Groot Aub groundwater quality and its suitability for domestic purposes, Namibia

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The Groot Aub (GA) settlement depends entirely on groundwater for domestic purposes and other development activities. Development activities are mainly agriculture, such as animal husbandry, chicken farming and crop farming using irrigation. However, these activities have the potential to contaminate the groundwater system. A total of 87 groundwater samples were collected from the boreholes in the study area during the dry and wet season. Water quality parameters (pH, salinity, total dissolved solids (TDS), electrical conductivity (EC) and hydrochemistry ($Na^+ > Ca^{2+} > Mg^{2+} > K^+$, and $HCO_3^- > SO_4^{2-} > Cl^-$) of 5 boreholes and 1 reservoir tank were analysed. The dominant cations were attributed to cation exchange processes as a coupled exchange of $Na^+ + K^+$ replacing Ca^{2+}; and Na^+ replacing Mg^{2+} ions in the rock–water interactions. The HCO_3^- anion is attributed to underlying rich carbonate rocks in the study area and chemical reactions between groundwater and silicate minerals. TDS ranged from 639.01 to 1 998.96 mg/L. The microbial levels as indicated by heterotrophic plate count (HPC) values exceed the limits imposed by the local Namibian and WHO drinking water regulations. The Piper diagrams showed a mixed water type of mainly HCO_3^- and SO_4^{2-} anions and Na^+ and $Ca^{2+} > Mg^{2+}$ cations. The study shows that the elemental composition of the groundwater is impacted significantly by primarily anthropogenic activities and secondarily geogenic processes. Based on the results of this study it is recommended that a buffer zone be created between human activities and production boreholes to avoid further groundwater contamination.

INTRODUCTION

Groundwater is one of the most essential sources of freshwater (Anil and Neera, 2016). Over 50% of the world's population relies on groundwater resources (Díaz-Alcaide and Martínez-Santos, 2019) to support socio-economic development and domestic use (Yin et al., 2020). However, in Africa, groundwater is unevenly distributed across the continent (Lapworth et al., 2017) and is divided into two groups, namely North Africa and Sub-Saharan Africa (SSA) (MacDonald et al., 2012). High-yield, high-storage, sedimentary aquifers are common in North Africa while low-yielding, low-storage, basement aquifers are more widespread in Sub-Saharan Africa (Xu et al., 2019).

At least 70% of the 250 million people living in Southern African countries depend on groundwater (The World Bank, 2017). In arid areas like Namibia, there is a heavy reliance (65%) on groundwater in both the rural and urban areas for domestic and development purposes, such as industry, agriculture, and mining (MacDonald et al., 2012). In Lusaka, Zambia, about 55% of water distributed by public utilities comes from groundwater (Foster, 2017; Pantaleo et al., 2018). In Botswana, groundwater accounts for 54% of the total water supply in the country (Ministry of Minerals, Energy and Water Resources, 2013). Across Zimbabwe, at least 38% of the population utilises groundwater for agriculture, household, and industrial use (Mambondiyani, 2020). In South Africa, 59% of the water use is from groundwater (Mouton, 2020).

Groundwater in unconfined aquifers gets contaminated by different anthropogenic activities and natural processes (Senarathne et al., 2019). Weathering, cell synthesis, organic decomposition, and microbiological growth can result in groundwater toxicity (Reham, 2018; Masindi and Foteinos, 2021). For example, in Pakistan, groundwater around the Faisalabad area was contaminated by open dumping of waste, leading to increased total dissolved solids (TDS) concentrations and microbial concentrations in groundwater (Muhammad et al., 2017). In Turkey, groundwater sources have been contaminated by nitrates, waste, and leachate infiltration at waste disposal sites (Mbemba et al., 2019). Furthermore, weathering releases natural substances such as arsenic, iron, chlorides, manganese, fluorides, and sulphates that dissolve in groundwater and contaminate it (He et al., 2020; Masindi and Foteinos, 2021).

In South Africa, for example, groundwater pollution has been largely identified to be due to livestock farming (Enitan-Folami et al., 2019) and on-site sanitation systems (Taonameso et al., 2019). In Zimbabwe, groundwater from 19 sites around the country confirmed contamination from *Escherichia coli* linked to contamination from sewage and landfill leachate (Matsa et al., 2021). A recent study done in Omaheke region, Namibia, on nitrate and bacterial contamination in groundwater, attributed this to livestock manure (Claasen and Lewis, 2017), which is composed of both nitrates and phosphates.

The contamination of groundwater means that less water is available for supply to communities, which can hamper development in many areas (Li et al., 2021). Protection of groundwater resources needs to be prioritized as cleaning up contaminated aquifers is a lot more expensive and takes a long time.

In this decade, and in line with the United Nation (UN) Sustainable Development Goals (SDGs), it is imperative to ensure that clean drinking water for urban and rural populations is made available. This paper aims to distinguish natural from anthropogenic sources of contamination and also to showcase a methodology to be employed when planning new settlements. The research presented in this paper has further highlighted the serious water issues at Groot Aub to local authorities, who have subsequently introduced measures that improve drinking water quality for the community.

METHODS AND MATERIALS

Study area and its geology

The Groot Aub village settlement is situated at a latitude of 22.9423° S, and longitude of 17.2031° E in the central part of Namibia (Fig. 1), approximately 55 km south of Windhoek, Namibia's capital city. The village is situated at a ground elevation of 1 647 m above mean sea level. The mean precipitation in Groot Aub is about 220 mm/yr (Mohd et al., 2016). The settlement experiences maximum temperatures of up to 34°C in summer and minimum temperatures of up to 4°C in winter (Meteoblue Weather, 2021).

Groot Aub has geological characteristics that encompass Mesoproterozoic rocks with granites, para and ortho gneisses, volcanic, and sedimentary rocks, with traces of base metals such as copper and iron. The lithologies are dominated by marble, quartzite, and schist/diamictite, (Simubali, 2019). Groundwater recharge is mainly through the fault zones, joints, and alluvial aquifers (Baumle et al., 2001). The main groundwater aquifers, as ascertained from boreholes, are the fractured granite, gneisses, and carbonate rocks. Soil types are mostly characterised by eutric cambisols (euCM), colluvic skeletic leptic regosols (coskleRG) and skeletic lithic leptosols (skliLP skliLP) (Coetzee, 2021).

Of the 27 drilled boreholes in Groot Aub, only 5 boreholes are utilized for production purposes and have sampling points. Groot Aub has a steel reservoir tank which is referred to as the Main Reservoir Tank (MRT) in the study. MRT is fed from water coming from Farmer's Borehole, the Main Borehole, Ndadi Borehole, and 2 additional boreholes, named WW205256 and WW205259. The Groot Aub Primary School Borehole feeds a Reservoir Steel Tank (RST) that supplies water to the school, regional offices, and the clinic. Water from RST at the Groot Aub Primary School is chlorinated before distribution into the network. Water from the Sandworks Borehole collects at a dosage point, where it is also chlorinated before distribution to the residents. In the study area, runoff water flows from the north toward the south (Fig. 2a), which ends at the Groot Aub Primary School Borehole (Fig. 2b).

Sampling procedures

Water samples were collected from the boreholes, MRT and RST and from tap water as a distribution point from the Sandwork borehole distribution network. Samples were collected from April to October (dry season) and November to March (wet season). The 5 boreholes sampled were the Groot Aub Primary School Borehole, Main Borehole, Farmer's Borehole, Ndadi Borehole and Sandworks Borehole (Fig. 2b). On-site parameters were obtained in the field, and laboratory water testing was carried out during the data collection period. The laboratory testing was carried out by an accredited laboratory for the City of Windhoek Scientific Services-Gammams Laboratory on all water samples to determine the physicochemical and microbiological parameters. Carbonate and bicarbonate ion concentrations were calculated from total alkalinity using the following formula: hardness Mg equivalent $CaCO_3$/L = 2.497 [Ca, mg/L] + 4.118 [mg/L]. Calcium ion calculation is given in Eq. 1.

$$Ca^{2+} = \frac{CaCO_3}{2.497} = \frac{120mg/L}{2.497} = 48.05 \frac{mg}{L} \qquad (1)$$

Sampling bottles were prepared in the laboratory by thoroughly washing them with dilute nitric acid (HNO_3) and then with distilled water. The bottles were rinsed with de-ionised water in readiness for water collection. The bottles were dried in air, and then sealed in zip-lock bags. The sampling bottles for the microbiological analyses were treated with sodium thiosulphate and sealed immediately to avoid reaction with the atmosphere. The sample bottles for cations were preserved with dilute nitric acid (HNO_3). The boreholes were purged for 5–10 min before sampling. A total of 48 samples were collected during the dry season and 39 samples were collected during the rainy season.
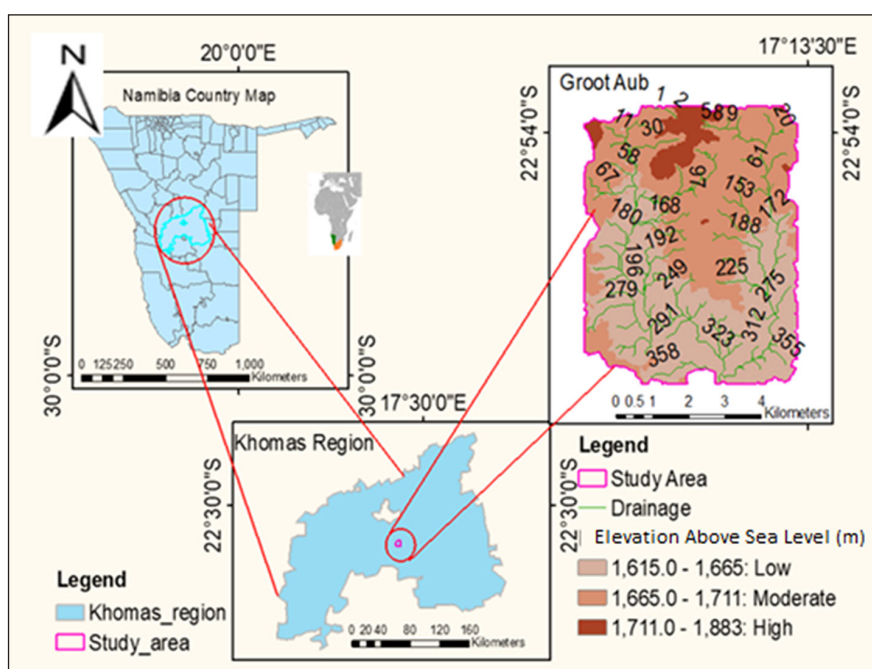

Figure 1. Map of the Groot Aub settlement, Namibia, showing elevations above sea level and numbers that indicate the difference in water head from the highest to the lowest elevation at designated points
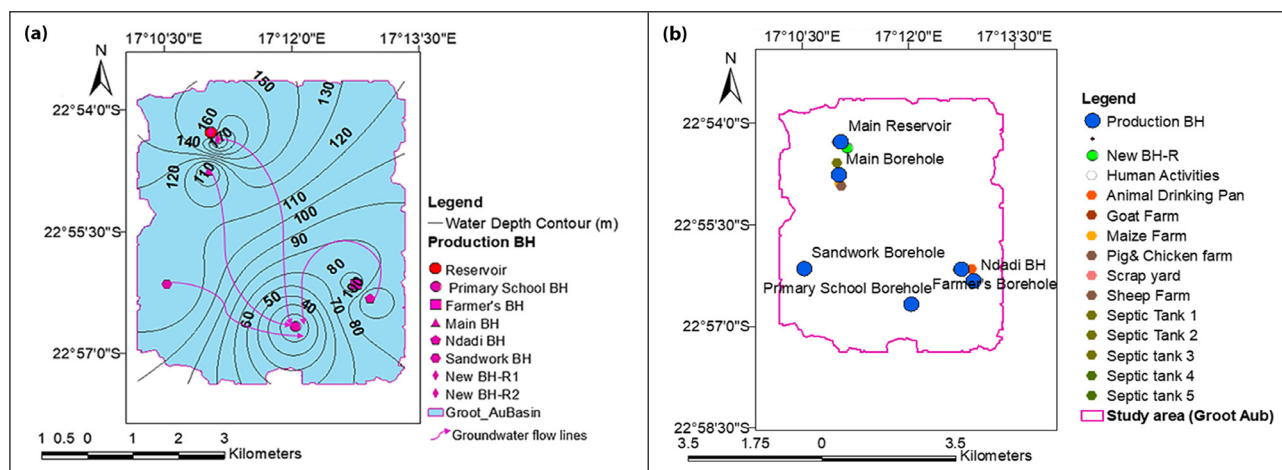
Figure 2. (a) Production and sampled boreholes; (b) anthropogenic activities around Groot Aub

Analysis

During sample collection, handling, preservation, and analysis; the standard methods recommended by the American Public Health Association (APHA, 1995) were followed to ensure data quality and consistency. The pH and EC were measured in the field using the Pocket Pro Multi-meter. The multi-meter is calibrated by the City of Windhoek Scientific Services-Gammams laboratory quality assurance personnel. Turbidity was measured using a turbidimeter; calcium carbonates and magnesium carbonates were determined using ethylenediamine tetra acetic acid (EDTA) titration, and calcium and magnesium ions were calculated from the concentration of calcium carbonates and magnesium carbonates. EC was determined on site by measurement of the resistance that is converted to conductivity on the instrument read-out using device HACH senION5 and TDS was calculated from EC. Cations such as potassium and sodium, and anions such as chloride and sulphates, together with other constituents such as fluoride and nitrate, were determined by ion chromatography. The carbonate and bicarbonate ion concentrations were calculated from total alkalinity. Bicarbonate (HCO_3^-) was calculated as per the APHA (1995) procedures at the accredited Analytical Laboratory Services Windhoek. The heterotrophic plate count (HPC) method was employed in this study for microbiological analysis. All colonies that grew on agar plates after incubation were counted and represent the total population of viable bacteria in the water.

For mapping and interpolation, the inverse distance weight (IDW) interpolation technique was used to construct the spatial maps. This method was chosen due to its deterministic model, which calculates unknown values based on close points rather than distant ones (Nafyad and Shankar, 2018). The dataset of water quality parameters was imported to ArcMap software 10.3 to produce the spatial maps. The geochemical evolution of groundwater can be understood by constructing a Piper diagram (Ravikumar et al., 2015). The Piper diagrams were drawn using the cations and anions. The Piper diagrams were used to classify the water type and hydrochemical facies of the groundwater samples.

RESULTS

Physical parameters (TDS, EC and turbidity)

High TDS values were recorded in Groot Aub and ranged from 1 406.98–1 998.96 mg/L in the dry season and 1 278.8–1 998.94 mg/L in the wet season (Fig. 3a). The southern part recorded high concentrations of TDS in the dry season (Fig. 3a). In the wet season, the highest TDS readings were found in the east and west, possibly reflecting the effects of rainfall recharge in the area (Fig 3a). The north-western part recorded the lowest TDS, during both the dry and wet seasons.

The EC values at Groot Aub were similar for both the dry and wet seasons. Maximum EC values were 298 mSm, with 95 mSm being the minimum (Fig. 3b). The highest EC was found in the dry season around the Primary School Borehole (298.33 mSm) in the south of Groot Aub (Fig. 3b). During the wet season, the highest concentration was found in the south-east, where EC ranged from 190.98–298 mSm (Fig. 3b). This is evidence of the ions migrating from the north toward the south-east. In the wet season, this movement is much more pronounced, especially around the Ndadi and Farmers Boreholes (Fig. 3b).

In the dry season, turbidity was relatively low (0.021–0.94 NTU) in most of the area to the west (around 50% of the area), where all boreholes except the Ndadi Borehole are located (Fig. 3c). The other half of the area displayed moderate turbidity of 0.9–1.72 NTU, and only a small area in the southeast recorded elevated values of 1.72–3.61 NTU (Fig. 3c). During the wet season, turbidity mirrored the dry season in terms of the areas with low and high values. The highest range of values recorded was 13.99–23.95 NTU, while the lowest readings were 0.21–5.42 NTU in the dry season (Fig. 3c).

Hydrochemistry

The pH values of the groundwater samples in the study area fell in the range of 7.1–7.7 for the dry season and 7.11–7.6 for the wet season (Fig. 4a). This indicates areas of high pH in the south extending towards the north for both seasons.

During the dry season, the average cation dominance was in the order of sodium (234.43 mg/L) > calcium (86.89 mg/L) > magnesium (38.39 mg/L) > potassium (18.83 mg/L). The anions in order of dominance were bicarbonate (621.83 mg/L) > sulphate (264.33 mg/L) > chloride (56.58 mg/L) > and fluoride (1.43 mg/L) (Fig. 4b and 4c).

The wet season cation dominance followed the same pattern with sodium (295.78 mg/L) > calcium (86.17 mg/L) > magnesium (79.08 mg/L) > potassium (24.50 mg/L). Anion dominance also followed a similar pattern to the dry season with bicarbonates (612.06 mg/L) > sulphate (264.33 mg/L) > chloride (56.58 mg/L) > fluoride (1.42 mg/L) (Fig. 4b and 4c). In both seasons, bicarbonate, sulphate and sodium occurred in the highest concentrations.

During the wet season, magnesium showed a substantial increase from 38.39 mg/L to 79.08 mg/L; similarly to potassium which increased from 18.83 mg/L to 24.5 mg/L (Fig. 4b and 4c). Calcium and chloride maintained similar concentrations for both seasons, while fluoride and nitrate recorded the lowest concentrations (Fig. 4b and 4c).
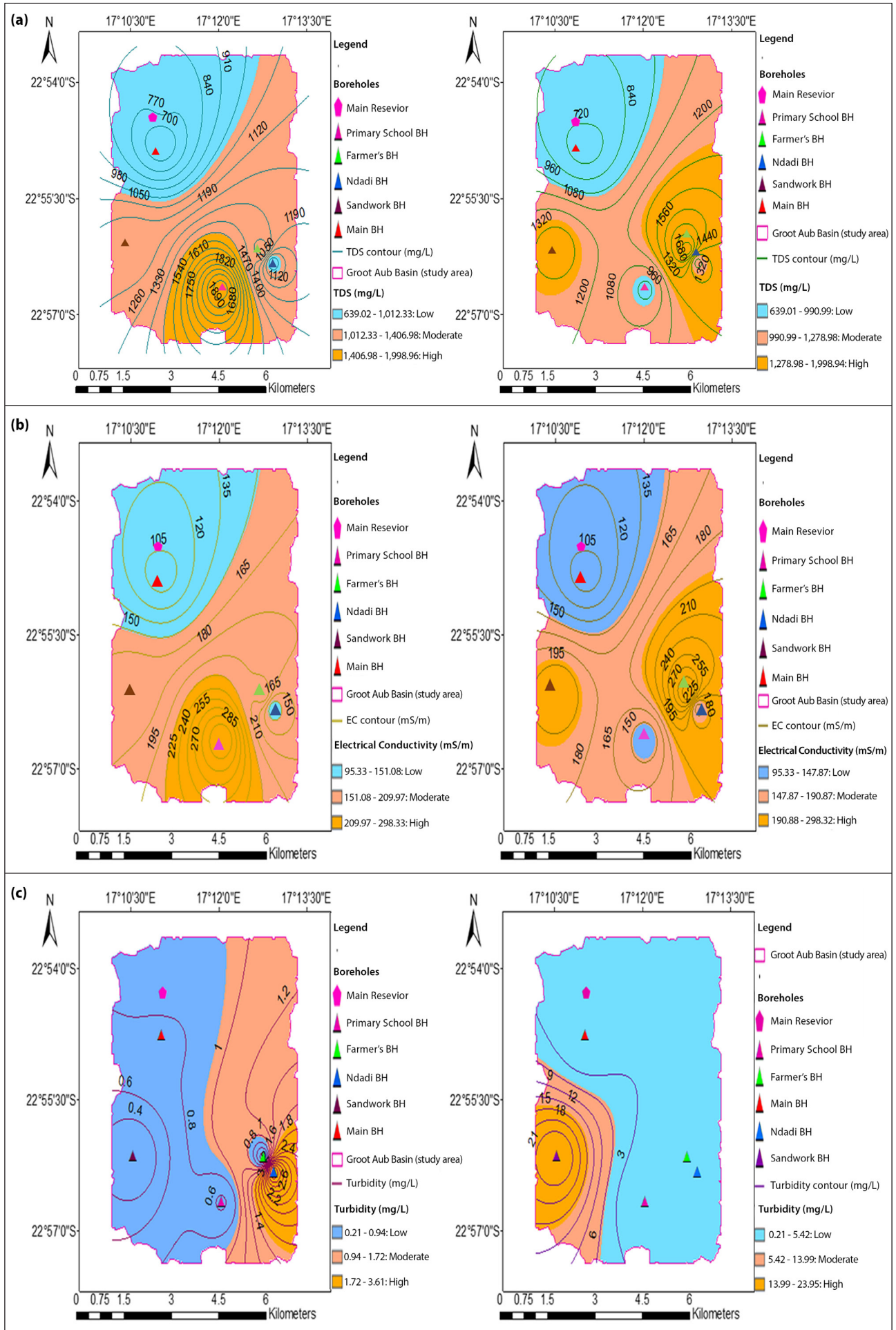
Figure 3. (a) TDS, (b) EC, and (c) turbidity, in the dry (left) and wet (right) seasons
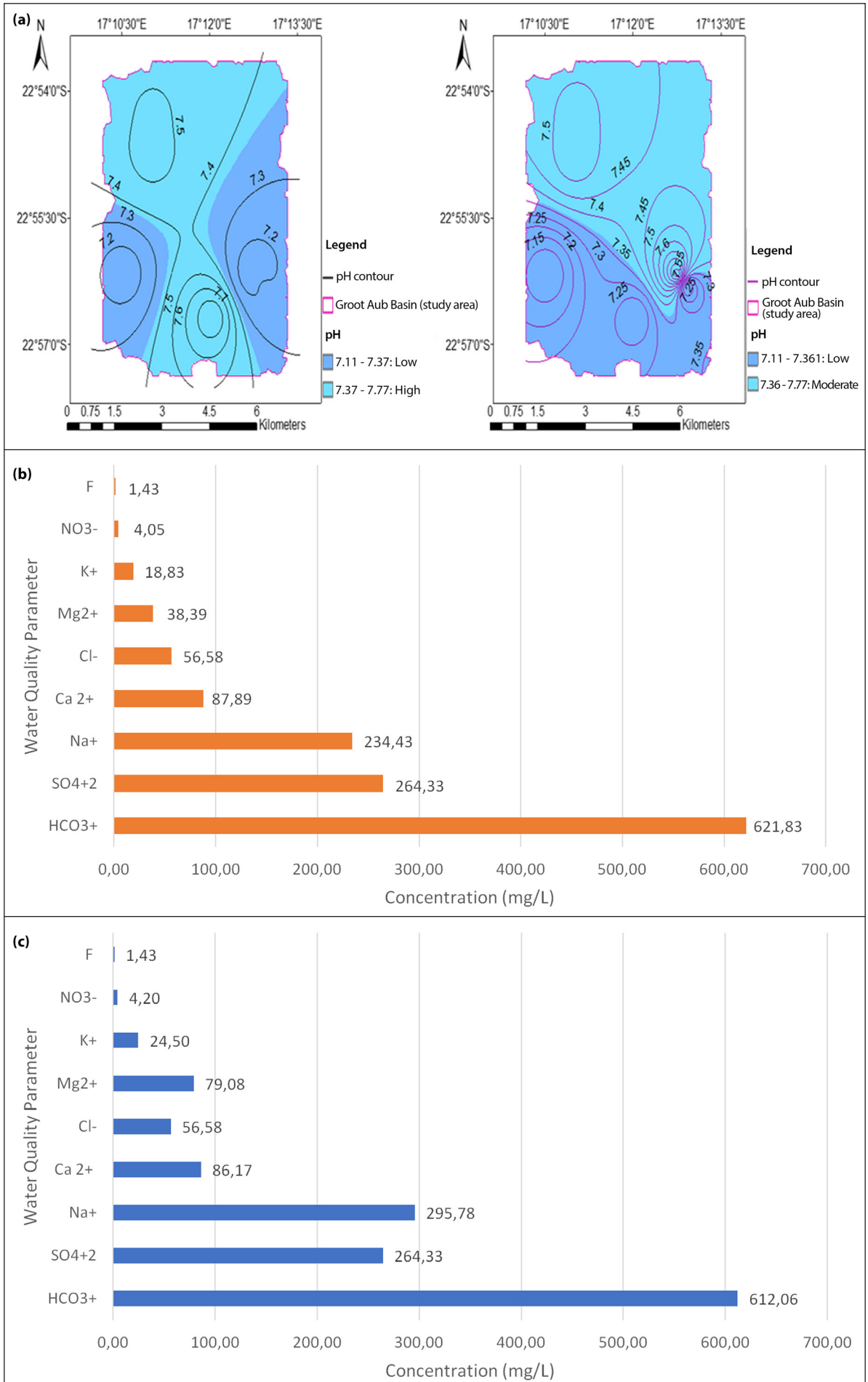
Figure 4. (a) pH in the dry and wet seasons, and (b) elemental water composition in the dry season, and (c) elemental water composition in the wet season
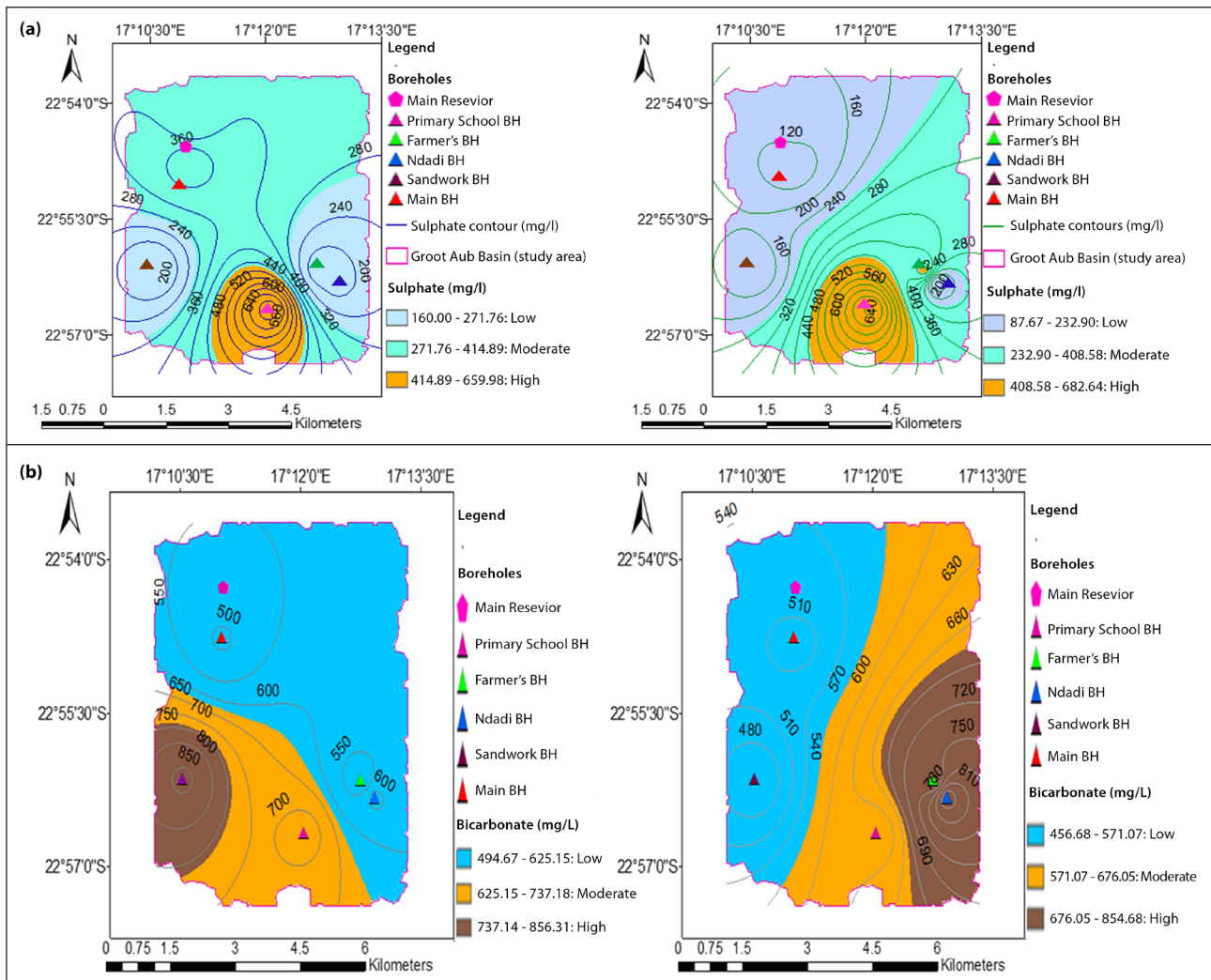
Figure 5. (a) Sulphate concentration and (b) bicarbonate concentration in groundwater, in the dry (left) and wet (right) season

In the dry season, SO_4^{2-} concentrations were highest in the same areas as TDS, in the southern part of Groot Aub, with the highest values ranging from 414.89–659.98 mg/L (Fig. 5a). In the wet season, SO_4^{2-} concentrations increased slightly, to a maximum of 682 mg/L (Fig. 5a). This increase in sulphate values reflects geogenic effects due to dissolution of mineralised sulphide-rich carbonate rocks in Groot Aub. Concentrations ranged from 408.48–682.64 mg/L in the southern part of Groot Aub (Fig. 5a), reflecting the trend in TDS and EC (Fig. 3b and 3c). Moderate SO_4^{2-} concentrations were observed in the central part of the region, at 232.90–408.58 mg/L (Fig. 5a). The lowest concentrations were recorded in the north-west with values of 87.67–232.90 mg/L (Fig. 5a). The WHO recommends a sulphate value of 250 mg/L, with a maximum permissible limit of 400 mg/L.

Bicarbonate (HCO_3^-) concentrations ranged from 494.67–856.31 mg/L in the dry season (Fig. 5b). The moderate levels recorded (500–676 mg/L) were mainly at one borehole at the Groot Aub Primary School in the south, in both seasons. In the dry season, HCO_3^- increased from the north-east towards the south-west, with the highest concentration being 856.51 mg/L and the lowest 494.67 mg/L (Fig. 5b). In the wet season high values of HCO_3^- generally occurred in the south-eastern part of Groot Aub, with values of 676.05–854.68 mg/L. It can further be observed from Fig. 5b, that there is a movement of bicarbonate from the north-east toward the south-east.

In the dry season, the highest Cl^- concentrations were recorded to the east (Fig. 6a), with intermediate values across most of the area,

except the northwest and a small area in the south that both show very low values (Fig. 6a). High Cl^- concentrations during the wet season were restricted to the areas surrounding the Groot Aub Primary School Borehole in the south and the Main Borehole in the north (Fig. 6a). These areas show a range of Cl^- concentrations from 95.93–147.50 mg/L. Intermediate values (65.73–95.93 mg/L) occur widely across the study area (Fig. 6a). The lowest values (29.02–65.73) occur to the west and east (Fig. 6a).

Nitrate (NO_3^-) concentrations were very similar in the dry and wet seasons, ranging from minimum values of 1 mg/L to maximum values of 17.50 mg/L (Fig. 6b). In both seasons, NO_3^- values increased from the north to the south and the highest concentrations were found at the Groot Aub Primary School Borehole at 9.47–17.50 mg/L (Fig. 6b), while the lowest NO_3^- concentrations were found at MRT and the rest of the other boreholes with values of 4.00 mg/L or lower (Fig. 6b).

Geochemical evaluation

Bedrock geology through groundwater–rock interaction imparts a particular water chemistry signature. The Piper diagram (Fig. 7a) indicates the dominant cations and anions in the area. The dry season Piper diagram shows us the groundwater chemistry that reflects bedrock geology. The cations Na+K are more enriched in the groundwater at Groot Aub, followed by Ca^{2+} and Mg^{2+}, while the highest anion concentration was HCO_3^- followed by SO_4^{2-}. In Fig. 7a, the upper panel shows that BH1, BH2 and BH5 reflect granitic, felsic gneiss, schist, and quartzite bedrock.
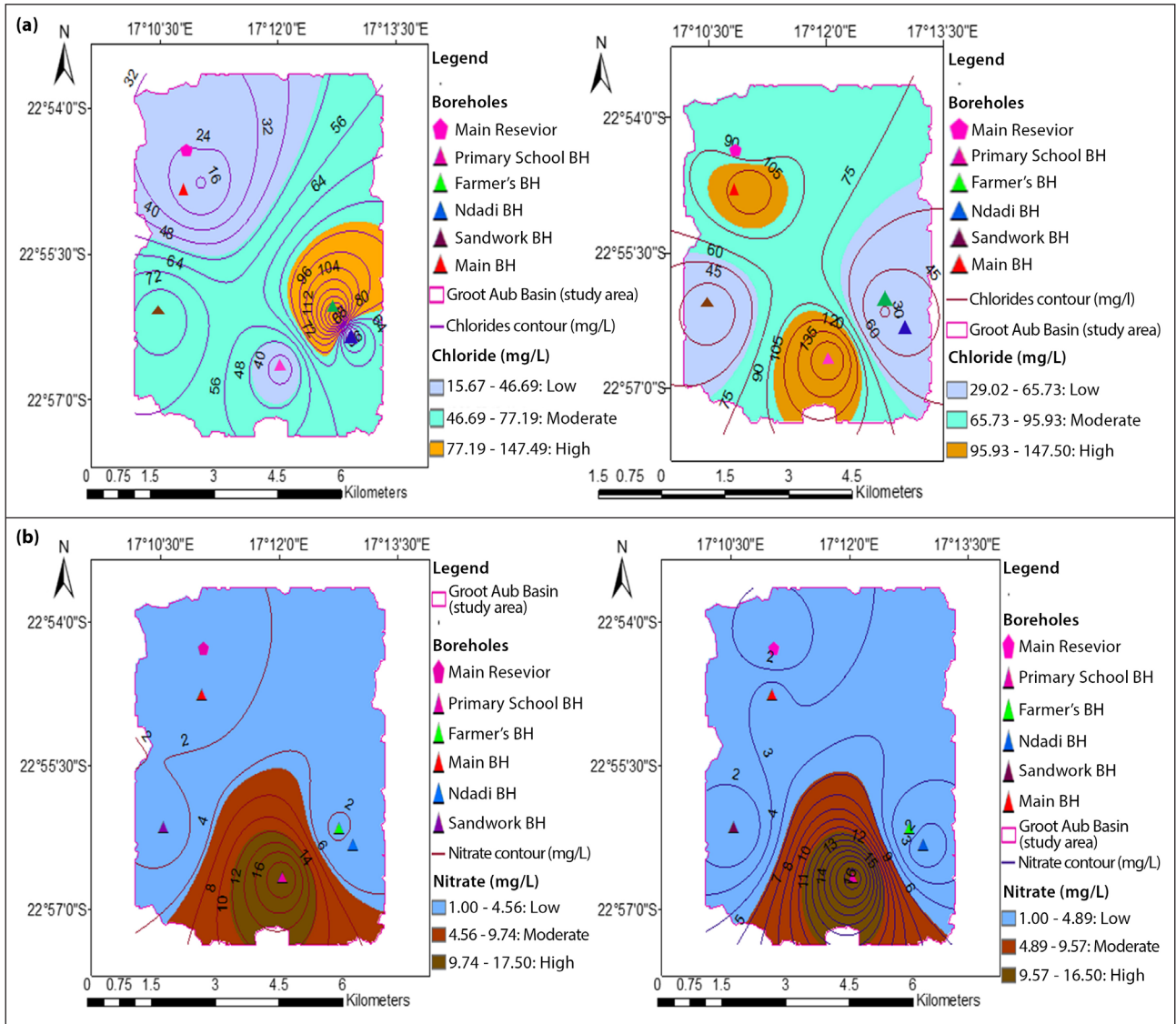
Figure 6. a) Chloride concentrations and (b) nitrate concentrations in groundwater in the dry (left) and wet (right) seasons
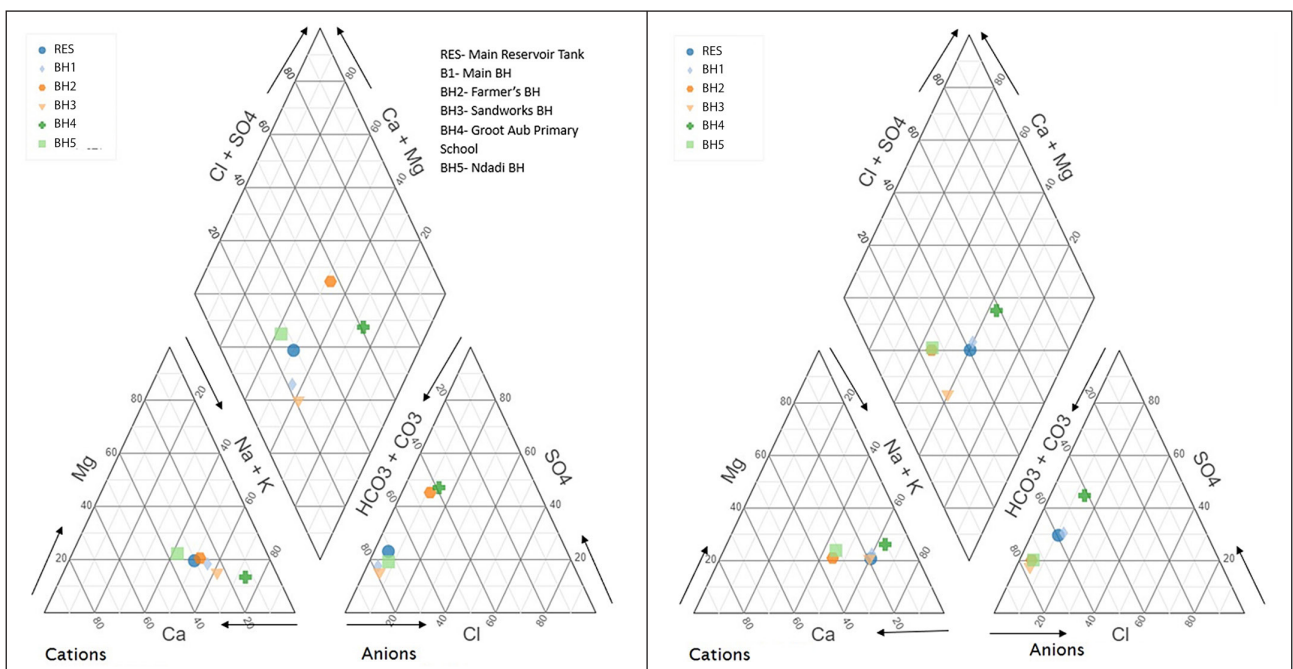

Figure 7. Plots of borehole water chemistry on the Piper diagram for (a) dry and (b) wet seasons. BH2 overlaps with BH5 in the upper panel and lower left panel.

BH2 and BH4 have high Ca^{2+} and Mg^{2+} and higher SO_4^{2-} levels. The lower left panel in Fig. 7a shows a high value of Na+K and moderate values of Ca^{2+} and Mg^{2+}, whereas the lower right panel shows higher values of HCO_3^- and SO_4^{2-}. These results show that Na+K is sourced from granitic and gneissic rocks. Ca^{2+} and Mg^{2+} are sourced from carbonate rocks. HCO_3^- is derived from the dissolution of calcite ($CaCO_3$), which reflects the presence of carbonate rocks (marbles). The dominant water facies are (Na+K), HCO_3^- and (Ca+Mg) SO_4^{2-} (Fig. 7a).

The wet season Piper diagram (Fig. 7b) shows the evolution of groundwater across the two seasons, and the effect of groundwater recharge. The groundwater chemistry is as a result of dilution and mixing due to recharge. In Fig. 5a, groundwater movement is implied from the north-west to the south-east of the area. In BH5 we observe an increase in SO_4^{2-} from the dry season to the wet season and this is reflected in both Figs 5a and 7b.

Microbiology

During the dry season, HPC values in the south of Groot Aub varied from 2.37–9 229.81 CFU/mL (Fig. 8a). A high HPC was found in the eastern (4 000–5 000 CFU/mL) and western (3 512.42–9 229.81 CFU/mL) part of the study area (Fig. 8a and 8b). Low values of HPC (2.37–1 486.00 CFU/mL (dry season) and 2.36–1 776.48 CFU/mL (wet season) were observed in the north-west, around the MRT and the Sandworks tank (Fig. 8a and 8b).

High HPC values were recorded in the south during the wet season, at4 564.434–9 243.93 CFU/mL at the Groot Aub Primary School Borehole.

In terms of *E.coli*, contamination was limited to the south in the dry season and to a slightly larger area in the south-east during the wet season (Fig. 8b). High concentrations of *E. coli* were observed over the same area in the southern part of Groot Aub in the dry season, at 0.1–0.3 CFU/100 mL. This area expanded toward the south-east in the wet season with concentrations ranging from 0.2–0.5 CFU/100 mL (Fig. 8b). The northern and central part of Groot Aub shows the lowest levels of *E.coli*, with concentrations that ranged from 0.0–0.2 CFU/100 mL (Fig. 8b).

DISCUSSION

Hydrochemistry

The water quality results are discussed in relation to the local water guidelines of the Ministry of Agriculture, Water, and Rural Development (MAWLR), published in the Water Affairs Act 54 of 1956 and referred to herein as the local Namibia Water Guideline (Ministry of Agriculture, Water and Forestry, 1956). The results are further compared with the World Health Organisation drinking water guidelines of 2018 (WHO, 2018).

The Groot Aub settlement has some water quality issues that need urgent attention from the City of Windhoek. Sulphate (Fig. 5a)
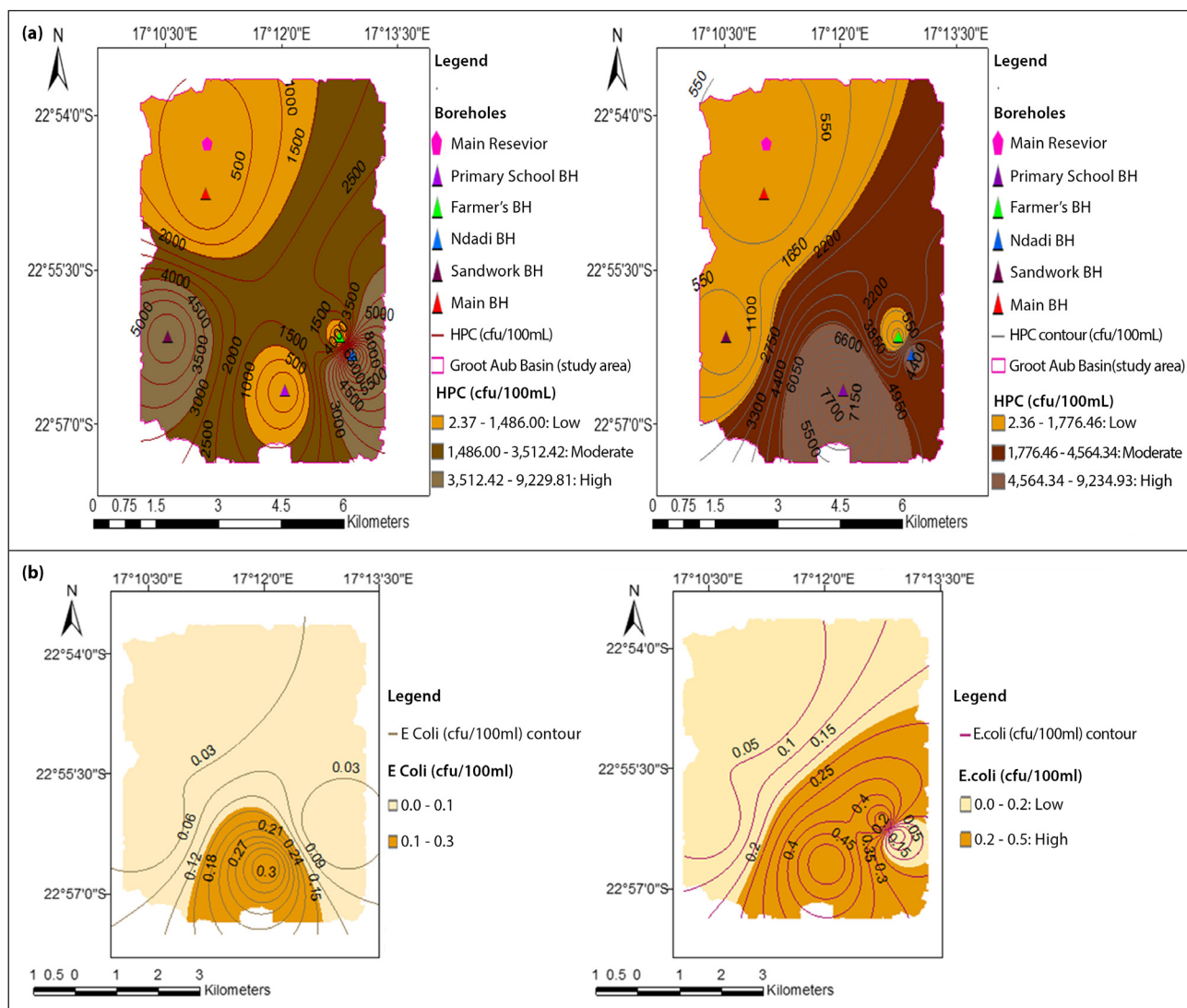

Figure 8. (a) HPC and (b) *E. coli* in dry (left) and wet (right) season

in the area shows varying concentrations, with areas that are within the limits for either Group A or B water types (200–600 mg/L) of the local Namibian water guidelines. There were, however, other areas within Groot Aub that showed sulphate concentrations exceeding the Namibia Water Guideline in the area surrounding the Groot Aub Primary School Borehole (Fig. 5a). The concentration of sulphate in the area further appears to have exceeded the WHO limit of 250 mg/L; this indicates that less than 40% of Groot Aub groundwater is enriched with sulphates, with unacceptable concentrations occurring at selected boreholes. This is true for the Groot Aub Primary School Borehole and its surrounding area (Fig. 5a). The high amount of sulphate can be attributed to the carbonate rocks and schists that are present in the area and possibly also anthropogenic activities such as use of pit latrines, septic tanks and agricultural fertilisers.

TDS values exceed 1 000 mg/L in certain areas, which is unacceptable in relation to the WHO guidelines (Fig. 3b). This could be due to the recharge of groundwater from rainfall and runoff that had dissolved various minerals in the catchment area (Reyes-Toscano et al., 2020). Recharge routes at Groot Aub are mainly through lineaments and faults present to the north and fracture zones on exposed basements to the west. The assay results for the wet and dry seasons are similar, with minor differences in concentration possibly due to differences in mineral solubilities in the wet season that to increase elemental ions in groundwater. This suggests that TDS is influenced by natural minerals present in the rock composition. A study done in West Virginia along the Monongahela River basin recorded high TDS values which were caused by excessive chloride and sulphate from the natural geological composition of the area (Eric et al., 2022).

The southern part of Groot Aub had the highest EC values in the settlement (Fig. 3c). The EC values in the south and east of Groot Aub were 209.97–285 mSm in the dry season and 190.88–298.32 mS/m in the wet season, and therefore exceed the Namibian Water Guideline limit for Group A, but are within this limit for Group B (150–300 mS/m). The high EC values of the groundwater in the study area may be attributed to geochemical processes such as ion exchange, silicate weathering, evaporation, and the solubilization processes that take place within the water-bearing rocks (Aghazadeh et al., 2017), together with sediment dissolution, and rainwater infiltration (Ehya and Marbouti, 2016).

The pH (Fig. 4a) in the area was within the acceptable range of Namibian Water Guideline (6–9.5) and the WHO (6.5–7.5) drinking water guidelines, and within the natural groundwater pH range of 6 to 10 (Nilsson et al., 2017). Furthermore, the concentration of calcium, magnesium, chloride and fluoride ions were also within the limits of the Namibian Water Guideline for Group B water, of 100 mg/L, 70 mg/L, 600 mg/L and 2.0 mg/L and also fall within the WHO limits of 150 mg/L, 100 mg/L, 250 mg/L and 1.5 mg/L.

Sodium and magnesium ion concentrations exceeded the Group A guideline limits (100 mg/L and 70 mg/L) of the Namibian Water Guideline and WHO thresholds of 200 mg/L and 10 mg/L, but were within the Group B permissible limits of the Namibian Water Guideline (Fig. 4b). Sodium and calcium ions are most likely to be from the sedimentary, igneous, and metamorphic rocks found at Groot Aub, which contain sodium-rich minerals and calcium carbonate minerals. Potassium and fluoride ions displayed the lowest concentrations, at 24.5 mg/L and 1.43 mg/L (Fig. 4b and 4c); this could be due to the slower weathering rate of potassium-bearing rocks at Groot Aub, such as gneisses, granites, sandstones, shale, and fluoride-bearing minerals such as micas and apatite.

Hydrochemical and geochemical evaluations

In the study area sulphate (SO_4^{2-}) and chloride (Cl^-) ion concentrations were within permissible limits of the Namibian Water Guideline (250 mg/L and 600 mg/L) and the WHO drinking water guideline (250 mg/L) for both the dry and wet seasons (Fig. 5a and 5b), except for the areas surrounding the Primary School Borehole. Sulphate is associated with schist and mineralized carbonate rocks that contain pyrite and other sulphides. These minerals, when dissolved in water, produce sulphate ions and associated cations such as Ca^{2+} and Mg^{2+}. However, in Groot Aub, the levels of SO_4^{2-} observed are higher than that expected from mineralised rocks. In arid climates, like that of Groot Aub, evaporation may lead to the precipitation of minerals in the soil. Such minerals include calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), and chloride salts. When these minerals undergo dissolution, it can produce the pattern observed on the Piper diagram (Fig. 7a). This suggests that the source of sulphates in Groot Aub is both natural and anthropogenic in origin. The use of septic tanks and agricultural fertilizers are the norm in Groot Aub and may also be contributing to the observed sulphate levels.

Domestic sewage contains 3–6 mg/L of organic sulphur which is converted into sulphide in the absence of dissolved oxygen (Boon, 1995). The concentration of sulphate in the study area remains more or less constant across both seasons, but the distribution changes between seasons. Lower values were recorded in the north-west in the wet season, likely due to dilution as a result of recharge from rainfall, and suggesting groundwater movement from north-west to south-east (Fig. 5a). The sources of SO_4^{2-} at Groot Aub were therefore determined to be threefold. First, there is sulphate from the carbonate rocks and schists, secondly, from evaporation and deposition processes that occur in arid climates, and finally from anthropogenic sources such as agricultural fertilisers, pit latrines, and septic tanks. An extensive amount of SO_4^{2-} can cause a series of environmental problems, such as laxative effects with a bitter taste in drinking water, which results in dehydration in mammals (Sharma and Kumar, 2020).

The distribution of bicarbonate (HCO_3^-) in the area (Fig. 5b) is likely to result from the dissolution of limestone (Powell and Larson, 1985). Carbonate chemistry is relevant to the evolution of groundwater, as bicarbonate (HCO_3^-) is produced from the dissolution of calcite (Earle and Krogh, 2004). The presence of CO_2 in the groundwater enhances calcite solubility (Wells, 1915), thus contributing to high levels of bicarbonate. HCO_3^-, Ca^{2+}, and Mg^{2+} in the groundwater are due to the dissolution of calcite (Appelo and Postma, 1993, Earle and Krogh, 2004). Some marbles that contain dolomite dissolve congruently, such that the quantities of the component appearing in the solutions are proportional to those in the dissolving minerals. Most likely this accounts for the nearly equivalent values of Ca^{2+} and Mg^{2+} in the Groot Aub groundwater (Fig. 4b).

The presence of bicarbonate (a weak acid), sodium and potassium (alkali) ions accounts for the pH range of 6.4–7.7 (Fig. 4a and 5b). This mixture type indicates chemically mature water, with respect to the parent rock, which is usually granite, gneisses, and minor carbonates (Chae et al., 2006). The Sandworks Borehole is enriched with high bicarbonate concentrations in the dry season and has moderate to low values in the wet season. This is possibly due to its location in an area with carbonate rocks intruded by granite rocks. However, the water uptake is from rocks composed of granite and carbonates. This is an example of how the geology impacts groundwater chemistry. The chloride (Cl^-) (Fig. 6a) ion concentration in groundwater can be due to the presence of chlorides from granite and granitic gneisses. The values of Cl^- observed at Groot Aub are generally due to the breakdown of Na-Feldspars in rocks, as the area is underlain by granites and K-Na-rich gneisses.

The Namibian Water Guideline limits NO_3^- to 10 mg/L and 20 mg/L (Group A and Group B water types), whereas the WHO

limit is 50 mg/L. The concentration of NO_3^- in the study area exceeds the permissible threshold of 10 mg/L for Group A water but falls within the Group B limit of 20 mg/L. The southern part of Groot Aub has the lowest elevation (Fig. 2a), which allows contaminants in surface runoff and subsurface flow to migrate towards the Groot Aub Primary School Borehole (Fig. 2a). Nitrate (NO_3^-) contamination is greater in the rainy season than the dry season (Fig. 6b). This is because of the permeable skeletal lithic leptosols soils in Groot Aub that allow for percolation during precipitation events. The upper soil cover is permeable and allows infiltration of contaminants into the aquifers (Huljek et al., 2019).

Nitrate has been revealed to be a major groundwater pollutant across the world (Abascal et al., 2022). For example, several countries in Africa (including Angola, Botswana, Ethiopia, Ghana, Morocco, Nigeria, Republic of Congo, South Africa, Zimbabwe), Asia (including Bangladesh, China, India, Nepal, Pakistan, Palestine, Saudi Arabia, Sri Lanka, Vietnam) and Europe (including Belgium, Germany, Luxemburg, Malta, Portugal and Spain) have in some parts recorded nitrate contamination exceeding the WHO standard of 50 mg/L (Abascal et al., 2022). The source of nitrate contamination in these regions points to various issues such as lack of adequate sanitation, increased usage of agricultural fertilisers and pit latrines that penetrate high porosity soils (Batsaikhan et al., 2018; Ismail et al., 2019), poor maintenance of septic tanks, boreholes, sewage discharge (Devaraj et al., 2020; Roy et al., 2020) and poor industrial wastewater treatment (Isla et al., 2018). Although nitrates are beneficial for plants, high concentrations of nitrates in drinking water are a health hazard that can lead to the formation of cancerous cells in the digestive tract (Ward et al., 2018), as well as stomach ulcers, tumours and oesophageal complications (Prabagar et al., 2020).

From the Piper diagram, the dominant water facies are Na+K, HCO_3^- and (Ca+Mg) SO_4^{2-} (Fig. 7a). These water facies do mix and as such we have good freshwater derived from granites that mixes with hard water mainly derived from carbonate rocks (Fig. 7a and 7b upper panel). Some of the boreholes at Groot Aub provide good quality water, i.e., BH1, BH3 and BH5 that meet drinking water standards. The HCO_3^- is associated with freshwater whereas the SO_4^{2-} is associated with hard water at Groot Aub.

Microbiology

Heterotrophic plate count (HPC) values are a measure of the total bacterial load in water expressed as the growth of bacteria per 1 mL. The study recorded extremely high values for HPC, above the permissible values in both the wet and dry season, at up to 9 224.7 CFU/mL and 4 500.09 CFU/mL, respectively (Fig. 8a). The Namibian Water Guideline limits HPC to 100 CFU/mL for Group A and 1 000 CFU/mL for Group B, while WHO limits HPC to 100 CFU/mL. In the dry season, HPC showed a maximal central distribution, with the area to the north-east and a smaller area to the south not being greatly affected. In the wet season, the water flows from the north toward the south-east, ensuring migration (similar to bicarbonate) of the high HPC values toward the boreholes in the south-east. This movement induces contamination of the boreholes in the south-eastern part of Groot Aub, which is anthropogenic in origin, with the Groot Aub Primary School Borehole being a major concentration point (Fig. 2b, 5a, 6b, 8a and 8b).

An increase in the concentration of HPC in the groundwater indicates a change in raw water quality, usually from good to poor and to very poor (WHO, 2003). It further indicates the availability of nutrients for bacterial growth and tuberculation in boreholes (Health Canada, 2013). Heterotrophic bacteria cause pneumonia and gastrointestinal diseases (WHO, 2003), and it is therefore crucial to build water surveillance monitoring systems (Invik et al., 2017).

The guideline value for *E. coli* in drinking water is 0 CFU/100 mL (zero) for both the Namibian and WHO drinking water guidelines. The wet season recorded slightly more (up to 0.5 CFU/100 mL) *E. coli* than the dry season (up to 0.3 CFU/100 mL) (Fig. 8b), and in both seasons the potable standards for Group A and B were slightly exceeded. This suggests that open defecation and pit latrines have impacted the groundwater quality. Faecal contamination occurs from poor sanitation infrastructure, leaking septic tanks, livestock and wild animal faeces. *E. coli* strains may be pathogenic and thus detrimental to human health (Health Canada, 2020).

CONCLUSION

Groundwater is contaminated by both geological and anthropogenic activities. Na^+ was recorded in high concentrations in both the dry and wet seasons, exceeding the values for other cations. The elements were recorded in the following order in terms of dominance: $Na^+ > Ca^{2+} >$, $Mg^{2+} > K^+$. For anions this order was: $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^- > F^-$. The concentrations for Ca^{2+}, Cl^- and K^+ were found to be within acceptable limits of the Namibian Water Guidelines but not the WHO guidelines. The geological contamination is attributed to the presence of granite and granite-gneiss, which give rise to Na^+, K^+, and Ca^{2+}, while limestones and marbles give rise to Ca^{2+}, Mg^{2+} and SO_4^{2-}, enriching the groundwater with these minerals that alter its chemical composition. Weathering of sedimentary and metamorphic rocks further releases mineral elements that dissolve in water. The groundwater is identified as mixed type, with bicarbonate, sodium, and potassium. It was observed that there is a natural movement of sulphate movement from the north to the southeast of the area, while bacterial contamination was observed to also migrate from the north to the south-east following the same groundwater flow lines. The HPC values exceed the Namibian and WHO drinking water guidelines at the lowest elevation area in the study area, which is around the Groot Aub Primary School Borehole. The general distribution of HPC values in groundwater mirrors the settlement pattern. Where the population is denser, HPC values are higher than in sparsely settled areas of Groot Aub. This presents a major threat to the quality of drinking water at Groot Aub. It is recommended that continuous monitoring of the impacts of anthropogenic activities on groundwater be implemented, that the water and sewerage infrastructure of Groot Aub be upgraded to provide adequate sanitation to the community, that ready-made engineer-designed septic tanks be made available to the resident community, and that buffer zones be created between human activities and groundwater production boreholes to avoid further groundwater contamination.

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