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Groundwater Vulnerability Assessment to Nitrogen Pollution Using a GIS-Based DRASTIC Model in the Area of the 9th District of N'Djamena, CHAD

Tidjani Bahar[1], Ousmane Mahamat[1], Djimadjimbaye Eraste[2]

[1]Ecole Nationale Supérieure des Travaux Publics (ENSTP), N'Djamena, Tchad
[2]Laboratoire de Géologie, Faculté des Sciences Exactes et Appliquées, Université de N'Djamena, N'Djamena, Tchad
Email: tidjanibahar@yahoo.fr

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Abstract

Groundwater resources are the primary source of water for human activities. Therefore, controlling groundwater contamination through the assessment of its vulnerability is crucial for effective water management and protection. In this work, the GIS-based DRASTIC model has been used to assess the groundwater vulnerability of the area of the 9th district of N'Djamena, CHAD. A total of 7 hydrogeological factors, such as depth to water level, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity, have been used for this study. The final groundwater vulnerability map was obtained by overlaying a weighted method with the help of the DRASTIC index. The results of the study showed that the DRASTIC vulnerability index (DI) value varies from 115 to 165, and the catchment area studied can be classified into three vulnerability classes (low, average, and high). The high vulnerability class covers 15% of the study area. The average and low vulnerability classes cover approximately 34% and 51% of the study site, respectively. In the northeastern portion of the 9th district of N'Djamena, namely Toukra, Walia, and Kabe, high vulnerability to contamination has been observed. To validate the groundwater vulnerability map, the water quality parameter—nitrate—has been used. The Pearson correlation coefficient between groundwater vulnerability (DRASTIC index) and nitrate concentrations showed a strong positive correlation ($r = 0.76$) when validating the groundwater vulnerability map. The groundwater vulnerability map obtained in this study can be widely used for better management of groundwater and land use planning.

Keywords

DRASTIC, GIS, Groundwater Vulnerability, Nitrate Concentration, 9th District of N'Djamena

1. Introduction

Groundwater resources play an important role in meeting demands on water supply (both natural and anthropogenic) in many parts of the world. This vital resource is utilized by human beings for drinking, domestic, and agricultural purposes. In CHAD, nearly 20% of Chad's groundwater withdrawal is used for human consumption, while the remaining 80% is used in agriculture [1]. In recent years, groundwater pollution has continued to increase and has limited the potential of groundwater resources for use [2]-[4]. The source of groundwater pollution could be natural (e.g., salinity) or anthropogenic (nitrogen, pesticides, sewage effluent, etc.). Among all contaminants, nitrogen contamination of groundwater has emerged as one of the most dangerous pollutants and is also considered the primary cause of deteriorating groundwater quality in arid and semi-arid regions of the world [5]-[8]. Groundwater contaminants are reported to occur in several parts of N'Djamena due to anthropogenic activities, which have drastically changed the groundwater quality [9]-[11]. For groundwater protection and restoration, it is essential to measure groundwater contamination in any area that could be potentially impacted. Nowadays, scientists and engineers worldwide are continuously studying contaminant fate and related phenomena, proposing many solutions for understanding and managing groundwater. The assessment of groundwater vulnerability is a growing concern in the scientific community in order to deal with groundwater contaminants.

The groundwater vulnerability concept was first introduced by Margat (1968) [12] in France. In Margat (1968) [12], groundwater vulnerability was defined as the ability of infiltration and diffusion of pollutants from the soil surface to the groundwater system. This concept is implemented in various climatic regions of the world, such as arid and semi-arid regions [13]-[16], tropical and sub-tropical regions [17]-[19], and temperate regions ([20] Luoma *et al.* 2017; [21] Minea *et al.* 2025). Along the same lines, groundwater vulnerability has been studied in various hydrogeological contexts, *i.e.*, coastal regions [22] [23], hard rock aquifers [24] [25], karst aquifers [26]-[28], alluvial aquifers [29] [30]. Groundwater vulnerability can be described as an intrinsic characteristic of an aquifer system that depends on the sensitivity of that system to natural and human impacts [31]. These intrinsic characteristics of an aquifer are the soil characteristics (soil structure, texture, etc.) and hydrological characteristics (drainage density, runoff volume, slope, etc.) according to several authors [32]-[34]. There is also a specific vulnerability that includes parameters related to anthropogenic activities, such as the nature of the pollutant and land use patterns [35]. Overall, the vulnerability of groundwater in a given zone is assessed to identify the areas that are susceptible to pollution due to anthropogenic activities.

Groundwater vulnerability assessment and derived vulnerability maps are important predictive tools dedicated to decision-makers in order to maintain and restore groundwater quality [3]. Several approaches are available for groundwater vulnerability assessment, such as: process-based models [36] [37], DRASTIC [38], GOD [39], AVI [40], SINTACS [41], EPIK [42], GOD [39], SIGA [31], PCA technique [43], decision random forest [44], tree-based data mining [45], fuzzy clustering [46], and boosted regression tree [47]. The choice of an appropriate model is highly dependent on the aquifer type, data availability, objective, and scope of a particular study [3] [48]. Among these groundwater vulnerability assessment models, DRASTIC (a combination of depth to aquifer (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C)) is the most popular model and has been applied by several researchers [3] [18] [48]-[54]. The DRASTIC approach is based on four main assumptions [3] [38]: the contaminant is introduced at the soil surface, the contaminant is transported to the groundwater by precipitation, the contaminant has the mobility of water, and the area to be applied is 0.4 km^2 or more. A combination of the DRASTIC model with GIS-based mapping techniques for obtaining maps and identifying vulnerable zones has been successfully used in the scientific community (e.g. [3] [48] [49]). This strategy, combining the Geographic Information System (GIS) and the DRASTIC model, is low-cost and time-effective [55].

In this study, the Drastic model combined with GIS technology was used to assess groundwater vulnerability and identify the risk-prone zones of the 9th district of N'Djamena, CHAD. Groundwater quality research in the city of N'Djamena has previously been performed by some researchers [9] [11] [56] [57]. Bon *et al.* (2021) [9] assessed groundwater quality in N'Djamena for user needs and identified areas that are more or less favorable for specific uses. Mfonka *et al.* (2025) [11] examined groundwater quality for domestic and agricultural purposes, using hydro-chemical modeling, Water Quality Index, and Geographical Information System techniques in N'Djamena city. Abderamane *et al.* (2017) [56] implemented a Drastic approach in order to assess the vulnerability of groundwater to pollution in N'Djamena. However, research related to nitrate contamination and the use of a GIS-based DRASTIC vulnerability model in the groundwater of the 9th district of N'Djamena has not been performed to date. The main goal of this work is to assess the groundwater vulnerability of the 9th district of N'Djamena using the GIS-based DRASTIC model and also discuss the spatial distribution of nitrate concentration in the groundwater. With a high population density, intensive agriculture, presence of open latrines, and absence of sewage disposal facilities in the 9th district of N'Djamena, this work will help policymakers and planners in preparing a groundwater management and protection plan in the near future.

2. Materials and Methods

2.1. Study Area

N'Djamena city is the capital of the Republic of Chad. It is located between latitudes 12˚02'N and 12˚12'N and longitudes 14˚58'E and 15˚10'E on a marshy area south of Lake Chad at the confluence of the Chari and Logone Rivers (**Figure 1**). The study area (the 9th district of N'Djamena) is located in the triangle formed by the confluence of the Chari and Logone Rivers and covers an area of 92.76 km^2. The majority of the area is used as agricultural land, and agricultural activities are practiced using water from the Chari and Logone Rivers. Based on meteorological data (precipitation and temperature) obtained from the National Agency of Meteorology covering the period from 1992 to 2022, the average annual rainfall of the region is 586.50 mm. The maximum duration of rainfall is eight months (from April to November). Temperatures vary between 27˚C and 41˚C, with an average of about 29.3˚C. The elevation of the study area ranges from 280 to 320 m. Lithologically, the study area is an integral part of the Lake Chad Basin, which is characterized by a thick sequence of Cretaceous, Tertiary, and Quaternary sediments [58]-[60]. Soils of Quaternary origin are made up of sands, sandy clay alluvium, clays, clay-sandy alluvium, and silts [61]. The hydrogeology of N'Djamena is mostly dominated by the Quaternary aquifer [61] [62]. The origin of the Quaternary aquifer is continental, and the deposits are essentially sandy with clay intercalations [63]. Two types of Quaternary aquifers can be distinguished [64]: one at about 10 m deep, which feeds the traditional wells of the city, and the other at a depth of about 60 m, drilled and typically operated by the Chadian Water Company.

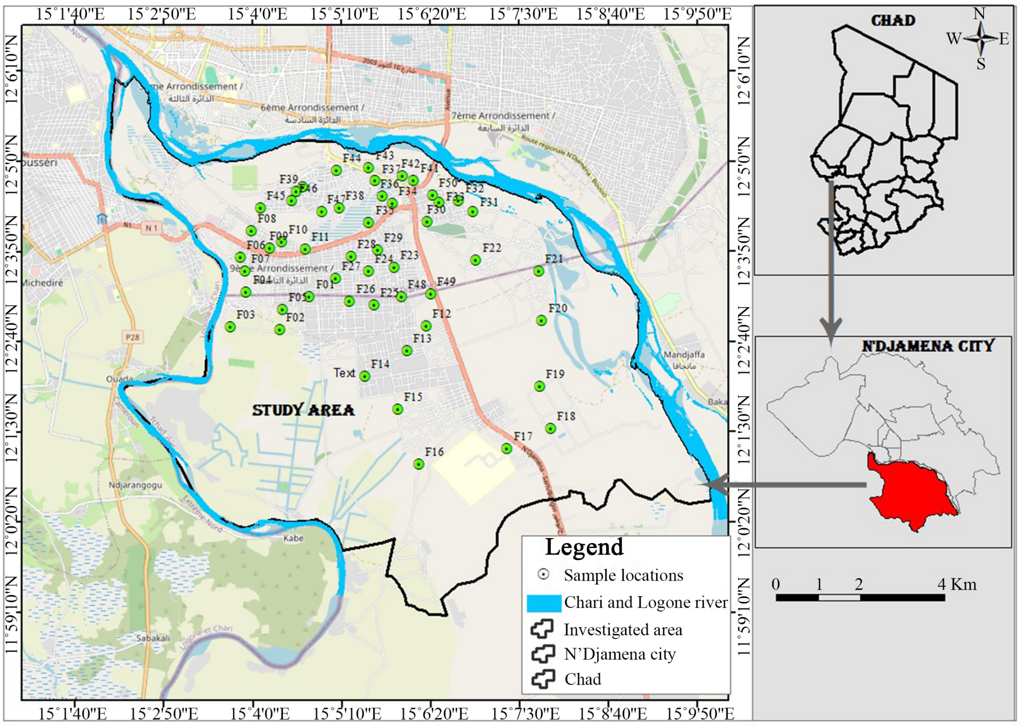

Figure 1. Location of the study area.

2.2. Aquifer Vulnerability Assessment Using the DRASTIC Model

DRASTIC is a popular and well-known model developed by the US Environmental Protection Agency for assessing aquifer vulnerability. The DRASTIC model assesses aquifer vulnerability based on a weighted combination of seven hydrogeological factors [38]: depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). Depending on their relative importance in influencing groundwater flow and contaminant transport, the seven (7) parameters have been assigned specific weights. Each parameter is considered as a sub-criterion and rated on a scale of 1 (least significant) to 10 (most significant) according to its relative importance. The total weight is computed by multiplying the rating of each sub-criterion by the weight of the main factor, as shown in **Table 1**. From the data shown in **Table 1**, thematic maps have been prepared for each hydrogeological factor using a 30 m × 30 m pixel cell size and reclassified according to their respective weights. All thematic maps related to different hydrogeological parameters were generated using ArcGIS Software. The final groundwater vulnerability map has been generated by the DRASTIC index weighted sum overlay method following the methodological flow chart (**Figure 2**).

DRASTIC Index (DI) is expressed in the form:

$$\text{DI} = \text{DrDw} + \text{RrRw} + \text{ArAw} + \text{SrSw} + \text{TrTw} + \text{IrIw} + \text{CrCw}$$

where D, R, A, S, T, I, and C represent the seven (7) parameters or hydrogeological factors, r is the rating, and w is the weight assigned to the respective parameters.

Note that a high Drastic Index (DI) number indicates a high risk of groundwater contamination, and in the same way, a low Drastic Index value signifies less groundwater vulnerability [48] [65].

Table 1. DRASTIC rating and weighting values for the various hydrogeological factors in the study area.

Parameters	Range	Rating	Weight	Total weight (rating × weight)
Depth to water level (in meters)	1.5 - 4.5	9	5	45
	4.5 - 9	7		35
	9 - 15	5		25
Net recharge (mm/year)	4 - 17	1	4	4
Aquifer media	Clayey sand	6	3	18
	Clay	3		9
	Medium sand	8		24
	Silty clay	5		15
Soil media	Silty clay	3	2	6
	Sandy clay	5		10
	Compacted clay	7		14
	Sand	9		18

Continued

Topography (slope in %)	0 - 2	10	1	10
	2 - 6	9		9
Vadose zone media	Sandy clay	6	5	30
	Clay	3		15
	Sand	8		40
	Silty clay	5		25
Hydraulic conductivity (m/s)	6.27×10^{-4}	8	3	24

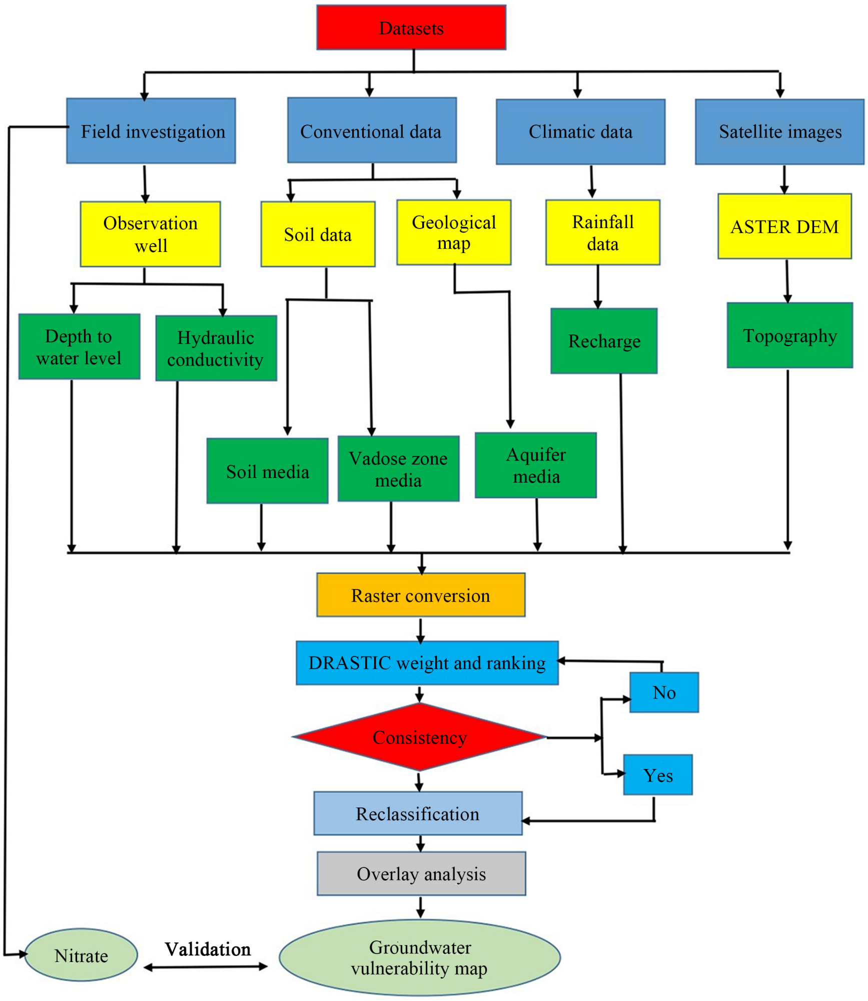

Figure 2. Methodological flow chart for groundwater vulnerability mapping.

2.3. Data Collection and Analysis

Along with the implementation procedure of the drastic approach, data collection was carried out. The raw data were collected or derived from various sources and are listed in Table 2.

For assessing the accuracy of the DRASTIC approach used for generating the final groundwater vulnerability map, hydrochemical data (*i.e.*, nitrate) are needed.

To reach this goal, a total of 50 sample locations were identified in the study area based on the densest residential, industrial, or agricultural area. The identified water wells were regularly used for drinking water supply or agricultural uses. The main groundwater quality parameter analysis, including nitrate, is performed in the LHGR Laboratory of the University of N'Djamena following the standard procedures recommended by the American Public Health Association [66]. The data for the aquifer media and vadose zone media were derived from twenty STE well logs. The maps related to these two parameters (aquifer media and vadose zone media) are obtained from data interpolation by using the IDW method provided in the spatial analyst tool of ArcGIS 10.8.1.

Table 2. Data used for generating hydrogeological parameters for the DRASTIC approach.

Parameter number	Raw data	Source	Output layer
1	Groundwater levels	Field survey (June 2024)	Depth to aquifer (D)
2	Recharge data	Data from Kadjangaba (2007) [67]	Net recharge (R)
3	Well log data	STE	Aquifer media (A)
4	Soil data	CNRD	Soil media (S)
5	Digital elevation model (DEM)	ASTER (https://asterweb.jpl.nasa.gov/gdem.asp)	Topography (T)
6	Well log data	STE	Impact of the vadose zone (I)
7	Pumping test data	STE	Hydraulic conductivity (C)

3. Results and Discussion

3.1. Depth to Water Level

The depth to water level is defined as the distance between the ground surface and the water table. This hydrogeological factor (*i.e.*, depth to water level (D)) plays an important role in the DRASTIC approach because pollutants, before dissolution in the groundwater, are retained by this thickness of soil separating the aquifer from the surface. The greater the depth to the water level, the lower the vulnerability of groundwater to contamination [38]. The depth to water level map has been created from water level data measurements performed during a field trip organized by our team in June 2024. Water level data from 50 sample locations were used to interpolate depth to water level by the inverse distance weighted (IDW) method provided in the spatial analyst tool of ArcGIS 10.8.1. The depth to water level in the study site varies from 1.5 to 15 m. These data related to depth to water level in the study area are classified into 3 depth categories, ranging from (1.5 - 4.5) m, (4.5 - 9) m, to (9 - 15) m, having weightages of 45, 35, and 25, respectively (**Table 1**). In the northeast of the study area (Toukra), the aquifer depth is high, ranging from 9 to 15 m, so the risk of contamination is low. In contrast, in the southwestern (Digangali) and northwestern (Walia) parts of the catchment studied, groundwater depth is much shallower (ranging from 4.5 to 1.5 m), and these areas are quite vulnerable to groundwater contamination. However, areas located in the middle of the study site (Gardole, Ngoumna) have a moderate risk of contamination, justified by the value of water level depth (ranging from 4.5 to 9 m). The depth to water level in the study site is shown below (**Figure 3**).

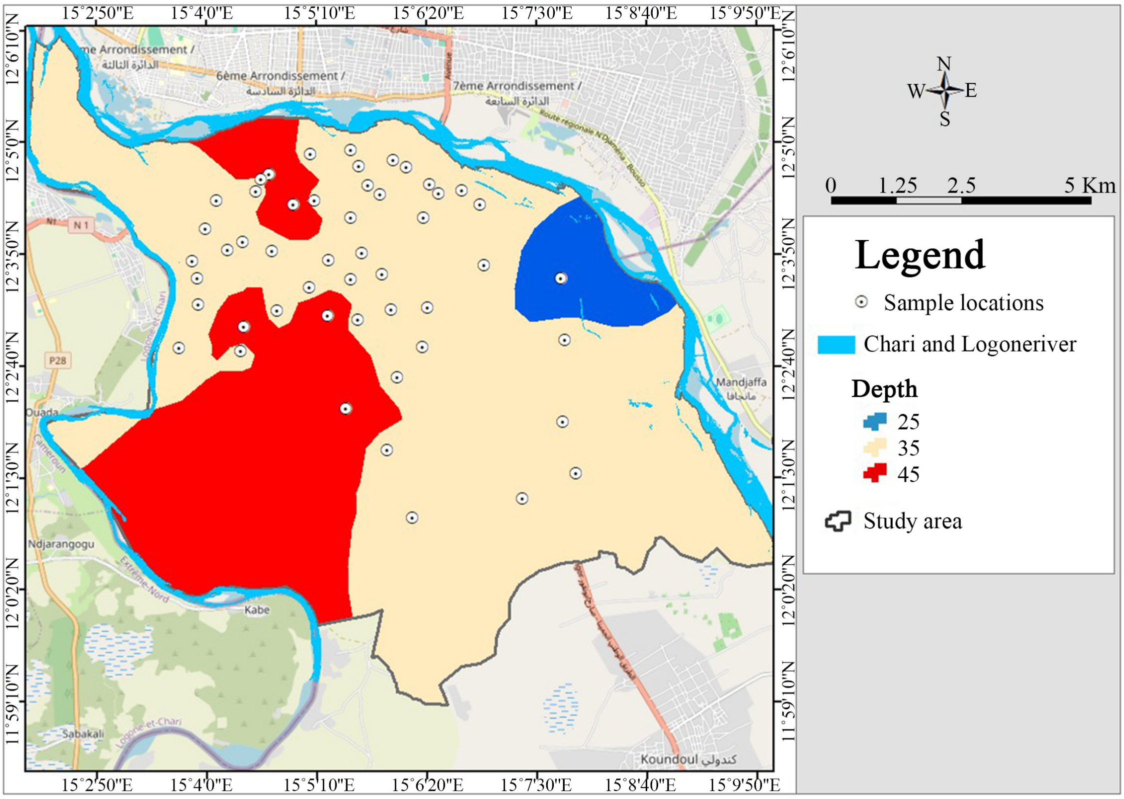

Figure 3. Depth to water level map.

3.2. Net Recharge

Net recharge is water percolating per unit area of soil and reaching the groundwater table [48]. This hydrogeological parameter is influenced by various factors such as slope, soil permeability, rainfall, land cover, and rate of water seepage [68]. High recharge indicates a greater chance for contaminants to reach the water table and vice versa. Net recharge values for the study area were obtained from Kadjangaba (2007) [67]. Based on the provided data, the net recharge of the study area varies from 4 to 17 mm/year. This made it possible to obtain a single class corresponding to the 4 - 17 mm/year, and the total weight assigned is 4 (**Table 1**). The net recharge map of the study area was developed from the recharge data sets and is shown below (**Figure 4**). The uncertainty associated with the net recharge value estimated for this study is related to the unavailability of reliable long-term data on precipitation and evapotranspiration. Furthermore, there is only one meteorological measurement station near the study site, resulting in low spatial resolution of the data. In the absence of an updated value for the net recharge, we have settled for the most recent value obtained from Kadjangaba (2007) [67], and this constitutes a limitation of our approach.

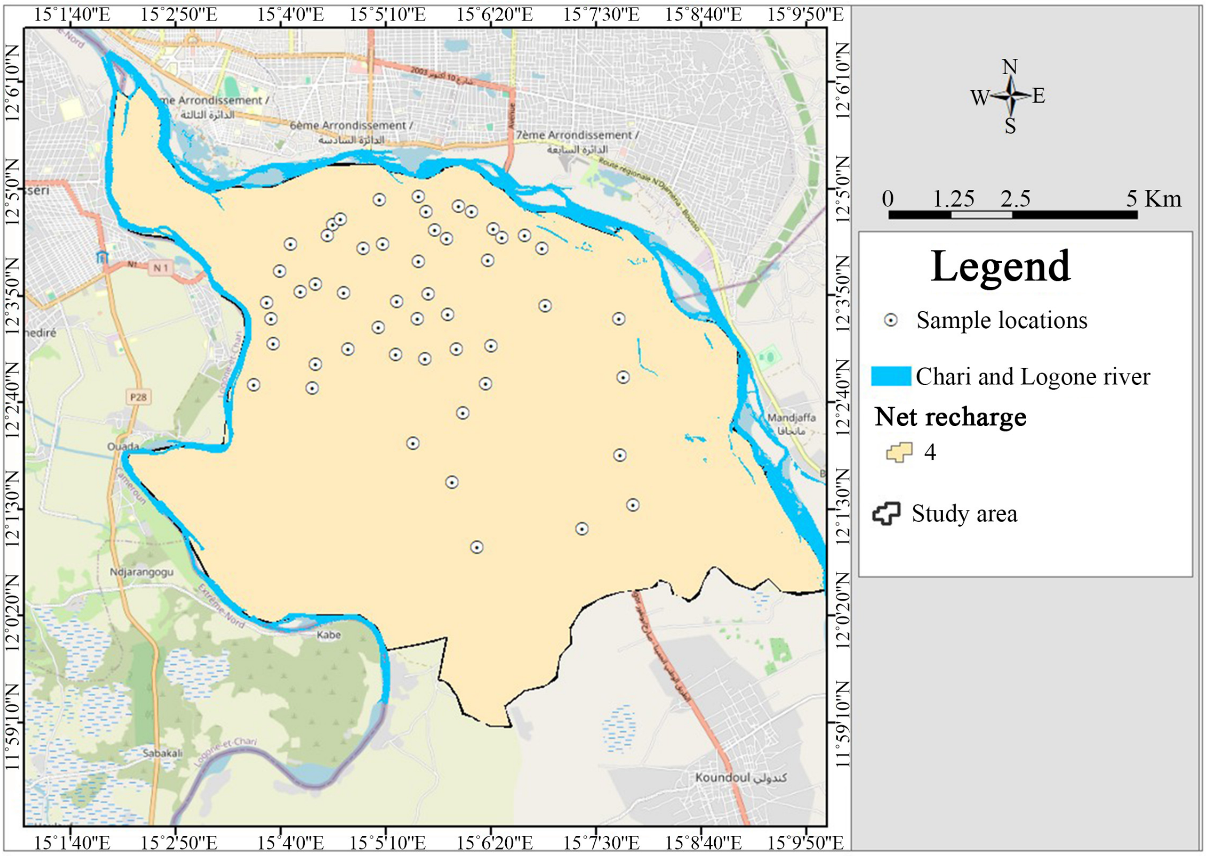

Figure 4. Net recharge map.

3.3. Aquifer Media

Aquifer media refers to the consolidated or unconsolidated formation that serves as an aquifer. It may include pores and fractures through which water circulates. Physicochemical mechanisms of aquifer contamination, such as sorption, cation exchange, filtration, dissolution, and other processes, take place in the porous structure of the aquifer. The nature and hydrodynamic properties (*i.e.*, porosity, permeability) of the aquifer porous structure impact the dissolution rate of the pollutant in the groundwater. Hence, the aquifer media is an important hydrogeological factor to be taken into account in assessing the quality of groundwater. The larger the grain size and the more fractures or openings within the aquifer formation, the higher the permeability, and thus it is categorized by a higher risk of contamination [69]. The DRASTIC parameter A (Aquifer media) was evaluated from the well log provided by STE (Société Tchadienne des Eaux) (Table 2). Based on these data, the study area has four different types of lithological formations, namely clayey sand, clay, medium sand, and silty clay. The aquifer media have been assigned a total weight according to their influence on the quality of groundwater as follows (Table 1): a total weight of 18 is assigned to clayey sand, 9 to clay, 24 to medium sand, and 15 to silty clay. The final map representing aquifer media is shown below (Figure 5).

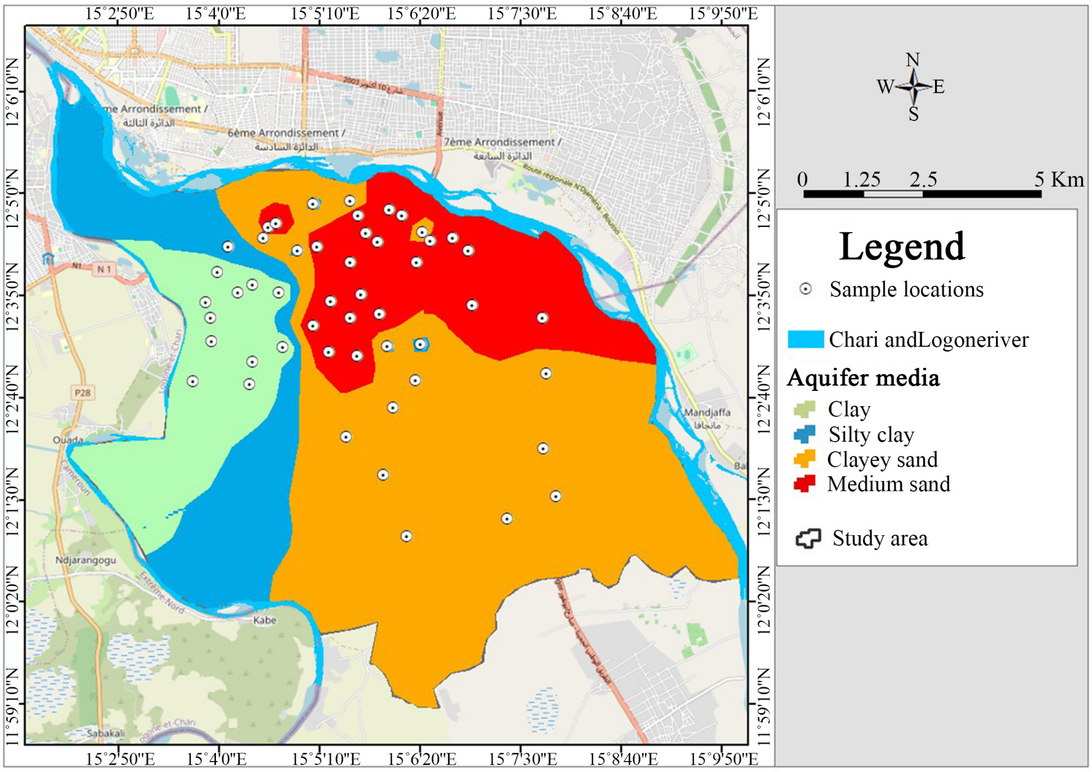

Figure 5. Aquifer media map.

3.4. Soil Media

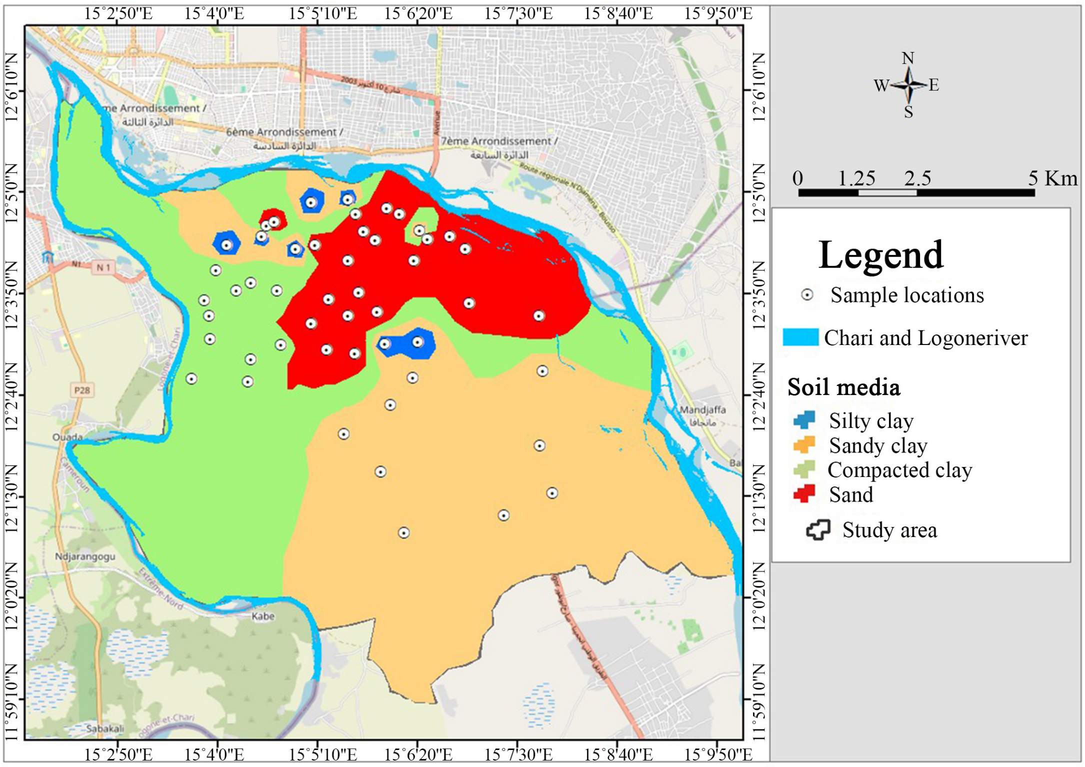

Figure 6. Soil media map.

Soil media is the uppermost portion of the vadose zone with active biological activities [48]. It plays a crucial role in the control of recharge processes and pollutant removal. In addition, through active biological processes, soil media have a predominant impact on the bioremediation of pollutants [70]. The soil media map of the study area (**Figure 6**) was obtained by digitizing an existing soil texture map obtained from CNRD-Chad (Centre national de recherche et developpement). Four soil textures were identified in the study area: silty clay, sandy clay, compacted clay, and sand. According to Aller *et al.* (1987) [38], each soil media type has been ranked according to its weightage (**Table 1**). In the southeastern side (Toukra), sandy clay is found, and in the southwestern catchment (Digangali), compacted clay soil is found. In particular, the presence of compacted clay in the southwestern side (Digangali) may contribute to decreasing soil permeability and hence limit contaminant migration.

3.5. Topography

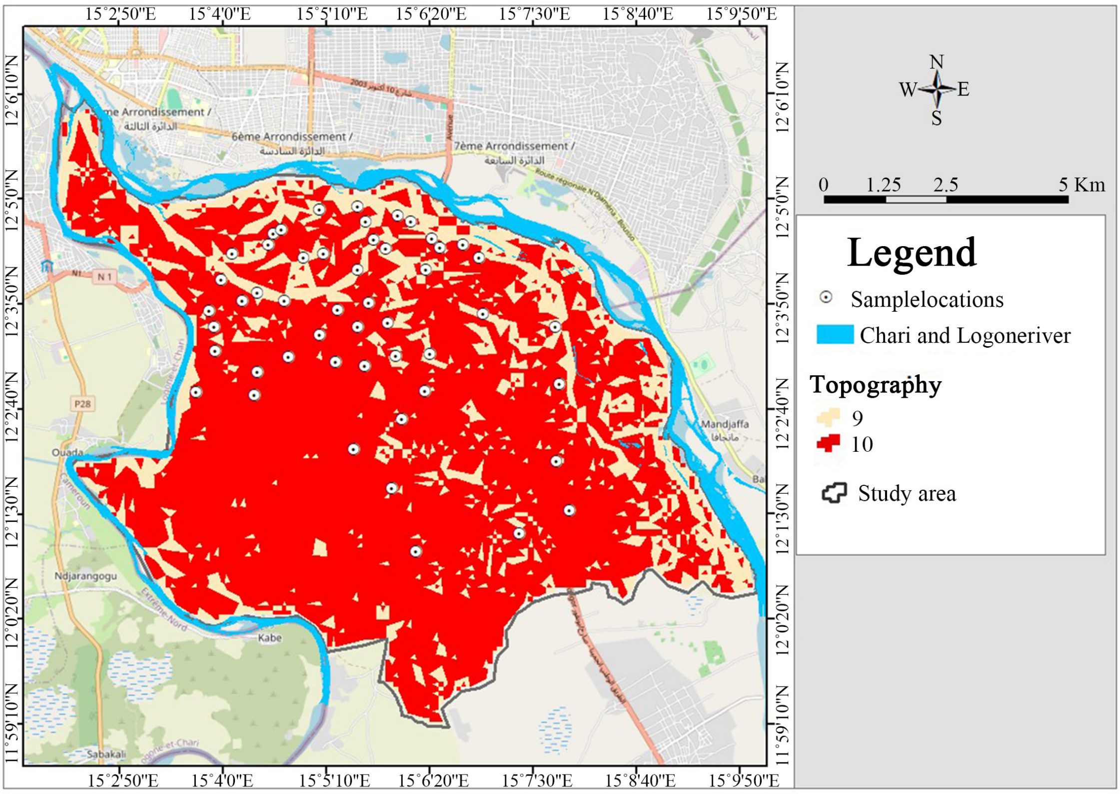

Figure 7. Topography map.

Topography refers to the slope of the study area. This parameter of the DRASTIC model greatly impacts the velocity of surface runoff and hence the rate of contaminant infiltration [38]. Where slopes are high, there is significant runoff, and the potential for contaminants to seep downward is lower. Conversely, where slopes are low, runoff capacity is high, and the potential for pollution of groundwater is greater. A topographic map of the study area (**Figure 7**) was obtained from the digital elevation model (DEM) and converted into a slope using the 3D Analyst tool of ArcGIS 10.8.1. The slope of the study area ranges from 0 to 6%, and has been categorized into 2 categories (0 - 2 and 2 - 6 percent). Each slope category has been ranked according to its weight, in agreement with Aller *et al.* (1987) [38]. The slope map obtained suggests that the study area is flat, particularly in the 0% - 2% slope category, allowing pollutants to percolate easily into the aquifer. These results lead to the conclusion that the aquifer presents a high vulnerability to pollution, given the slope map obtained.

3.6. Impact of the Vadose Zone

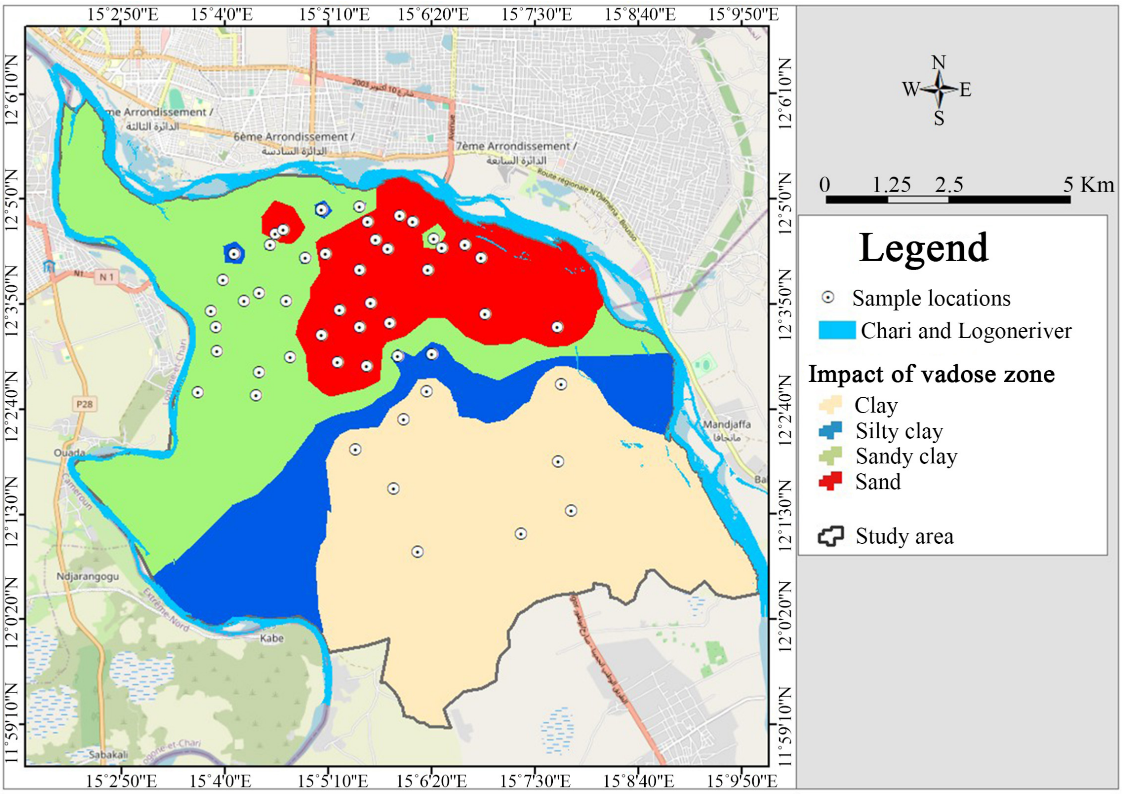

Figure 8. Vadose zone map.

The vadose zone, also called the unsaturated zone, is the undersaturated zone above the water table. The unsaturated zone controls the amount of contaminant-rich water percolating down [71]. Many hydrogeochemical processes, such as mechanical filtration, biodegradation, dispersion, and volatilization, take place in this zone, and they are responsible for pollutant attenuation [38]. Hence, the vadose zone acts as a protection zone for the groundwater depending on the lithological characteristics of the unsaturated zone. The data of the variable I (vadose zone) were retrieved from the well log provided by STE (**Table 2**) using similar techniques that were adopted for the aquifer media. Based on these data, the vadose zone of the study area is comprised of sandy clay, clay, sand, and silty clay. A high total weight of 40 has been assigned to the sand covering the northeastern part of the study area, with a high risk of contamination. Conversely, a low total weight of 10 is attributed to the clay covering the southeastern part of the catchment studied, which is characterized by lower vulnerability to contamination. The final map representing vadose zone media is shown below (**Figure 8**).

3.7. Hydraulic Conductivity

Hydraulic conductivity refers to the flow rate of groundwater into the saturation zone of an aquifer. It is an important parameter that influences the amount of contaminants moving downward in the groundwater system. High values of hydraulic conductivity are associated with a high risk of contamination [72]. A hydraulic conductivity map (**Figure 9**) of the study area was created using pumping test data obtained from STE (**Table 2**). The mean value of hydraulic conductivity obtained in the study area is 54.17 m/day. The total weight associated with this hydraulic conductivity value is 24 and has been assigned to the study area. We considered an average value due to the lack of sufficient data on pumping tests in the study area. Similarly, an average conductivity (a single value) was considered across the study area by Abderamane *et al.* (2017) [56] for this parameter of the DRASTIC model. It should be noted that hydraulic conductivity is influenced by several factors, such as particle size distribution, porosity, soil anisotropy, etc. However, estimating hydraulic conductivity accurately is challenging, and it is considered a limitation of the DRASTIC approach.

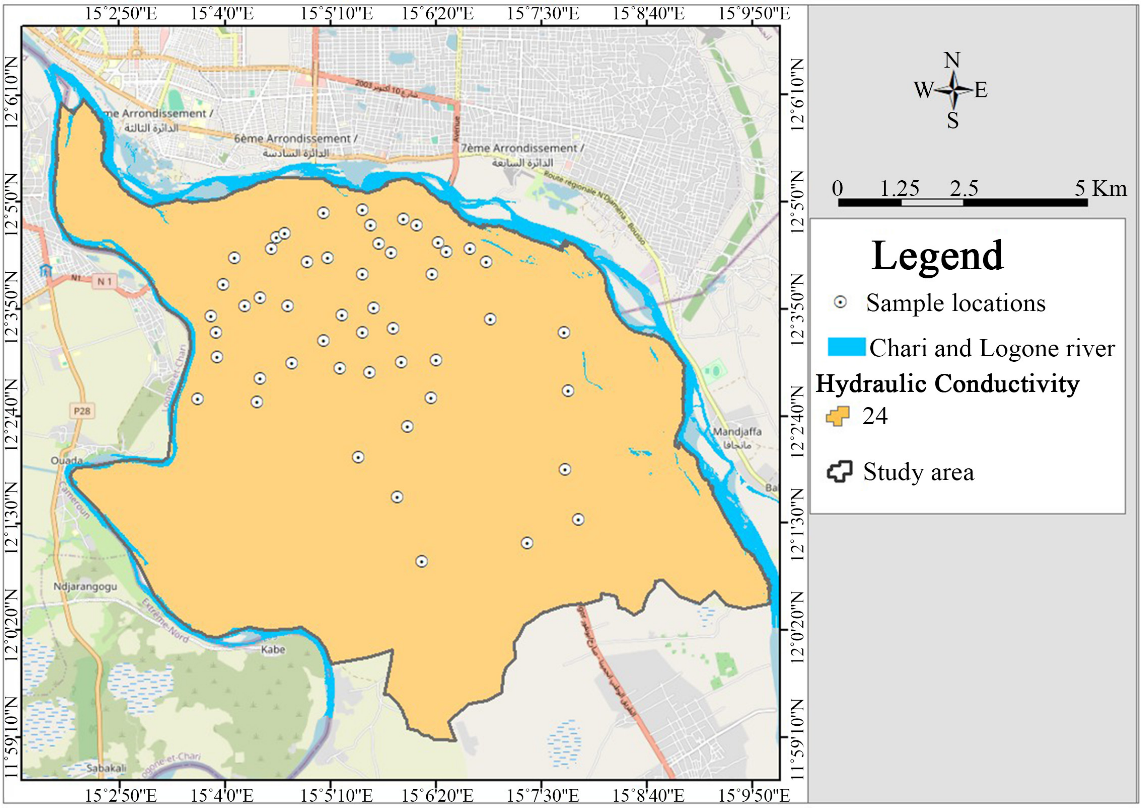

Figure 9. Hydraulic conductivity map.

3.8. DRASTIC Index

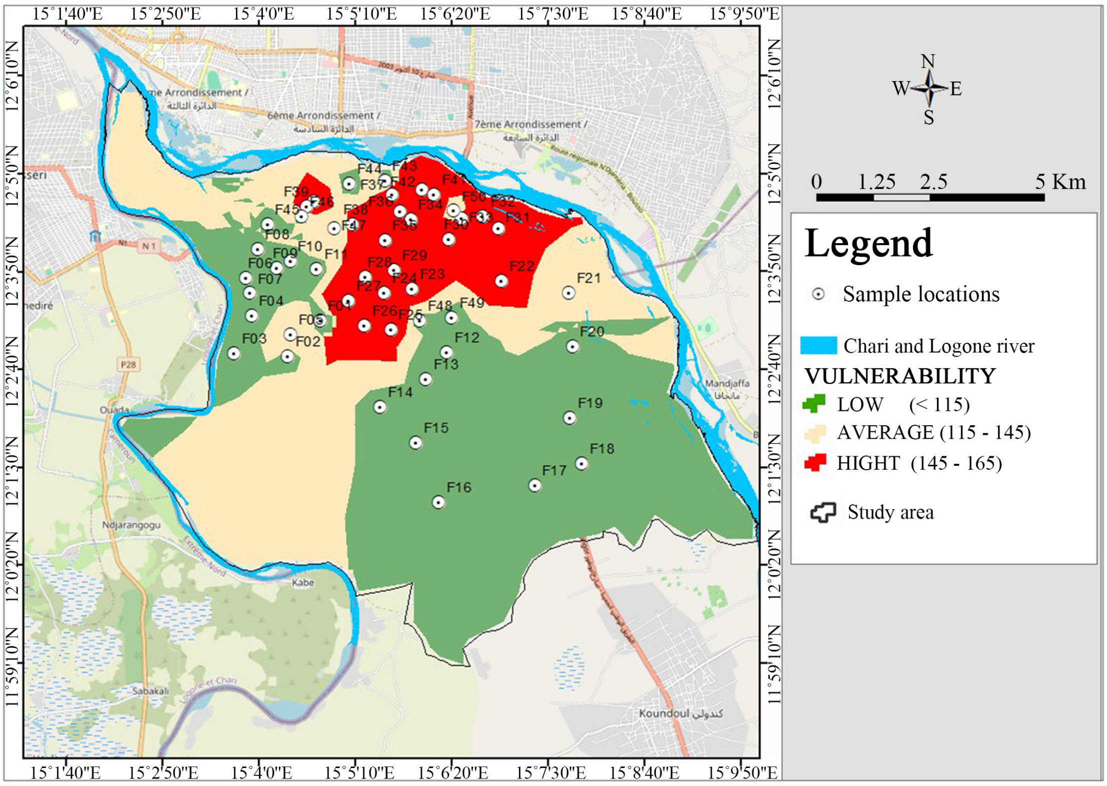

Figure 10. Groundwater vulnerability map of the 9th district of N'Djamena.

The groundwater vulnerability map of the 9th district of N'Djamena (**Figure 10**) was calculated according to the formula of the Drastic Index with overlay analysis of 7 thematic layers. Note that each thematic layer corresponds to one of the parameters of the DRASTIC method. In the study area, the Drastic Index ranges from 115 to 165, where 3 classes of vulnerability are identified according to the classification of Aller *et al.* (1987) [38]. A low vulnerability class is assigned for DI values less than 115, an average vulnerability class is assigned for DI values between 115 and 145, and a high vulnerability class is assigned for DI values between 145 and 165. In **Table 3**, the area covered by each class of vulnerability is specified. The northeastern portion of the basin shows high vulnerability to contamination. This part covers 15% of the study area (**Table 3**), and the areas concerned are: Toukra, Kabe, and Walia. According to the field data obtained, the soil type of Toukra, Kabe, and Walia is sand (**Figure 6**), and the aquifer depth in these areas is also shallow (1.5 - 9 m). In addition, Toukra, Kabe, and Walia are situated in areas with gentle slopes (0% - 6%). These combined hydrogeological factors considerably increase the degree of vulnerability of these areas, in this case, Toukra, Kabe, and Walia. Similar studies conducted by Saidi *et al.* (2011) [73], [48] Bera *et al.* (2021), and Elmeknassi *et al.* (2021) [3] noted that the shallow depth of the aquifer is a parameter that increases groundwater vulnerability. On the contrary, the southern and western sides of the basin have shown low groundwater vulnerability covering 51% of the study area (**Table 3**). In these areas, Digangali and Gueli are located. From the field data obtained, these areas are characterized by compacted clay soil type, and groundwater depth is also deep (9 - 15 m). These hydrogeological factors lead to a low degree of vulnerability, in particular due to the nature of groundwater depth. Bera *et al.* (2021) [48] demonstrated that infiltration of contaminants through the vadose zone takes a longer time to reach the groundwater table in the case of high groundwater depth. However, in the southwestern, middle, and north-western parts of the study area, where Gardole-Djedid and Ngoumna are located, low to moderate groundwater vulnerability was observed.

It should be emphasized that the DRASTIC model has many limitations in terms of accuracy, such as the assignment of weights and ratings, because that is subjective and based on the Delphi technique [74]. Mathematical procedures such as multi-criteria decision analysis (MCDA) techniques could give realistic results, as they were applied by Sharma *et al.* (2022) [74].

Table 3. Classification of the drastic index according to groundwater vulnerability zone areas.

Groundwater vulnerability class	Drastic index classes	Area (sq.km)	Area (%)	Well locations
Low	<115	47.66	51	Digangali, Gueli
Average	115 - 145	31.52	34	Gardole-Djedid, Ngoumna
High	145 - 165	13.58	15	Toukra, Walia, Kabe

3.9. DRASTIC Index Validation

The accuracy of the Drastic approach used for generating the groundwater vulnerability map (**Figure 10**) has been validated using the nitrate parameter. Gogu and Dassargues (2000) [75] indicate that contaminant datasets obtained on-site from wells throughout the study area could be used to validate the vulnerability map. Nitrate, as a common pollutant that is introduced into groundwater mainly through fertilizer application, was selected as a validation parameter for the groundwater vulnerability map by some studies [3] [48]. The spatial distribution of nitrate concentrations in groundwater is shown in **Figure 11**. Nitrate was collected from 50 locations within the basin area. Results of sample analysis indicated nitrate concentration values ranging from 0 to 36 ppm in the study area. Naturally, nitrate concentration in groundwater is very low; if an increasing trend is observed, there is contamination from wastewater and nitrogen fertilizers [76]. It can be seen from the spatial distribution of the concentration of nitrate in the center and northeastern parts of the study sites, namely Kabe, Walia, and Toukra, that they show relatively high concentrations of nitrate ranging from 12 to 36 ppm. These sites (Kabe, Walia, and Toukra) possess a high groundwater vulnerability scale (**Figure 11**). Kabe, Walia, and Toukra are known as irrigated areas where agriculture is regularly practiced using the waters of the Chari River. In this case, the agricultural contaminants mix with the recharge water and further contaminate the groundwater over time [48]. The northwestern and southeastern parts of the study area have shown low concentrations of nitrate ranging from 0 to 4 ppm. These parts of the catchment studied, which cover Digangali and Gueli, show lower groundwater vulnerability. A higher concentration of nitrates in areas of high vulnerability and, in the same way, a lower concentration of nitrates in areas of low vulnerability allows the validation of the vulnerability map obtained [48].

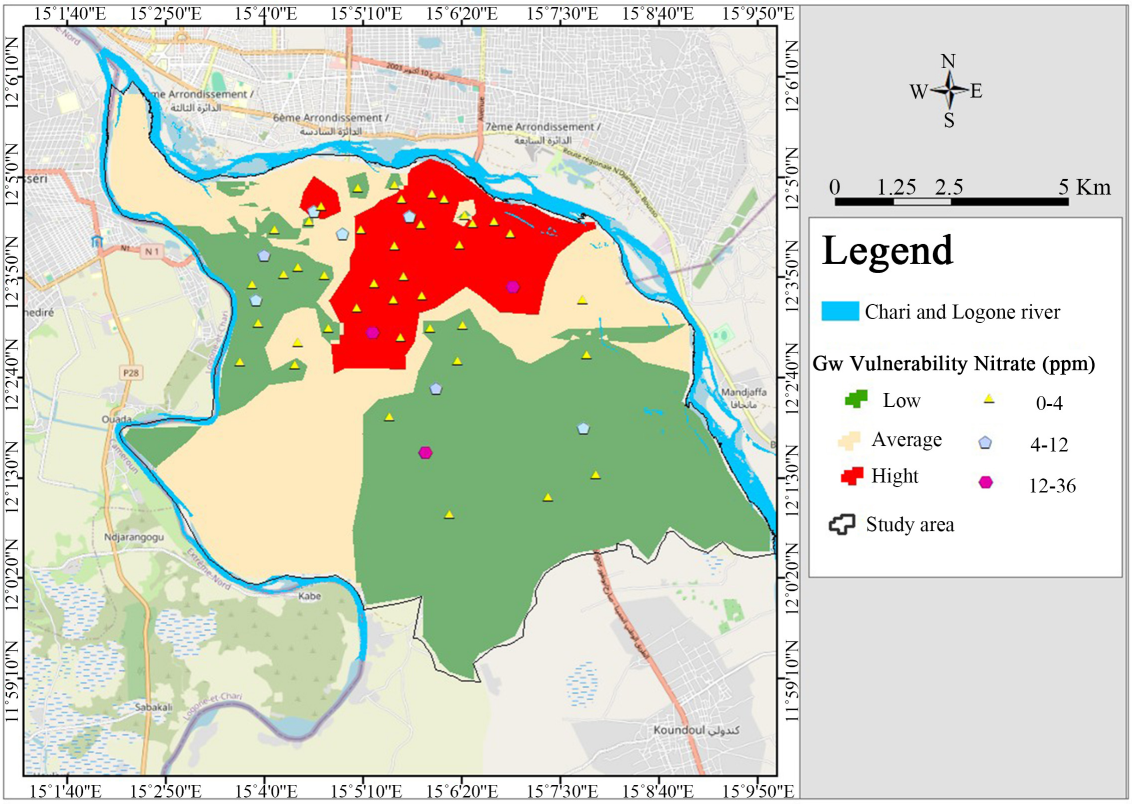

Figure 11. Spatial distribution of the Drastic index with nitrate concentrations.

The relationship between groundwater vulnerability (DRASTIC index) and nitrate concentrations is evaluated using the Pearson Correlation Coefficient (*r*). The Pearson Correlation Coefficient (*r*) is calculated using the following formula:

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

where r = Pearson coefficient, n represents the number of pairs, and x and y are the two variables.

We aggregated the maximum concentration of nitrate for each vulnerability class and compared it with the corresponding Drastic index. It has been observed from the correlation analysis (**Figure 12**) that the r value between groundwater vulnerability (Drastic index) and the maximum concentration of nitrate is r = 0.76. A positive Pearson's correlation coefficient value and a significantly higher nitrate concentration in the high vulnerability areas also validate the groundwater vulnerability map [3].

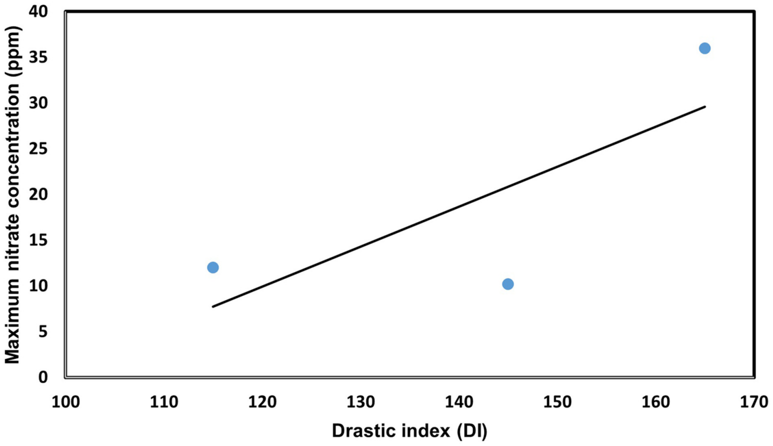

Figure 12. Relationship between the DRASTIC index and maximum nitrate concentrations.

4. Conclusion

Groundwater quality is a worldwide issue. For its protection and restoration, it is essential to measure groundwater contamination in any area that could be potentially impacted. In this study, the groundwater vulnerability of the 9th district of N'Djamena has been assessed through the GIS-based DRASTIC model, and 7 hydrogeological parameters have been considered. The results of the study showed that the DRASTIC vulnerability index (DI) value varies from 115 to 165, and the catchment area studied can be classified into three vulnerability classes (low, average, and high). The highly vulnerable class covers 15% of the study area. The average and low vulnerability classes cover about 34% and 51% of the study area, respectively. When validating the groundwater vulnerability map derived from a 7-hydrogeological parameter map, it is observed that a higher concentration of nitrates coincides well with areas of high vulnerability, and in the same way, a lower concentration of nitrates coincides with areas of low vulnerability. The conclusion of this result leads to validation of the GIS-based DRASTIC model. In addition, the Pearson correlation coefficient between groundwater vulnerability (DRASTIC index) and nitrate concentrations showed a strong positive correlation, where the r value is 0.76. The northeastern portion of the 9th district of N'Djamena showed high vulnerability to contamination. Here, the groundwater depth is shallow, and the soil is of a sandy type. The major land use of the northeastern part of the catchment studied (Toukra, Walia, and Kabe) is agricultural land, and agriculture is regularly practiced using the waters of the Chari River. Therefore, protecting an aquifer from contamination is both a very important and difficult task. Based on the vulnerability assessment outcomes for groundwater of the 9th district of N'Djamena, it is evident that the Toukra, Walia, and Kabe areas are in high-vulnerability zones. Therefore, it is recommended to take effective, actionable measures to control groundwater pollution and implement agricultural best management practices for the Toukra, Walia, and Kabe areas. The groundwater vulnerability map obtained in this study can be widely used for environmental management and land use planning in order to achieve the sustainable development goal in the study area.

Author Contribution

Tidjani Bahar: Conceptualization, Investigation, Resources, Supervision, Methodology, Writing—original draft and editing; Ousmane Mahamat: Conceptualization, Investigation, Resources, Methodology and editing; Djimadjimbaye Eraste: Conceptualization, Fieldwork, Investigation, Mapping.

Conflicts of Interest

The authors declare that they have no competing interests.

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