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Vulnerability mapping as a tool to foster groundwater protection in areas subject to rapid population expansion: The case study of Abuja Federal Capital Territory (Nigeria)

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A R T I C L E I N F O

Keywords:
Abuja FCT
Groundwater contamination
DRASTIC-LU model
Land use changes
Nitrate contamination

A B S T R A C T

Study region: Abuja Federal Capital Territory (FCT; Nigeria).
Study Focus: Rapid population growth has led to significant land use changes, with potential negative impacts on groundwater quality. However, the lack of understanding of hydrogeological settings, often due to limited data availability, is one of the main obstacles to sound planning in rapidly changing environments. To assess the specific groundwater vulnerability to nitrate, a DRASTIC-LU model was applied, combining the land use data from the last 20 years with the intrinsic aquifer vulnerability. This study represents the first attempt to assess aquifer vulnerability in the region.
New hydrogeological insights for the region: Results show that the Abuja FCT has been affected by a dramatic change in land use with an increase in urbanized and agricultural areas and may induce nitrate contamination in groundwater. Currently, several wells in the region are showing nitrate concentrations that exceed the statutory limit for drinking purposes. The comparison of DRASTIC-LU results with nitrate concentrations shows that the highest concentrations are found in urban/peri-urban areas. Although fertilizers are generally considered to be the main source of nitrate contamination, these results suggest a possible mixed (urban and agricultural) pollution origin. This investigation therefore represents a starting point for future nitrate monitoring assessments and for supporting decision makers with adequate information for urban planning in view of the expected population growth in the area.

1. Introduction

The overall impact of climate change on groundwater resources in Africa is expected to be relatively smaller than the non-climatic drivers, such as population and urbanization growth (MacDonald and Calow, 2009; Carter and Parker, 2009; MacDonald et al., 2009; Niang et al., 2014 and references therein; Taylor et al., 2009). Since the 1950s, the urban population in Africa has experienced a rapid twenty-fold increase (ranging from 27 million in 1950 to 567 million people in 2020) due to high population growth, urban sprawling, and the reclassification of rural settlements (OECD/SWAC, 2020). In Nigeria, the urban population has experienced a rapid rise over the last fifty years and is expected to grow from the current 170 million people to more than 300 million within the next 30 years (Bloch

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et al., 2015). As a result, in 2050, Nigeria will become the country with the second largest urban population after India (Opoko and Oluwatayo, 2014). In Abuja, the capital and eighth most populous city in the country, population growth is basically driven by political, economic, and social drivers. A population growth of about 400% between 2000 and 2020 has been reported (UN DESA, 2022).

Clearly, such rapid and significant changes cannot fail to have serious repercussions on the natural environment and on the resources that are necessary to support population growth. As far as water resources are concerned, on a national scale, groundwater supplies nearly 73% of the drinking purposes in rural areas and 45% in urban ones (Japan International Cooperation Agency, 2014), with some cities being totally dependent on groundwater for their water supply. Consequently, increasing pressure is exerted on groundwater resources, both in terms of abstraction to supply domestic and industrial needs, and in terms of contaminant loads (Oni et al., 2019).

In Abuja city, recent investigations (Enoguanbhor et al., 2019, 2020) showed an increase in urban/built-up areas of nearly 20 times in 40 years (from 1.8% in 1987 to 19% in 2017), with the largest observed transition featuring urban growth in place of vegetation. A similar trend can be observed in other countries in Africa and worldwide (De la Barrera and Henríquez, 2017; Gao and O'Neill, 2020; Hassan, 2017), and will have inevitable social and economic consequences, potentially contributing to an increase in both water scarcity and water quality degradation (Abubakar, 2014).

Therefore, in view of the ongoing and future changes, it is of paramount importance to assess the vulnerability status of groundwater resources (i.e., the potential for seepage and diffusion of contaminants from the soil surface into the groundwater system; Oroji, 2018) and to apply this information to future development plans.

Given the possible co-existence of multiple contamination sources and the potential increase in contaminant loads due to population growth, the understanding of groundwater intrinsic vulnerability (defined by the inherent hydrogeological and geological characteristics that determine the susceptibility of groundwater to contamination by human activities (Doerfliger et al., 1999; Barbulescu, 2020)) is a fundamental prerequisite for more advanced assessments and planning. In addition, it may serve as a reference for subsequent research targeted to assessing specific aquifer vulnerability.

Many approaches are used for estimating groundwater vulnerability; they may be divided into three types: i) the index-overlay (Aller et al., 1987; Civita and De Maio, 1994; Doerfliger et al., 1999, 2021), ii) statistical (Burkart et al., 1999; Johnson and Belitz, 2009; Teso et al., 1996; Troiano et al., 1997), and iii) process-based (Anane et al., 2013; Connell and van den Daele, 2003; Guekie Simo et al., 2013; Milnes, 2011; Zhang et al., 2013).

The choice of method is largely dependent on the scale of the study, the type of aquifer, data availability, and, in the case of specific vulnerability assessment, the pollutant type. The index-overlay method is the most widely used due to its simplicity, clarity, and limited data requirement. It integrates several factors that control the migration of contaminants into the saturated zone, but its major limitation is the assumption of uniform rates of nominal values over an area. Therefore, results should be used with caution on a local scale, especially in areas with high geological variability and complex structures. Despite this limitation, the method represents an excellent basis for providing policy makers with a rapid appraisal of the state of an area.

Among index-overlay methods, the DRASTIC (Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of

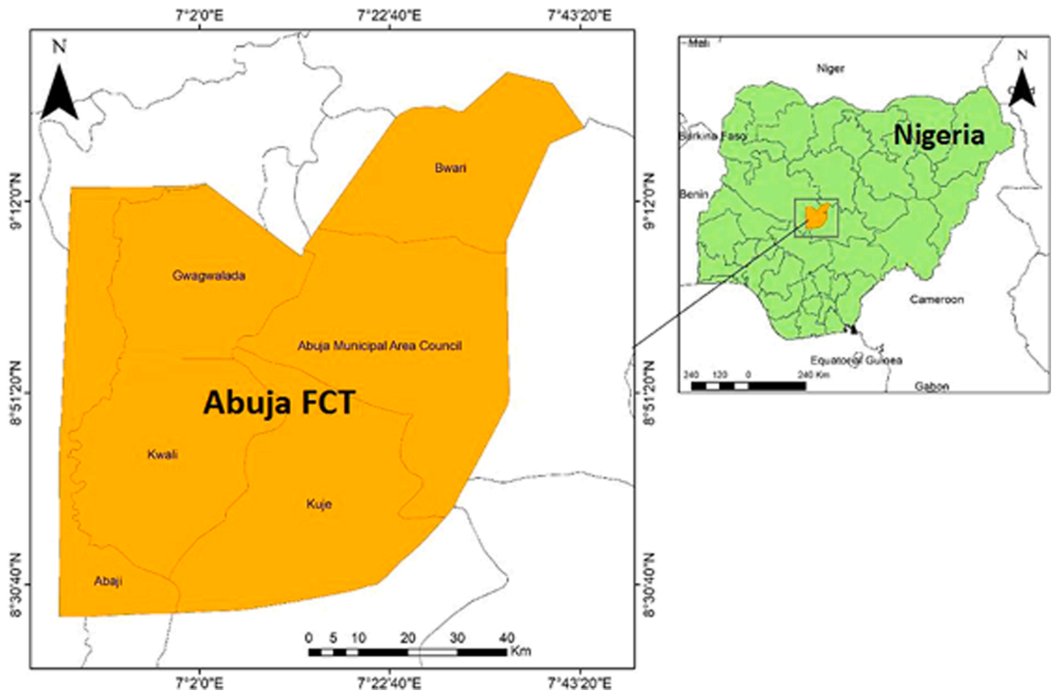

Fig. 1. Location map of the study area and the districts of Abuja FCT.

vadose zone, and hydraulic Conductivity; Aller et al., 1987) model is the most widely used for groundwater vulnerability mapping, and it has been modified by several authors to fit the specific needs of different study areas (Jimeneze-Madrid et al., 2013; Malakootian and Nozari, 2020; Saha and Alam, 2014; Singh et al., 2015; Zhou et al., 2010; Lad et al., 2019; Khosravi et al., 2018). The DRASTIC model has previously been applied in groundwater vulnerability assessment in several parts of Nigeria (Oke, 2020; Ahmed et al., 2017; Ekwere and Edet, 2017; George, 2021; Hamza et al., 2017; Ibe et al., 2001; Ojuri and Bankole, 2013). The present study reports its application to the aquifer in Abuja Federal Capital Territory (FCT), i.e. the administrative region in central Nigeria that includes Abuja city, where there is a lack of hydrogeological and groundwater vulnerability assessments.

In the study area, as in other parts of sub-Saharan Africa, groundwater abstraction and the placement of sewage systems are often indiscriminate and unregulated, even where responsible government agencies exist, leading to the use of poorly structured and poorly maintained facilities, and inappropriate siting of anthropogenic sources of contaminations relative to water sources (Ekwere and Edet, 2017).

This study aims at forestalling the possible negative impact of groundwater deterioration associated with an increase in anthropogenic pressure (with special attention to nitrate contamination, as one of the main threats in the region; Dan-Hassan et al., 2012) by mapping out the intrinsic aquifer vulnerability of the Abuja FCT aquifer, and assessing the specific vulnerability associated with land use changes (compared to field data on NO_3^- concentrations). This valuable, but currently lacking, information will aid the sustainable development of the area as well as groundwater management policies in one of the fastest growing cities in Sub-Saharan Africa (Abubakar, 2014).

2. Study area

Abuja FCT is located in North Central Nigeria. It approximately lies between longitudes 6° 46′ and 7° 37′E and latitudes 8° 21′ and 9° 18′ N. It covers an area of approximately 8000 km^2 with a mean elevation of 476 m above sea level (NGDPR, 2020) (Fig. 1). Geologically, the study area belongs to the western province of the basement complex. The observed tectonic structures are N–S to NNE–SSW trending, resulting from the pan African Orogeny, which involved the collision between the West African craton and pan African mobile belts (Alagbe, 1979). Crystalline and sedimentary rocks extensively outcrop in the study area, representing 85% and 15%, respectively. These rocks can be divided into four main groups (Dada, 2008):

- The Migmatite-Gneiss units (Pan African to Eburnean) of the crystalline basement constitute the most widespread rock type in the area.
- The Metasediments (Upper Proterozoic) consist of amphibolite, schist, phyllites, quartzites and serpentinites. They have low-grade, metasediment-dominated belts N–S trending.
- The older granites (Late Proterozoic) are the deep-seated, usually concordant or semi concordant granites of the basement complex.
- The sedimentary units are deposited in the Bida basin (Upper Cretaceous): a sequence of alluvial to marine deposits ranging from clay to gravel (Rahaman et al., 2019). The sedimentary deposits directly covering the basement units filled the tectonically-controlled Bida Basin. The thickness of this unit ranges between 900 and 2000 m and it extensively outcrops in the SW section of the study area.

In addition, alluvial deposits are located along the river courses. They are made up of heterometric loss deposits (from clay to gravel) with a thickness that depends on the depositional capability of each river.

In tropical Africa, the hydrogeological conceptual model is usually schematically divided into two main layers: a weathered/regolith layer and the underlying crystalline bedrock (Chilton and Foster, 1995). Bianchi et al. (2020) proposed a more detailed

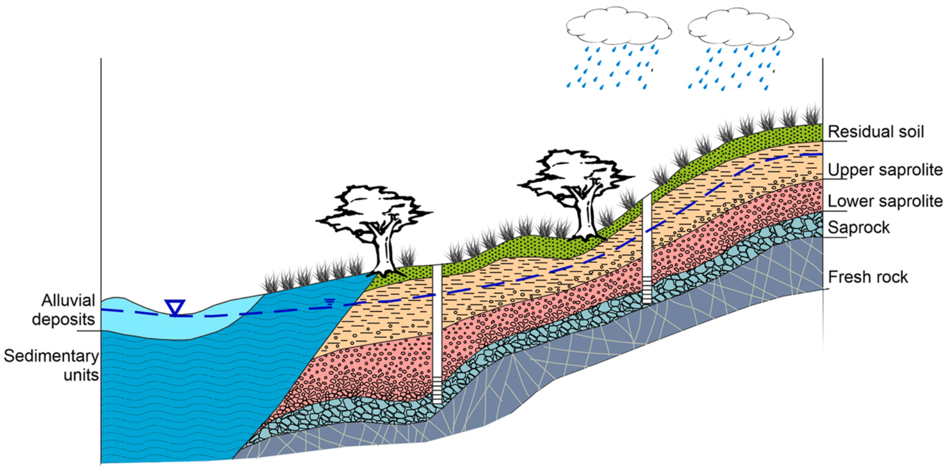

Fig. 2. Simplified hydrogeological model (not in scale) of the study area after Bianchi et al. (2020).

hydrogeological model composed of five layers, defined as follows:

1. Residual soil: this layer often comprises ferralitic soils with laterite pisoliths, with a thickness of a few meters. Even though the presence of laterite may enhance its permeability, the overall permeability of this layer is low due to the high clay content.
2. Upper saprolite: this layer is rich in secondary clay minerals with a thickness ranging from a few to tens of meters. Its permeability is very low, hence this layer is not suitable for groundwater abstraction.
3. Lower saprolite: this layer is similar to the Upper saprolite but with a higher percentage of primary minerals in direct relationship with its depth. Its permeability also increases with depth, reaching its maximum values at the base of the lower saprolite layer.
4. Saprock: this is a fractured layer with a thickness of up to ten meters, covering the fresh rock basement. This layer is characterized by a good permeability decreasing with depth toward the unfractured basement.
5. Fresh rock: low fractured rocks. The permeability of this layer is assumed to be mainly representative of the rock matrix.

The main aquifer layers in the area are the lower saprolite layer and the underlying Saprock (Fig. 2) which have sufficient permeability to support successful boreholes for small scale village water supply. The groundwater discharge direction of the regolith aquifer is mainly from NE to SW indicating that the aquifer is strictly influenced by its surface morphology. Groundwater flows toward gaining streams supporting the base flow of the rivers.

The aquifer hosted in the fresh rock basement is characterized by secondary permeability, depending on the frequency and magnitude of rocks fractures. This aquifer is usually characterized by low productivity.

There is no large difference on the regolith derived from the different crystalline units. However, some evidence should be considered: weathered crystalline and coarse-grain rocks such as gneiss and migmatite evolved in sandy deposits; argillaceous meta-sediment rocks more likely weather into clayey and low permeability units. The thickness of the regolith layer is highly variable within the basin, ranging up to tens of meters (Dan-Hassan, 2015). The shallow aquifers are mainly exploited by rural communities using hand dug wells with a depth of approximately 10 m.

The study area lies in the tropical Sudan savannah region of Nigeria. The vegetation is forest and savannah, mostly comprised of woody plants (Agbelade et al., 2017). The temperature is usually between 18 °C and 37 °C. The Harmattan wind, a dust laden continental tropical air mass from the Sahara Desert, prevails throughout the period. The rainy season is between April and October, with most of the precipitation occurring in August or September (Jimoh and Wojuola, 2009). The mean annual precipitation in the area is approximately 1200 mm (FCT Handbook, 1994). Despite the amount of annual precipitation, the tropical temperatures are reflected in high evapotranspiration rates, which account for the major water loss. The mean recharge rate estimated in Nigeria is lower than 15% of the total rainfall (Japan International Cooperation Agency, 2014) with small differences in each catchment (Ashaolu et al., 2020).

3. Materials and methods

3.1. Vulnerability maps

The DRASTIC index-overlay model was used to define the most vulnerable zones in Abuja FCT. This model is a probabilistic representation of nominal values of surface and subsurface features that control the aquifer vulnerability. The DRASTIC index model is based on seven parameters which indicate possible groundwater contamination (Aller et al., 1987): depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), the impact of vadose zone (I), and hydraulic conductivity (C). In addition, the land use maps from 2000 and 2020 were included in the elaboration of DRASTIC-LU maps. These maps reflect the specific vulnerability to nitrates according to the different land uses and the variation of the anthropic pressure over the last 20 years. All the DRASTIC layers have been categorized with different rates and weight values.

The data used and their references are listed in Table 1.

Discrete data usually have a scattered distribution. Additionally, environmental data usually show a higher degree of similarity and correlation when the observation points are close together than when they are far apart, showing both random and regional trend distributions. We applied the ordinary kriging geostatistical technique in ArcGIS 10.8.1 to assess the spatial variability of each

Table 1
References of the data used for the realization of the DRASTIC Vulnerability map of Abuja FCT.

Layer	References
Depth to Groundwater	Rural water supply Program China –FGN (2006)
Net Recharge	Monthly satellite data acquired from the National Centee for Environmental Prediction CFSR (2021) in the 1979–2013 interval provided climatic data which was used to calculate the Net Recharge
Aquifer Media	Geological Map from Nigerian Geological Survey Agency
Soil Media	Soil Map from Obasanjo Space Centre
Topography	DEM/SRTM (Shuttle Rader Topographic Mission Digital Elevation Model)
Impact of Vadose	Geological Map from Nigerian Geological Survey Agency
Hydraulic Conductivity	Rural water supply Program China –FGN (2006);
Land Use	Ministry of Natural Resources of the Peoples Republic of China Land use Map (2000, 2020)

variable. A variogram was elaborated to estimate the parameter distributions between the observation points.

The final vulnerability index of the DRASTIC model consists of a linear combination of the seven parameters each multiplied by a corresponding weight. In the elaboration of the specific vulnerability maps the land use layer (LU) was included in the elaboration:

$$Vulnerability_{DRASTIC} = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r + LU_w LU_r$$

where D, R, A, S, T, I, and C are the abbreviations of the seven hydrogeological parameters, LU corresponds to the land use map; "*r*" and "*w*" define parameters' rating and weight, respectively. The chosen rates and weight for each parameter are mostly based on Aller et al. (1987). The detailed description of each layer is reported below.

3.1.1. Depth to static water level (D)

D is the depth to static water level, which describes the thickness of the unsaturated zone that a pollutant has to travel through to reach the water table from the surface. It is the vertical distance from the ground surface to the saturated zone of the phreatic aquifer. The depth to ground water has direct impacts on the degree of attenuation of the contaminant. The aquifer vulnerability has an inverse relationship with depth to static water level.

D was calculated as the difference between the surface elevation and the groundwater level measured in 141 wells (locations in Fig. S1). The available data were previously explored in a Q-Q Plot diagram to identify and discard the points that did not belong to the investigated aquifer.

3.1.2. Net recharge (R)

The Net Recharge (R) is the quantity of water that infiltrates from the surface toward the aquifer. R is just a fraction of the rainfall (P), as most of the water is lost due to the evapotranspiration (ET) and surface runoff (SR) processes: $R = P - ET - SR$.

Long-term climatic data were acquired from the National Centers for Environmental Prediction. Climate Forecast System Reanalysis (2021) provides data on rainfall and temperature between 1979 and 2013 at a horizontal resolution of 0.5°. Twenty-five weather points covering the Abuja FCT area were used in this study (Fig. S2). Cumulate P and the mean temperature (T_m) were calculated for each weather point once a year and then spatialized using ordinary kriging. The yearly ET was calculated by applying the Turc's formula $ET = 0.0133\frac{T_m}{T_m+15}(R_s + 50)$, where Rs is the incoming shortwave solar radiation, using the Raster Calculator tool. Direct quantification of the surface runoff was not possible due to the lack of reliable hydrographic data within the study area. The mean SR was then estimated according to the runoff rate ([SR/P]*100) reported by Japan International Cooperation Agency (2014) for the Abuja FCT catchment. The mean R was then calculated from the yearly R values.

R is responsible for contaminant conveyance to the aquifer and its lateral movements. Areas with higher R are expected to be more vulnerable.

3.1.3. Aquifer media(A)

Aquifer Media refers to the structural texture of consolidated or unconsolidated rock materials that serve as aquifer. The aquifer media information was extracted from a geological map of Abuja FCT. Despite the limited differences that are expected to be inside the regolith deposits, we decided to distinguish the aquifer media according to the underlying parental material. The similar ratings between the crystalline rocks demonstrate these limited differences.

3.1.4. Soil media (S)

This is defined as the uppermost portion of the vadose zone, characterized by significant biological activity (Anane et al., 2013). It has the potential to adsorb and attenuate surface and near-surface-derived pollutants. The soil media was defined from the soil map of Nigeria. It was reclassified and rated into two subclasses: silt loam and silt clay.

3.1.5. Topographic map (T)

Topographic refers to the slope and slope variability of the land surface (Anane et al., 2013) and it affects the velocity of surface runoff. This map was realized from the data of the shuttle radar topography mission (SRTM). The topography of the study area was classified into four subclasses.

3.1.6. Impact of vadose zone (I)

The Vadose zone is defined as the zone above the water table and is generally unsaturated or discontinuously saturated (Aller et al., 1987). The vadose zone media and its permeability determine the nature of attenuation processes between the topsoil and the water table. The layer was computed using the geologic map of the area.

3.1.7. Hydraulic conductivity (C)

Hydraulic conductivity refers to the ability of an aquifer to transmit water and control the rate of groundwater flow. It determines the migration velocity of pollutants thereby controlling residence time and attenuation potential. High conductivity values will be associated with higher vulnerability. The hydraulic conductivity map was realized using the permeability data obtained by pumping tests performed on the same wells used for the elaboration of the "D" layer (Rural water supply Program China – FGN, 2006; Fig. S1). Discrete data were interpolated in ArcGIS 10.8.1 to create the layer.

3.1.8. Land Use (LU)

Maps representing the land use in 2000 (Fig. 3a) and in 2020 (Fig. 3b) were included in the elaboration in order to evaluate the variation of the anthropic pressure in the study area. The maps provide information of the extension of built-up areas, cultivated lands and natural areas (forest and grassland) with a cell resolution of 30 m. Higher details of cultivations or type of land properties (e.g. residential, commercial) are not currently available. The increase of the population between 2000 and 2020 is directly reflected in the increase of the built up areas (from 2% to 7%) (Table 2). At the same time, the higher food demand also drives the spread of cultivated lands, which increased from 19% to 47% of the study area (Table 2). The urban and agricultural expansion mainly affected the grassland areas (-30%) whereas the extension of forest cover seems to be almost stable.

3.2. Field activities

Between March and April 2021, 46 groundwater samples were collected in Abuja FCT (Fig. S3; detail in Table S1) from private and public boreholes and hand dug wells. pH and Electrical conductivity (with automatic compensation to 25 °C) were measured in the field using portable probes (Hanna Equipment H198191). Chemical analyses were performed at the Centre National de l'Energie des Sciences et des Techniques Nuclaires (CNESTEN) in Rabat (Morocco). Major elements were analyzed by ion chromatography on unacidified (HCO_3^-, Cl^-, NO_3^- and SO_4^{2-}) and acidified (Na^+, K^+, Mg^{2+} and Ca^{2+}) samples. All samples were filtered in the field using 0.45 µm Minisart sterile cellulose acetate membrane filters and then an aliquot was acidified (~1%) with ultra-pure Merck HNO_3. All reported water analyses show charge balances of less than ±5%.

4. Results

4.1. DRASTIC and DRASTIC LU maps

The rates and weights assigned to each parameter are reported in Table 3.

The rates vary from 1 to 10, while the weights range from 1 to 5, with higher values describing greater susceptibility to pollution except for values of depth to water table and topography, which have an inverse relationship with vulnerability.

The depths to groundwater in the study area range between 5.5 and 12.5 m. They are grouped into three classes 5.5–7.5 m, 7.5–10 m and 10.0–12.5 m (Table 3). The lowest depth range is mainly defined around Bwari, in the central part of the municipal council area, and southern parts of Abaji and Kwali (Fig. 4a).

The principal source of groundwater recharge is the local precipitation which infiltrates into the ground and percolates toward the water table. The recharge also plays an important role in the nitrate contamination process, being the main vehicle for leaching and transport of contaminants toward the aquifer. The estimated mean recharge was grouped into Five (5) classes (Table 3). The highest recharge values were defined in the Bwari and Municipal Area council. The estimated recharge progressively decreases moving toward south-west. The lowest recharge values were expected around the Kwali and Abaji areas (Fig. 4b).

The regolith aquifer is mostly constituted by weathered deposits of Migmatite Gneiss and Schist and Metasediments, covering more than 80% of the study area. A very limited Section (5%) corresponds to the Granitic units in the western sector of Bwari and Municipal at the Niger State border. Rates 3 and 4 were respectively assigned to the regolith deriving from these units which are characterized by similar hydrogeological features (Fig. 4c). Sedimentary units are mostly present in southwestern parts of Abaji, Kwali and Kuje, covering 12% of the study area. A higher rate was assigned to these units (6).

The soil may have a noteworthy impact on the ability of pollutants to migrate toward the vadose zone due to attenuation, filtration,

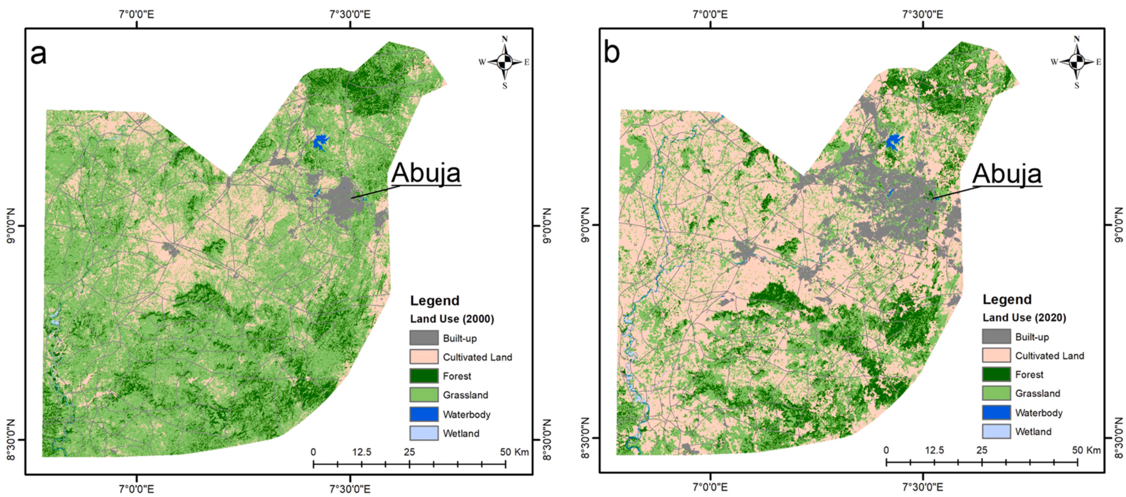

Fig. 3. Land use maps in 2000 (a) and 2020 (b) (Ministry of Natural Resources of the Peoples Republic of China Land use Map (2000, 2020).

Table 2
Percentage distribution of the land use in Abuja FCT in 2000 and 2020 and difference between the two scenarios. (Ministry of Natural Resources of the Peoples Republic of China Land use Map (2000, 2020).

	2000	2020	Difference
	%	%	%
Cultivated land	19.00	46.42	27.42
Forest	13.25	12.71	-0.54
Grassland	60.97	31.35	-29.62
Shrubland	4.33	1.53	-2.79
Wetland	0.05	0.14	0.09
Waterbody	0.22	0.43	0.21
Built-up	2.16	7.37	5.21
Bare land	0.03	0.05	0.02

Table 3
Attributes of different thematic layers for groundwater vulnerability mapping (subclasses, rates and weights mainly according to Aller et al. (1987).

Variables	Subclasses	Assigned rate	Percentage of area in a class	Assigned weight
Depth to water Table (m)	4.5–7.5	8	36.4	
	7.5–10.0	7	63.5	5
	10.0–12.5	6	0.1	
Recharge(mm/yr)	11–50	1	32	
	50–100	3	23	4
	100–175	6	21	
	175–250	8	12	
	250–500	9	12	
Aquifer Media	Migmatite/ Schist and Metasediment	3	70	
	Granitic Rocks	4	18	3
	Sandstone and River Alluvium	6	12	
Soil Media	Silty Clay	3	80.5	
	Silty Loam	4	19.5	2
Topography (% rise)	0.1–2	10	4	
	2–6	9	23	1
	6–12	5	73	
Impact of Vadose Zone	Migmatite	3	65	
	Schist and	4	12	5
	Metasediment	5	11	
	Granite	6	12	
	Sandstone and River Alluvium			
Hydraulic Conductivity (m/day)	0.57–0.95	1	55	3
	0.95–1.38	2	20	
	1.38–1.81	3	18	
	1.81–2.16	4	7	
Land use 2000	Built up	9	2	5
	Cultivated land	5	19	
	Forest	1	13	
	Grassland	1	66	
	Waterbody	1	0.2	
	Wetland	1	0.1	
Land use 2020	Built up	9	7	5
	Cultivated land	6	47	
	Forest	1	13	
	Grassland	1	33	
	Waterbody	1	0.4	
	Wetland	1	0.1	

biodegradation, sorption and volatilization processes. The predominant soil type in the area is silty clay, covering 80%, and was thus assigned the rating of 3 (Fig. 4d). It has a very high attenuation ability. Approximately 20% of the study area is covered by Silty loam soil type, with a rating of 4.

The topography represented in the study area was classified into three classes (Fig. 4e). The topography map indicates that the slope distribution of the study area is steep in the eastern parts of the study area along the mountain range, and gentler along the western parts.

The impact of the vadose zone is an important variable in the estimation of vulnerability. The data used to define the impact of vadose is the same as that used for the Aquifer media. Crystalline basement rocks comprising of Migmatites were assigned a rating of 3, Schist and meta sediments were assigned a rating of 4, and granite was assigned a rating of 5. Sandstone and river alluvium deposits were assigned a rating of 6 (Fig. 4f).

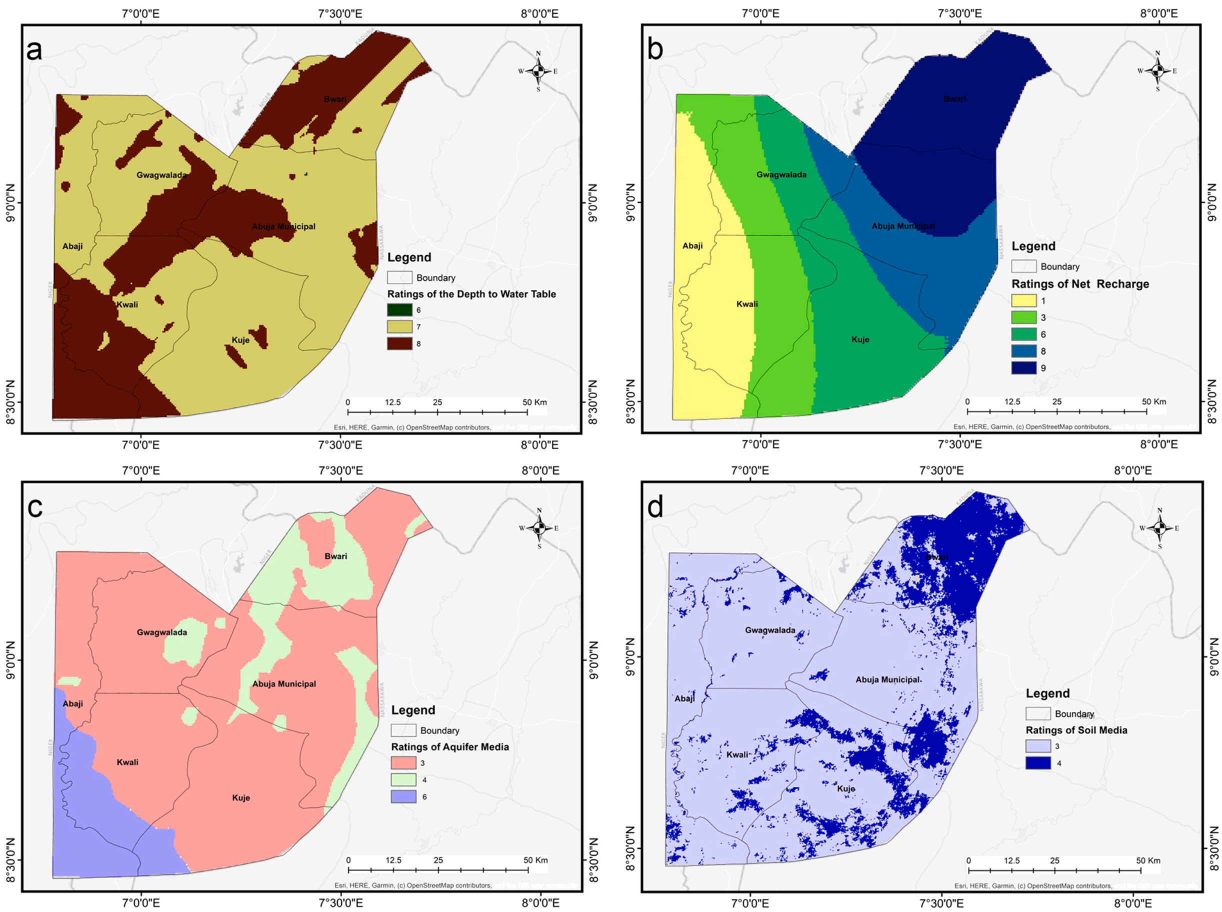

Fig. 4. Maps of seven thematic layers of groundwater vulnerability: a) Depth to water Table, b) Net Recharge, c) Aquifer Media, d) Soil Media, e) Topography, f) Impact of Vadose Zone, g) Hydraulic Conductivity.

Hydraulic conductivity determines the migration velocity of pollutants and hence the residence time and attenuation potential. High conductivity values will be associated with higher contamination risk. The hydraulic conductivity in the study area was grouped into four classes (Fig. 4g). The permeability values range between 0.57 and 2.16 m/d, in agreement with the interval reported in Jimoh and Wojuola (2009). The narrow range of the hydraulic conductivity values reflects the small variability of the characteristics of the saprolite deposits.

The seven layers were combined to form the DRASTIC intrinsic vulnerability model of the Abuja FCT area. The vulnerability values range between 77 and 134 (Fig. 5). The five vulnerability classes (very low, low, medium, high, and very high) are defined on the basis of the geometrical interval classification on ArcGis. Based on this classification, the Bwari, Abuja municipal and the Southwestern parts of Abaji are characterized by very high to high vulnerability.

Land use was considered to be closely related to the nitrate specific vulnerability map and therefore the highest weight (5) was assigned to this layer. Within this layer, three main groups were defined and rated: natural areas (forest, grassland, and wetland) characterized by a low natural load of nitrate (rate 1), cultivated areas (rate 5 in the 2000 land use map) where additional inputs of nitrate are related to the fertilization of the crops, and urbanized areas (rate 9) where the main sources of nitrate are the untreated waste waters and the open defecation (Table 3). Differently from previous groundwater vulnerability assessments developed in other countries (e.g. Busico et al., 2017b; Persaud and Levison, 2021; Alam et al., 2014; Stigter et al., 2005), we proposed a smaller rating of the agricultural areas. In fact, the available data on the fertilizer consumption (World Bank, 2022) highlight a lower use of fertilizers in Nigeria compared to other areas of Africa or in different continents (Table 4). Looking in detail at the fertilizer consumption trend (Table S2), a significant increase in fertilization is visible between 2000 (5.3 kg/ha of arable land) and 2018 (19.7 kg/ha of arable land). Different rates were assigned to the cultivated lands in 2000 (rate 5) and 2020 (rate 6) in order to account for this increase in fertilizer use.

The resulting DRASTIC-LU maps of 2000 and 2020 are reported in Fig. 6a and b.

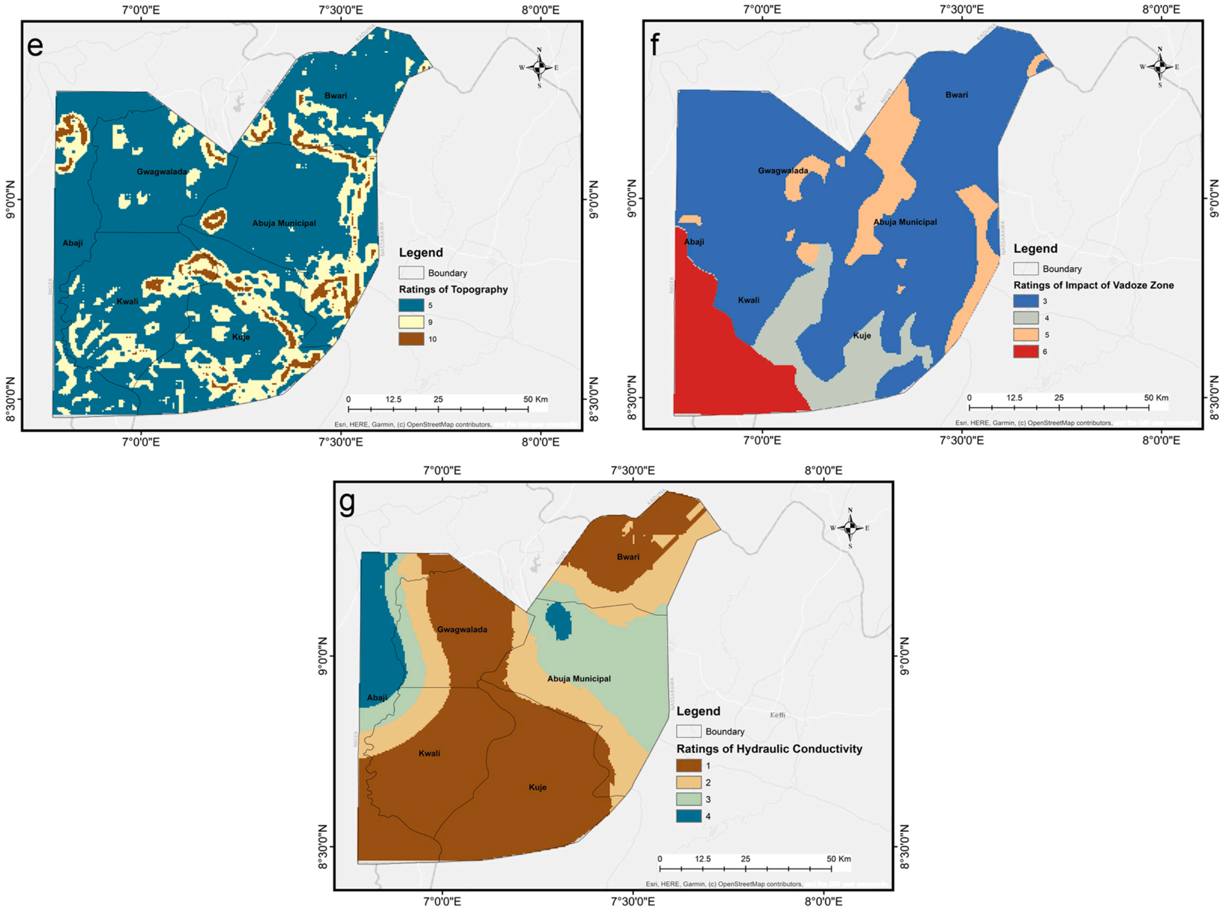

Fig. 4. (*continued*).

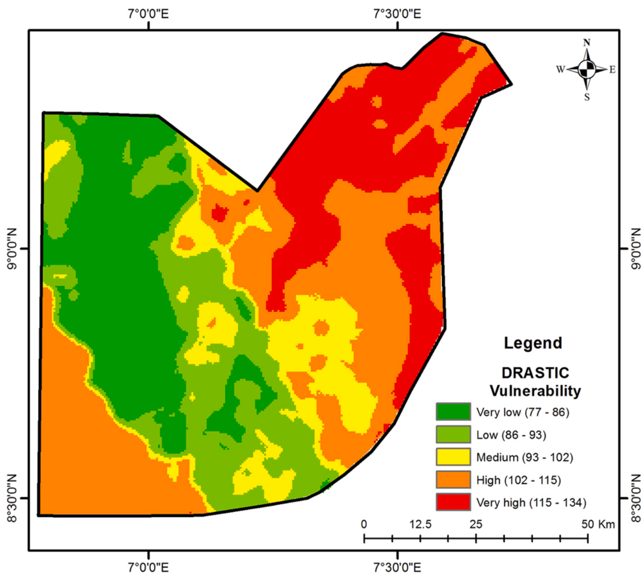

Fig. 5. DRASTIC intrinsic Groundwater Vulnerability Map for Abuja FCT.

Table 4
Summary of the mean fertilizer consumption in Nigeria, in portions of Africa and in other continents (World Bank, 2022). (Mean yearly data from 1961 to 2018 except *from 1992, and ** from 2002).

	Fertilizer consumption *(kg/ha of arable land)*
Nigeria	9.5
Sub-Saharan Africa* *	14
Middle East & North Africa*	75
China	220
East Asia & Pacific	295
Europe & Central Asia	76
Euro area	207
Latin America & Caribbean	77
North America	93

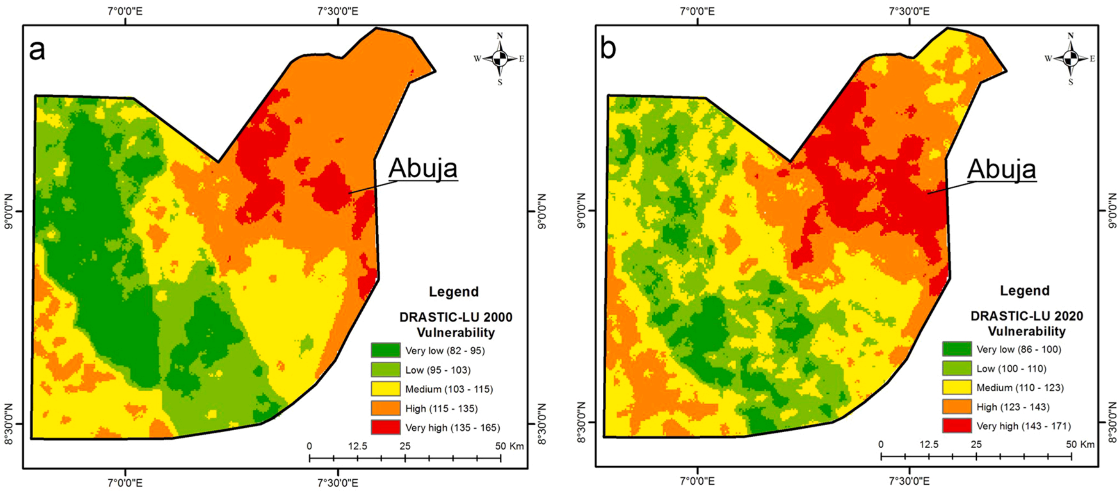

Fig. 6. Comparison of the DRASTIC-LU vulnerability maps between the 2000 (a) and 2020 (b).

4.2. Hydrogeochemistry

The samples collected during the 2021 campaign show a dominance of Ca(Mg)-HCO_3 facies (Fig. S4). A synthesis of the hydrochemical results for the groundwater samples is reported in Table 5.

Nitrate concentrations in groundwater range from 0.2 to 294.5 mg/L (Average = 56.2 mg/L; Standard deviation = 77.4; n = 39) with 33% of the wells (n = 15) exceeding the statutory limit for drinking water (50 mg/L; World Health Organization, 2017).

5. Discussion

Basement aquifers are generally classified as a two-layer system comprising of the fractured bedrock overlain by a weathered/regolith sequence (Bianchi et al., 2020). The focus of the present study is that the base of the regolith is the more productive layer, more exploited by the population. The DRASTIC map (Fig. 5) can only provide a physically based characterization of the aquifer and its intrinsic capacity to be contaminated. The simplified model reported in Fig. 7A highlights the contamination pathways in the natural environment according to the hydrogeological settings described in the "Study area" section. Additionally, the comparison between land use maps of Abuja FCT in 2000 and 2020 (Fig. 6a and b) allows us to constrain the specific vulnerability to nitrate contamination

Table 5
Synthesis of the hydrochemical results for the groundwater samples collected in Abuja FCT in 2021.

	EC µS/cm	pH	HCO_3^- mg/L	Cl^- mg/L	NO_3^- mg/L	SO_4^{2-} mg/L	Na^+ mg/L	K^+ mg/L	Mg^{2+} mg/L	Ca^{2+} mg/L
Min	13.8	6.0	5.5	0.3	0.2	0.2	0.7	0.6	0.3	0.9
Max	1510.0	8.5	292.9	177.7	294.4	968.1	69.2	105.2	50.9	380.5
Average	347.3	7.3	117.9	27.1	54.8	27.2	20.3	7.3	11.0	41.0
St.Dev	311.2	0.6	79.9	41.4	76.9	142.5	15.7	14.9	11.6	57.4

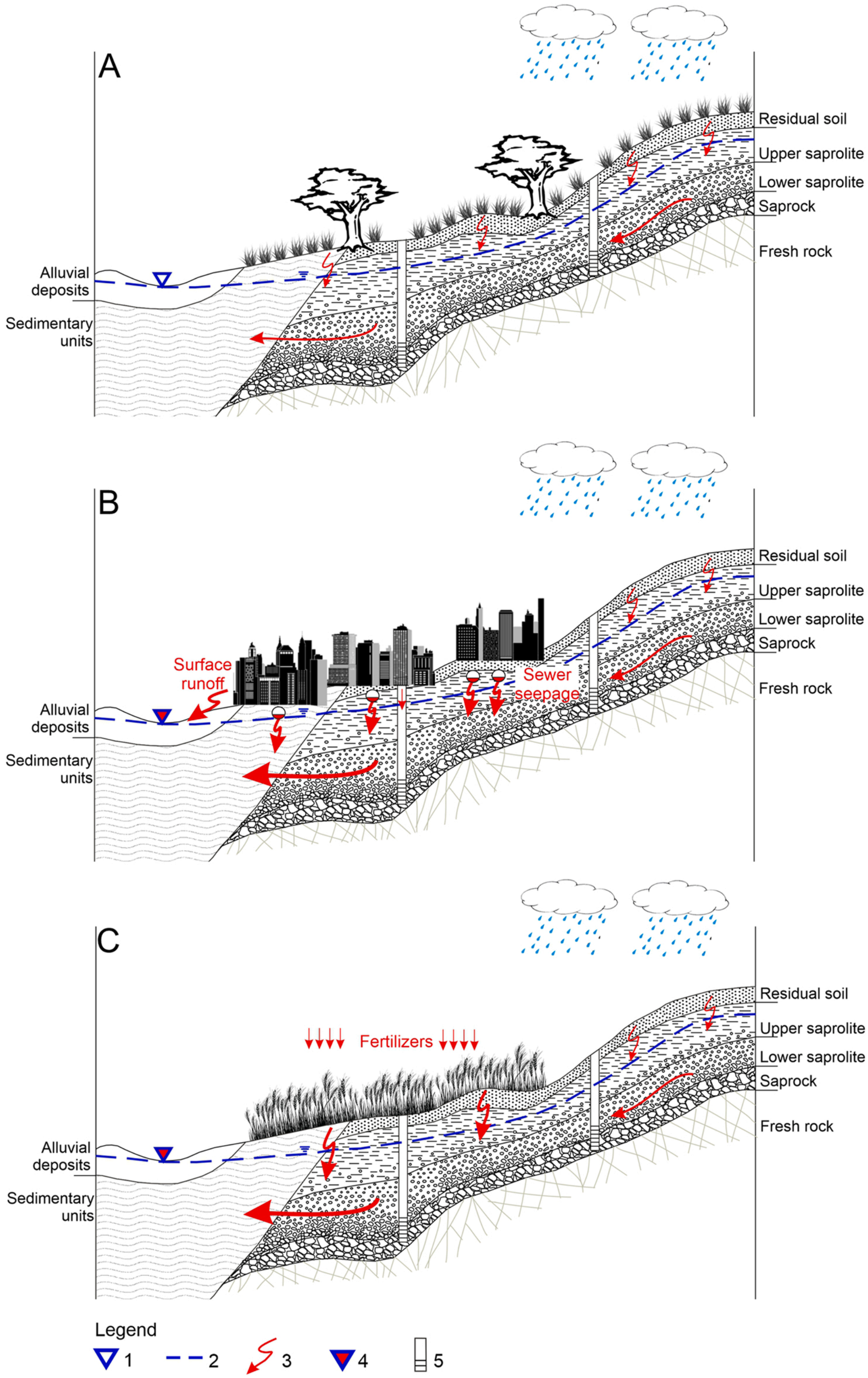

Fig. 7. Simplified conceptual models (not in scale) of the groundwater contamination according to different land use scenarios: natural conditions (A), urbanized areas (B) and agricultural areas (C). Legend: 1) Gaining stream; 2) Water table; 3) Nitrate pathways (the thickness of the arrow is directly related to the contamination load); 4) Gaining stream with higher expected contamination; 5) Wells.

induced by both agricultural and domestic activities.

The rapid population expansion registered in Nigeria reflects both the urban sprawling of the urban settlements and the expansion of small villages throughout the region (Fig. 3). In most cases, the fast urbanization is not associated with the realization of adequate systems for the collection and treatment of liquid and solid waste, which are therefore often dispersed in the natural environment (Aniekwe and Igu, 2019). In addition, excavations of the ground surface may remove the lower permeability soil layer, reducing the depth to groundwater ("D" layer), and eventually increasing the intrinsic vulnerability of the aquifer. This effect may also be indirectly induced by the installation of sewage systems, which may accidentally act as a source of nitrate, being located close to the saturated portion of the aquifer (Fig. 7b). At the same time, the increased extension of urbanized areas reduces the possibility of water infiltration and therefore the local net recharge. Consequently, the higher amount of surface runoff may be a new pathway for contamination of surface waters, in the absence of adequate collection and treatment systems. (Fig. 7b). Additional fast pathways for local groundwater contamination may also be the wells themselves. Like groundwater from shallow permeable lenses, polluted surface waters may in fact be conveyed in the borehole and thus eventually directly reach the water table. More detailed information on the human activities in urban areas may allow for a more accurate estimation of the pollution loads, as tested by Dumedah et al. (2021).

The aforementioned impacts of land use changes on aquifer vulnerability are already absorbable from the specific vulnerability analyses. In the DRASTIC–LU 2020 map, very low to low vulnerability classes are attributed to parts of Abaji, Kwali, Gwagwalada and Kuje. These areas were mainly covered by grasslands in 2000, but over the years they have been converted to agricultural lands. This change affects the vulnerability to nitrate of all agricultural areas due to both plowing, which may improve soil permeability, and dispersion of fertilizers (Fig. 7c). Although the current impact of fertilization seems to be moderate (World Bank, 2022), the rapid increase observed over the last 20 years (+400%) and the ongoing development of the fertilizer industry to cope with the global food crisis should be taken into account in future regional planning.

A comparison with the current state of nitrate contamination in groundwater and the 2020 DRASTIC-LU is shown in Fig. 8. At present, 53% of the sampled wells with nitrate concentration exceeding the statutory limits for drinking water (50 mg/L; World Health Organization, 2017) are located in "very high" vulnerable zones and 13% in "high" vulnerable zones. Taking into account the 2020 land use map there is a strong relationship between NO_3 and urban/peri-urban areas, where 87% of wells with nitrate concentration exceeding the statutory limits for drinking water are located, contrary to the more widespread hypothesis that nitrate contamination is essentially associated with agricultural practices. This can be induced by several processes: i) local impact of point source pollution of domestic (e.g. informal settlements, open defecation) or industrial origin, ii) nitrogen legacy associated to previous land use (e.g. urban settlements erected on land previously used for agricultural purposes), iii) a mix of both. Results of the present study show that the contaminated groundwater samples located in the medium-low vulnerability areas are generally located near small villages, suggesting the possible contribution of domestic activities rather than the sole impact of the widespread use of fertilizers. Regardless of the cause, which is the subject of an ongoing study on groundwater geochemistry, focused on environmental isotopes (δ^2H_{H2O}, $\delta^{18}O_{H2O}$, $\delta^{15}N_{NO3}$, $\delta^{18}O_{NO3}$), this process cannot be underestimated, especially if the wells are used for drinking consumption (only 20% of the study area is equipped with improved domestic water supply (Jimoh and Wojuola, 2009)). As for the wells located in areas classified as medium to high vulnerability, but not exceeding the nitrate drinking water limits, it will be crucial to identify the possible nitrate sources in order to prevent future higher contamination in these vulnerable areas. The possible occurrence of denitrification in these areas (therefore resulting in low nitrate concentrations) will be verified with future studies of nitrate isotopes ($\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$). Validating the vulnerability assessment with land use change and nitrate concentration made it possible to highlight how, in a relatively vulnerable context from a geological point of view, the impact of anthropogenic activities (especially in view of the predicted population growth) may significantly alter aquifer vulnerability. This may lead to possible dangerous effects on the environment and population. Moreover, the latter is not well prepared to manage possible restrictions on groundwater use, the primary source for domestic and agricultural purposes. Therefore, the results of the present study represent an important starting point for raising awareness of the need for environmental planning in the region, and for coping with environmental changes in a timely manner.

The paucity of hydrogeochemical, hydrogeological and detailed land use data for the study area is a great limitation for developing future scenarios on groundwater contamination; therefore, a priority for local water managers should be to set up a monitoring network to track the evolution of chemical water properties. This would allow them to balance the need to ensure that the growing population of the region will meet the goals living in sustainable urban settlements (SDG 11; United Nations High Commissioner for Refugees, 2017), achieving zero hunger (SDG 2), and having access to safe drinking water (SDG 6).

6. Conclusions

Like many other countries worldwide, Nigeria is experiencing rapid population growth, with serious repercussions on groundwater quality and population wellbeing. The population increase led to the rapid expansion of previously existing urban settlements, and to the creation of new ones. The increase in food demand boosted the conversion of grassland into cultivated areas. Both land use changes potentially exacerbate groundwater quality and quantity issues in the region.

In this context, the DRASTIC model was applied to assess the intrinsic vulnerability of Abuja FCT. The results were integrated with the representation of land use in 2000 and 2020 in order to define the specific vulnerability to nitrate, and to map its variation over the last 20 years. A comparison with the results of a hydrogeochemical assessment carried out in 2020 highlighted that most of the contaminated waters were collected in urbanized areas both in major cities as well as in small villages, although the possible mixing with agriculturally contaminated waters is under investigation. Results provide an important basis to support the sustainable development of the region, providing information to managers and policy makers relative to the current state of aquifer vulnerability, and insights into possible contamination drivers. As previously mentioned, the paucity of data does not allow for a complete assessment,

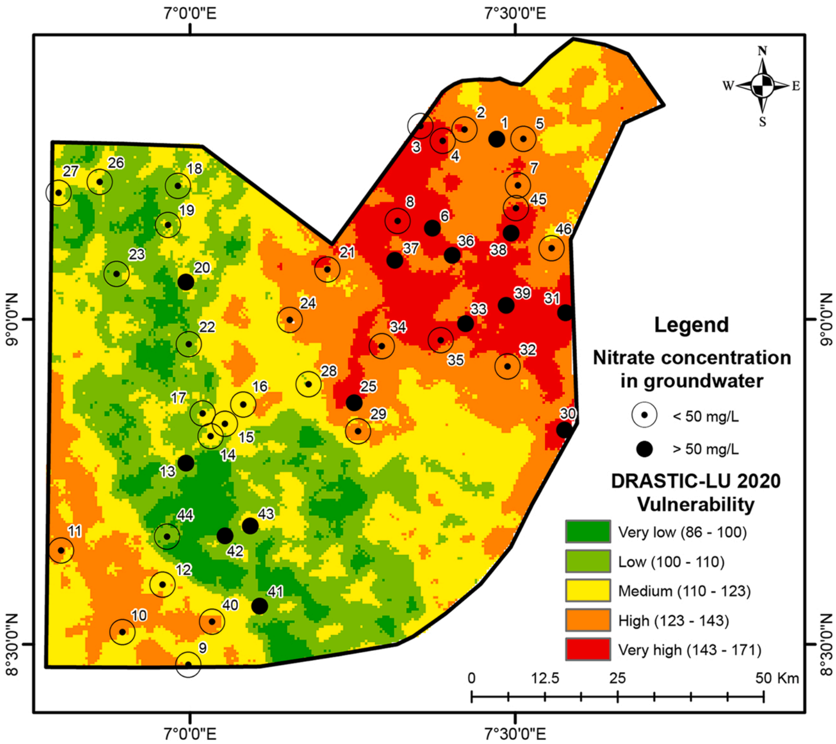

Fig. 8. DRASTIC-LU 2020 map and groundwater samples distinguished by a higher or lower concentration of nitrate than the limit for drinking purposes (50 mg/L). The labels correspond to the ID of each sampling point (Table S1).

but there are some valuable results that can respond to the current needs of the local population. As highlighted by Re et al. (2018) and by Re et al. (2022) it is often the case that while the scientific community is focused on providing the most complete information based on long-term monitoring and assessments, business as usual actions (often associated to population growth, water demand increase and recurrent droughts/extreme events) keep degrading the studied system. Therefore, preliminary results represent a valuable support to inform local populations about the quality of local water resources and policy makers about the priority actions to undertake.

Future research development will focus on specific vulnerability mapping in the region and on the identification of the main sources of nitrate pollution using a multi-tracer approach and include more specific details of the urban activities. In order to reduce the uncertainty about specific vulnerability, we will perform calibration and validation of the rates and weights of the DRASTIC-LU once the extensive monitoring that is currently underway has finished and we have a robust monitoring dataset with more detailed information about land use, including agricultural and human activities.

Finally, besides its impact on intrinsic groundwater vulnerability, land use change should also be addressed in terms of internal migrations from rural to urban areas. This is common practice in many areas worldwide (International Organization for Migration, 2016) as cities are generally considered more attractive due to a broader job market. As a result of these internal migrations, it is not only rural lands that are abandoned, but cities get overcrowded (eventually exacerbating ongoing urban sprawling), and there is even more pressure on (ground)water resources and competition on their use (Kammoun et al., 2018). Limited access to safe water supply may increase conflicts due to the vertical (among different uses: e.g. domestic, industrial and agricultural) and horizontal (among households sharing the same water sources) competition on water use (Sunkari et al., 2021). For this reason, it is of paramount importance to integrate both intrinsic and specific vulnerability mapping in regional planning as a useful tool to support long-term groundwater protection in areas subject to rapid population growth.

CRediT authorship contribution statement

Mary Etuk: Conceptualization, Methodology, Sampling, Software, Writing – original draft. **Stefano Viaroli**: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Igwe Ogbonnaya:** Funding acquisition, Writing – review & editing, Project supervision. **Viviana Re:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101158.

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