ISSN: 2639-7455

Research Article

Earth & Environmental Science Research & Reviews

Application of Remote Sensing, Gis, and the Sintacs Method for the Assessment of Groundwater Vulnerability and Quality in the Mefou Watershed (Cameroon)

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Submitted: 2026, Jun 05; **Accepted:** 2026, Jun 30; **Published:** 2026, Jul 06

Citation: Juscar, N., Adama, A., Pascaline, M. N., Elvis, K. (2026). Application of Remote Sensing, Gis, and the Sintacs Method for the Assessment of Groundwater Vulnerability and Quality in the Mefou Watershed (Cameroon). *Earth & Envi Scie Res & Rev, 9*(2), 01-12.

Abstract

Groundwater constitutes the primary source of domestic and agricultural water supply in the Mefou watershed, Centre Region, Cameroon. Rapid urban expansion, agricultural intensification, and inadequate sanitation infrastructure increasingly threaten its sustainability. This study integrates the SINTACS parametric model, Remote Sensing (RS), and Geographic Information Systems (GIS) to assess intrinsic and specific groundwater vulnerability, coupled with physicochemical and bacteriological quality analyses. Seven hydrogeological parameters (Depth to water, Effective infiltration, Vadose zone, Soil texture, Aquifer characteristics, Hydraulic conductivity, and Slope) were spatially analyzed and weighted under the SINTACS framework. Land use derived from Sentinel-2 imagery was incorporated to evaluate specific vulnerability to nitrates (NO_3^-) and Escherichia coli. Results indicate that 58% of the watershed exhibits moderate vulnerability, 27% high vulnerability, and 8% very high vulnerability, primarily associated with shallow groundwater depths (<5 m), permeable lateritic soils, and fractured crystalline formations. Water quality analysis reveals nitrate concentrations exceeding WHO guidelines in 32% of sampled points and widespread bacteriological contamination in shallow wells. The Groundwater Quality Index (GWQI) classified 46% of samples as poor to very poor. The integration of SINTACS with RS–GIS proved effective for identifying priority protection zones. Immediate management measures are recommended in high-vulnerability urban–agricultural interfaces.

Keywords: Groundwater Vulnerability, Sintacs, Gis, Remote Sensing, Water Quality, Mefou Watershed, Cameroon

1. Introduction

Groundwater is a critical component of global water security, providing nearly half of the world's drinking water and supporting a large share of irrigated agriculture [1,2]. Its relative resilience to climatic variability makes it essential in regions facing water stress. However, increasing anthropogenic pressures such as urbanization, agricultural intensification, and inadequate sanitation have significantly degraded groundwater quality worldwide [3-5]. Nitrate pollution and pathogenic contamination are particularly widespread, posing serious health and environmental risks [6,7].

In Sub-Saharan Africa, groundwater is the main source of potable water due to limited surface water infrastructure [8]. However, it remains poorly monitored and increasingly exposed to contamination from agriculture, sanitation systems, and uncontrolled urban growth [9]. These challenges are evident in Cameroon, particularly in the rapidly urbanizing region of Yaoundé, where reliance on shallow wells and boreholes is growing [10,11]. The Mefou watershed, characterized by fractured crystalline basement rocks and shallow aquifers, is highly vulnerable to pollution due to rapid infiltration and limited natural filtration [12].

Although several methods exist for groundwater vulnerability assessment, including DRASTIC and SINTACS models, many studies focus only on intrinsic vulnerability and neglect specific contamination risks [13,14]. Advances in Remote Sensing and GIS have improved spatial analysis capabilities, yet integrated approaches combining modeling with field-based water quality validation remain limited in tropical African contexts [15].

This study addresses these gaps by integrating the SINTACS model, RS–GIS techniques, and water quality analysis to assess both intrinsic and specific groundwater vulnerability in the Mefou watershed. It provides a comprehensive framework linking hydrogeological conditions, land-use dynamics, and contamination patterns for improved groundwater management.

2. Material and Methods

2.1. Study Area

The study was conducted in the Mefou watershed, located in the Centre Region of Cameroon, within the peri-urban zone of Yaoundé. The watershed extends approximately between latitudes 3°57′–4°27′ N and longitudes 11°27′–11°45′ E, covering an estimated surface area of about 1,200 km² (figure 1).

The region experiences a humid equatorial climate characterized by a bimodal rainfall regime, with annual precipitation ranging from 1,500 to 1,700 mm and mean temperatures between 22°C and 25°C. The drainage network is dominated by the Mefou River and its tributaries.

Geologically, the area is underlain by Precambrian crystalline basement formations (gneisses, granites, and schists), overlain by a weathered mantle and lateritic soils. Groundwater occurs mainly within the weathered regolith and fractured bedrock, forming discontinuous aquifers with variable transmissivity. The shallow depth to groundwater (2–20 m) and high permeability of surface formations increase aquifer susceptibility to contamination.

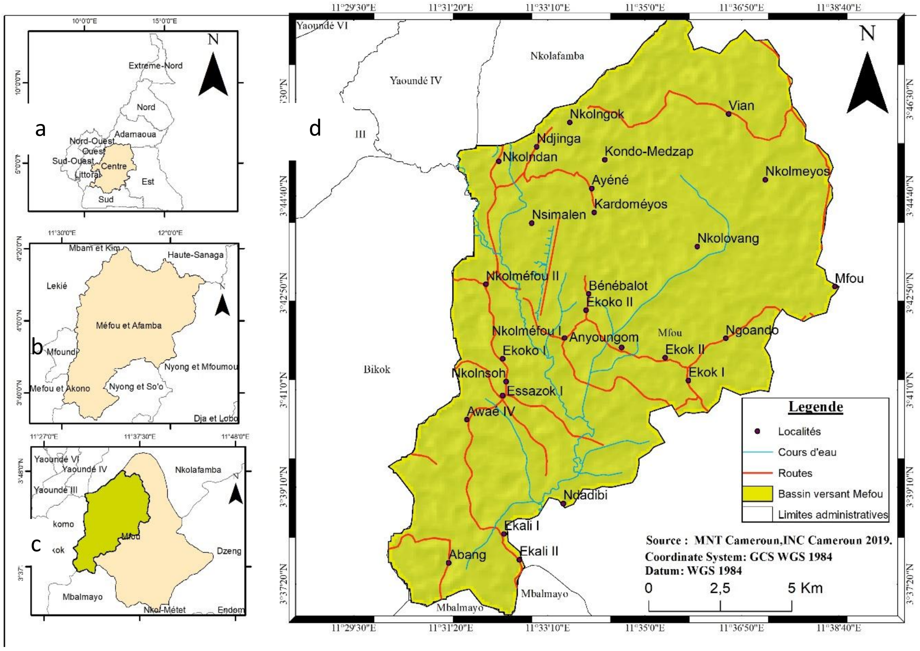

Figure 1: Location of the Mefou Watershed

a- Centre Region of Cameroon, b- Position of the Mefou and Afamba Department within the Centre Region, c- Position of the Mfou watershed within the Mfou Municipality, d- Study area.

2.2. Data Collection

A total of 50 groundwater sampling points (wells and boreholes) were selected using a stratified spatial sampling approach to ensure representative coverage of the watershed. Field campaigns were conducted during both dry and wet seasons to capture seasonal variability.

At each site, geographic coordinates were recorded using a handheld GPS (±3 m accuracy), and static water levels were measured using an electronic water level meter. Groundwater samples were collected following standard sampling protocols to minimize contamination and preserve sample integrity.

Physicochemical samples were stored at 4°C and transported to the laboratory within 24 hours, while bacteriological samples were collected in sterile containers and analyzed within 6 hours.

Supplementary datasets included a 30 m resolution Digital Elevation Model (DEM), geological and soil maps, meteorological data, and Sentinel-2 satellite imagery. High precipitation enhances aquifer recharge but also promotes pollutant leaching.

2.3. SINTACS Model Application

The intrinsic groundwater vulnerability was assessed using the SINTACS parametric model, which integrates seven hydrogeological parameters: depth to groundwater (S), effective infiltration (I), vadose zone characteristics (N), soil texture (T), aquifer media (A), hydraulic conductivity (C), and slope (S).

Each parameter was classified into rating classes ranging from 1 (low vulnerability) to 10 (high vulnerability), based on established SINTACS guidelines. Weights were assigned according to the "anthropogenic pressure (agricultural–urban)" scenario, reflecting the dominant land-use conditions in the study area.

The SINTACS index was computed as:

SINTACS=∑(Ri×Wi)SINTACS = ∑(Ri \tx Wi) SINTACS=∑(Ri×Wi)

where RiR_iRi represents the rating and WiW_iWi the weight of parameter *i*.

All parameters were converted into raster format and processed within a GIS environment. A weighted overlay analysis was performed to generate the final vulnerability map, which was classified into four categories: low, moderate, high, and very high vulnerability.

2.4. Remote Sensing Processing

Sentinel-2 multispectral imagery (10 m spatial resolution) was used to derive land-use/land-cover (LULC) information. Preprocessing steps included atmospheric correction (Sen2Cor), geometric correction, and subsetting to the study area.

Supervised classification was performed using the Maximum Likelihood algorithm to identify major land-use classes: urban areas, agricultural land, forest/vegetation, and wetlands.
Classification accuracy was evaluated using ground control points and confusion matrix analysis, with overall accuracy exceeding 85% and a Kappa coefficient above 0.80, indicating strong classification reliability.

The resulting LULC map was incorporated into the analysis to assess specific vulnerability to anthropogenic contamination

2.5. Water Quality Analysis

Physicochemical parameters analyzed included pH, electrical conductivity (EC), total dissolved solids (TDS), nitrate (NO_3^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), and turbidity. Analyses were conducted in accordance with standard methods (APHA, 2017).

Bacteriological analyses focused on total coliforms, fecal coliforms, and Escherichia coli, using the membrane filtration technique. Results were expressed as colony-forming units per 100 mL (CFU/100 mL).
Measured values were compared against guideline limits established by the World Health Organization for drinking water quality

2.6. Statistical Analysis

Statistical analyses were conducted using SPSS (version XX) and Microsoft Excel. Descriptive statistics (mean, median, standard deviation, and range) were computed to characterize groundwater quality parameters.

Pearson and Spearman correlation analyses were used to examine relationships between hydrochemical variables and vulnerability indices. Principal Component Analysis (PCA) was applied to identify dominant processes controlling groundwater chemistry.
The non-parametric Kruskal–Wallis test was used to assess seasonal variations, with statistical significance set at $p < 0.05$.
GWQI=∑(Wi×Qi)

where QiQ_iQi is the quality rating of parameter i, and WiW_iWi is its relative weight based on its significance to human health.

Quality ratings were derived by comparing measured concentrations with WHO guideline values. The GWQI was classified into five categories (table 1).

GWQI Range	Water Quality Classification
<50	Excellent
50–100	Good
100–200	Poor
200–300	Very Poor
>300	Unsuitable for drinking

Table 1: GWQI Classified Into Five Categories

Spatial distribution of GWQI was mapped using the Inverse Distance Weighting (IDW) interpolation method within a GIS environment.

2.7. Geology and Hydrogeology

The Mefou watershed (figure 2) lies within the northwestern margin of the Congo Craton in Cameroon and is dominated by Precambrian crystalline basement rocks, including gneisses, granites, migmatites, and schists [12,16]. These formations are overlain by a variable weathered mantle composed of lateritic soils and saprolite, with thickness ranging from a few meters to over 30 m depending on lithology and topography [11]. Structural features such as fractures, joints, and faults play a crucial role in controlling groundwater occurrence by enhancing secondary porosity and permeability (Wright, 1992; Edet & Okereke, 2005).

Hydrogeologically (figure 2), the area exhibits a typical two-layer aquifer system of tropical basement terrains: a shallow unconfined aquifer within the weathered regolith and a deeper fractured bedrock aquifer [8]. Groundwater recharge occurs mainly through direct rainfall infiltration, facilitated by permeable soils and gentle slopes. The depth to groundwater generally ranges from 2 to 20 m, with significant seasonal fluctuations linked to rainfall variability [10]. Hydraulic conductivity varies between 10^{-6} and 10^{-4} m/s, depending on the degree of weathering and fracture density [12].

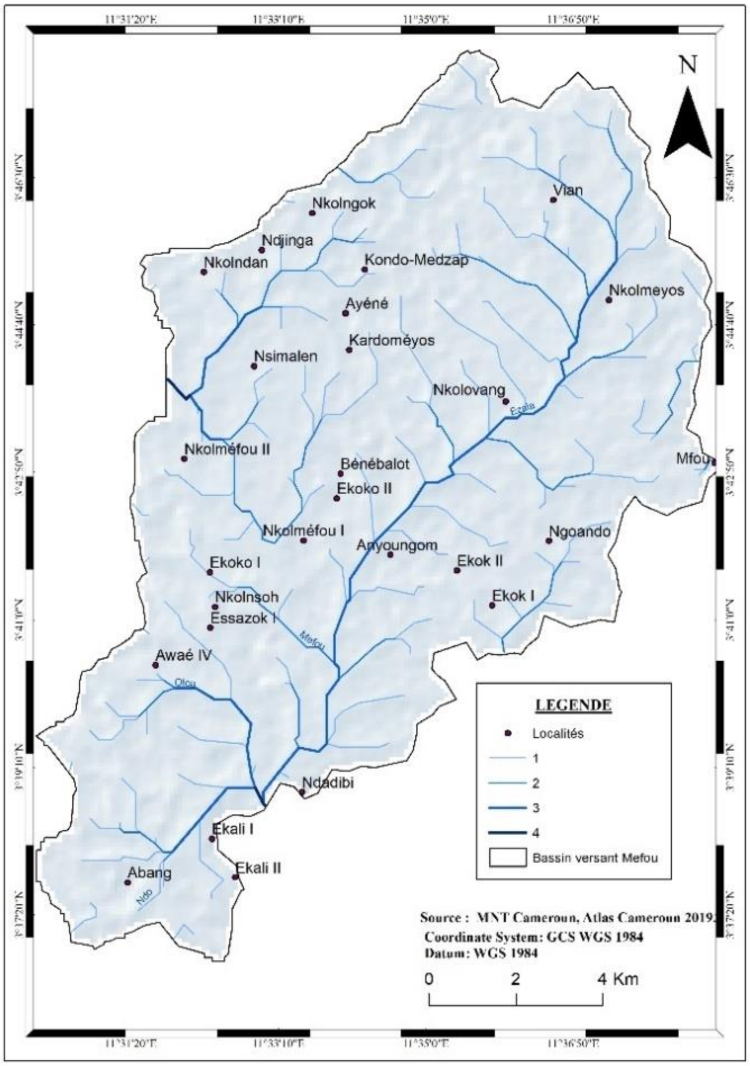

Figure 2: Hydrographic Network of the Mefou Watershed

2.7. Land Use

The study of the Mefou watershed (Mfou, Cameroon) characterizes land use through five primary classes: agricultural zones, urban/built-up areas, forests, bare soils, and water bodies. Agriculture is the dominant land use, driven by the cultivation of food crops like plantain and cassava by approximately 75% of the population. Rapid, unplanned urbanization—growing at 3.5% annually—is concentrated in areas such as Ekok and Nkolmeyos, where the proximity of latrines to shallow water tables poses significant contamination risks.

In the SINTACS vulnerability model, land use is weighted as a critical anthropogenic factor. High-vulnerability indices are assigned to urban and agricultural sectors (scoring 6–8) due to the potential for nitrate and bacterial infiltration (E. coli), whereas forested areas provide protective cover (scoring 1). Consequently, moderate-to-high vulnerability characterizes 75% of the basin, primarily where human activity has replaced natural vegetation.

3. Materials and Methods

3.1 Data Collection

The data used in this study is categorized into three main types:

Cartographic and Satellite Data: Includes Sentinel-2 imagery (2024) for land use mapping and SRTM (Shuttle Radar Topography Mission) DEM data with 30m resolution for extracting topographic parameters like slope.

Hydrogeological Data: Technical data from 55 water points (boreholes and wells) collected from the Ministry of Water and Energy (MINEE) and field inventories. This includes static levels, total depth, and lithological logs.

Hydrochemical Data: Results from physico-chemical analyses of 14 specific water samples. Parameters measured include pH, electrical conductivity, TDS, and concentrations of major ions (Ca{2+Mg{2+}ClNO).

3.2. SINTACS Model

The SINTACS method is used to assess intrinsic vulnerability. It evaluates seven environmental parameters: (i) S (Soggiacenza): Depth to groundwater, (ii) I (Infiltrazione): Effective infiltration (recharge), (iii) N (Non saturo): Attenuation capacity of the unsaturated zone, (iv) T (Tipologia della copertura): Soil type, (v) A (Acquifero): Hydrogeological characteristics of the aquifer. (vi) C (Conducibilità): Hydraulic conductivity, (vii) S (Superficie): Topographic slope.

Each parameter is assigned a rating (P) and a weight (W), with the final index calculated as I = Σ(Pi x Wi).

3.3. Remote Sensing and GIS

Digital processing was conducted using ArcGIS 10.8 and ENVI 5.3. A supervised classification (Maximum Likelihood) was applied to Sentinel-2 bands to produce the land use map. The Inverse Distance Weighting (IDW) method was used within the GIS environment to create continuous surfaces from point data (e.g., depth to water, chemical concentrations).
The different thematic layers were intersected to produce the final vulnerability map.

3.4. Groundwater Quality Index (GWQI)

The GWQI was calculated to provide a single value expressing the overall water quality for human consumption. The process involved:

- Weight Assignment: Each chemical parameter was assigned a weight (w_i) based on its relative importance to health
- Relative Weight Calculation: Ensuring the sum of weights equals 1.
- Quality Rating ($q_i): Comparing the measured concentration against WHO standards [20].
- Sub-index Calculation:
- SIi = Wi x qi, where the final GWQI = ∑SIi.

4. Results

4.1. Intrinsic Vulnerability

The intrinsic vulnerability, determined using the SINTACS method, reveals three main classes of vulnerability across the basin.
Primarily located in the forested northern and eastern sections where the water table is deep and soil cover is thick. Moderate Vulnerability covers approximately 75% of the study area. This zone dominates the central part of the watershed, characterized by moderate slopes and average soil permeability and high Vulnerability concentrated in the southwestern part (near Mbalmayo) and urban centers like Mfou. This is due to shallow groundwater levels (less than 5m) and high effective infiltration rates (figure 3).

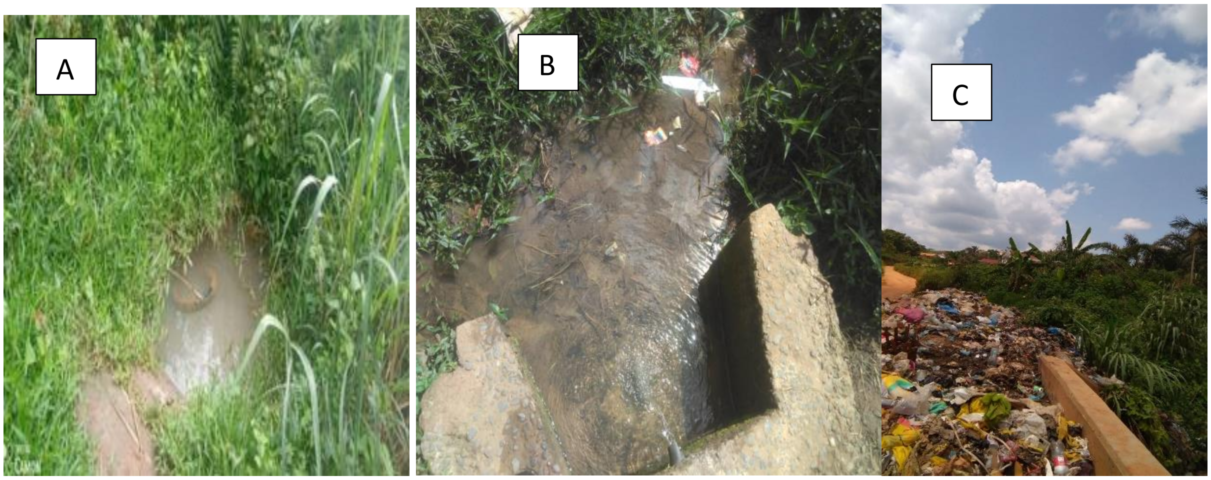

Figure 3: Anthropogenic Risk Factors and Water Point Vulnerability in the Mefou Watershed, 2024 Field Campaign

This figure illustrates the direct sources of contamination and structural deficiencies observed during the 2024 field campaigns in the Mfou commune.

Photo A show unprotected traditional well. The absence of a wellhead (curbing) and cover, which facilitates the direct entry of surface runoff, dust, and surface debris into the water table. Photo C, Illegal waste dump. The presence of open-air waste disposal sites in immediate proximity to water points promotes the leaching of pollutants (nitrates, phosphates) and the transport of pathogens toward the shallow aquifer. And photo B: Open-air water spring. This water source lacks a protection perimeter and is exposed to all forms of environmental and animal contamination, drastically increasing bacteriological risks for the local population.

These field observations corroborate (table 2) the high vulnerability indices obtained via the SINTACS method, confirming that the lack of physical protection at water points is a critical factor exacerbating groundwater quality degradation in the study area.

I (infiltration)	Interpolated precipitation	291–302 mm	4 à 7	4
N (unsaturated zone)	Logs de forage	Sandy clay	5–6	5
T (sol)	Soil map	Ferrallitic	5–6	3
A (aquifer)	Geological map	Fractured base	6–8	4
C (conductivity)	Borehole data (IDW)	1,7–42 m/j	5–8	5
S (slope)	MNT	0–25,75 %	6–10	2

Table 2: Summary of SINTACS des Parameters

The final vulnerability map, generated through the weighted overlay of the various factors of the SINTACS model, reveals that the majority of the Mefou watershed exhibits moderate vulnerability (approximately 75%), particularly in the areas of Mfou, Ekok, Nkolmeyos, and their surroundings. The low-vulnerability classes (approximately 10%) are primarily concentrated in the northwest of the basin, in urbanized and impervious areas such as Nkolondom or Nkolngok. Zones of high vulnerability (approximately 12%) and very high vulnerability (approximately 3%) are located in the far southwest, around Mbalmayo and Bikok, where the water table is shallow, soils are highly permeable, and vegetation cover is reduced, making these areas more susceptible to pollutant infiltration. This spatial distribution highlights the significance of geology, topography, and land use in controlling groundwater vulnerability. The final map is consistent with the SINTACS methodology and provides an accurate interpretation of the intrinsic vulnerability within the Mefou watershed (figure 4), table 3 indicate the syntax index.

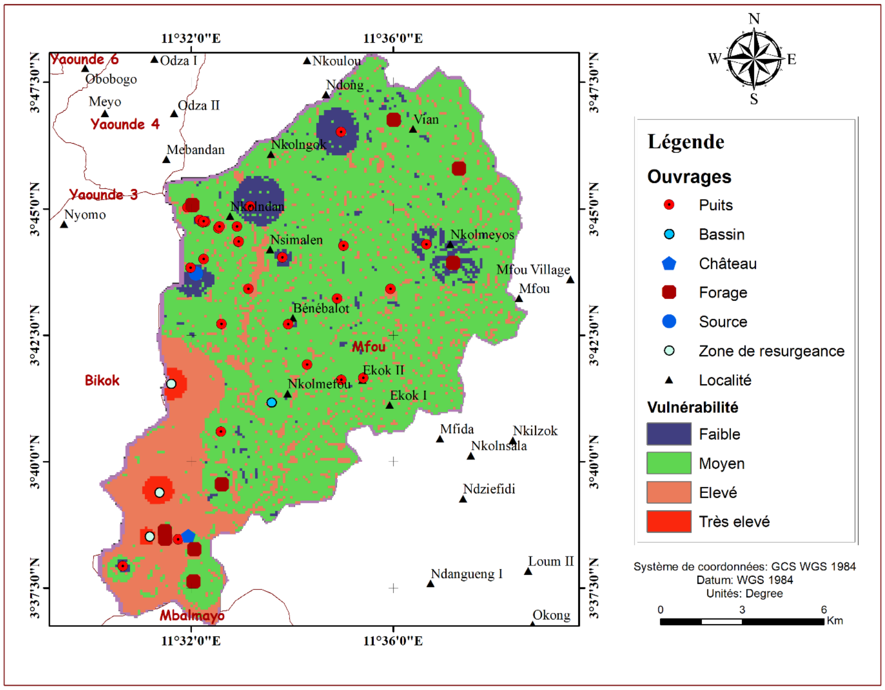

Figure 4: Spatial Distribution of SINTACS Index

Vulnerability Class	Area (%)
Low	7%
Moderate	58%
High	27%
Very High	8%

Table 3: The SINTACS Index Ranged from 104 to 214

High vulnerability zones correspond to: Shallow water table (<5 m), permeable sandy soils, fractured bedrock and agricultural plains

4.2. Specific Vulnerability to NO_3^- and E. coli

By overlaying land use data (anthropogenic pressure) onto the intrinsic vulnerability map:

- Nitrate (NO_3^-) Risk:
  Areas of intensive agriculture show high specific vulnerability. Infiltration of fertilizers is facilitated by the porous nature of the soil in cultivated zones.
- Bacteriological Risk (E. coli):
  High risk is mapped directly over densely populated areas (Mfou town). The lack of standardized sanitation systems and the proximity of latrines to wells significantly increase the specific risk of fecal contamination

4.3. Physicochemical Characteristics

The analysis of 14 water samples provided the following insights with analysis of pH, mineralization and major lons:

Most samples are acidic to slightly neutral (ranging from 4.7 to 6.8), which is typical for the crystalline basement of southern Cameroon. Generally low, with Electrical Conductivity (EC) values often below 400 µS/cm. The water is predominantly of the Calcium-Magnesium-Bicarbonate (Ca-Mg-HCO3) type. Nitrate levels in some urban wells exceeded 50 mg/L, indicating human-induced pollution.

4.4. Bacteriological Assessment

Microbiological tests revealed significant contamination in several water points:

- Total Coliforms present in nearly 80% of the wells sampled.
- Pathogens presence of Escherichia coli and Faecal Streptococci was confirmed in several samples located in Ekok and Mfou.
- Most shallow wells in urbanized areas do not meet WHO standards for drinking water without prior treatment.

4.5. Spatial Correlation Analysis

A spatial correlation was performed to validate the vulnerability maps:

- There is a strong positive correlation between high SINTACS indices and high concentrations of Nitrates and E. coli.
- It was observed that water points located in topographic lows (valleys) show higher levels of contamination due to the accumulation of runoff and shallower water tables.
- The spatial analysis confirms that the transition from forest to urban/agricultural land is the primary driver for the degradation of groundwater quality in the Mefou basin.

The classification varies spatially across the basin. "Good" quality water is more common in the less-disturbed forested northern regions, while "Poor" and "Very Poor" classifications are concentrated in the south-central sectors where human activity and shallow water tables intersect

4.6. Water Quality Assessment

Physico-chemical Results

While many chemical parameters meet international standards, several key indicators show non-conformity with World Health Organization (WHO) guidelines (table 4):

- pH Levels of water is slightly acidic, ranging from 4.85 to 6.27, which is below the recommended range of 6.5–8.5.
- Alcalinity measured values are between 2 and 14 mg/L, significantly lower than the recommended > 40 mg/L, making the water highly vulnerable to acidification.
- Nitrates (NO3): Concentrations range from 0.6 to 1.6 mg/L, well within the 50 mg/L WHO limit.
- Phosphates (PO4{3): Values range from 0.06 to 0.84 mg/L, with some sites exceeding the 0.5 mg/L indicative threshold.
- General Parameters: Conductivity (26–184 µS/cm) and Total Dissolved Solids (13–92 mg/L) are well within safe limits, indicating low mineral content.

Parameter	Observed Interval	WHO Standard	Compliance	Risks
pH	4.85 – 6.27	6.5 – 8.5	Non-compliant	Acidity, corrosion, heavy metals
Conductivity	26 – 184 µS/cm	< 2500 µS/cm	Compliant	Soft water, low mineralization
TDS	13 – 92 mg/L	< 1000 mg/L	Compliant	Chemically unstable water
NO_3^-	0.6 – 1.6 mg/L	< 50 mg/L	Compliant	N/A (No immediate risk)
NH_4^+	0.04 – 0.30 mg/L	< 0.5 mg/L	Limit reached	Recent organic contamination
NO_2^-	0.00 – 0.02 mg/L	< 0.1 mg/L	Compliant	Infant toxicity, recent pollution
PO_4^{3-}	0.06 – 0.84 mg/L	< 0.5 mg/L*	Locally high	Eutrophication, bacterial proliferation
Alkalinity	2 – 14 mg/L	> 40 mg/L (recommended)	Low	Water vulnerable to pH variations

Table 4: Summary of Physico-Chemical Parameter Compliance

The most significant chemical non-compliance is the acidic pH, which is naturally occurring due to the crystalline basement (granite/gneiss) and the decomposition of organic matter. This acidity can promote the corrosion of metallic pipes and the leaching of heavy metals. The low conductivity and TDS values indicate "young" water with a short underground residence time, characteristic of shallow aquifers in the South Cameroon region. While Nitrates are currently well below the toxicity threshold, the elevated Phosphates in certain locations (above 0.5 mg/L) suggest the beginning of impact from agricultural activities and household detergents.

Chemically, the water is generally of good quality for most parameters. However, the Global Water Quality Index (GWQI) is primarily degraded by acidic pH and, more critically, by high bacteriological loads (fecal contamination) not shown in this chemical table in table 3.

4.7. Bacteriological Results

Bacteriological analysis shows a quasi-general non-conformity with health standards, posing a major sanitary risk (table 5):

- Significant levels of Escherichia coli, fecal coliforms, streptococci, Salmonella, and Vibrio cholerae were detected.
- Concentrations often reach several thousand Colony Forming Units (UFC/100 mL), indicating active fecal pollution.

Parameter	Observed Concentration	WHO Standard	Interpretation
Escherichia coli	1650 – 1750 CFU/100 mL	0 CFU/100 mL	Non-compliant. Recent fecal contamination, high health risk.
Fecal coliforms	7701 – 8250 CFU/100 mL	0 CFU/100 mL	Non-compliant. Severe fecal pollution.
Total coliforms	40140 – 47650 CFU/100 mL	0 CFU/100 mL	Non-compliant. Chronic organic pollution.
Staphylococcus aureus	~87000 CFU/100 mL	Not specified	Very high. Contamination through direct human contact.
Salmonella typhi	~330 CFU/100 mL	Must be absent	Present. Risk of typhoid fever.
Vibrio cholerae	78 – 92 CFU/100 mL	Must be absent	Alarming presence. Risk of waterborne epidemic.
Fecal streptococci	74 – 78 CFU/100 mL	0 CFU/100 mL	Non-compliant. Human or animal fecal pollution.
TAMB (BHAM)	~285000 CFU/mL	Not specified	Very high. Significant overall bacterial load.

Table 5: Summary of Bacteriological Parameter Compliance

Nearly 80% of the sampled water points (primarily shallow wells) fail to meet drinking water standards. The systematic presence of E. coli and Fecal Streptococci is an indisputable indicator of recent fecal pollution. The detection of Vibrio cholerae and Salmonella in urbanized sectors such as Ekok and Mfou poses an immediate risk of waterborne disease outbreaks (cholera, typhoid fever) for the local population. This critical level of contamination is directly linked to the high density of unlined pit latrines located uphill or in close proximity to shallow, poorly protected wells.

The bacteriological results strongly correlate with the "High" and "Very High" vulnerability classes identified by the SINTACS model, confirming that the aquifer lacks sufficient natural filtration to attenuate microbial transport.

The groundwater in the Mefou watershed, particularly from hand-dug wells in peri-urban areas, is biologically unsafe for direct consumption. It requires systematic disinfection (boiling, chlorination, or filtration) before use.

4.8. Water Quality Indices (WQI)

The study calculated two main indices to summarize the overall state of the water (table 6): Global Water Quality IQE = ∑ (Qi × Wi). The calculated value of 50.3 classifies the overall quality as bad (mauvaise). This poor rating is primarily attributed to high concentrations of fecal coliforms, moderate turbidity, and acidic pH.

Index Type	Calculated Value	Quality Classification	Status
Global Water Quality Index (GWQI)	**50.3**	**Poor (Mauvaise)**	**Non-compliant**
Physico-chemical Sub-Index	42.1	Good	Compliant
Bacteriological Sub-Index	78.4	Very Poor	**Critical**

Table 6: Summary of Water Quality Indices (WQI)

The Global WQI score of 50.3 places the groundwater in the "Poor" category. This indicates that while the water may appear clear, it is not safe for direct consumption without prior treatment. The index is heavily penalized by the bacteriological sub-index. The high density of fecal coliforms and E. coli in urban areas like Mfou and Ekok significantly lowers the overall quality score, outweighing the relatively good chemical results. The physico-chemical sub-index remains in the "Good" range, suggesting that the geological framework of the crystalline basement still provides a degree of protection against heavy mineral or industrial pollution.

Spatial Heterogeneity: in Urban Sectors the lowest scores (WQI > 75), classified as "Very Poor," due to the impact of pit latrines. Forested sectors maintain higher scores (WQI < 40), classified as "Good," where natural vegetation still protects the recharge zones

4.9. Correlation and Spatial Findings

- The poorest water quality is found in zones identified as having "high" or "moderate" vulnerability by the SINTACS model.
- Over 60% of water points fail potability standards due to agricultural intensity and poorly managed urban sanitation.
- Statistical tests (Kruskal-Wallis) show no significant variation in most parameters between sampling campaigns, suggesting stable, long-term pollution issues. (table 7)

4.10. GWQI Classification

GWQI Value	Water Quality Status	Suitability for Consumption
0 – 25	Excellent	Pristine, safe for all uses.
26 – 50	Good	Generally safe, minor impurities.
51 – 75	Poor (Mauvaise)	Requires treatment before drinking.
76 – 100	Very Poor	Highly contaminated, high health risk.
> 100	Unsuitable (Inapte)	Dangerous for human consumption.

Table 7: The Study Uses a Standard Indexing Scale to Categorize the Quality of the Sampled Water Points:

Poor-quality water mostly overlaps high vulnerability zones.
The application of this classification to the study area yielded the following findings:

- The calculated global index for the basin is 50.3, placing the overall groundwater status at the threshold of the "Poor" (Mauvaise) category.
- Hand-dug wells in urbanized areas like Mfou and Ekok frequently fall into the "Poor" or "Very Poor" categories due to high concentrations of fecal bacteria and moderate turbidity. Deep boreholes (forages) generally exhibit better scores, often falling into the "Good" category, as they are better protected from surface infiltration.
- The classification is most negatively impacted by bacteriological contamination (fecal coliforms and E. coli),

acidic pH levels (often below 6.0), and phosphate levels in agricultural zone

5. Discussion

5.1. Reliability of the SINTACS Model in Tropical Saprolites

The predominance of moderate vulnerability (75% of the basin) reflects the characteristic hydrogeology of the South Cameroon crystalline basement. The SINTACS model's accuracy is validated by the spatial correlation between high-index zones and observed concentrations of NO_3^- and $E. coli$. This aligns with Civita, who argued that SINTACS provides superior sensitivity in anthropogenized environments compared to the DRASTIC method by allowing for more nuanced weighting of land use and effective infiltration [17]. In the Mefou basin, the "S" (Soggiacenza/Depth to Water) and "I" (Infiltration) parameters emerge as the primary drivers of vulnerability, particularly in the southern sectors where the water table is frequently less than 5 meters deep.

5.2. Hydrochemical Evolution and Geogenic Controls

The observed acidic pH (4.8–6.3) and low electrical conductivity are consistent with the results of Fantong et al. regarding the African crystalline shield [10]. The dominance of the Calcium-Magnesium-Bicarbonate (Ca-Mg-HCO3) facies indicates that groundwater chemistry is primarily governed by the silicate weathering of gneissic and granitic parent rocks. As noted by Ako et al., the short residence time of water in these shallow alterite aquifers limits mineral dissolution, resulting in the "young," weakly mineralized water observed across the Mfou Council [18].

5.3. Anthropogenic Drivers and the "Urban Syndrome"

The transition from forest to an agro-urban mosaic has created a "vulnerability-pollution" nexus.

- Bacteriological Crisis: The quasi-general presence of E. coli and Vibrio cholerae in urban hubs like Mfou and Ekok confirms the "Sub-Saharan Urban Syndrome" described by Kuitcha et al. [19]. This occurs when rapid, unplanned urbanization outpaces sanitation infrastructure, leading to direct fecal leaching from pit latrines into shallow aquifers.
- Agricultural Trends: While NO3 levels currently remain below the WHO limit of 50 mg/L, the high specific vulnerability mapped in agricultural zones suggests a trajectory similar to that observed by Wirmvem et al. in the Western Highlands of Cameroon, where intensive fertilizer use eventually led to localized nitrate spikes [20,21].

5.4. Comparison with Regional Tropical Studies

When compared to the Abiergué watershed (Yaoundé), the Mefou basin shows similar levels of biological degradation but lower overall chemical loading. This suggests that while Mfou is currently less industrially impacted than the capital, its natural hydrogeological "shield" (the unsaturated zone) is equally thin and fragile. The findings reinforce the regional conclusion by Foster et al. that in humid tropical environments, the protection of the "recharge area" is more critical for water safety than the depth of the well itself [3].

5.5. Implications for Water Resource Management

The Global Water Quality Index (GWQI) of 50.3 (Poor/Mauvaise) indicates that the aquifer is at a critical tipping point. The spatial overlap between high SINTACS indices and high-density settlements necessitates the immediate implementation of "Protection Perimeters" around community water points. Integrating these vulnerability maps into the Communal Development Plan (PCD) of Mfou is essential to prevent the installation of future sanitation facilities or industrial zones in the high-vulnerability southwestern sectors.

While the DRASTIC method is a global standard, this study aligns with Civita in choosing SINTACS [22]. The comparison highlights that SINTACS is more effective in the Mefou basin because it allows for flexible weighting of anthropogenic factors (Land Use), which is the primary driver of pollution in the Mfou Council, unlike the more rigid DRASTIC parameters. Similar to studies conducted in the Yaoundé region and the Pan-African crystalline backbone, the Mefou results confirm that groundwater is naturally acidic (pH < 6) and weakly mineralized. The "Calcium-Magnesium-Bicarbonate" facies found in Mfou is a hallmark of silicate weathering in the Southern Cameroon plateau, reinforcing the regional consistency of the hydrochemical data. The high bacteriological risk (E. coli and Faecal Streptococci) identified in the urban hubs of Mfou and Ekok mirrors findings from the Abiergué watershed and Douala. The comparison underscores a recurring "Sub-Saharan Urban Syndrome": where rapid urbanization without centralized sewerage leads to the systematic degradation of shallow aquifers by pit latrines. Comparison: While many tropical studies report soaring nitrate levels, the Mefou study shows NO3 levels are currently below the WHO 50 mg/L limit. However, the "High Specific Vulnerability" mapped in this study warns that Mfou is on the same trajectory as agricultural zones in West Africa, where nitrate loading eventually breached safety thresholds after decade-long intensive farming (table 8).

Aspect	***Mefou Study Result***	***Comparable Literature***	***Degree of Correlation***
Dominant Facies	$Ca-Mg-HCO_3$	*Ako et al. (2012)*	High (Regional Trait)
Vulnerability Driver	Land Use / Water Depth	*Civita (1994)*	High (Model fit)
Main Threat	Bacteriological (Fecal)	*Kuitcha et al. (2010)*	Very High (Urban issue)
Nitrate Levels	Low (< 2 mg/L)	*Wirmvem et al. (2013)*	Moderate (Lower than Yaoundé)

Table 8: Summary Table of Comparison

5.6. Management Recommendations and Policy Integration

To mitigate the risks identified, local authorities should prioritize "Groundwater Protection Zones" (GPZ) around high-yield boreholes. Specifically, a buffer of at least 30 meters should be enforced between latrines and water points. Integrating the SINTACS vulnerability map into the Mfou Council Development Plan (PCD) is essential for future land-use zoning to prevent high-impact agricultural or industrial activities in the southwestern high-vulnerability sectors.

The SINTACS results should be used to delineate spatial "no-go" zones. Implement a tiered protection system around high-yield community boreholes an immediate "Inner Protection Zone" (25–30m radius) should strictly prohibit any construction or waste disposal to prevent rapid vertical infiltration of pathogens.

To prevent the Mefou basin from following the high-nitrate trends seen in other tropical regions: introduce Best Management Practices (BMPs) for food crop farming (plantains, cassava, maize) in the southwestern high-vulnerability sectors and promote organic fertilizers over synthetic nitrogen-based inputs and regulate the timing of application to avoid peak rainy seasons when leaching is most intense.

The presence of E. coli and Vibrio cholerae underscores a systemic infrastructure failure need transition from traditional unlined pit latrines to "Ecosan" or ventilated improved pit (VIP) latrines that are sealed from the water table and prioritize urban hubs like Mfou and Ekok, where the housing density and shallow water table create a critical contamination nexus.

Because many "Poor" quality ratings were due to surface runoff entering through unprotected well openings, promotion of Wellhead Protection Measures include implement physical engineering standards for all private and public wells. And mandate the construction of concrete aprons (slabs), raised curbing to divert runoff, and secure covers to prevent direct manual contamination of the water column.

Thers is need for the implementation of Periodic Groundwater Monitoring. The "Global Water Quality Index" (GWQI) of 50.3 indicates the system is at a tipping point. Establishing a sentinel monitoring network using the 55 water points identified in this study and conducting bi-annual testing (dry vs. rainy season) for fecal indicators and nitrates. This data should be integrated into the Mfou Communal Development Plan (PCD) to allow for evidence-based decision-making and early warning of pollution plumes.

6. Conclusion

The integrated assessment of the Mefou watershed provides a critical diagnostic of groundwater resources in the Southern Cameroon plateau, leading to several fundamental conclusions regarding environmental monitoring and public health. This study demonstrates that the synergy between the SINTACS model, Remote Sensing, and Geographic Information Systems (GIS) provides a highly robust framework for mapping groundwater vulnerability in tropical crystalline basement terrains. By utilizing Sentinel-2 satellite imagery and digital elevation models, the study successfully translated complex environmental variables into a spatially explicit vulnerability index. The SINTACS method, in particular, proved superior for this humid tropical context due to its flexible weighting system, which accurately captured the rapid vertical migration of surface contaminants through the thin, porous saprolite (alterite) layers typical of the Pan-African backbone.

The spatial analysis reveals that the Mefou watershed is characterized by moderate to high vulnerability, with the highest risks concentrated in urbanizing sectors like Mfou and Nkolmeyos. These findings are physically validated by the confirmed presence of nitrate and bacteriological contamination (notably E. coli and Vibrio cholerae) in several shallow water points. This degradation is a direct consequence of unplanned land-use changes and the proximity of unlined sanitation facilities to the water table. The calculated Global Water Quality Index (GWQI) of 50.3 serves as a critical warning; without immediate policy interventions—such as the establishment of protected wellhead perimeters and the regulation of agricultural nitrogen inputs—the aquifer faces irreversible qualitative degradation.

Beyond the local scale, the methodology developed in this study offers a validated template for water resource management across Central Africa. Many watersheds in the Congo Basin share identical hydrogeological characteristics (crystalline basement) and socio-economic pressures (rapid peri-urbanization). The successful application of this "low-cost, high-precision" geomatic approach demonstrates that it can be replicated in other data-scarce regions to identify "hotspots" of contamination and prioritize infrastructure investment. Ultimately, this research underscores that protecting groundwater in the tropics is a multidisciplinary challenge that must bridge the gap between advanced geospatial modeling and local communal governance [23-26].

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