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Research paper

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Mapping the vulnerability of groundwater and assessing the health risks of deficiencies in essential elements in the Lukunga watershed of Kinshasa city

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Summary

The increasing reliance on boreholes in Kinshasa reflects the ongoing inadequacy of the public water supply, raising concerns about the management of groundwater and the potential health risks connected to aquifer contamination. This study assesses the vulnerability of groundwater in the Lukunga watershed using the GOD method, complemented by a health risk analysis focusing on deficiencies in essential minerals: calcium (Ca) and magnesium (Mg). Hazard quotient (HQd) was applied to evaluate the risk of chronic exposure. Physico-chemical data from 23 water samples (September 2023) supported the generation and validation of vulnerability maps. Integration the GOD model and HQd approach offers a cost-effective and scientifically robust framework, especially suited for data-limited urban settings. The GOD model provided a rapid classification of aquifer sensitivity, while HQd refinement incorporated hydrochemical data to improve exposure risk estimates. The results revealed that nearly 30% of the watershed falls under the 'very high' vulnerability category, particularly in downstream areas and along major rivers. The main source of pollution is linked to domestic waste due to poor urban sanitation. Although chemical contamination remains low, the predominant health risk arises from insufficient Ca and Mg levels, with average concentrations of 1.19 mg/L and 1.07 mg/L, respectively.

These suggest very soft water and an insufficient daily intake, especially for vulnerable populations. Elevated HQd values indicate potential long-term health consequences, including an increased risk to bone and cardiovascular conditions. This study highlights the urgent need for improved monitoring of groundwater and mineral supplementation strategies to protect public health and ensure the sustainable management of Kinshasa water resources.

Keywords

Lukunga • vulnerability map • groundwater • essential elements • calcium and magnesium • health risks.

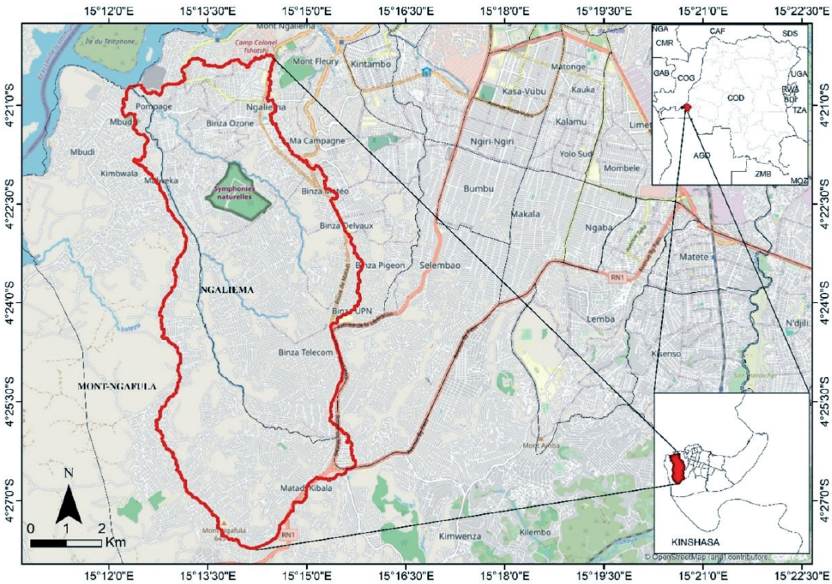
1. Introduction

Groundwater is naturally drinkable and often requires little to no treatment before use. For people in developing countries with resource shortages, access to drinking water is critical (Foster, 2002]. The quality of water is protected by the soils and rocks of the unsaturated zone above the water table. These elements filters out bacteria and protect the groundwater from surface contaminants [Rukmana et al. 2020, Ju et al. 2022]. Assessing aquifer vulnerability is crucial for sustainable management of groundwater, guiding decision-makers in pollution mitigation, resource allocation, land use planning, and raising awareness of contamination risks [National Research Council 1993]. However, groundwater is under threat from overexploitation and pollution, which can lead to depletion and increased treatment costs, and can even make it unusable. It is therefore crucial to protect this invisible yet essential resource to avoid these harmful consequences [Baazi Houria and Drifi Naima 2023, Machiwal et al. 2018, Ducommun et al. 2010]. The significant increase in pollutants generated by modern agriculture, industry and inefficient sanitation infrastructure can exceed the capacity of the unsaturated zone to filter contaminants and protect groundwater. Once the groundwater is polluted, its decontamination becomes a very costly process, and can take a long time [Moges et al. 2021]. Currently, the city of Kinshasa (DR Congo) is experiencing a proliferation of boreholes, particularly within the Lukunga catchment area, due to a shortfall in the supply of drinking water from the main provider of this essential resource. Moreover, for over ten years, Kinshasa has been facing problems with waste management, rainwater and wastewater drainage, gully erosion, especially in hilly areas, and recurrent flooding [Vuni et al. 2022, Makanzu 2014, Lelo 2011]. Due to the precariousness of the water supply, its absence in some households, and outdated connections and equipment, access to drinking water is not guaranteed for the entire population to cover their needs in terms of food, hygiene and other daily activities. As a result, numerous sources of pollution linked to human activities have emerged, including uncontrolled urbanization, unregulated industries, unauthorised dumps, illegal agricultural activities, etc. [Katalayi 2015, Mfumu et al. 2016]. Daily waste production is estimated at 90,000 tons, but only 20,000 tons are collected every day due to a lack of sufficient resources. Furthermore, the exact volume of biomedical and industrial waste produced is unknown [Holenu 2016]. Because the inhabitants of Kinshasa are unaware of proper waste disposal methods, they resort to landfilling and illegal dumping in rivers and streams [Lelo 2008, Ndembo 2009]. This leaves the groundwater vulnerable to pollution. This situation is of particular concern as local urban populations increasingly rely on borehole water for their drinking water supply and domestic use. In the current context of sustainable water resource management policy, predicting the risk of pollution is paramount, hence the need to map areas of the watershed that are vulnerable to aquifer pollution. A person's health over the course of their life depends largely on their daily intake of essential elements needed by their body's various organs. These elements are found in water, food and air. Health risk is defined as the probability of human injury, illness or death resulting from exposure to an environmental risk factors [US EPA 1989]. Many studies on essential elements focus on the effects of their excess on human health. The methodology for assessing health risks was formulated in the 1980s by the US Environmental Protection Agency [US EPA), known as the Human Health Risk Assessment Method [US EPA 1989]. Current methodological procedures for calculating health risks are only concerned with increased levels of harmful substances/elements. They assess the possible adverse effects of various substances/elements in case of their levels exceeding the reference limit or dose [Rapant et al. 2020]. However, these procedures do not assess health risk due to deficiencieslevels of various essential elements, particularly biogenic elements, necessary for healthy human development [Rapant et al. 2020]. A common examples is a deficiency in iodine, fluorine, iron, and several other trace elements (Se, Zn and Cu) or essential macro-elements, e.g. Ca and Mg [Yang et al. 2006, Rayman 2012, Prasad 2013, Schwarz et al. 2013, Fuge and Johnson 2015, Rapant et al. 2017, Arredondo 2018, Rapant et al. 2020]. Water is essential for life. The development of the geochemical elements that make up water remains relatively the same without prolonged human intervention. Its use for drinking and cooking helps maintain the necessary daily intake of elements, if the water source remains unchanged. Consequently, it also maintains the deficit in these elements, if it has poor quality. Studies by Rubenowitz et al. [1996], Rubenowitz [1999], Catling et al. [2008], Yang et al. [2006], Rapant et al. [2017], Rosborg and Kožíšek [2020], Tam [2003], Schwarz et al. [2013], Rosborg [2015] on low levels of important essential elements, including Ca and Mg in drinking water, show that they are often correlated with increased incidence and mortality of several serious chronic diseases, such as cardiovascular disease, death from acute myocardial infarction and various types of cancer. These studies assess groundwater deficiency in calcium (Ca) and magnesium (Mg) adopting health and population growth indicators, known as environmental indicators. This method is more complex yet offers greater objectivity, as it directly considers the Ca and Mg levels in drinking water along with the health status of the consuming population [Rapant et al. 2020]. Due to limited data on population health status, however, our approach relies on actual Ca and Mg content in drinking water, referencing World Health Organization [2017] standards.

2. Materials and methods

2.1. Study area

The Lukunga watershed, situated in western Kinshasa (15°12’0”–15°22’0” E / 4°20’0”–4°28’0” S), covers an area of approximately 57.3 km² with a perimeter of 41.5 km. It forms a deep valley with rivers emerging from the base of hills with gradients that exceed 20%, and often create erosive cirques as they descend [Lelo 2008]. This watershed, which lends its name to the surrounding district, lies between the communes of Ngaliema and Mont-Ngafula within Kinshasa, the capital city of the Democratic Republic of Congo (Fig. 1).



Source: Authors’ own study

Fig. 1. Location of study area (OSM)

The study area falls within the Aw4 climatic zone, as classified by Köppen-Geiger [1930], characterized by a hot, humid tropical climate with a prolonged rainy season lasting approximately eight months, from mid-September to mid-May. This period may be interrupted by a brief dry spell between January and February, while the remaining months are the dry season. The mean annual rainfall is 1,620.5 mm. Average temperatures range from 20–25°C during the dry season and 24–27°C in the rainy season, with recorded extremes of 20°C in July and 27°C in November [Ntombi et al. 2004, 2006, Makanzu et al. 2014]. Topographically, the area is shaped like an amphitheatre, which is typical for Kinshasa. It features elevated hills to the south and east, low-lying plains to the northwest, and marshlands adjacent to the Congo River [Van Caillie 1997]. Elevations vary from approximately from 640 m to 250 m. The geological profile includes Kalahari cover formations overlying the schisto-sandstone basement of the Inkisi Group, stratified as follows: Holocene alluvium (5–6 m), Pleistocene sandy deposits (20–30 m in the plains, 50–150 m in the hills), Neogene ochre-coloured sands (~75 m), Paleogene polymorphous sandstones (~75 m), and Cretaceous soft to silicified sandstones (100–200 m), which overlie basement rocks dating from the Late Precambrian to Pre-Permian [Lateef et al. 2010]. Hydrogeologically, the area contains an unrestrained aquifer that becomes semi-confined and multilayered in places. This aquifer, composed primarily of Quaternary sands and soft Cretaceous sandstones, varies in thickness from 5 to 100 meters and rests atop relatively impermeable Inkisi sandstones. The high permeability of these formations increases the vulnerability of the groundwater to surface pollution [Mulowayi et al. 2021, Mfumu et al. 2016, Ndembo 2009, Van Caillie 1983].

2.2. Assessment of the Lukunga aquifer vulnerability using the GOD method

In order to address and assess groundwater pollution, many authors have applied mathematical models that account for physical and hydrogeological parameters associated with an aquifer's intrinsic vulnerability [Aller et al. 1987, Foster 1987, Tiktak et al. 2004, Chenini et al. 2015, Houria and Naima 2023]. Subjective element involved in assigning parameter ratings and classifications limits the explanatory power of these models, as noted by Panagopoulos et al. [2006]. To mitigate this, studies have introduced calibration techniques to adapt model parameters according to environmental factors and pollutant impact, thereby reducing subjective decision [Sulmon et al. 2006, Huan et al. 2012, Hamza et al. 2014, Mfumu et al. 2016].

In our study area, groundwater vulnerability was analysed using the GOD method [Foster, 1987], which involves three key environmental parameters influencing aquifer contamination. The GOD vulnerability index (IGOD) is calculated by multiplying scores for each of these parameters [Murat et al. 2000]. IG (GOD index) = Ca × Cl × Cd; where Ca represents aquifer type, Cl refers to aquifer lithology, and Cd denotes water table depth. The range of GOD index values and their respective vulnerability classes according to Murat et al. [2003] (Table 1).

Table 1. GOD index values and corresponding classes

Interval	GOD class
0–0.1	Very low vulnerability
0.1–0.3	Low vulnerability
0.3–0.5	Moderate vulnerability
0.5–0.7	Very high vulnerability
0.7–1	Extreme vulnerability

Source: Foster et al. [1987], in: Murat et al. [2003]

The choice of the GOD method in this study was motivated by the limited availability of hydrogeological data from the used boreholes. As a preliminary study in the region, this method allows us to conduct a quick assessment of groundwater vulnerability in the Lukunga watershed with minimal resources.

Based on field campaign data (September 2023), which inventoried 58 water points (48 boreholes, 7 springs, and 3 wells), and a borehole database, we employed inverse distance weighting (IDW) interpolation to assess water table depths (from geophysical survey data), geological layers in the vadose zone, and aquifer characteristics. These parameters were integrated within a geographic information system (GIS) to calculate groundwater vulnerability values using the GOD index. The final maps, generated using ESRI ArcMap 10.8 and applying vulnerability ratings from Murat et al. [2003], display spatial variations in groundwater vulnerability.

2.3. Ca and Mg contents and water hardness in the Lukunga aquifer

According to WHO standards [2017], the threshold values for calcium (Ca) and magnesium (Mg) in drinking· water, above which toxicity issues may arise, are around 50 mg/L for each element (Table 5). Water hardness is expressed as the sum of concentrations of Ca and Mg in mmol · L^{-1}. Water hardness is divided into three levels: soft with a value of ((Ca+Mg) mmol · L^{-1}) < or equal to 1.5 in mmol · L^{-1}; medium-hard with 1.6 mmol · L^{-1} < ((Ca+Mg) mmol · L^{-1}) < or equal to 2 mmol · L^{-1}; and hard with ((Ca+Mg) mmol · L^{-1}) > to 2 mmol · L^{-1}. As a result, the population in our study area is supplied with drinking water that has a low average Ca content (=1.19 mg · L^{-1}), Mg = 1.07 mg · L^{-1} and total water hardness ((Ca+Mg) mmol · L^{-1}) (= 0.08 mmol · L^{-1}) (Table 2).

Table 2. Ca, Mg and hardness contents of Lukunga water

	Ca	Mg	(Ca + Mg)
	mg · L^{-1}	mg · L^{-1}	mmol · L^{-1}
Average	1.19	1.07	0.08
Minimum	0.1	0.15	0.01
Maximum	10.94	8.88	0.67
Median	0.68	0.51	0.04
SD	2.20	1.76	0.13

2.3.1. Calculation methodology

In cases where the health risk is caused by an excess of harmful elements, the US EPA has established a reference dose (RfD) for various contaminants with a threshold-type toxicological effect on health. This reference dose (RfD) is established for individual elements or contaminants, so the average daily dose (ADD) is then calculated for each site based on the actual levels and the likely exposure scenario. The notion of risk quotient (HQ) for an element refers to the ADD/RfD ratio, and its value indicates the level of possible health risk. No adverse health effects are expected if the HQ value is less than 1, but if the HQ value is greater than 1, i.e. the daily dose taken is higher than the reference dose, then there is a high probability of health damage. In our case, health risk is caused by a deficiency in essential elements. From the point of view of human health, Ca and Mg have not yet been considered by regulatory bodies as risk elements and, consequently, the minimum necessary or admissible daily doses for the various environmental components are not defined in global toxicological databases [Rapant et al. 2020].

For the assessment of human health risks related to essential element deficiency, the calculation is based on the following types of average daily doses (in $mg \cdot kg^{-1}$ bw $\cdot$ day^{-1}): Daily dose requirement (DRD), accepted daily dose (ADD), missing daily dose (MDD).

The proposed doses are required to calculate the risk quotient for an essential element deficiency (HQ_d) according to the following equation: $HQ_d = DRD/DAD$ (1)

DRD represents the average daily dose of an essential element from a given exposure source that is necessary for healthy development. If you don't consume this amount, your health may be at risk. This quantity is similar in many nutritional recommendations, such as the RDA (recommended dietary allowance). In the case of this study it is reduced to drinking water. DAD represents the average daily intake of an essential element from individual components of the environment, in this case drinking water. DMD represents the average daily dose of an essential element that is absent from the diet. When assessing the health risks associated with deficiencies in essential elements, average daily intakes are calculated in accordance with US EPA [2004] methodological procedures, but are modified if necessary, as these are health risk calculations associated with deficiencies in essential elements.

Health risk calculations use input of exposure data, as defined by the US EPA [2004], such as body weight, duration and frequency of exposure, daily water consumption, etc. [Rapant et al. 2020]. In our case study, the mean body weight (BW) values for infants (4.85 ± 0.95 kg) and adults (64.36 ±17kg) presented in Table 3 were obtained from the survey carried out by Egbi et al. [2020] in the Lower Volta basin of Ghana. These values were also adopted in the study by Afrifa et al. [2023] on the Densu river basin located in the southern part of Ghana. The corresponding mean water intake rates from the same survey [Egbi et al., 2020] were 1.034 ± 0.4 L.day-1 and 3.4 ± 1.0 L.day-1, respectively for infants and adults. This is consistent with the mean intake rate values (1.7 and 3.3 L.day-1 respectively for infants and adults) obtained by Craig et al. [2015], and in the northern part of Ghana by Afrifa et al. [2023]. Given the relatively homogeneous influence of weather conditions, we used the same values for Congo.. The input data used to calculate the health risk of Ca and Mg deficiencies in drinking water are presented in Table 3.

Table 3. Input data for the estimation of health risk in case of Ca and Mg deficiencies in drinking water

Parameter	Value		Unit	Source
	Adult	Nourishing		
Body weight (BW)	64.36	4.85	kg	US EPA [1997, 2008]
Average duration of exposure (AT)	365	365	day	US EPA (2) [1989]
Chemical element content in water (CW)	Specific site	Specific site	$Mg \cdot L^{-1}$	US EPA [1997]
Daily water consumption (IR)	3.4	1.034	$L \cdot day^{-1}$	US EPA (2) [1989]
Exposure frequency (EF)	365	365	$Day \cdot year^{-1}$	US EPA (1) [1989]
Exposure time (ED)	1	1	year	US EPA (2) [1989]

The average daily doses defined above are calculated according to the following equations:

$$DMD = (MRC - CW) \times IR \times ED \times EF/BW \times AT \quad (2)$$

$$DAD = CW \times IR \times ED \times EF/BW \times AT \quad (3)$$

$$DRD = MRC \times IR \times ED \times EF/BW \times AT \quad (4)$$

CW represents the average Ca and Mg content, i.e. hardness, of the water (Table 2); MRC – the minimum required concentration, that is the minimum content of an element for which there is no known health risk. It is determined on the basis of drinking water standards: BW – body weight; AT – average exposure time; IR – daily water concentration; EF – exposure frequency; ED – exposure duration.

Example of calculation with minimum required concentration (MRC) based on standard values for an adult

The minimum threshold standards for Ca and Mg, and hardness, which were derived from the average of several research studies, were set to avoid any risk of chronic disease due to deficiency of the three parameters. Yang et al. [2006] proposed a range of 33.6–36.3 $mg \cdot L^{-1}$ for Ca and 11.6–11.8 $mg \cdot L^{-1}$, for Mg, while Yang and Chiu [1999] proposed a variation between 32.9–34.8 $mg \cdot L^{-1}$ and 10.9 and 11.2 $mg \cdot L^{-1}$ for Ca and Mg respectively. Rosenlund et al. [2005] proposed a mean value of 25.1 $mg \cdot L^{-1}$ for Ca, 4.4 $mg \cdot L^{-1}$ for Mg and 4.5° dH for water hardness. For Rosborg and Kožíšek [2020] Ca ≈ 50 $mg \cdot L^{-1}$ (30–80 $mg \cdot L^{-1}$), Mg ≈10 $mg \cdot L^{-1}$ (10–50 $mg \cdot L^{-1}$) and an absolute hardness of 5°dH. In our case study, we took average values used by Rapant et al. [2020] with Ca > 30 $mg \cdot L^{-1}$, Mg 10–30 $mg \cdot L^{-1}$ and a water hardness (Ca + Mg) of 1.1–5.0 $mmol \cdot L^{-1}$.

The provided here DMD calculation for Ca assumes an average Ca content of 35 mg $\cdot L^{-1}$, Mg of 20 $mg \cdot L^{-1}$ and hardness (Ca + Mg) of 2 $mmol \cdot L^{-1}$ and for an adult:

$$DRD = 35 \times 3.4 \times 1 \times 365/64.36 \times 365 = 1.8489 \ mg \cdot kg^{-1} \cdot day^{-1} \quad (5)$$

$$DMD = (30 - 2.51) \times 3.4 \times 1 \times 365/64.36 \times 365 = 1.7163 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{day}^{-1} \quad (6)$$

$$DAD = 2.51 \times 3.4 \times 1 \times 365/64.36 \times 365 = 0.1359 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{day}^{-1} \quad (7)$$

This calculation clearly indicates that the daily minimum deficit (DMD) represents the difference between the daily required dose (DRD) and the daily actual dose (DAD). Accordingly, the local population lacks approximately 1.7163 mg · kg^{-1} · day^{-1} of calcium (Ca) in their drinking water to meet the recommended daily intake.

Calculating the risk quotient – HQ_d

The US ESPA (1) [1989] defines the risk quotient as the risk of developing chronic diseases for individual elements/substances. Exposure to several elements/substances with an identical mechanism of action defines the risk index (HI). The risk index represents the sum of the HQ for each element. According to US EPA methodology [1989], HQ is calculated by equation (8), which expresses by how much the average daily intake is exceeded and what the risk is expressed in terms of HQ:

$$HQ = DAD/RfD \quad (8)$$

However, as Ca and Mg are involved in different biochemical reactions and processes in the body, calculating HI does not seem fitting. According to [Rapant et al. 2020], the risk is not caused by an excess of a harmful element but by a deficiency of essential elements, so this equation is modified as an inverse ratio of RfD (DRD) to ADD (DAD), according to the equation (1).

In this way, it demonstrates how much the received dose is below the required dose, and indicates the level of health risk in the form of HQ_d. Following the previous calculation (5, 6 and 7), the calculation of HQ_d (9) is presented for the Ca content in drinking water. DRD and DAD values derived from the actual Ca content in drinking water were used. The reference dose of Ca that a person should take daily from drinking water is the average daily requirement (ADR), which is 1.5845 mg · kg^{-1} · day^{-1}. The average daily intake (ADI) is 0.1325 mg · kg^{-1} · day^{-1}. The calculation of HQ_d (see equation (1)) for Ca is as follows: HQ_d = 1.8489 /0.1359 = 13.94 (9). Table 4 shows the US EPA (2004) assessment of the level of risk of developing chronic disease.

Table 4. The level of chronic disease risk

Risk level	HQ_d	Chronic disease risk
1	≤ 0.1	Risk-free
2	> 0.1	Low risk
3	> 1.0	Medium risk
4	> 4.0	High risk

3. Results and discussion

Hadrochemical analysis (Table 5) of 23 samples from the Lukunga basin (2023) shows acidic groundwater (pH 3.88–5.9, average 4.37) with low mineral content (EC 1.17–88.1 $\mu S \cdot cm^{-1}$), characteristic of the Kinshasa region due to the presence of sandstone and sand. This spatial variability aligns with earlier findings in Kinshasa [Ndembo 2009, Mfumu et al. 2016]. Most parameter concentrations are below WHO [2017] recommendations, with trace elements (As, Cd, Pb) detected in wells and springs, though all remain within potability limits.

Table 5. Results of chemical analysis of water samples collected in 2023

Parameters	No. Ech.	Min	Max	Average	Standard deviation	CV %	WHO (2017)
Temperature °C	23	25	35	30.070	1.639	5.45	–
pH	23	3.88	5.95	4.367	0.332	7.61	6.5–8.5
Redox potential (mV)	23	63	245	173.261	22.272	12.85	500
EC ($\mu S \cdot cm^{-1}$)	23	1.17	88.1	18.038	12.087	67.01	2000
TDS ($mg \cdot L^{-1}$)	23	1.14	44.1	9.013	5.936	65.87	1000
Salinity (pSu)	23	0.01	0.05	0.019	0.006	29.05	–
Resistivity ($\Omega \cdot m$)	23	1.82	74.9	20.091	11.953	59.50	–
Ca^{2+} ($mg \cdot L^{-1}$)	23	0.1	10.94	1.188	1.009	84.88	50
Mg^{+} ($mg \cdot L^{-1}$)	23	0.15	8.88	1.070	0.801	74.85	50
K^{+} ($mg \cdot L^{-1}$)	23	0.22	8.93	1.133	0.836	73.74	250
Na^{+} ($mg \cdot L^{-1}$)	23	0.48	11.9	1.973	1.080	54.71	250
$HCO3^{-}$ ($mg \cdot L^{-1}$)	23	0	98.36	4.277	8.181	191.30	500
Cl^{-} ($mg \cdot L^{-1}$)	23	0.13	6.82	3.233	1.148	35.50	250
$NO3^{-}$ ($mg \cdot L^{-1}$)	23	0.3	39.1	19.14	0.736	384.59	50
$NH4^{+}$ ($mg \cdot L^{-1}$)	23	0	0.41	0.093	0.103	109.97	0.5
$SO4^{-2}$ ($mg \cdot L^{-1}$)	23	0.05	5.36	2.299	1.070	46.56	250
$PO4^{-3}$ ($mg \cdot L^{-1}$)	23	0	0.56	0.100	0.119	119.84	–
Fe^{2+} ($mg \cdot L^{-1}$)	23	0.1	0.3	0.207	0.028	13.72	1.5
Cd^{2+} ($mg \cdot L^{-1}$)	4	0.01	0.14	0.049	0.038	78.99	0.003
Pb^{2+} ($mg \cdot L^{-1}$)	4	0.08	2.07	0.423	0.471	111.29	0.01
As^{2+} ($mg \cdot L^{-1}$)	4	0	0.11	0.051	0.030	58.73	0.01

The application of the GOD parametric method facilitated the analysis of key variables, including groundwater depth at each sampling point, the nature of geological formations overlaying the aquifer, and the type of aquifer encountered. The resulting data (Tables 6, 7, and 8) were subsequently used to generate individual thematic maps corresponding to each GOD parameter (Figs. 2a, 2b, and 2c). In comparison with more elaborate vulnerability assessment models such as DRASTIC and SINTACS, the GOD method offers a rapid, first-tier evaluation of aquifer vulnerability. This makes it particularly suited for settings where high-resolution hydrogeological or contaminant transport data are lacking [Foster 1987]. Its proven utility at regional and watershed scales, as demonstrated by the Lukunga watershed, enhances its value as a tool for preliminary screening prior to conducting more detailed analyses [Zwahlen 2004]. Furthermore, the model's widespread use in groundwater protection and resource management confirms its reliability and adaptability to varied hydrogeological contexts [Hölting et al. 1995], thereby affirming its suitability for the current study.

Table 6. Aquifer type and assigned rating (GOD method)

Aquifer type	Lithology of the ZNS	Dimensions	Surface area [%]	Degree of vulnerability
Free	Coarse sand	0.7	62.26	High
Semi-captive	Clayey sand	0.5	37.73	Moderate

Table 7. Lithology and assigned rating (GOD method)

Lithology	Dimensions	Surface area [%]	Degree of vulnerability
Clayey sand (fine)	0.4	31.68	Moderate
Yellow ochre sand (coarse)	0.7	35.92	High
Soft sandstone	0.7	32.38	High

Table 8. Water table and assigned rating (GOD method)

Depths [m]	Dimensions	Surface area [%]	Degree of vulnerability
>100	0.1	12	Very low
50–100	0.3	38.25	Low
20–50	0.5	35.59	Moderate
10–20	0.7	10.74	High
2–10	0.9	3.19	Very high
0.1–2	1	0.22	Extreme

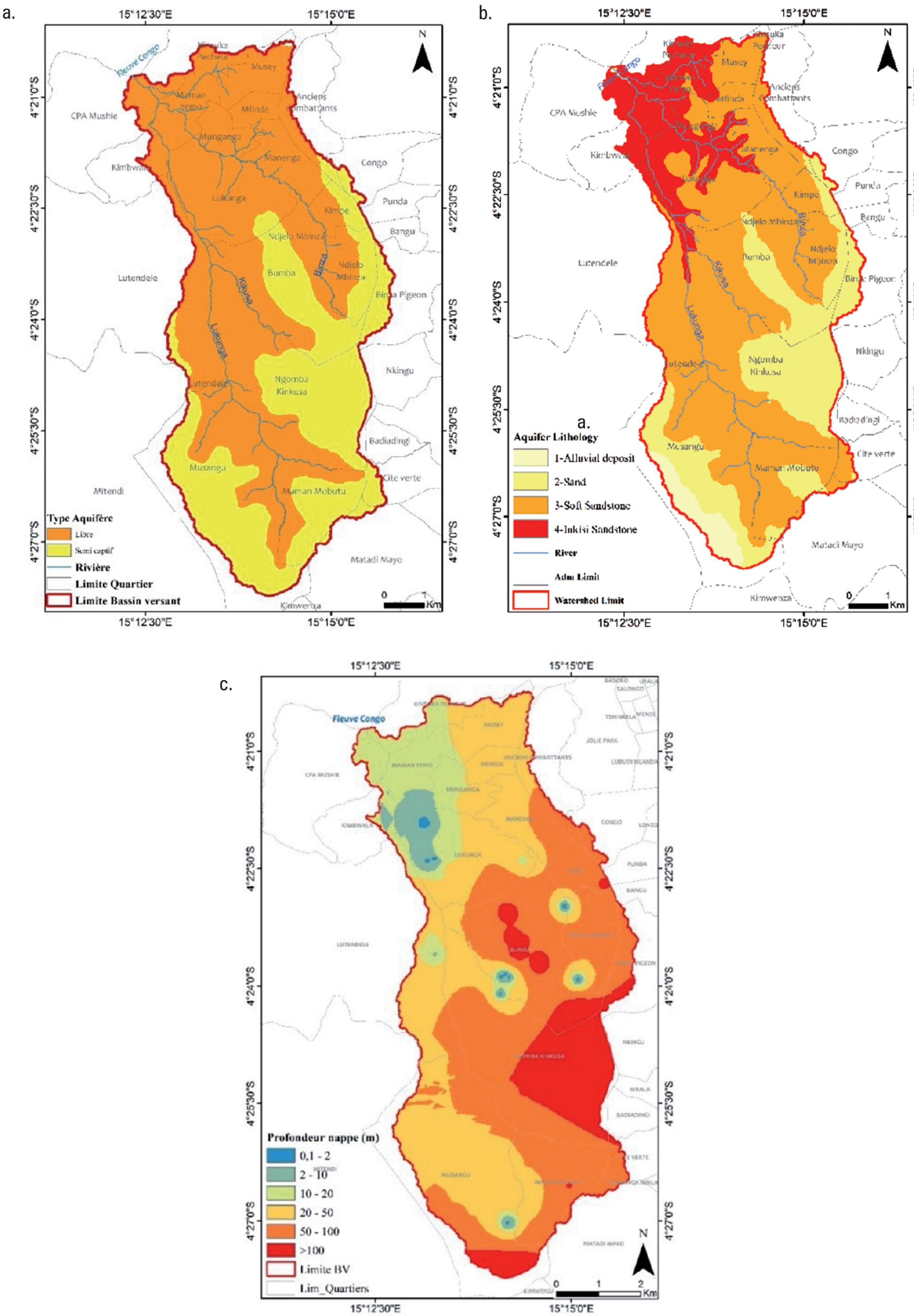


Fig. 2. a. Parametric map '**G**' (aquifer type). b. Parametric map '**O**' (Lithology). c. Parametric map '**D**' (water table)

Table 9. Vulnerability classes and nitrate concentration at water table

No.	Classes GOD index	Surface area	Degree of vulnerability	NO_3 (mg · L^{-1})
1	0–0.1	12.85	Very low	0.3–6.4
2	0.1–0.3	24.82	Low	6.4–16.5
3	0.3–0,5	15.86	Moderate	16.5–22.3
4	0.5–0.7	16.93	High	22.3–30.3
5	0.7–1	29.54	Very high	30.3–39.1

Based on these GOD parametric maps (Figs. 2a, 2b and 2c), we have produced the final vulnerability maps (Fig. 3a) confirmed by nitrate concentration (Fig. 3b).

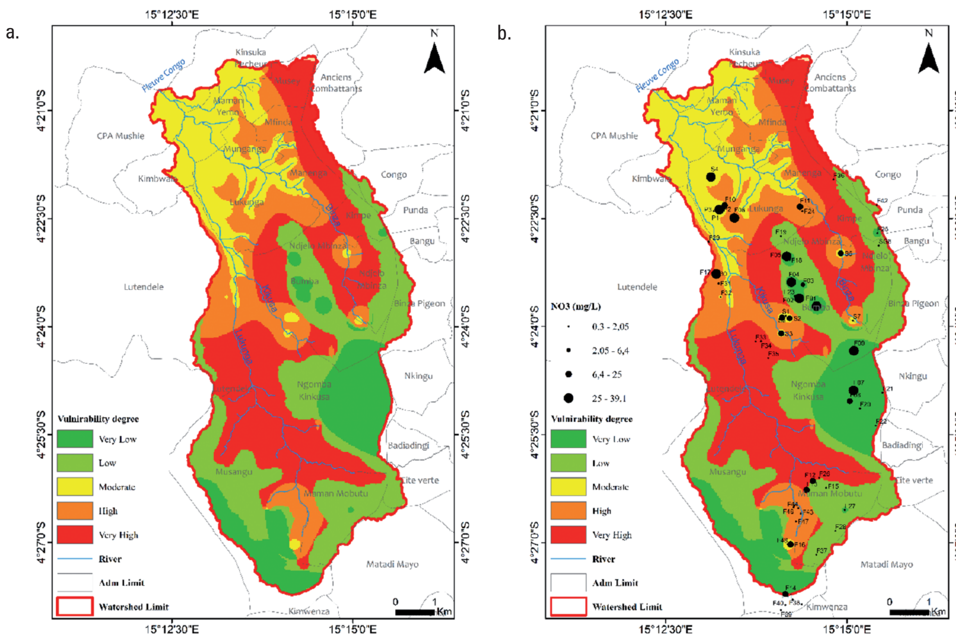


Fig. 3. a. The Lukunga catchment groundwater vulnerability map (GOD method). b. Nitrate concentration map of groundwater in the Lukunga catchment

In this study, hydrogeological and hydrochemical data were compiled through numerical and geostatistical calculations. These data were then integrated into a GIS environment for further analysis. Table 4 presents the average daily intake (ADI) values and health risk (as HQd) for both adults and infants. The HQd indicates that the drinking water in the study area is soft and poses a very high risk of chronic disease (HQd (Ca + Mg) > 4.0) at 22 of the 23 water points. Only one water point shows a medium risk level (1.0 < HQd (Ca + Mg) < 4.0), represented by the highest recorded value.

This pattern holds for both adults and nursing children, with no significant difference in health risk values (HQd (Ca + Mg)) between these groups. Both adults and infants exhibit extremely low daily intake (DAD) values, as shown in Table 10.

Table 10. HQd calculated by MRC based on standard values

	DAD Ca 1	DAD Mg	DAD (Ca + Mg)	HQ_d Ca 2	HQ_d Mg	HQ_d (Ca + Mg)
Adult						
Average	0.063	0.057	0.004	92.48	46.05	55.52
Median	0.036	0.027	0.002	51.47	39.22	44.52
Minimum	0.005	0.008	0.001	3.20	2.25	3.00
Maximum	0.578	0.469	0.035	350	133.33	192.14
Children						
Average	0.253	0.228	0.016	92.48	46.05	55.52
Median	0.145	0.109	0.010	51.47	39.22	44.52
Minimum	0.021	0.032	0.002	3.20	2.25	3.00
Maximum	2.332	1.893	0.142	350	133.33	192.14
1 DAD in mg · kg^{-1} · day^{-1}, 2 Risk Quotient						

The mean HQ_d values for Ca, Mg and (Ca + Mg) shown in Table 4 show a variation of around double between the HQ_d risk for Ca and the HQ_d risk for Mg of 92.48 and 46.05, respectively. On the other hand, the variation is slight between the HQ_d of Mg and HQ_d of (Ca + Mg), with values of 46.05 and 55.52, respectively. According to the US EPA [2004], these values correspond to a very high risk of developing a chronic disease ($HQ_d > 4$). Several studies such as Yang et al. [2006], Yang [1997] and Jiang et al. [2016] have shown the relationship between both Ca and Mg deficiencies and water hardness with mortality caused by myocardial infarction, cerebrovascular disease and cardiovascular disease, not to mention other types of illness. Depending on water quality, low levels of calcium (Ca) can increase the risk of chronic disease, while inadequate levels of magnesium (Mg) and low water hardness (soft water) can pose a significant risk of fatal diseases. Meta-analyses by Kousa et al. [2006], Catling et al. [2008], Jiang et al. [2016], Gianfredi et al. [2017], and Rapant et al. [2017, 2020] have all indicated a strong link between magnesium deficiency in drinking water and cardiovascular disease. Rosenlund et al. [2005] identified an inverse relationship between the risk of cardiovascular disease and the levels of magnesium (Mg) and calcium (Ca) in drinking water. Similarly, Gianfredi et al. [2017] observed that higher concentrations of Ca in water offer a protective effect against cardiovascular disease.

The drinking water from the Lukunga watershed presents a high health risk of Kinshasa population at 22 out of 23 water points. Only one site shows medium risk. This poses a serious threat to public health. Urgent measures must be taken to address this national health issue, requiring action at various levels. At the community level, calcium (Ca) and magnesium (Mg) deficiencies can be mitigated by promoting a more divers diet containing foods rich in these essential elements. However, this will not lead to an immediate increase in these elements within the body, and achieving the desired levels will take time. Additionally, ensuring consistent availability and affordability of these foods could present challenges. A more comprehensive solution would involve an intervention from the relevant authorities to enhance water quality by re-mineralizing it with calcium hydroxide ($Ca(OH)_2$ or calcium carbonate ($CaCO_3$) before it reaches consumers. This treatment could be applied jointly to groups of wells or boreholes, or even in the form of small, pre-measured doses for individual use.

4. Conclusion

The application of the GOD methodology has provided a robust framework for assessing the vulnerability of groundwater in the Lukunga watershed. The resulting vulnerability maps indicate elevated susceptibility to contamination in the lower northwestern regions and along the Lukunga and Binza rivers, where unregulated waste disposal by local populations contributes to significant pollution loads. Five distinct vulnerability classes were delineated: 'Very Low' (12.85%), 'Low' (24.82%), 'Moderate' (15.86%), 'High' (16.93%), and 'Very High' (29.54%), highlighting spatial variability in groundwater protection status. Correlation with hydrochemical analyses confirms that zones classified as 'High' and 'Very High' vulnerability exhibit increased nitrate concentrations, albeit within permissible limits established by the World Health Organization (WHO). These areas are further characterized by shallow water tables and minimally confined aquifers, which exacerbates the risk of contamination. The main cause of groundwater contamination is domestic pollution, with wastewater and solid waste from households along the Lukunga, Kikusa, and Binza rivers being discharged directly into these watercourses due to inadequate urban sanitation infrastructure. These findings are consistent with regional groundwater vulnerability classifications reported by Mfumu et al. [2016] and Ndembo [2009]. The HQd indicates that the drinking water in the Lukunga watershed is soft and poses a very high risk of chronic disease ($HQd\ (Ca + Mg) > 4.0$) at 22 of the 23 water points. Only one water point shows a medium risk level ($1.0 < HQd\ (Ca + Mg) < 4.0$), represented by the highest recorded value. This pattern holds for both adults and nursing children, with no significant difference in health risk values (HQd (Ca + Mg)) between these groups. To reduce contamination risks in the Lukunga watershed, priority interventions should focus on (i) securing areas surrounding potable water sources, (ii) developing adequate wastewater management systems, and (iii) implementing structured waste collection in high-risk zones. Furthermore, the persistently low concentrations of essential minerals such as calcium and magnesium in drinking water raise concerns over potential long-term health effects. Accordingly, further epidemiological and hydrogeochemical investigations that take into account population health data are warranted. Such relatively low-cost interventions could significantly improve public health and reduce long-term reliance on expensive healthcare systems.

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