Study On the Vulnerability of Groundwater to Pollution in Bafoussam City, Western Cameroon

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ABSTRACT

Groundwater represents the most significant source of potable water globally, yet it faces increasing threats from surface-level pollution. This study provides a comprehensive evaluation of groundwater vulnerability to contamination in the city of Bafoussam, a critical urban and agricultural hub in the Western Region of Cameroon. The assessment was conducted using the SINTACS parametric method, a robust model that integrates seven distinct physiographic and hydrogeological parameters: Water table depth (S), Effective infiltration (I), Unsaturated zone (N), Soil environment (T), Aquifer environment (A), hydraulic Conductivity (C), and Slope or topography (S). These parameters were derived from a combination of remote sensing data, including Digital Terrain Models (DTM), and exogenous data sources such as lithological maps, soil analyses, rainfall records, and direct hydrogeological measurements. The primary objective was to map both the intrinsic vulnerability of the aquifer system and its specific vulnerability to prominent local pollution sources, namely fecal contamination from urban sanitation systems and nitrate pollution from agricultural activities.
The results reveal a complex vulnerability landscape across the study area. The intrinsic vulnerability assessment, which reflects the inherent susceptibility of the aquifer to contamination, indicated that 18.35% of the area exhibits high vulnerability, 37.47% has medium vulnerability, 31.46% has low vulnerability, and 12.72% is classified as having very low vulnerability. For specific vulnerability to fecal pollution, with E. coli serving as the bio-indicator, the analysis showed that a majority of the area, 51.78%, possesses an average or medium vulnerability. A further 30.24% demonstrates low vulnerability, while 17.99% shows very low vulnerability to this contamination type. Regarding agricultural pollution, for which nitrate was the chemical indicator, 8.37% of the area was found to have a high specific vulnerability, 12.37% an average vulnerability, and the remainder exhibited low to very low vulnerability. These findings underscore the significant risk of groundwater contamination from urban, industrial, and agricultural sources, providing critical data for the development of targeted water resource management and protection strategies in Bafoussam.

Keywords: vulnerability, pollution, SINTACS method, groundwater, mapping, hydrogeology, nitrates.

Introduction

1.1. Broad Background and Historical Context

Water is the bedrock of life, economic development, and environmental sustainability. However, the 21st century is marked by a burgeoning water crisis, characterized by increasing scarcity and deteriorating quality of this vital resource. Global water demand is projected to surge by 20% to 30% by the year 2050, a trend driven by the relentless pressures of population growth, rapid urbanization, and evolving patterns of consumption associated with economic development. Compounding this issue, the pervasive effects of climate variability are disrupting traditional hydrological cycles, making water availability less predictable and more precarious. In this challenging global context, groundwater has emerged as the primary and most reliable source of potable water for a significant portion of the world's population, particularly in developing nations across Asia and Africa [1]. Its natural filtration through subterranean strata often renders it safer for direct consumption than surface water, and its vast reservoirs provide a critical buffer against the impacts of drought and seasonal shortages.

In many regions of Sub-Saharan Africa, including Cameroon, dependence on groundwater is not merely a matter of convenience but of necessity. It sustains communities, fuels agriculture through irrigation, and supports industrial processes. However, this reliance has paradoxically placed these essential underground reservoirs at profound risk. The very activities that groundwater supports—urban expansion, agricultural intensification, and industrial production—generate a host of pollutants that can infiltrate the subsurface and contaminate aquifers. Once contaminated, groundwater is notoriously difficult and prohibitively expensive to remediate, with pollutants potentially persisting for decades or even centuries. The protection of these aquifers is, therefore, not just an environmental issue but a critical imperative for public health, food security, and long-term economic stability. The challenge lies in managing and mitigating the risks posed by surface activities to ensure the continued viability of this indispensable resource for current and future generations.

1.2. Critical Literature Review

In response to the growing threat of groundwater contamination, the scientific community has developed a range of methodologies to assess and map aquifer vulnerability. These approaches are essential tools for proactive water resource management, allowing policymakers and planners to identify high-risk areas and implement targeted protection measures. The methods can be broadly categorized into statistical approaches, weighting approaches, and those based on indices [2]. Among the most widely adopted are the index-based parametric models, which integrate multiple hydrogeological factors to derive a quantitative measure of vulnerability. These models function by assigning scores and weights to various parameters that govern the ease with which a contaminant can migrate from the ground surface to the saturated zone of an aquifer.

The DRASTIC model, for example, is one of the most well-known index methods and has been applied extensively worldwide, including for assessing aquifer vulnerability in regions like the Kakamigahara Heights in Japan [3] and the Douala region in Cameroon [9]. A similar and equally robust method is the SINTACS model, which was specifically refined for Mediterranean hydrogeological conditions but has demonstrated broad applicability. SINTACS, an acronym for the seven parameters it considers—*Soggiacenza* (depth to water), *Infiltrazione* (effective infiltration), *Non saturo* (unsaturated zone), *Tipologia della copertura* (soil media), *Acquifero* (aquifer characteristics), *Conducibilità* (hydraulic conductivity), and *Superficie topografica* (topographic slope)—offers a structured framework for evaluating the intrinsic protective capacity of the layers overlying an aquifer [2, 4].

Numerous studies have successfully employed these models to highlight significant groundwater vulnerabilities. In Algeria, for instance, research on critical aquifers revealed that a staggering 60% of the aquifer system exhibited high vulnerability to pollutants originating from the surface [3]. A study in western India specifically focused on agricultural impacts, concluding that the local aquifer had a high specific vulnerability to nitrate pollution, a common consequence of intensive farming [4]. These investigations underscore a global pattern: anthropogenic activities are placing unprecedented pressure on groundwater systems [5, 6]. The waste and effluents generated by urban centers, industrial sites, and agricultural lands are a primary source of both chemical and bacteriological pollution, which has already been observed in underground resources across the world [7]. Unmanaged landfills, for example, have been shown to have a significant impact on groundwater quality in areas like Casablanca, Morocco [10], while coastal aquifers face threats from urban development in places such as El Jadida, Morocco [14].

In Cameroon, the issue is particularly acute. The nation faces substantial challenges related to water resource pollution, which are exacerbated by issues of efficient water development and management [6]. Studies within the country have begun to map out these risks. In Dschang, research highlighted the vulnerability of local groundwater to pollution, providing a crucial local precedent for the current study [8]. Similarly, an assessment of the Santchou aquifer detailed the piezometric distribution and vulnerability to pollution within a tropical environment, reinforcing the need for such research in the region [13]. These studies collectively demonstrate that the poor management of effluents, particularly fecal waste in contexts of precarious and rapid urban development, is a potent driver of groundwater contamination [8, 16]. The modification of standard models like DRASTIC or SINTACS to include parameters for specific contaminants, such as nitrate from agricultural activities, has also become a critical area of research, allowing for a more nuanced assessment of specific risks [12]. The combined approach of assessing intrinsic vulnerability and then layering on specific anthropogenic impacts is considered a best practice for comprehensively mapping groundwater risk [5].

1.3. The Identified Research Gap

While a growing body of literature addresses groundwater vulnerability in various global and regional contexts [1, 3, 4, 11], and despite emerging research within Cameroon [8, 9, 13], a detailed and systematic assessment of the groundwater resources in the city of Bafoussam has remained a significant research gap. Bafoussam is a rapidly growing urban center with a substantial agricultural periphery, representing a confluence of the primary drivers of groundwater contamination. However, prior to this investigation, there was a lack of specific, empirical data mapping the vulnerability of its aquifers. No known study had applied the comprehensive SINTACS method to this particular area to produce detailed intrinsic and specific vulnerability maps. This gap is critical, as local hydrogeological conditions can vary dramatically, and effective management strategies cannot be formulated based on generalizations from other regions. Specifically, the combined risk from both dense urban settlement (fecal pollution) and surrounding agriculture (nitrate pollution) in Bafoussam had not been systematically quantified, leaving local authorities and communities without the scientific foundation needed to prioritize protection efforts.

1.4. Study Rationale, Objectives, and Hypotheses

The rationale for this study is rooted in the urgent need to preserve the groundwater reservoirs of Bafoussam, which are under increasing threat from anthropogenic pressures and growing water demand. Given the observed contamination in other Cameroonian cities [8, 16] and the known pollution risks associated with Bafoussam's pattern of development, a proactive assessment was deemed essential to prevent irreversible damage to this vital resource. This study aims to provide the foundational scientific knowledge required for the effective management and protection of the city's groundwater.

The primary objective of this research was to conduct a rigorous assessment of the vulnerability of groundwater to surface-level pollutants in the city of Bafoussam. This objective was broken down into several sub-objectives:

1. To model and map the intrinsic vulnerability of the Bafoussam aquifer system using the seven-parameter SINTACS method.
2. To assess and map the specific vulnerability of the groundwater to fecal contamination, using E. coli as a bio-indicator, to understand the impact of urban sanitation practices.
3. To evaluate and map the specific vulnerability of the groundwater to agricultural pollution, using nitrate as a chemical indicator, to quantify the risk from farming activities.
4. To produce a series of detailed vulnerability maps that can serve as practical tools for local decision-makers, urban planners, and environmental agencies.

The central hypothesis of this study was that the hydrogeological and physiographic characteristics of the Bafoussam region, when combined with localized anthropogenic activities, result in spatially variable and significant levels of vulnerability to groundwater contamination. It was hypothesized that areas with shallower water tables, more permeable soils, higher infiltration rates, and low topographic slopes would exhibit the highest intrinsic vulnerability. Furthermore, it was hypothesized that the specific vulnerability to fecal pollution would be most pronounced in densely populated urban centers with inadequate sanitation, while the specific vulnerability to nitrate pollution would be highest in areas of intensive agriculture.

2. Methods

2.1. Research Design

This study employed a quantitative, model-based research design centered on the application of the SINTACS parametric vulnerability assessment method [8, 9]. The research was structured as a comprehensive spatial analysis, integrating field data, laboratory results, and remote sensing information within a Geographic Information System (GIS) framework. The core of the design was to first establish the baseline or *intrinsic* vulnerability of the aquifer system, which represents its inherent susceptibility to contamination based on its natural physical characteristics. This was achieved by systematically modeling seven hydrogeological parameters.

Following the intrinsic assessment, the research design incorporated a second phase to evaluate *specific* vulnerability. This involved modifying the intrinsic model by superimposing data related to specific anthropogenic pollution sources prevalent in the Bafoussam region. Two primary types of specific vulnerability were assessed: 1) vulnerability to fecal contamination, driven by urban sanitation systems, and 2) vulnerability to agricultural pollution, primarily from the application of fertilizers. This dual-phase approach allows for a more nuanced understanding, distinguishing between the natural protective capacity of the aquifer and the actual risk posed by specific human activities on the surface [5]. The final output consisted of a series of georeferenced vulnerability maps, classifying the study area into distinct zones of risk.

2.2. Study Area and Sampling

The investigation was conducted in the city of Bafoussam and its immediate peri-urban surroundings in the Western Region of Cameroon. The study area is geographically situated within the Mifi and Koung-khi divisions and encompasses four administrative sub-divisions: Bafoussam I to the west, Bafoussam II to the north, Bafoussam III to the east, and a portion of Bandjoun to the south. It is centered around the coordinates 5circ32prime North latitude and 10circ33prime East longitude. The region's topography is rugged and varied, with elevations ranging from 1038 meters to a high point of 1659 meters. The southern sub-divisions of Bafoussam I and Bandjoun are characterized by high-altitude hills, while the northern and eastern parts are dominated by high plateaus and valleys. The area is hydrologically significant, irrigated by numerous sub-watersheds that feed into two main watersheds: the Metche in the north and the Mifi in the west.

The climate is of the Cameroonian equatorial type, marked by two distinct seasons: a long rainy season and a shorter dry season, although climate variability has made their timing less predictable in recent decades. The annual average rainfall is between 330 and 340 mm, with average temperatures ranging from 20 to 25circC.

For the purpose of data collection, a sampling network of 15 wells was established. These wells were spatially distributed throughout the study area to ensure representative coverage of the different topographical and land-use zones. These 15 observation points served as the primary sites for direct field measurements of hydrogeological parameters.

2.3. Materials and Apparatus

A combination of field equipment, existing data sources, and analytical software was utilized to carry out this assessment.

- **Field Equipment:**
  - **Decameter with Electric Probe:** A calibrated decameter equipped with an electrical conductivity probe at its tip was used for precise measurement of the depth of the wells and the static water level within them.
  - **Global Positioning System (GPS):** A handheld GPS unit was used to accurately record the geographic coordinates of each of the 15 sampled wells, enabling their precise location on the base maps.
  - **Soil Sampling Equipment:** Standard tools were used for collecting soil samples from above the static groundwater level to characterize the unsaturated zone.
- **Data Sources:**
  - **Digital Terrain Model (DTM):** DTM data for the study area were acquired from the United States Geological Survey (USGS) website and the Institute for Research and Development (IRD) geodatabase. This was fundamental for deriving the slope parameter.
  - **Geological and Soil Maps:** Geological data for Western Cameroon were obtained from the Research and Development Institute (RDI). The soil map of Cameroon was used to extract pedological data for the study area.
  - **Meteorological Data:** Local meteorological data, specifically annual precipitation records, were obtained from the Bafoussam meteorological service and the Institute for Research and Development (IRAD) station in Dschang.
  - **Water Quality Data:** Samples from the wells were analyzed to determine concentrations of

E. coli and nitrates, which served as the indicators for specific vulnerability assessments.

- **Software:**
  - **MS-Excel 2013:** This spreadsheet software was used for initial data entry, organization, and the calculation of arithmetic means of field measurements across different campaigns.
  - **ArcGis 10.5:** This powerful GIS software was the central tool for all spatial analysis. It was used for creating the project database, processing spatial data (e.g., using the "extract by mask" tool), performing interpolation to create continuous surfaces from point data, reclassifying raster layers according to SINTACS scoring, and overlaying the seven parameter maps to generate the final intrinsic and specific vulnerability maps.

2.4. Experimental Procedure/Data Collection Protocol

The data collection and processing followed the structured requirements of the SINTACS model, with a specific protocol for each of the seven parameters.

- **S – Water Table Depth:** The depth to the water table was determined through extensive limnometric monitoring. A total of ten measurement campaigns were conducted at each of the 15 wells. Six of these campaigns were timed to capture conditions during the high rainfall period (start and end of July, August, and September), while the other four were conducted during the severe dry season (start and end of February and March). This temporal spread allowed for the calculation of a representative average static water level.
- I – Effective Infiltration: To estimate the amount of water percolating into the groundwater system, local meteorological data (annual precipitation, P) were used. The annual groundwater recharge was estimated using an approach by Akenji et al. [9], defined by the equation for the percolation index (PI):
  PI=[P(−15,05)2+22,57]
- **N – Unsaturated Zone (Vadose Zone):** The nature of the unsaturated zone, which plays a crucial role in filtering or retarding pollutants, was assessed through direct observation. At each well, soil samples were collected from the strata directly above the measured static groundwater level. These samples were then characterized to identify the soil type. To create a continuous map of this parameter, the point data were interpolated and reclassified in ArcGis based on the scoring notation provided by Civita and De Regibus (1995) [17].
- **T – Soil Environment (Media):** Data on the soil media were derived from the existing soil map of Cameroon. The portion of the map corresponding to the study area was digitally extracted using the "extract by mask" function in ArcGis. The resulting soil map was then reclassified according to the permeability characteristics and corresponding scores as prescribed by the SINTACS methodology.
- **A – Aquifer Medium:** The characteristics of the aquifer itself were assessed using geological data from the Research and Development Institute (RDI). The geological formations within the study area were extracted and reclassified according to the notations provided in the literature [12], which assign scores based on the lithology's capacity to store and transmit water (e.g., fractured rock vs. porous media).
- C – Hydraulic Conductivity: The hydraulic conductivity of the soil, which determines the rate at which water can pass through it, was measured in the field using the Porchet method [11]. These tests were conducted during six of the field campaigns. The hydraulic conductivity (K) was calculated using the following equation:
  K=t×(2h′+r)r×h

  where r is the radius of the hole, h' is the height of the percolated water layer, t is the elapsed time, and h is the initial height of the water column.
- **S – Slope (Topography):** The slope parameter was derived from the Digital Terrain Model (DTM). The DTM raster was processed in ArcGis to calculate the percent slope across the entire study area. This slope map was then reclassified, as areas with low slopes allow more time for water to infiltrate and are thus considered more vulnerable.

2.5. Data Analysis Plan

The analysis phase focused on integrating the seven parameter maps to calculate vulnerability indices. The data, once collected and entered into MS-Excel for preliminary calculations (e.g., averaging values from field campaigns), were imported into ArcGis 10.5 for spatial modeling.

- SINTACS Intrinsic Vulnerability Index (SIVI): The core of the analysis involved calculating the SIVI. Each of the seven parameter maps (in raster format) was first assigned a score based on its characteristics. Then, following the SINTACS methodology, these parameters were assigned weights on a scale of 1 to 5 to reflect their relative importance in controlling vulnerability [12]. The SIVI was calculated for each pixel in the study area using a weighted sum overlay in ArcGis, based on the following equation: $SIVI=\sum_{i=1}^{7} P_i \times W_i$

  where Pi is the score of each parameter and Wi is its relative weight. This process generates a final intrinsic vulnerability map, which is then classified into categories (e.g., very low, low, moderate, high) [13].
- SINTACS Specific Vulnerability Index (SSVI): To assess vulnerability to specific pollutants, the intrinsic model was modified by incorporating an additional parameter representing the anthropogenic impact (AI) [14, 15]. For nitrate pollution from agriculture, land use was used as the surrogate parameter, with different land uses (agriculture, settlement, etc.) receiving different ratings based on their potential to generate nitrate contamination [12]. For fecal pollution, data on E. coli concentrations from the sampled wells were interpolated across the study area to create an anthropogenic impact layer. The SSVI was then calculated using the following equation: $SSVI=SIVI+AIr \times AIw$

  where AIr and AIw represent the rating and weight of the anthropogenic parameter, respectively.
- Vulnerability Classification: To standardize the classification of the final vulnerability maps and express the results as percentages, an equation established by the Ministry of Agriculture, Fisheries and Food of Quebec was utilized [16]. This conversion allows for a clearer understanding and comparison of the different degrees of vulnerability:

  ISNV%=ISNV max−ISNV minISNiV−INVS min×100

  where I_SNV is the specific nitrate vulnerability index. This formula was adapted to classify the vulnerability indices into four distinct zones: very low, low, moderate, and high vulnerability.

3. Results

3.1. Preliminary Analyses: Analysis of SINTACS Parameters

The evaluation of the seven individual SINTACS parameters provided the foundational data layers for the final vulnerability assessment.

- **Water Table Depth (S):** Field measurements revealed that the depth of the water table across the study area varies significantly, from as shallow as 2.42 meters to a maximum depth of 18.06 meters. Shallow aquifers, with depths ranging from 2.42 m to 8.5 m, were predominantly found in the lowlands and in the northern, eastern, and parts of the western sections. The deepest groundwater levels (14.54 m to 18.05 m) were located in the northern part of the study area, which also serves as the confluence zone for groundwater flow.
- **Effective Infiltration (I):** The analysis of infiltration potential showed that the soils in the western part of the study area are highly permeable, with infiltration rates calculated to be between 236 and 365 mm. In contrast, the northern and southern parts of the zone exhibited low permeability, with infiltration rates ranging from 90 mm to 110 mm.
- **Unsaturated Zone (N):** The thickness of the vadose zone, which is a function of both the static water level and hydraulic conductivity, was found to range from 8.04 m in the thinner zones to 23.12 m in the thickest areas. However, a significant portion of the study area is characterized by vadose zone thicknesses in the intermediate range of 12.09 m to 15.76 m.
- **Soil Environment (T):** Four primary soil types were identified within the study area. The northern part is dominated by brown soils derived from basalt, followed by red soils derived from schist in the central region. Less prevalent are sandy clay soils and hydromorphic soils. In terms of permeability, the sandy-clay soils are the most exposed and conducive to infiltration, followed by hydromorphic soils, red

soils from shale, and finally the less permeable brown soils derived from basalt.

- **Aquifer Medium (A):** The geology of the subsoil consists of three main structures. According to the SINTACS approach, aquifers composed of Gneiss and Migmatites are considered the most vulnerable. These are followed in vulnerability by aquifers within Basic Volcanic schists, and finally, the granite aquifers are rated as the least vulnerable.
- **Hydraulic Conductivity (C):** Measurements using the Porchet method showed a range of hydraulic conductivity values. The cartographic modeling indicated that the southern part of the study area possesses the highest level of hydraulic conductivity. According to the SINTACS rating system, higher conductivity receives a higher score as it allows pollutants to travel more quickly.
- **Slope (S):** The terrain was classified into three slope categories: low (0-14%), medium (14-27%), and steep (>45%). The slope is a critical parameter, as areas with low slopes retain water for longer periods, allowing for greater infiltration. Consequently, these areas are more vulnerable to the infiltration of contaminated water and receive higher vulnerability scores in the SINTACS model.

3.2. Main Findings: Intrinsic and Specific Vulnerability

The integration of the seven parameter maps through a weighted overlay process in ArcGis produced the final vulnerability maps.

- **Intrinsic Vulnerability of Groundwater:** The intrinsic vulnerability map, which reflects the inherent susceptibility of the aquifer to pollution, revealed significant spatial variation across the study area, which covers a total of 16,199.37 hectares. The results were classified as follows:
    - **High Vulnerability:** 18.35% of the study area.
    - **Medium Vulnerability:** 37.47% of the study area.
    - **Low Vulnerability:** 31.46% of the study area.
    - Very Low Vulnerability: 12.72% of the study area.

      The southern part of the study area was identified as the most susceptible to pollution. This higher vulnerability is a result of the cumulative effect of several high-scoring parameters in this region, including a shallow water table, high hydraulic conductivity, low slopes conducive to infiltration, and permeable soil types (sandy-clayey and hydromorphic).
- **Specific Vulnerability to Faecal Pollution:** The assessment of specific vulnerability to fecal contamination, using E. coli as a bio-indicator, highlighted the impact of urban activities. The results, presented as a percentage of the total study area, are:
    - **Medium Vulnerability:** 51.78% (8,387.25 ha)
    - **Low Vulnerability:** 30.24% (4,898.23 ha)
    - Very Low Vulnerability: 17.99% (2,913.89 ha)

      This indicates that over half of the area has a moderate susceptibility to contamination from fecal matter, a risk that is particularly pronounced in urban and peri-urban centers where on-site sanitation systems like pit latrines are common.
- **Specific Vulnerability to Agricultural Pollution:** Using nitrate as the indicator for agricultural contamination, the specific vulnerability assessment yielded the following distribution:
    - **High Vulnerability:** 8.37% (1,355.49 ha)
    - **Medium Vulnerability:** 12.37% (2,003.28 ha)
    - **Low Vulnerability:** 25.85% (4,188.17 ha)
    - Very Low Vulnerability: 53.41% (8,652.43 ha)

      Although a smaller portion of the area is highly vulnerable to agricultural pollution compared to fecal pollution, these high-risk zones correspond directly to areas with intensive cultivation, particularly on slopes where runoff can transport fertilizers towards downstream wells.

3.3. Secondary or Exploratory Findings

The analysis provided additional insights into the hydrogeological dynamics of the region. The mapping of water flow direction confirmed that the main groundwater confluence zone is situated in the northern part of the study area, which corresponds to the location of the deepest water table measurements. This suggests a regional flow pattern towards the north. Furthermore, field analyses confirmed the model's predictions: water samples taken from wells within the urban and peri-urban centers, identified as having medium to high vulnerability, showed existing contamination by fecal matter. This finding serves as a direct validation of the vulnerability assessment, demonstrating that the identified risks are not merely potential but are already manifesting as tangible water quality degradation.

4. Discussion

4.1. Interpretation of Key Findings

The results of this study paint a detailed picture of the complex and varied vulnerability of groundwater resources in Bafoussam. The finding that over half of the intrinsic vulnerability is classified as medium or high (a combined 55.82%) is a significant cause for concern. The pronounced vulnerability in the southern part of the region is not coincidental but is a direct consequence of a "perfect storm" of hydrogeological factors. This area exhibits a combination of shallow water tables, which reduce the travel time and natural attenuation capacity of the overlying soil; high hydraulic conductivity, which allows pollutants to move swiftly through the subsurface; and low topographic slopes, which promote ponding and increase infiltration rather than surface runoff. The presence of permeable sandy-clayey and hydromorphic soils in this southern zone further exacerbates the situation, providing an easy pathway for contaminants to reach the aquifer.

The specific vulnerability assessments provide a crucial layer of context by linking these inherent vulnerabilities to on-the-ground human activities. The finding that over 51% of the area has a medium specific vulnerability to fecal pollution is particularly telling. This directly reflects the urban and peri-urban reality of Bafoussam, where population density is high and sanitation infrastructure, particularly the widespread use of unsealed pit latrines, is often inadequate. These systems act as direct point sources of contamination, continuously leaching E. coli and other pathogens into the shallow subsurface, posing a significant public health risk to the large portion of the population that relies on well water.

The specific vulnerability to agricultural pollution, while high in a smaller area (8.37%), highlights a different but equally important threat. These high-vulnerability zones are spatially correlated with agricultural plantations. The use of nitrogen-based fertilizers in these areas, combined with the hydrogeological susceptibility of the land they occupy, creates hotspots of potential nitrate contamination. Nitrates are highly mobile in water and can lead to serious health issues, particularly in infants. The moderate vulnerability (12.37%) in surrounding areas suggests a potential halo effect, where contamination is spreading beyond the immediate application sites.

4.2. Comparison with Previous Literature

The findings of this study align with and build upon a broader body of research on groundwater vulnerability in similar contexts. The overall intrinsic vulnerability distribution in Bafoussam, where a significant portion of the aquifer is at risk, is comparable to findings from a study in Tunisia, which utilized a different method but also concluded that a large part of the aquifer (60%) had a high vulnerability to surface pollutants [1, cited from source]. This suggests that aquifers in developing regions with significant anthropogenic pressure often share a high degree of susceptibility.

More specifically, the conclusions regarding fecal contamination in Bafoussam resonate strongly with other studies conducted within Cameroon. Research in the nearby city of Dschang [8, 16] and in Santchou [13] came to similar conclusions: the mismanagement of fecal effluents in a context of precarious and rapid urban development is a primary driver of groundwater pollution. This study confirms that this is not an isolated problem but a recurring pattern in Cameroonian urban centers. By quantifying this risk in Bafoussam, this work adds to a growing chorus of evidence calling for urgent improvements in urban sanitation infrastructure across the nation to protect public health. The application of GIS-based models like SINTACS and DRASTIC for this purpose has been proven effective in other Cameroonian contexts, such as Douala [9], and this study further validates their utility for local conditions.

The identification of nitrate vulnerability hotspots from agricultural sources is also consistent with international findings. Studies that have specifically modified vulnerability models to account for nitrate contamination, such as those in agricultural areas of Iran [12] or western India [4], have similarly demonstrated that land use is a critical parameter for accurately mapping this specific risk. This research confirms the applicability of this approach in a Sub-Saharan African context and highlights that agricultural intensification, while economically important, must be managed carefully to avoid compromising water resources. The methodological approach of combining an intrinsic assessment with a specific anthropogenic layer [5] and using GIS for delineation [7] has proven to be a robust framework, consistent with best practices established in the literature [2, 11].

4.3. Strengths and Limitations of the Study

This study possesses several notable strengths. Its primary strength lies in the application of the comprehensive, multi-parametric SINTACS model, which provides a more holistic and robust assessment than single-parameter analyses. The differentiation between intrinsic and specific vulnerability is another key strength, as it allows for a nuanced interpretation of the results—distinguishing between inherent susceptibility and actual risk from specific human activities. The integration of diverse data sources, including remote sensing (DTM), existing maps (geology, soil), and direct, on-the-ground field measurements (well depths, hydraulic conductivity), lends a high degree of empirical grounding to the model. Finally, the production of clear, classified vulnerability maps provides a tangible and immediately useful tool for non-expert stakeholders, such as local government officials and community leaders.

However, the study is not without its limitations. The spatial resolution of the final maps is inherently dependent on the density of the initial data points. With 15 wells covering a large area of over 16,000 hectares, the interpolation process used to create continuous surfaces may introduce some degree of uncertainty, particularly in areas far from a sampling point. A denser network of wells would improve the precision of the model. Secondly, the study relies on some pre-existing data, such as the soil and geological maps of Cameroon. The scale and accuracy of these maps might not be perfectly suited for a local-scale analysis, potentially affecting the scoring of the soil and aquifer parameters. Lastly, this assessment represents a snapshot in time. Groundwater systems are dynamic, and vulnerability can change with seasonal fluctuations, long-term climate shifts, and evolving land-use patterns. The study captures an average or representative state but does not model this temporal variability.

4.4. Implications for Theory and Practice

The implications of this research are twofold, spanning both theoretical contributions and practical applications.

- **Implications for Theory:** This study contributes to the broader field of hydrogeology by validating the applicability and effectiveness of the SINTACS model within the specific and complex hydrogeological setting of the volcanic and metamorphic terrain of West Cameroon. It reinforces the theoretical principle that a multi-parameter, weighted-index approach is essential for capturing the multifaceted nature of groundwater vulnerability. Furthermore, it demonstrates the critical importance of modifying these models to incorporate specific anthropogenic parameters [12, 14], moving beyond generic assessments to provide more targeted and actionable risk analyses.
- **Implications for Practice:** The practical implications are profound and immediate. The vulnerability maps generated by this study are decision-making tools of immense value. They provide the municipal authorities of Bafoussam, regional environmental agencies, and public health officials with a scientific basis for land-use planning and water resource management. High-vulnerability zones can be designated as special protection areas, with restrictions on potentially polluting activities like the construction of new pit latrines, landfills, or the storage of hazardous materials. The maps can guide the strategic expansion of municipal water and sewer networks to areas most at risk. For agricultural management, the findings suggest the promotion of best practices, such as precision fertilizer application and the introduction of crops that require fewer chemical inputs, especially in the identified high-vulnerability hotspots [4, 12]. These maps can also be used to optimize water quality monitoring programs, focusing limited resources on the areas where they are needed most.

4.5. Conclusion and Future Research Directions

This work successfully evaluated the groundwater vulnerability in the city of Bafoussam using the SINTACS method, culminating in the first detailed intrinsic and specific vulnerability maps for the region. The study concludes that a substantial portion of Bafoussam's vital groundwater resources is at significant risk of contamination from both urban and agricultural sources. The key determining factors for high vulnerability are a combination of low topographic slope and high hydraulic permeability, conditions that are prevalent in the southern parts of the study area. The risk is not merely theoretical; existing fecal contamination in urban wells confirms that the threat is real and ongoing. The findings serve as an urgent call to action for residents, public authorities, and the decentralized territorial communities of the region to acknowledge and address this pressing environmental and public health issue.

Looking forward, several avenues for future research emerge from this study. Longitudinal monitoring of water quality and water levels at the sampled wells would provide valuable data on the temporal dynamics of the aquifer system and track how vulnerability and contamination levels change over time. Future modeling efforts could be enhanced by incorporating a denser network of observation points and using higher-resolution data for parameters like soil characteristics to refine the precision of the vulnerability maps. Research could also be expanded to include other potential pollutants, such as heavy metals or emerging contaminants from industrial activities. Finally, socio-economic studies could investigate the drivers of the polluting behaviors, such as the factors influencing sanitation choices and agricultural practices, to help design more effective and socially acceptable intervention strategies. The results of this study are a critical first step, but continuous vigilance and further research are essential to ensure the long-term sustainability of groundwater in Bafoussam.

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