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Microbiological and Physicochemical Quality of Groundwater and Risk Factors for Its Pollution in Ouagadougou, Burkina Faso

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Abstract: Ouagadougou is a city with three million inhabitants and an increasing demand for water of sufficient quality. New boreholes are drilled to match demand, but their protection from anthropogenic contamination is insufficient. To assess the quality of urban groundwater in Ouagadougou for the first time, a total of 32 borehole water samples were collected and assessed for bacteriological and physicochemical features using established methods. Health risk inspections and hazard assessments were undertaken at sampling sites to identify potential hazards and contributing factors. Statistical analysis was used to identify associations between risk factors and water pollution. The study revealed poor quality of groundwater in Ouagadougou with major nonconformities related to total coliforms, *Escherichia coli*, and turbidity. Water samples from 19 boreholes (59%) were contaminated with coliforms, and 11 (34%) with *E. coli*. Additionally, *Pseudomonas aeruginosa*, *Enterococcus*, and anaerobic sulphite-reducing bacterial spores were detected. Deviations from physicochemical quality requirements were observed for water turbidity, pH, nitrate, fluorine, and iron. Risk analysis showed the major high-risk practices to be sludge spreading or having a garbage heap, a latrine, a septic tank, or dirty water near a borehole. Based on these results, for public health protection, authorities must take strict measures to prohibit such practices around these important sources of drinking water in Ouagadougou.

Keywords: groundwater; boreholes; microbiological quality; physicochemical quality; risk factors; Africa

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1. Introduction

The provision of clean and safe water is paramount to human health, and is considered a priority concern by the United Nations, featuring as Sustainable Development Goal (SDG) number six [1]. In developing countries, increases in human population size, animal farming, and industrialization exert an enormous pressure on the provision of safe drinking water [2]. Microbiologically contaminated water is a potential source of human enteric infections and indicates poor maintenance of hygiene-related infrastructure, as well as problems in the implementation of control measures [3]. Deficient basic sanitary practices are often due to lack of awareness among the population. As a consequence, contaminated water is a major cause of diarrhoeal deaths and disease, especially for young children less than five years old, and other vulnerable populations [4].

In many areas in Africa, groundwater is the major source of drinking water for people, as groundwater is considered to be free from impurities and less susceptible to contamination, and more resilient to climate variability compared to surface water bodies [5–7]. However, groundwater quality is impacted by climate, slope, drainage conditions, water–rock interactions, and anthropogenic activities [8,9]. Factors such as storm water runoff, leakage of animal waste into the environment, agricultural practices, industry, energy production, mining, wastewater, and infiltration of inadequately treated domestic sewage can lead to deterioration of underground water sources [10–15].

In West Africa, particularly in rural areas, where access to safe drinking water can be limited, studies have been carried out to assess the risk that people are exposed to by consuming unsafe water. Previous studies in the region have reported microbiological pollution, high levels of mineralization, and much higher concentrations of nitrate and nitrite than the maximum limits set by WHO standards [16,17]. In Burkina Faso, previous studies carried out on the quality of groundwater have focused on heavy metal and chemical contamination in rural areas and the midwestern part of the country [18,19]. However, a recent study by Faye et al. [20] detected microbiological contamination as well as chemical deterioration in groundwater quality in the southwest part of the country. To date, no studies have been conducted on the microbiological and physicochemical quality of groundwater in the central region, including the capital city Ouagadougou. Therefore, we sought to assess water quality and analyze related sanitary risk factors in this area.

In Ouagadougou, many people use water from boreholes due to frequent ruptures in the public water supply system, and also due to the reputation of healthiness and good quality of groundwater. However, due to high population density (1025 inhabitants/km^2), boreholes are often constructed near pit latrines, and thus faecal matter from pit latrines can potentially contaminate groundwater [21,22]. Furthermore, some boreholes are deficiently protected, and penetration of surface water may cause transmission of animal waste or sewage to groundwater [23]. Therefore, the use of vulnerable groundwater aquifers without water purification or disinfection measures for drinking purposes poses a public health concern.

The objective of this work was to investigate the quality of groundwater and reveal its most important risk factors by examining water samples and the maintenance of selected borehole sites in Ouagadougou. The suitability of water for drinking from these groundwater sources was assessed by analyzing total coliforms, *Escherichia coli*, *Pseudomonas aeruginosa,* and enterococci that are commonly used as bacterial indicators in drinking water quality assessments. Additionally, detection of anaerobic sulphite-reducing bacterial spores was used to indicate faecal and/or soil contamination, since their presence indicates the failure of natural or artificial filtration measures [24]. In addition, physical and chemicals parameters including pH and electrical conductivity, turbidity, total hardness, total alkalinity, calcium and magnesium, chlorides, nitrite, nitrates, orthophosphate, sulfate, fluoride, and total iron were analyzed. This is the first study in the Ouagadougou region to consider both contamination risk levels based on sanitary inspection and physicochemical and microbiological parameters.

2. Materials and Methods

2.1. Study Area and Design

This study was conducted in Ouagadougou, the capital and largest city in Burkina Faso. It covers a total area of 600 square kilometers, with a population size of approximately 3,000,000 inhabitants (in 2020). The city has a tropical savannah climate, comprising dry and rainy seasons, and the weather is hot all year round. This study was conducted during the rainy season, extending from April to October, when rain characteristically falls in the form of thunderstorms. Sampling took place from July to September 2018. The study design is shown in Figure 1.

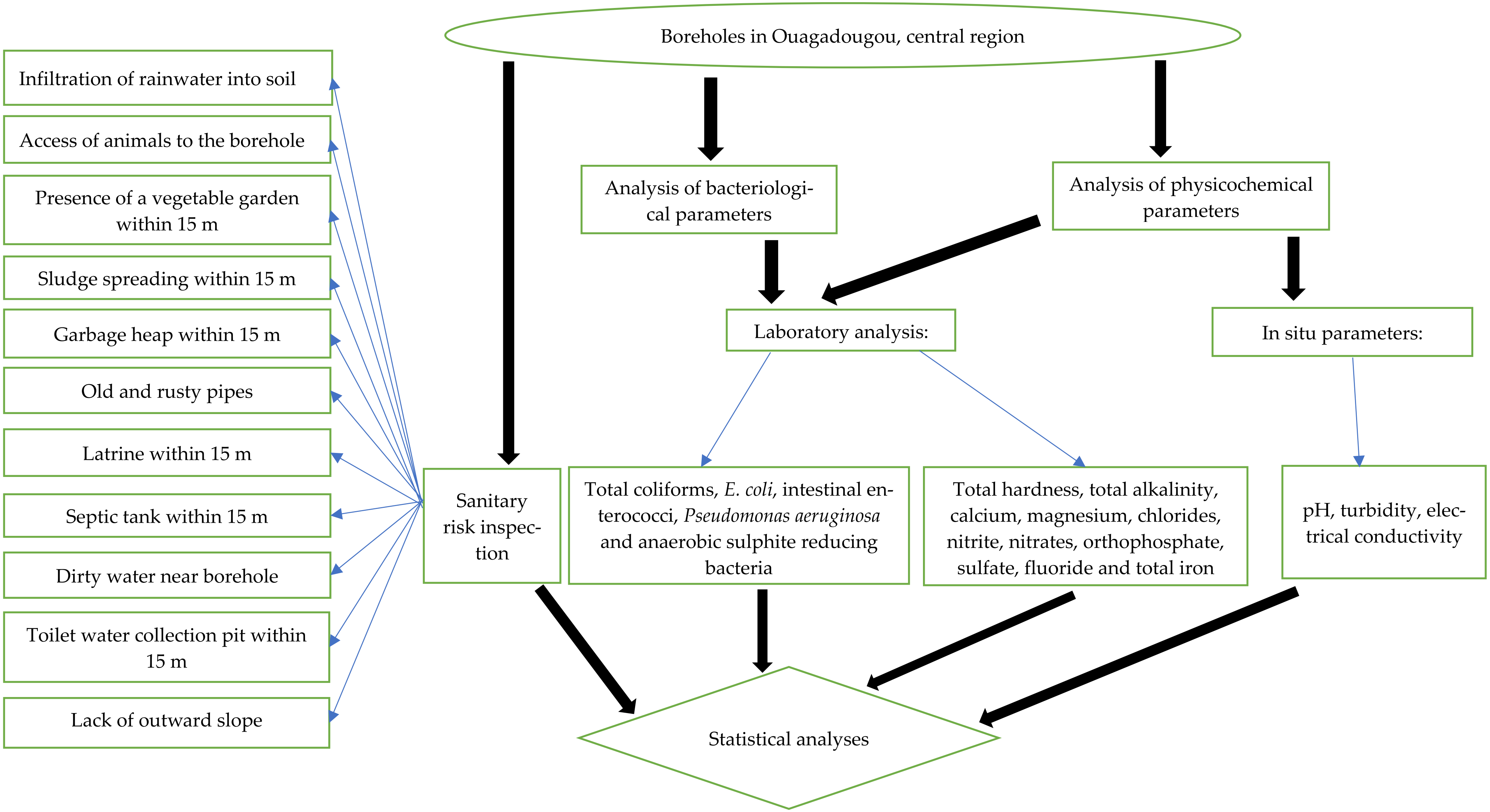

Figure 1. Flowchart for borehole sanitary risk inspection and water analyses.

Hydrogeologically, the study area consists mainly of granitoids intersected with NESW and NWSE oriented fractures. Most of the drilled boreholes are located directly above these fractures. Soil composition is key to determining the physicochemical features affecting water quality. The granitoids are covered with alterites composed of laterites, clayey, sandy, and granular arenas. These alterites have a high porosity of interstices, which provides them with good capacitive function, and are generally in hydraulic connection with underlying cracks and fractures [25].

Water from thirty-two (32) boreholes was sampled in Ouagadougou in a densely populated area with anthropogenic pressure (Figure 2). Boreholes were chosen according to their spatial distribution and frequency of use. The area is also subject to frequent flooding, resulting in poor hygienic conditions and sanitation.

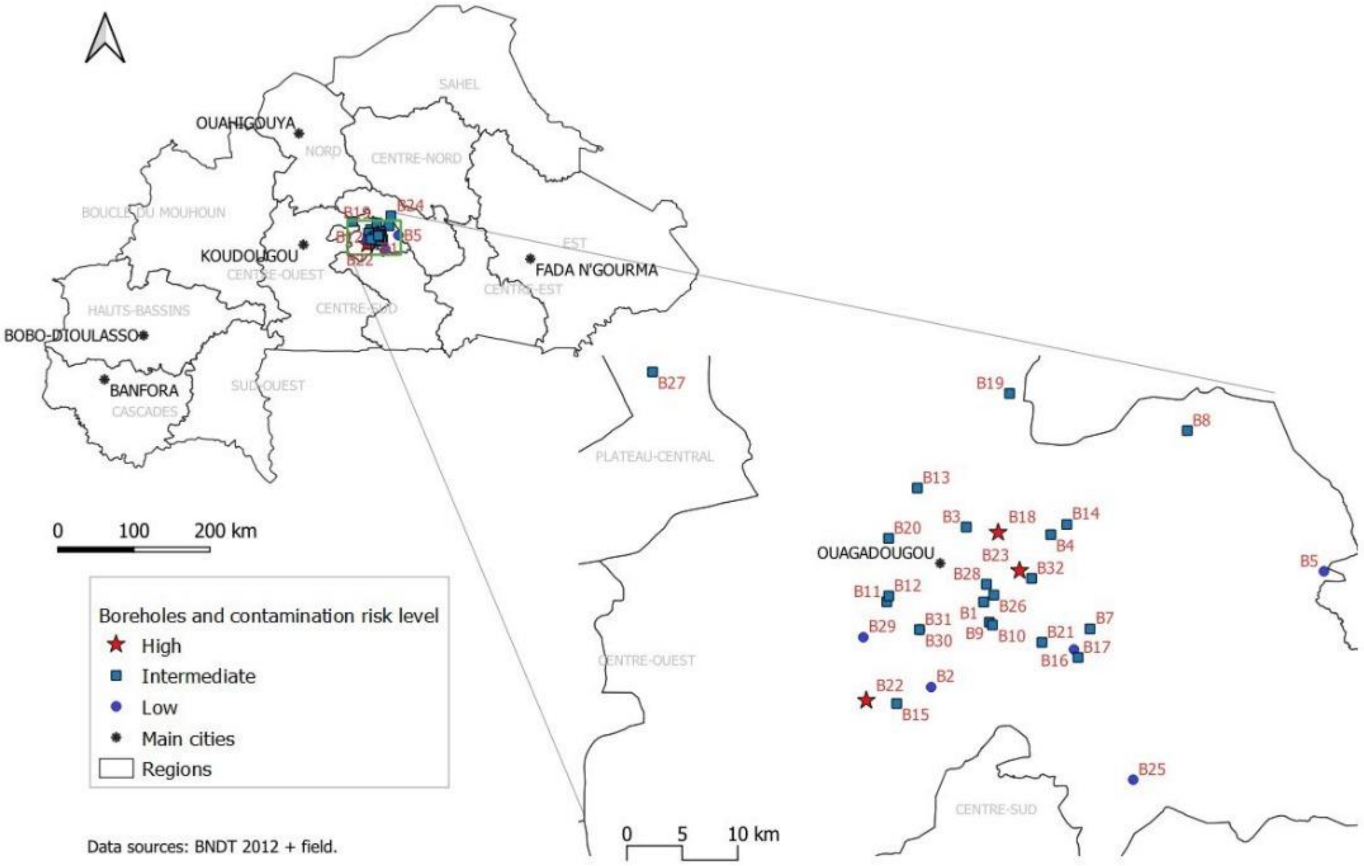

Figure 2. Contamination risk level for groundwater of 32 boreholes in Ouagadougou.

2.2. Sanitary Risk Inspection

At each site, during water sampling, a sanitary risk inspection involving the identification of potential point sources of microbial contamination was performed, as adapted from Lutterodt et al. [26]. The purpose was to collect data on drilled well maintenance and daily hygienic practices likely to protect or deteriorate the quality of groundwater.

Our procedure involved physical inspection of the boreholes, followed by inspection of the surrounding environment and recording their risk factors (Table 1). The parameters measured were: (1) infiltration of rainwater into soil (IRS), (2) access of animals to the borehole (AAB), (3) presence of a vegetable garden within 15 m (PVG), (4) sludge spreading within 15 m (SS), (5) garbage heap within 15 m (GH), (6) old and rusty pipes (POR), (7) latrine within 15 m (L), (8) septic tank within 15 m (ST), (9) dirty water near borehole (DWB), (10) toilet water collection pit within 15 m (TWCP), and (11) lack of outward slope (LOS) around the borehole.

Table 1. Contamination risk factors for groundwater of 32 boreholes in Ouagadougou.

Risk Factors for Borehole Water	Borehole Code	Number of Boreholes (%)
Infiltration of rain water into soil (IRS)	B04, B11, B15, B19, B21, B22, B23, B24, B26, B27, B28, B31, B32	13 (40.6)
Access of animals to borehole (AAB)	B03, B12, B13, B18, B22, B23, B29	7 (21.9)
Presence of vegetables garden within 15 m (PVG)	B04, B09, B10, B14	4 (12.5)
Sludge spreading within 15 m (SS)	B01, B18, B20	3 (9.4)
Garbage heap within 15 m (GH)	B03, B06, B07, B08, B12, B17, B18, B21, B22, B23, B24	11 (34.4)
Old and rusty pipe (POR)	B08, B11, B12, B19, B20, B22, B23	7 (21.9)
Latrine within 15 m (L)	B01, B02, B03, B05, B06, B07, B08, B12, B13, B16, B17, B18, B20, B22, B24, B26, B31, B32	18 (56.3)
Septic tank within 15 m (ST)	B04, B09, B10, B11, B14, B15, B19, B21, B23, B25, B27, B28, B29, B32	14 (43.8)
Dirty water near borehole (DWB)	B01, B02, B03, B06, B07, B08, B12, B13, B14, B17, B18, B20, B21, B22, B23, B24, B26	17 (53.1)
Toilet water collection pit within 15 m (TWCP)	None	0 (0)
Lack of outward slope (LOS)	B01, B03, B04, B06, B07, B08, B09, B10, B13, B14, B15, B17, B18, B19, B20, B21, B22, B23, B24, B25, B26, B27, B28, B31, B32	25 (78.1)

Inspection results were recorded as yes/no, with yes indicating the presence of a risk factor for contamination of the borehole, and no indicating the absence of risk for contamination. A final risk score was obtained on a scale of 1–11. A total score of 9–11 was considered very high-risk, 6–8 high-risk, 3–5 intermediate-risk, and 0–2 low-risk.

2.3. Water Sample Collection

After visual inspection of contamination factors, water samples were collected according to standard methods of the American Public Health Association [27]. In situ analyses of water samples were carried out by the measurement of pH, turbidity, and electrical conductivity. Samples were collected in borosilicate glass bottles for microbiological, and polypropylene bottles for physicochemical analyses. All samples were transported to the laboratory in a cooler box containing ice blocks for analysis conducted on the same day.

2.4. Microbiological Analyses

The water samples were analyzed for total coliforms (TC), *E. coli*, intestinal *enterococci* (IE), and *Pseudomonas aeruginosa* (colony-forming units, CFU/100 mL) by using a membrane filtration system. For each microbiological parameter, one blank sample (using sterilized water) was analyzed to verify that there was no contamination due to the handling process.

For enumeration of total coliforms and *E. coli,* water was filtered through nitrocellulose membrane filters with 0.45 µm pore size (Sigma Aldrich, St. Louis, MO, USA), after which filters were placed on Chromocult Coliform Agar Extra Selective CCAES plates (Merck, Darmstadt, Germany). After incubation at 37 °C for 24 h, colonies were counted using a colony counter. Dark blue to violet colonies were recorded as *E. coli*, and all pink, salmon, red, dark blue, or violet colonies were recorded as total coliforms.

For enumeration of intestinal *enterococci*, water was filtered through nitrocellulose membrane filters with 0.45 µm pore size (Sigma Aldrich, St. Louis, MO, USA), after which filters were placed on Slanetz and Bartley medium (Oxoid, Basingstoke, UK) and incubated at 37 °C for 48 h. If typical red/brown/pink colonies were observed after incubation, the membrane was transferred on a prewarmed (44 °C) plate of Bile Aesculina Azide agar

(Merck, Darmstadt, Germany), and incubated at 44 °C for 2 h. Typical black colonies were identified as intestinal *enterococci*.

For enumeration of *Pseudomonas aeruginosa*, 0.22 µm cellulose membrane filters were used, placed on Cetrimide agar (Liofilchem, Roseto degli Abruzzi, Italy), and incubated at 37 °C for 48 h. Blue/green colonies were considered to potentially be *P. aeruginosa*, regrown on Plate Count Agar (Liofilchem, Roseto degli Abruzzi, Italy) at 37 °C for 24 h, and confirmed by the presence of blue/green colonies on King A (SIGMA, Aldrich St. Louis, MO, USA) (poured into tubes with a slope) after 72 h of incubation at 22 °C.

For enumeration of anaerobic sulphite-reducing bacteria, the 50 mL water samples in flasks were placed in a water bath at 80 °C for 10 min. The samples were then cooled to 45–50 °C and filtered with pump vacuum through a 0.22 µm cellulose membrane filter. The membranes were placed inside meat liver (Oxoid, Basingstoke, UK) medium in a Petri dish before it had solidified. After solidification, the dishes were placed in a jar containing an anaerocult reagent (Merk, Darmstadt, Germany) generating an anaerobic atmosphere. The jar was incubated at 37 °C for 48 h. Black colonies were considered positive.

2.5. Physicochemical Analyses

All of the physicochemical parameters were determined by standard methods recommended by the American Public Health Association [21]. In situ physical parameters including pH and electrical conductivity (EC) were measured using a portable pH meter (WTW 3110) precalibrated with buffer solutions (pH 4 and 7), and a SCHOTT conductivity meter, respectively. The turbidity of the samples was determined using a portable 2100Q HACH turbidity meter.

Chemical parameters, including total hardness, total alkalinity (TA), the major cations calcium (Ca^{2+}) and magnesium (Mg^{2+}), and major anions such as chlorides (Cl^-), of borehole water samples were analyzed by titrimetric methods. Nitrite ($NO_2{}^-$), nitrates ($NO_3{}^-$), orthophosphate ($PO4^{3-}$), sulfate ($SO4^{2-}$), fluoride (F^-), and total iron (Fe^{2+}) were determined using a UV spectrophotometer (HACH).

2.6. Statistical Analyses

R 4.0.2. [28] was used to produce box plots depicting the physicochemical data and to perform principal component analysis (PCA) on 14 physicochemical and 5 microbiological parameters to determine relationships that may exist between these parameters.

R 4.2.1 [28] was used to analyze the risk factors in two stages. First, multivariate data analysis was performed to identify the environmental risk factors (11 factors and the combined risk score) significantly affecting water parameters. This was done using nonmetric multidimensional scaling (metaMDS function) and fitting environmental factors onto the NMDS ordination (envfitfunction with 999 permutations) with the vegan package [29]. Second, for the thus identified significant risk factors, separate binomial generalized linear models (GLMs) were constructed to detect the water parameters associated with the risk factor. For total risk score, linear regression was used. Prior to analyses, all bacterial count data were log (x + 1) transformed. In addition, one data point (B12) was removed as an outlier, as it had several parameter values a magnitude higher than the other samples and would have been too influential in the statistical analyses.

3. Results

3.1. Sanitary Inspection Results

Contamination risk factors for the 32 boreholes are shown in Table 1. The most common risk factors were the lack of outward slope that would allow surface water to run away from the well (25 boreholes), latrine within 15 m from the borehole (18), dirty water on the ground in the vicinity of the borehole (17), and a septic tank within 15 m from the borehole (14). Based on risk categorization of the 32 boreholes, three were in a high-risk, 23 in an intermediate risk, and 6 in a low-risk environment. None were in a very high-risk environment (Figure 2).

Microbiological Quality of Water Samples

Noncompliance of the borehole waters with microbiological and physicochemical quality criteria is shown in Table 2. Based on microbiological analyses, 19 (59.4%) borehole water samples were contaminated by coliforms, with three samples having a contamination level greater than 100 CFU/100 mL. *E. coli* was isolated from 11 samples, with maximum contamination of 33 CFU/100 mL in one sample. *Pseudomonas aeruginosa* was isolated from four samples, with maximum contamination exceeding 100 CFU/100 mL in one sample. *Enterococcus* was isolated from two samples, and anaerobic sulphite-reducing bacteria from one sample.

Table 2. Noncompliance of borehole water with microbiological and physicochemical quality criteria.

Parameters	**Microbiological Parameters**					**Physicochemical Parameters**				
	Total Coliforms	**EC**	**IE**	**PA**	**ASRBS**	**pH**	**Turbidity**	**Fluoride**	**Iron**	**Nitrate**
Units	CFU/100 mL	CFU/100 mL	CFU/100 mL	CFU/100 mL	CFU/100 mL	-	NTU	mg/L	mg/L	mg/L
Values	B01 (89), B02 (>100), B04 (14), B05 (>100), B06 (8), B07 (14), B08 (>100), B09 (10), B10 (9), B13 (92), B14 (68), B17 (66), B18 (88), B20 (56), B21 (57), B22 (69), B23 (87), B24 (6), B26 (69)	B01 (16), B08 (3), B13 (33), B14 (5), B17 (3), B18 (18), B20 (16), B21 (16), B22 (16), B23 (16), B26 (20)	B18 (3), B26 (1)	B03 (>100), B06 (75), B14 (66), B17 (56)	B18 (12)	B03 (6.2), B04 (6.4), B07 (6.4), B08 (6.3), B09 (6.4), B14 (6.3), B15 (6.3), B16 (6.4), B20 (6.4), B22 (6.4)	B08 (6.02), B12 (218), B14 (9.1), B18 (13.2), B20 (34.4), B22 (34.4), B24 (41) B32 (12.2)	B06 (3.5)	B08 (0.39)	B12 (469.9)
Total (%)	19 (59.4)	11(34.4)	2 (6.3)	4 (12.5)	1 (3.1)	10 (31.3)	7 (21.9)	1 (3.1)	1 (3.1)	1 (3.1)
WHO standards	0	0	0	0	0	6.5–8.5	5	≤1.5	≤0.3	≤50

TC = total coliforms; EC = *E. coli*; IE = intestinal enterococci; PA = *Pseudomonas aeruginosa*; ASRBS = anaerobic sulphite-reducing bacteria spores; CFU = colony-forming units; NTU = nephelometric turbidity unit. The CFU count for the microbiological parameters and the values for the physicochemical parameters are mentioned in parentheses.

In terms of microbiological quality, 62% of borehole water samples were noncompliant with WHO and national standards (0 CFU/100 mL) for containing total coliforms, *E. coli*, intestinal enterococci, *Pseudomonas aeruginosa*, or anaerobic sulphite-reducing bacteria spores (Table S1).

3.2. Physicochemical Quality of Water Samples

Major noncompliances of physicochemical water quality were related to turbidity, pH, nitrate, fluoride, and iron (Table S1). Box plots for the measured physicochemical parameters show the concentrations of each physicochemical parameter (Figure 3).

Turbidity values varied between 0.19 and 218 nephelometric turbidity units (NTUs). The national maximum value for drinking water is 5 NTUs, and it was exceeded in eight borehole water samples. An exceptionally high value was obtained for water from one borehole: the value was 43.6 times higher than the maximum value according to the national guideline.

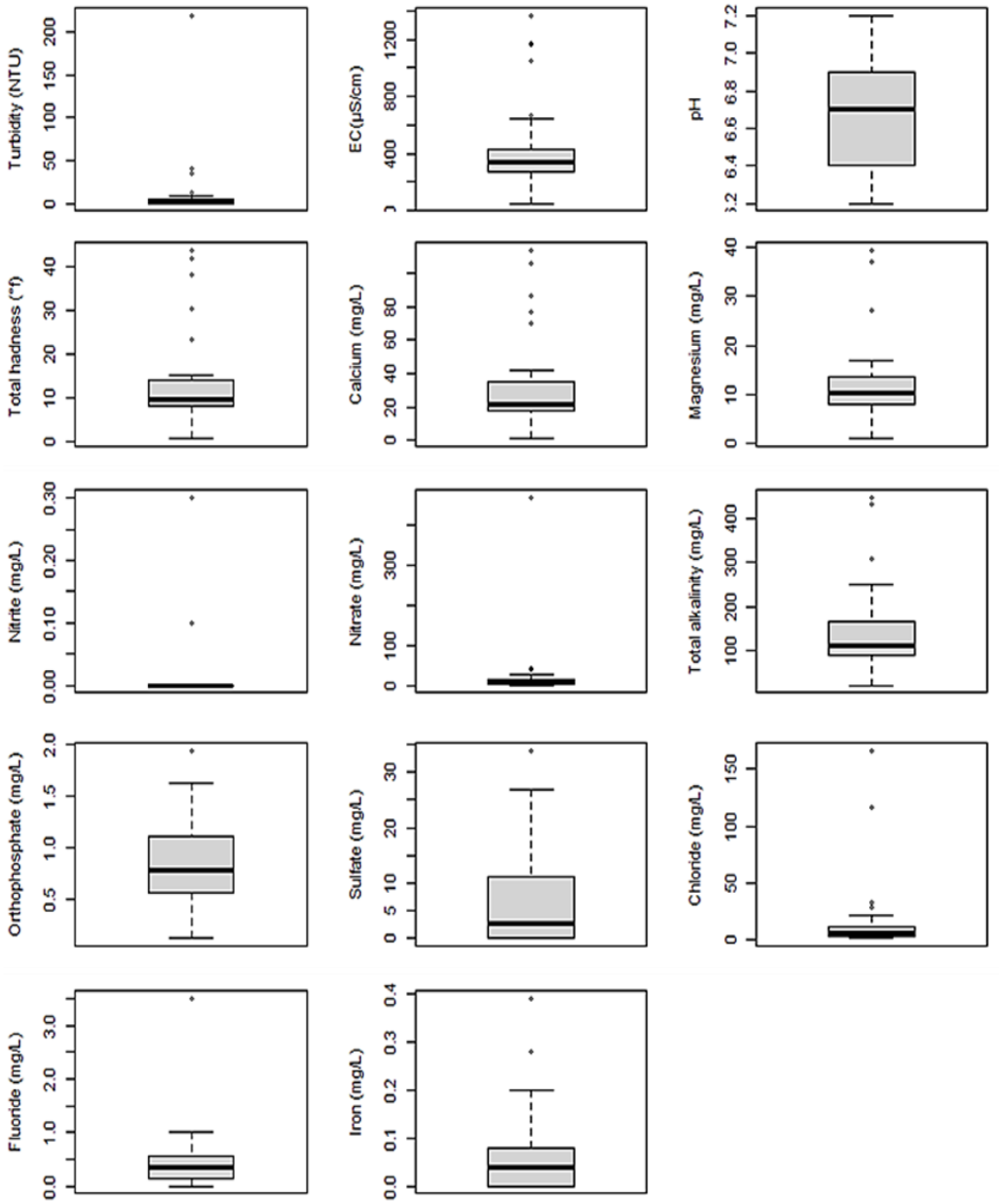

Figure 3. Box plots for physicochemical parameters quantified for 32 borehole water samples. The hinges represent the lower and upper quartiles, within which 50% of the data lie. The horizontal line within the box represents the median. The whiskers extend to the most extreme value within 1.5 interquartile range above or below the hinges, with dots beyond the whiskers indicating outliers. EC= electrical conductivity.

Electrical conductivity (EC) provided a general overview of the mineralization of borehole water in Ouagadougou. The values obtained varied between 50.1 and 1365 µS/cm, which are in compliance with the WHO guideline of ≤2500 µS/cm. There is no national standard for this parameter. EC represents total dissolved ions in groundwater samples, and impacts the taste of water. Low EC indicates a low amount of salt associated with good taste.

pH represents the concentration of hydrogen ions in a solution. Ten borehole water samples were not in the acceptable pH range, which is between 6.5 and 8.5 according to the national guideline.

The concentration of calcium varied from 0.9 to 114.2 mg/L, with the WHO guideline being ≤ 200 mg/L. The concentration of magnesium ranged from 0.9 to 39.5 mg/L, with the WHO guideline being $\leq$ 50 mg/L. The total hardness of water is the sum of all calcium and magnesium salts present, carbonated and noncarbonated.

Nitrite and nitrate concentration ranged between 0 and 0.3 mg/L and 0 and 469.9 mg/L, respectively. According to national standards, nitrite and nitrate should not exceed 3 mg/L and 50 mg/L, respectively. Thus, the value of 469.9 mg/L for nitrate was much higher than the standard for drinking water.

Total alkalinity concentration ranged from 69.6 to 446.5 mg/L. Total alkalinity is a measure of the ability of water to resist changes in pH.

Orthophosphate concentration varied from 0.13 to 1.94 mg/L. There is no standard for this parameter, but orthophosphates are effective in limiting corrosion.

Sulfate concentration ranged from 0 to 34 mg/L, and was compliant with the national guideline which is $\leq$250 mg/L. High sulfate concentration in water can cause diarrhoea, leading to severe dehydration over the long term.

Chloride concentration varied between 0.7 and 166.9 mg/L. All the borehole water samples thus complied with the national guideline of $\leq$250 mg/L.

Fluoride values varied between 0 and 3.5 mg/L. The national guideline for drinking water is 1.5 mg/L, with only one borehole water sample exceeding this.

Iron concentration varied from 0 to 0.39 mg/L. The national guideline for drinking water is 0.3 mg/L, and only one borehole water exceeded this.

In conclusion, based on physicochemical parameters, 17 (53.1%) borehole water samples met the quality standards.

3.3. Overall Water Quality

Overall, 75% of the borehole water samples were not potable due to their noncompliance with the acceptable microbiological or physicochemical parameters or both. Most of the nonconformities were related to microbiology, as the microbiological and physicochemical noncompliance of the borehole waters were 62% and 44%, respectively.

Principal component analysis (PCA) was performed to detect possible correlations between the parameters measured (Figure 4, Tables S2–S4). Three main groups were formed: The first one included variables positively correlated with both axes (F1). It included chlorides (Cl^-, turbidity, nitrite ($NO_2{}^-$), and nitrate ($NO_3{}^-$). The second group was positioned positively on the x-axis (F1) and negatively on the y-axis (F2). It included calcium, magnesium, EC, TH, TA, pH, SO $SO_4{}^{2-}$, and F^-. The third group was positioned mainly on the negative side of the F1 axis, with a contribution of 42.7%. It included iron (Fe^{2+}) and orthophosphate ($PO4^{3-}$). The analysis showed that the biological factors are not correlated with any physical or chemical parameters.

3.4. Risk Factors for Borehole Contamination

According to multivariate data analysis (NMDS), water parameters were significantly affected by the environmental variables SS ($p = 0.026$), GH ($p = 0.038$), ST ($p = 0.029$), DWB ($p = 0.002$), and total risk score ($p = 0.010$).

Sludge spreading within 15 m (SS) was significantly associated with higher levels of ammonium and *E. coli* (ANOVA for binomial GLM: ammonium χ^2 (1.23) residual deviance RD = 2.8, $p = 0.002$; *E. coli* χ^2 (1.12) RD = 0.0, $p < 0.001$).

Garbage heap within 15 m (GH) was significantly associated with higher levels of ammonium, bicarbonate, and *P. aeruginosa*, and with lower levels of calcium (ANOVA for binomial GLM: ammonium χ^2 (1.23) RD = 24.1, $p = 0.03$; bicarbonate χ^2 (1.20) RD = 2.8, $p < 0.001$; *P. aeruginosa* χ^2 (1.11) RD = 144, $p < 0.001$; calcium χ^2 (1.25) RD 31.1, $p = 0.02$).

Presence of a septic tank within 15 m (ST) was significantly associated with higher levels of water hardness, nitrite, and nitrate, and with lower levels of ammonium (ANOVA for binomial GLM: water hardness χ^2 (1.26) RD = 32.6, $p = 0.01$; nitrite χ^2 (1.22) RD = 17.2, $p = 0.002$; nitrate χ^2 (1.21) RD = 0, $p < 0.001$; ammonium χ^2 (1.23) RD 27.0, $p = 0.048$).

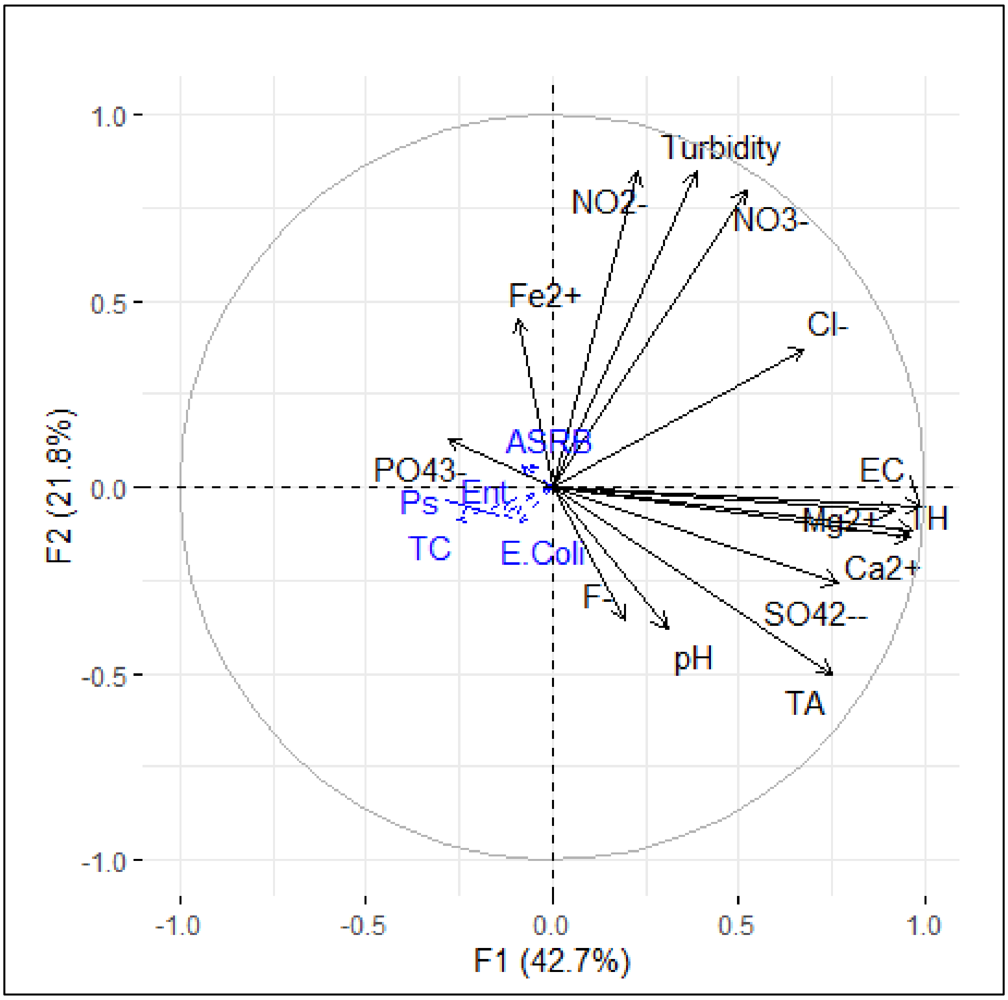

Figure 4. Correlation circle from principal component analysis (PCA) showing three main groupings for the physicochemical characteristics of the waters studied.

Dirty water near borehole (DWB) was significantly associated with higher levels of turbidity and sulphate, and with lower levels of nitrate (ANOVA for binomial GLM: water turbidity χ^2 (1.29) RD = 37.8, $p = 0.02$; sulphate χ^2 (1.18) RD = 0, $p = 0.001$; nitrate χ^2 (1.21) RD = 12.6, $p < 0.001$).

Total risk score was significantly associated with higher levels of turbidity, calcium, silica, total coliforms, and, marginally significantly, with *E. coli* (ANOVA for linear regression: turbidity F (1.29) = 27.7, $p < 0.001$; calcium F (1.25) = 41.2, $p = 0.003$; silica F (1.14) = 21.3, $p = 0.04$; total coliforms F (1.13) = 15.4, $p = 0.002$; *E. coli* F (1.12) = 9.2, $p = 0.05$).

4. Discussion

Thirty-two (32) boreholes were studied to assess their microbiological and physiological water quality and the anthropogenic risk factors correlated with water quality. The majority of the water samples (75%) did not comply with official sanitary requirements. Total coliforms and heterotrophic bacteria in water are indicators for poor hygienic quality, while *E. coli* and faecal coliforms indicate potential faecal contamination [30]. *E. coli* was detected in 34.4% of the borehole water samples. The standards set by the WHO or Burkinabe government for potable water require 0 CFU/100 mL for total coliforms, *E. coli*, intestinal enterococci, and *Pseudomonas aeruginosa*. However, many of the studied boreholes contained these bacteria. Of the anthropogenic risk factors observed, sludge spreading and a garbage heap within 15 m were significantly associated with high levels of *E. coli* and *P. aeruginosa*. The total risk score was significantly associated with higher levels of total coliforms and, marginally significantly, with higher levels of *E. coli*. In other studies conducted in Africa, the presence of surface water and wastewater, potentially carrying harmful microorganisms, near boreholes was the greatest hazard identified as a source of groundwater contamination [10,31,32]. Connections between microbiological contamination and anthropogenic activities such as land application of wastewater biosolids, municipal solid waste landfills, agricultural operations, and poor sanitary practices have also been reported [32].

In the present study, intestinal enterococci and anaerobic sulphite-reducing bacterial spores were used as additional indicators for faecal contamination, as suggested previously [33]. They are more resistant than coliforms in the natural environment, and thus their presence in some of our borehole water samples can be due to past contamination.

In the present study, only one borehole water sample was noncompliant for nitrates, which seems rare compared to a previous study. Previously, in an analysis on the relationship between urban centers in sub-Saharan Africa and aquifer pollution risk for nitrate, Ouagadougou was shown to be at high risk for nitrate pollution [34]. High nitrate content is also frequently associated with a high number of faecal indicator bacteria, indicating faecal contamination of urban groundwater in Africa [35,36]. Generally, leaching of chemicals, agricultural fertilizers, animal manure, pollution from septic tanks, sewage discharge, atmospheric deposition, decomposition of plant and animal organisms, other wastewater and refuse released to the environment from domestic work are the main sources of nitrates and nitrite in water [10,31,33,37–40]. Long-term exposure to nitrate can result in adverse health effects such as headache, stomach cramps, vomiting, or increased heart rate [6]. Nitrate transformation into nitrites is more toxic and can potentially have a negative impact on health. In this study, the high content of nitrate in one borehole could be due to the presence of a septic tank nearby. The presence of a septic tank within 15 m was significantly associated with higher levels of water hardness, nitrite, and nitrate. However, this particular borehole is not the only one whose distance is less than 15 m from a septic tank, and thus other reasons such as the depth of the borehole, which was not taken into account in this study, should be considered. Only one borehole water sample was noncompliant for fluoride, although Burkina Faso is located in a region where relatively high geogenic fluoride concentration in groundwater has been predicted [41]. The main intake pathways of fluoride for humans are drinking water and food intake. Potential risks associated with high concentrations of fluorides ingestion include tooth damage and pronounced skeletal fluorosis following long-term exposure [13,41].

Water from one borehole was noncompliant for iron. Iron is known to cause an unpleasant metallic taste in water and a reddish colour, which could be linked to deoxygenation of water by organic activity in the soil and in the unsaturated zone [42]. Taste alteration is also the main impact of increased electrical conductivity in water [43]. Strongly correlated parameters such as Mg^{2+}, Ca^{2+}, total hardness, total alkalinity, and electrical conductivity were observed in the present study, similar to observations made in Niger by Amadou et al. [16].

Dirty water near a borehole can lead to the flow of runoff water into the borehole, and a consequent increase in turbidity affecting the acceptability of water to consumers [44]. Dirty water near a borehole was also found to be significantly associated with high levels of turbidity. Turbidity could also be due to the presence of suspended solids such as clay or silt, which give the water a cloudy appearance [45]. A significant association was not detected between turbidity and microbiological contamination in this study, although out of eight borehole water samples that did not comply with turbidity guidelines, six were also microbiologically noncompliant. A parameter not taken into account in our study was the depth of the boreholes. This can have an impact on the quality of the water, and several previous studies have indeed revealed shallow groundwaters to be polluted by chemicals and biological contaminants [31,46–48]. In addition to the depth of the borehole, seasonal variability and the number of people drawing water from each borehole were not considered in this study, but should be considered in subsequent studies. New methods based on, for example, geographical information systems (GIS) and machine learning, have been utilized to improve surface water quality assessment [49,50]. Additionally, for groundwater quality assessment, new techniques including geoinformatics, remote sensing, and big data science are needed [7].

5. Implications

The common detection of deviations from water quality standards in groundwater samples indicates a need for continuous efforts by the government through the Ministry of Health and Public Hygiene to ensure the safety and quality of groundwater in Ouagadougou. By strengthening training programs, raising awareness, and implementing effective monitoring systems, the quality of borehole water can be maintained, safe-guarding public health. Moreover, there is need for regular surveillance of water quality and the environment surrounding boreholes.

6. Conclusions

This study showed that the groundwater in Ouagadougou is vulnerable to microbiological contamination due to anthropogenic activities. Most of the boreholes were in an intermediate-risk or a low-risk environment due to risks related to practices in the vicinity of the boreholes. Therefore, in order to prevent pollution, more attention must be paid to the maintenance of borehole surroundings. This requires both increased awareness among the population and enforcement of good practices by city authorities. Practices such as sludge spreading and having a garbage heap, a latrine, a septic tank, or dirty water near the borehole must be abolished. Outward slopes must be constructed around boreholes. Additional treatment measures such as filtration or disinfection of borehole water would also reduce the risks for public health. These changes can protect the boreholes as important sources of drinking water in Ouagadougou.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15213734/s1, Table S1: Physicochemical and microbiological parameters of borehole water; Table S2: Extraction Method, Principal Component Analysis; Table S3: Contribution of physicochemical parameters in the main components; Table S4: Correlation matrix between the microbiological and physicochemical parameters.

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