning electron microscope, is necessary to profile the microbial strains [46]. Conventional or traditional disinfection methods such as boiling and addition of bleach concurrently with qualitative measurement of bacterial contamination using H₂S kits are recommended approaches to reduce and predict health risks from these water sources [47, 63, 75, 78, 100, 101].

As presented in table 5, the analysed preliminary and basic physicochemical quality parameters included pH, a measure of acid-base balance mainly affected by carbon dioxide, carbonate or bicarbonate levels. No acute health threats are related to the pH of water. However, it is an important parameter to measure because it determines the effectiveness of disinfection and corrosivity that can affect metallic taps and lead to leaching and subsequent consumption of trace metals [110]. In most drinking waters and according to the [94] drinking water specification and [110], the recommended pH ranges between ≥5 to ≤9.7 and 6.5 to 8.5, respectively. The observed pH values of the water samples from all sites are within the recommended standards (table 5). The pH of site 3 water

Table 5. Physicochemical quality of drinking water

Site	Parameters (Mean±SD)				
	pH	EC, mS/cm	TSS, mg/L	Turbidity, NTU	Surface tension, mN/m
1	6.77±0.12	0.03±0.00	0	0	71.27±0.16
2	6.53±0.09	0.06±0.00	0	0	71.23±0.44
3	6.24±0.03	0.06±0.00	0	0	70.84±0.22
4	7.13±0.04	0.01±0.00	0	0	71.27±0.44
5	6.59±0.02	0.11±0.00	10.67±2.28	11.11±1.36	71.30±0.33
6	8.61±0.02	0.03±0.00	0	0	71.17±0.15
7	7.60±0.01	0.18±0.00	0	0	70.90±0.10
8	8.39±0.08	0.16±0.00	0	0	70.70±0.61
ANOVA (P-value)	5.70×10 ⁻¹⁴	3.70×10 ⁻²³	3.40×10 ⁻⁵	3.01×10 ⁻⁸	2.38×10 ⁻¹
Quality guidelines					
[94]	≥5.00 to ≤9.70	≤170.00	Not specified	≤1.00	Not specified
[109, 110, 111]	6.5 to 8.5	≤300.00 to 600.00 mg/L TDS	Not specified	≤1.00	Not specified

sample is probably associated with the optimum condition for the observed *S. aureus* colonies [32] (fig. 5). The observed pH values across the water samples from all sites are related to the observed pH values from previous studies [3]. A significant difference was observed between the pH values across all the water samples (table 4). The pH values of site 7 and 8 water samples seem to have favoured microbial proliferation, showing the need for disinfection (table 4).

To quantify the amount of dissolved inorganic salts or Total Dissolved Solids (TDS) in the water samples, Electrical Conductivity (EC) was measured. The TDS concentration is reported to be an indirect measure or a related measure to EC, which measures the ability of water to conduct an electrical current due to the presence of various ions that include carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium and magnesium. These various ions are present in drinking water for nutritional purposes, particularly in bottled water from vendors (e.g., site 1). At the same time, their presence is natural because the water has passed through a series of rocks and soils (e.g., site 5). Amongst the water samples, the site 4 water sample has the lowest EC. The observed EC in the site 5 water sample is due to the leaching of natural ions from underground rocks and soil, contributing to unfavourable microbial conditions (table 4) and the taste (table 3). The tank plumbing system and municipal tap water distribution network have mainly contributed to the ECs of site 7 and 8 water samples, respectively (table 4). The concentration levels of EC across all the water samples are significantly different (table 4) and are within the acceptable drinking water standard because they do not threaten human health [94, 97].

The Total Suspended Solids (TSS) and turbidity are conjugate parameters useful for quantifying suspended matter and clarity of water, respectively. The presence of TSS and turbidity in site 5 water sample is due to the underground rock and soil particles. These suspended small particles do not pose health risks, and they are rarely ingested because they descend and settle at the bottom of the storage container, a drinking water bottle or larger barrel [75]. Except for the site 5 water sample, the absence of TSS and turbidity in other water samples is due to the efficiency of the treatment methods, which are mainly RO system and settling/filtering during storage (sites 7 and 8). Installation of a filtering treatment system in site 5 is essential for the removal of TSS and turbidity.

Along with the basic parameters, surface tension is mainly based on the connection of the water intermolecular forces and hydrogen bonds. In clean water, strong intermolecular forces result in high surface tension and range from 70 to 72 mN/m at room temperature [23, 85]. The factors that affect the surface tension of water include temperature, mineral or salt content, and contaminants [29, 85]. For instance, hot water may have low surface tension due to the relaxation of hydrogen bonds and intermolecular forces, while mineral water has slightly higher surface tension compared to pure water

and the addition of soaps or surfactants can significantly decrease surface tension [23, 29, 85]. Analysis of surface tension in drinking water is important for observing detergent contamination and for fast prediction of ionic salts and mineral composition [29, 85]. Studies from elsewhere are reporting and researching the surface tension of drinking water and its relation to nephrolithiasis, which is a health-threatening condition that is caused by the deposition of ionic salts in the urinary tract (kidney stones) [85]. As presented in table 5, the surface tension of the water samples from all sites is not significantly different (P-value) and is comparable to the results from [85]. The slightly high surface tension in site 5 water sample is probably due to the dissolved minerals from the underground rocks and soils. Analysis of surface tension in drinking water is rare; it needs to be added to the [94] and WHO standards [110] as an aesthetic and important physicochemical quality parameter to predict long-term public health risks.

The results from the e-tongue analysis provide additional and important aesthetic quality because the function of a human tongue is mimicked to identify the taste of the drinking water samples [16, 28, 68, 103]. The taste of the water varies due to the ionic or mineral composition and microbial contamination that may affect human health in the long term; for instance, high mineral content or salinity can lead to nephrolithiasis, while microbial contamination can lead to various waterborne diseases. A wide range of companies and researchers from various fields have recognised the Artificial Intelligence (AI) equipped e-tongue technology as a powerful tool for tasting to avoid challenges such as time consumption, expenses, exhaustion of the tasting panellists and complex data collection [4, 12, 33, 49, 87, 98, 106, 113].

The e-tongue technology is a sensory system for testing various liquid samples using arranged sensor electrodes [37, 38]. Generally, e-tongue instruments are composed of four compartments, which are autosampler, arrangement of selective and cross-discriminatory sensors, response system for sensors and sample interaction, and data collection and processing algorithm [33, 87, 98]. The naming of the e-tongue instruments is reported to be based on the sensor architecture used in their design which can be electrochemical (potentiometric, voltammetric, amperometric, and impedimetric), optical, mass, and biosensors [38, 87, 107]. This study used the popular potentiometric-based e-tongue instrument (*Astree, Alpha MOS*, Toulouse, France) to measure and analyse water samples via outer membrane sensors and reference electrodes. According to the manufacturer and previous studies, the e-tongue sensor electrodes are coated (outer membrane) to have sensitivity to varying specific tastes, which are sourness (AHS), saltiness (CTS), umami (NMS), sweetness (ANS), bitterness (SCS) and complex (PKS and CPS) [67, 68]. Studies have employed e-tongue for taste analysis of drinking water from different sources [28, 103].

Based on the SOP, the selected data output and presentation of the preliminary results from the operated

e-tongue instrument included a PCA plot (fig. 2) and distance table (table 1). These results are important because they show the differences or similarities of samples based on their overall chemical composition. As visible in fig. 2, site 0 (reference/control water sample) is related to site 4 water sample while it is distant to site 5 water sample. This can be also judged by the distances and pattern discrimination index (%) in table 1. The water samples from sites 1 and 6 seem related and have a pattern discrimination index of 72.78 %; this is the case for sites 5 and 8 with a pattern discrimination index of 78.53 % (fig. 2; table 1). Amongst the water samples, site 3 water samples seem to be very distinct, and this is evident in fig. 2 and the pattern discrimination index range of 87.47 to 97.16 %, and this is the case for site 2 followed by site 7 (fig. 2; table 1).

As described, PCA is an essential and preliminary data analysis approach because it provides a level of correlation or relationship and difference between the analytes (water samples) according to their taste; for instance, the first principal component (PC1) indicates the maximum total variance while the second (PC2) indicates maximum excess variance that is not recognised by PC1 [37, 67]. Studies have used PCA as a multivariate approach during the use of e-tongue for taste analysis of different water samples [28, 37, 38, 67]. The obtained PCA results seem to be related to the EC (mS/cm) of the water samples from the respective sites, for instance, site 4 water samples have the lowest EC (table 5); hence it is associated with MilliQ water that has resistivity of 18.20 MΩ/cm which is equivalent to EC of 0.000055 mS/cm (site 0). This is the case for site 1 and 6 water samples which have similar EC (table 5). The EC values of site 5 and 8 water samples are also not significantly different. All in all, the PCA are useful for predicting the taste difference and relation across the water samples.

In addition to the PCA results, the average intensity of taste parameters for the reference/control and water samples is presented. The water samples from all the sites seem to have a high intensity of sourness (AHS) and bitterness (SCS); this is evident from the bar graph and radar plot (fig. 3). Amongst the water samples, site 3 samples seem to have higher intensity bitterness and sourness (fig. 3B). All the water samples have lower saltiness intensity (SCS), which is associated with their low EC values (table 5). However, the positive saltiness in site 8, 7, and 5 water samples confirms the significant presence of dissolved salts that caused higher EC values than other water samples (fig. 3A; table 5).

The sensor bar graph, the radar plot (fig. 4AB) and table 2 compare the intensity of taste parameters in each of the water samples. In site 6, 1 and 2 water samples, the intensity of sweetness (ANS) seems to be dominant and accurate compared to the other standard taste parameters (AHS, CTS, NMS and SCS); this can be judged by the radar plot (fig. 4B) and standard deviation (SD) in table 2. In the site 3 water sample, the average intensity of bitterness is high and accurate compared to the other taste parameters (fig. 4AB; table 2). Judging by the radar

plot (fig. 4B) and SD in table 2, sourness (AHS) taste dominates in the reference and site 4 water samples. In contrast, umami (NMS) taste dominates in sites 8, 7 and 5 water samples.

The data presented in fig. 4 and table 2 provide an idea of the taste profile of the water samples, which is presented in table 3. The reference (site 0) and site 4 water samples have a sour taste, while water samples from sites 1, 2 and 6 have a sweet taste (table 3). Site 3 water sample has a bitter taste, while sites 5, 7 and 8 have an umami taste (table 3). The varying tastes of these water samples are due to their chemical and mineral composition, which is mainly affected by the source or plumbing material of the treatment system (RO). For instance, site 2, 3 and 4 water samples are from different RO systems installed at the local vendors, while site 1 is bottled water from the local vendor. Site 5 water sample is sourced from a local natural spring, site 6 is an installed RO system at a private household, and sites 7 and 8 are private household tanks and taps, respectively. There is a limitation of studies that have analysed and identified the taste of drinking water from different sources. Hence, continuous taste analysis is needed concurrently with the mineral composition using efficient techniques and instruments such as flame Atomic Absorption Spectrometry (AAS) [83]. For instance, the related South African study in this context was conducted by [113]. Continuous analysis of microbiological, chemical/mineral composition, and taste of the drinking water from local sources will not only inform about acute and aesthetic health risks and preferences of the consumers but will also allow prediction of risks to long-term non-communicable diseases such as the kidney stone diseases [39, 41, 85, 86].

Surface water

Surface water flows on top of the land's surface, including runoff, dams, rivers, wetlands, reservoirs, lakes and oceans. Availability and access of water to communities is mainly dependent on management of surface water and groundwater, which are both dependent on rainfall (*i.e.*, climate) [42]. The quantification, quality analysis and protection of groundwater and surface water is important to ensure consistent WASH and health across South African communities [50, 51, 56, 57, 60, 61, 64]. According to the National Integrated Water Information System from the DWS intranet, South Africa has about 2481 surface water stations (dams, rivers and reservoirs), and 1331 are open while 1150 are closed. The closing of the surface water stations is due to the mentioned challenges, such as inefficient management, incapacitating infrastructure and climate change, *i.e.*, drought and floods (siltation). Continuous local surface water management is an important approach for sustainable water security and the prediction of public health risks.

This study sampled surface water, *i.e.*, river and runoff, for quality analysis as described in the Methodology (fig. 1). The motivation for sampling and analysis of the chosen surface waters is based on observing public

health risks that may arise over time due to harvesting for reuse in toilet flushing and irrigation and also severe contact or accidental ingestion during heavy rains or floods. The mentioned challenges (inconsistent WASH and climate change impacts) make local communities prone to these scenarios. Harvesting and reusing surface water is encouraged to reduce potable water use. Hence, quality standards and guidance are important to ensure safety. The South African Water Quality Guidelines for Domestic Use, Irrigation and Livestock Watering [18, 19] are used along with the previous ones to evaluate and discuss the results obtained.

Microbiological quality. The total bacteria and fecal coliform concentration of the water samples from all the sites are significantly above the drinking water quality standards. In all the sites, the concentration of fecal coliforms is visible to be above the concentration of total bacteria and this is a rare case (table 6). The leaking sewage and open defecation result into high fecal coliform contamination of surface water, particularly during flooding or heavy rain events. These microbial concentrations indicate serious health complications and dermatological infections may arise in the case of accidental ingestion and severe contact with these waters. Amongst the sites, Belmont Valley River has the most polluted water due to its downstream location (fig. 1). The conditions in the upstream communities badly affect the microbial quality of water at Belmont Valley River; these conditions include bursting of sewage pipes, open defecation due to limited sanitation services, and plastisphere due to improper solid waste management [8, 17, 48]. The downstream farmers harvesting the river water for irrigation and livestock watering are at serious health risk [18, 19].

The second highest microbial concentrations are in the water sample from Fitzroy River (stormwater drainage channel), and this is also due to a broken sewage network in the upstream residences. Animal defecation and natural soil microbiome have contributed to the high microbial concentration at Fitzroy Street and Fitzroy River runoff. The runoff from the Rhodes University campus has a lower total bacterial concentration than the runoff sample from Fitzroy Street, possibly due to the paved surface around the campus. However, the broken sewerage network on campus is causing high fecal coliform concentrations in the runoff. The upstream surface water flows to the downstream (fig. 1); hence, the Belmont Valley River has higher microbial pollution, as observed in other studies elsewhere [31]. There are ongoing investigations and previous reports on microbial quality of surface waters through profiling of antibiotic resistance microorganisms and quantitative microbial risk assessment [1, 14, 48, 55, 96, 105]. These approaches are important for predicting public health risks and estimating microbial load received at the local Wastewater Treatment Works (WWTW); for instance, Belmont Valley WWTW receives some of its influent from the Belmont Valley River. Management of solid waste (*i.e.*, avoiding plastic disposal on streams), renovation of broken sewage networks, and provision of efficient sanitation ser-

Table 6. Microbiological quality of surface

Site	Parameters	
	Total bacteria, CFU/100 ml	Fecal coliforms, CFU/100 ml
Fitzroy Street	$2.10 \times 10^3 \pm 1.75 \times 10^2$	$2.27 \times 10^4 \pm 5.15 \times 10^3$
Fitzroy River	$2.13 \times 10^3 \pm 1.95 \times 10^2$	$6.80 \times 10^4 \pm 2.43 \times 10^3$
Belmont Valley	$2.34 \times 10^3 \pm 5.15 \times 10^1$	$1.45 \times 10^5 \pm 5.05 \times 10^3$
Rhodes University	$1.38 \times 10^3 \pm 3.21 \times 10^2$	$2.69 \times 10^4 \pm 5.53 \times 10^3$
ANOVA (P-value)	1.20×10^{-2}	1.78×10^{-8}
Quality guidelines		
[18]	$\leq 1.00 \times 10^4$	1.00 to 1.00×10^3
[19]	0 to 2.00×10^2	0 to 2.00×10^2

vices to the local communities could reduce the microbial content in surface water (*i.e.*, runoff and rivers).

Physicochemical quality. The observed neutral pH conditions are common and ideal for surface water reuse [80]. However, these pH levels have favoured the observed microbial loads (table 6), which may pose health risks when irrigated crops are consumed raw. High EC values in Fitzroy River and Belmont Valley water samples are caused by the dissolved metallic ions from the rocks, corroded resident infrastructure and disposed solid waste (plastics and cans) [5, 27, 88]. The observed EC values in Fitzroy Street and Rhodes University campus are associated with dissolved ions from the soil and the paved (cement and rocks) surface. The water samples from the upstream sites (Fitzroy Street and Rhodes University campus) had lower TSS and turbidity values, and this is due to the paved surfaces that limit the suspended solids from soil (table 7). In Belmont Valley and Fitzroy River water samples, the high TSS and turbidity values are proportional to the observed microbial loads (table 6). Soil erosion during stormy rains has resulted in high TSS and, subsequently, turbidity in these sites. The high TSS and turbidity are a threat to the river capacity and ecosystem because they can result in siltation and opaque water, which can affect circulation and visual of the planktonic organisms [5, 90]. The reduced river capacity through siltation can result in overflow and floods, which can badly affect the downstream farmers and workers at the WWTW (fig. 1).

The surface tension is analysed in this section to estimate detergent contamination in the surface water samples. As visible in table 7 (P-value), surface tension is not significantly different across the water samples from all the sampling sites. However, the water sample from Rhodes University has the highest surface tension, which is closer to drinking water (table 5), indicating the absence of detergent contaminants. The observed lower surface tension in other water samples is due to the upstream communities' surface disposal of trace soluble contaminants; this includes untreated greywater, pesticides and fertilisers from home gardens, and plastic waste [26]. Contamination of surface water by soluble substances may pose a health threat to the river ecosystem, particularly the plankton [17].

Table 7. Physicochemical quality of surface water

Site	Parameters				
	pH	EC, mS/cm	TSS, mg/L	Turbidity, NTU	Surface tension, mN/m
Fitzroy Street	7.51±0.03	0.237±0.005	68.83±2.58	78.50±1.80	66.02±2.55
Fitzroy River	7.51±0.01	0.651±0.014	132.50±4.84	131.00±1.55	66.08±1.88
Belmont Valley	7.53±0.01	0.392±0.016	460.17±9.09	389.33±15.50	66.03±1.34
Rhodes University	7.31±0.01	0.295±0.002	82.00±3.41	61.17±8.90	70.35±1.64
ANOVA (P-value)	1.43×10 ⁻⁶	3.72×10 ⁻¹¹	4.03×10 ⁻¹⁴	3.82×10 ⁻¹⁰	5.06×10 ⁻²
Quality guidelines					
[18]	6.50 to 8.40	≤40.00	≤50.00	Not specified	Not specified
[19]	Not specified	0 to 1000.00 mg/L TDS	Not specified	Not specified	Not specified

Additionally, the water temperature in the sites was recorded during sampling and was 16.50, 14.50, 17.00 and 16.00 °C at Fitzroy Street, Fitzroy River, Belmont Valley, and Rhodes University campus, respectively. The observed temperatures do not seem to be significantly different. They are all below the standard environmental temperature range of 18 to 27 °C due to the weather conditions (stormy rains) during the days of sampling.

Apart from the analysed and reported parameters in this study, various studies across South Africa have reported intensive investigation and findings on the physicochemical quality of surface waters [2, 21, 43, 59]. For instance, [88] employed microscopy and Fourier-Transformed Infrared (FTIR) to analyse microplastic pollution, while [73] profiled hormonal contents and pharmaceutical contaminants using chromatography and spectrometry-based instrumentation. Continuous extended analysis and reporting of local surface water quality is essential. The solutions for the reduction of surface water pollution include the provision of proper sanitation services in all human settlements, solid waste management, monitoring of the water distribution infrastructure, and incorporation of surface water treatment systems along the water distribution networks [5, 58, 59, 102, 112]. These solutions must be addressed, with firm engagement with the local communities and an emphasis on water use and quality awareness to ensure public health.

This observational study encouraged continuous drinking and surface water quality assessment in South African communities such as the local Makhanda. Evaluating drinking and surface water quality is an efficient approach for observing and addressing challenges resulting in inconsistent WASH in local communities. Through the reviewed studies, this study has mentioned the challenges to WASH, quality assessment and monitoring methods, findings and solutions for obtaining adequate WASH in prone communities. The microbiological and physicochemical analysis of drinking water from different sources is important for predicting public health risks that may arise over time. The observed bacterial colonies in site 3 drinking water samples need further investigation, such as genomic sequencing and antibiotic resistance profiling. At site 3 and other drinking water vendors (sites 1, 2 and 4), there is a need for consistent maintenance of hygiene practices that may be compromised due to over-crowding.

Retrofitting the replaceable filtering system at site 5 is essential to ensure the removal of TSS and turbidity from the drinking water. The water samples from sites 7 and 8 show the need for microbial disinfection and testing before consumption; this can be done using home-based methods such as boiling and H₂S kits, respectively.

The surface tension and taste analysis of the drinking water samples are rare and important aesthetic quality parameters that can also be used to predict short-term and long-term health risks such as water-borne diseases (microbial contamination) and kidney stones (nephrolithiasis due to high mineral/ionic salt content). Further analysis of mineral content using AAS in conjunction with taste analysis would be important to predict long-term health risks from different drinking water brands/sources. In addition to the conventional quality parameters (microbiological and physicochemical), including aesthetic and rare quality parameters such as surface tension and taste analysis of drinking water has added insight to this study by communicating health risks that may arise over time. Further analysis is recommended for establishment of the quality index or standards of these parameters.

The microbial and physicochemical quality of surface water has shown the need for the provision of sanitation services, renovation of the sewage networks and adequate solid waste management in all settlements. The observed surface water quality poses high health risks to communities that intend to harvest and reuse it for irrigation or livestock watering. Innovations for surface water treatment (runoffs and river flows) are needed. For instance, incorporating filtering systems within the drainage networks can reduce TSS, leading to siltation of the downstream water bodies.

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Тривала оцінка якості питної та поверхневої води: вирішення ключових проблем сталого доступу до води в Маханді, Східна Капська провінція, Південна Африка

Сіпхумзе Бані¹, Санділе М. М. Хаманга¹, Роман Тандліх^{1*}, Брендан Вільгельмі²

*r.tandlich@ru.ac.za; roman.tandlich@gmail.com

¹Університет Родса, фармацевтичний факультет, Артилері-роуд, а/с 94, Маханда, 6140, Південна Африка

²Університет Родса, кафедра біохімії та мікробіології, Артилері-роуд, а/с 94, Маханда, 6140, Південна Африка

Невелике місто Маханда протягом багатьох років стикається з проблемами обмеженого доступу до води, що негативно впливає на здоров'я населення, добробут та соціально-економічне функціонування. Це обсерваційне дослідження заохочує постійну оцінку якості питної та поверхневої води як підхід до комунікації та пошуку рішень цих проблем. У зразках води з ділянки 3 не було знайдено фекальних колиформних бактерій, проте було виявлено, що $0,42 \pm 0,09$ КУО/100 мл загальної кількості бактерій були стійкими до ампіциліну, хлорамфеніколу, доксицикліну, пеніциліну G та сульфаметоксазолу, а також чутливими до ципрофлоксацину, канаміцину та рифампіцину. Фарбування за Грамом і тест з гідроксидом калію показали, що цими бактеріями є *Staphylococcus aureus*. На додаток до звичайних фізико-хімічних параметрів якості, для аналізу естетичної якості (смаку) було використано потенціометричний електронний язик. Зразки питної води з точок 3 та 4 були гіршими та кислими відповідно, тоді як зразки води з точок 1, 2 та 6 були солодкими, а з точок 5, 7 та 8 мали смак уламів. Смакові профілі корелюють з мікробною та фізико-хімічною якістю питної води та можуть бути використані для прогнозування довгострокових ризиків для здоров'я — як-от нефролітіаз. Безперервне профілювання мікробіому та стійкості до антибіотиків є важливим для прогнозування та кількісної оцінки ризиків для здоров'я населення через питну та поверхневу воду.

Ключові слова: електронний язик, якість води, фекальні колиформні бактерії, тривала оцінка