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ASSESSMENT OF THE INTRINSIC VULNERABILITY OF GROUNDWATER TO POLLUTION IN THE ANGOVIA MINING AREA (CENTRAL-WESTERN CÔTE D'IVOIRE): THE PAPRI APPROACH AND HYDROCHEMICAL VALIDATION

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ABSTRACT

Gold mining can place significant pressure on groundwater resources, particularly in fractured bedrock aquifers characterised by high hydrodynamic heterogeneity. This study aims to assess the chemical quality and intrinsic vulnerability of the groundwater in the Angovia mining area, in central-western Côte d'Ivoire. Physico-chemical and chemical analyses were carried out on the groundwater to characterise the distribution of several elements associated with mining activities, notably copper (Cu), cadmium (Cd), cyanide (CN^-), arsenic (As), lead (Pb) and mercury (Hg). The data were analysed using statistical methods, notably Wilk's alpha test and ANOVA. Intrinsic vulnerability was assessed using the PaPRI approach, based on the criteria of Protection, Reservoir and Infiltration. The results show spatial variability in the chemical quality of groundwater. Cu, Cd, CN^- and As generally exhibit low concentrations and low spatial variability, whilst Pb and Hg show significant variations between sampling points. The vulnerability assessment indicates that 80 per cent of the area is highly vulnerable and 10 per cent is extremely vulnerable, meaning that 90 per cent of the area is characterised as being highly or extremely vulnerable. This situation reflects the aquifer's significant susceptibility to potential contaminant transfer from the surface. The combination of hydrochemical data and PaPRI mapping therefore provides a useful tool for identifying priority monitoring areas and contributing to the sustainable protection of groundwater resources in the Angovia mining area.

Keywords: Groundwater; Gold mining; Hydrochemistry; Vulnerability; PaPRI

1 INTRODUCTION

Mining is a major sector of the economy in many African countries, particularly in West Africa, where the boom in gold mining is contributing to export earnings and economic development. However, the intensification of mining activities is placing increasing pressure on natural resources, particularly water resources. Ore extraction and processing operations can facilitate the mobilisation and transfer of contaminants into soils and aquatic systems through runoff, leaching and infiltration of water from mining areas and tailings. These processes can, in particular, lead to the dispersal of potentially toxic elements such as arsenic (As), lead (Pb), cadmium (Cd) and mercury (Hg), as well as cyanide (CN^-) used in certain gold processing methods [1–3]. Groundwater contamination is a particular concern in rural mining regions where communities rely heavily on boreholes and wells for their water supply. The production of acid mine drainage, leaching from tailings and the infiltration of effluents can alter the physico-chemical conditions of the environment and promote the mobilisation of metals and metalloids into aquifers [4–5]. However, the presence of contaminants in groundwater does not depend solely on the intensity of mining activities. It is also governed by the natural characteristics of the environment, notably lithology, weathering, fracturing, the thickness of the unsaturated zone, the gradient and infiltration conditions. This interaction between sources of pollution and hydrogeological properties is particularly significant in fractured bedrock aquifers, where fractures can act as preferential pathways for the movement of water and contaminants. In Côte d'Ivoire, several studies have highlighted the presence of metallic elements in environments affected by mining activities and have emphasised the risks associated with the degradation of water resources [6–9]. Recent research carried out in gold-mining regions of West Africa has also confirmed the presence of contaminants such as As, Cd, Pb and Hg in groundwater and demonstrated the importance of hydrochemical and hydrogeological factors in their distribution [3]. However, the chemical characterisation of the water alone is not sufficient to assess the aquifer's inherent susceptibility to contamination from the surface. The assessment of intrinsic vulnerability provides an essential complement to hydrochemical analysis. It enables the identification of areas where the natural characteristics of the environment further facilitate the infiltration and transfer of contaminants into the groundwater. In fissured bedrock aquifers, the PaPRI method, derived from PaPRIKa, allows the protective characteristics of the aquifer and the reservoir, as well as infiltration conditions, to be integrated in order to map intrinsic vulnerability [10–12].

The Angovia mining site, situated in the central-western part of Côte d'Ivoire, provides a particularly relevant context for this issue. The area has undergone several phases of industrial gold mining and is currently the site of significant mining activity as part of the exploitation of the Yaouré deposit. The local population relies heavily on groundwater sourced from domestic and community boreholes. The proximity of certain water points to mining areas and mining infrastructure therefore raises concerns regarding water quality and vulnerability to contamination.

Against this background, this study aims to assess the potential impact of gold mining on the quality and vulnerability of groundwater in Angovia. It is based on two complementary approaches: (i) the physico-chemical characterisation of groundwater and the statistical analysis of concentrations of Pb, Hg, Cd, As and CN^- to identify the main signatures and potential sources of contamination; and (ii) the assessment and mapping of the aquifer's intrinsic vulnerability using the PaPRI method. Combining these approaches thus enables a better understanding of the relationship between the observed contamination and the aquifer's natural sensitivity, and helps to identify priority areas for the protection of groundwater resources.

2 DATA AND METHODOLOGY

2.1 Study area

The Angovia gold mine is situated in central-western Côte d'Ivoire, in the Marahoué region, within the Yaouré gold-bearing district. The site is located in a rural area where groundwater is an important resource for local communities. The regional climate is of the transitional tropical type, characterised by alternating wet and dry seasons. The average annual rainfall recorded at Bouaflé is approximately 1,106 mm over the period 2000–2018 [13]. Rainfall is a major factor in aquifer recharge and can facilitate the transfer of substances present on the surface into the subsoil. Geologically, Angovia belongs to the Birimian domain of the Palaeoproterozoic, characteristic of the West African crystalline basement. The local formations consist mainly of volcanic and volcano-sedimentary rocks, notably tholeiitic and calc-alkaline basaltic series. Gold mineralisation is associated with tectonic structures, fractures and quartz veins. The structural setting thus plays an important role in fluid circulation and the concentration of mineralisation. From a hydrogeological perspective, groundwater resources are mainly contained within alterite aquifers and fracture aquifers. Fractures and discontinuities in the bedrock constitute preferred pathways for groundwater flow. [13], based on 17 boreholes, have shown that the groundwater at Angovia has a generally neutral to slightly alkaline pH and variable mineralisation. The authors indicate that this mineralisation is controlled in particular by residence time, redox processes and exchanges with surface water.

The Angovia gold mine has a long history, beginning with artisanal mining activities prior to the development of industrial-scale operations. The Compagnie Minière d'Afrique (CMA) mined the area industrially between 1999 and 2003, primarily through open-cast mining and heap leaching. A new phase of mining was subsequently carried out by Cluff Gold between 2008 and 2011. The Yaouré gold project was then developed by Perseus Mining from 2019 onwards, with the first gold production taking place in December 2020. The coexistence of former mining areas and recent industrial activities provides a favourable context for studying the potential impacts of mining on groundwater.

Consequently, the geological, structural, hydrogeological and climatic characteristics of Angovia may influence the mobilisation and transport of potentially contaminating substances. This configuration makes the Angovia area a suitable site for assessing groundwater quality and its intrinsic vulnerability to pollution [13].

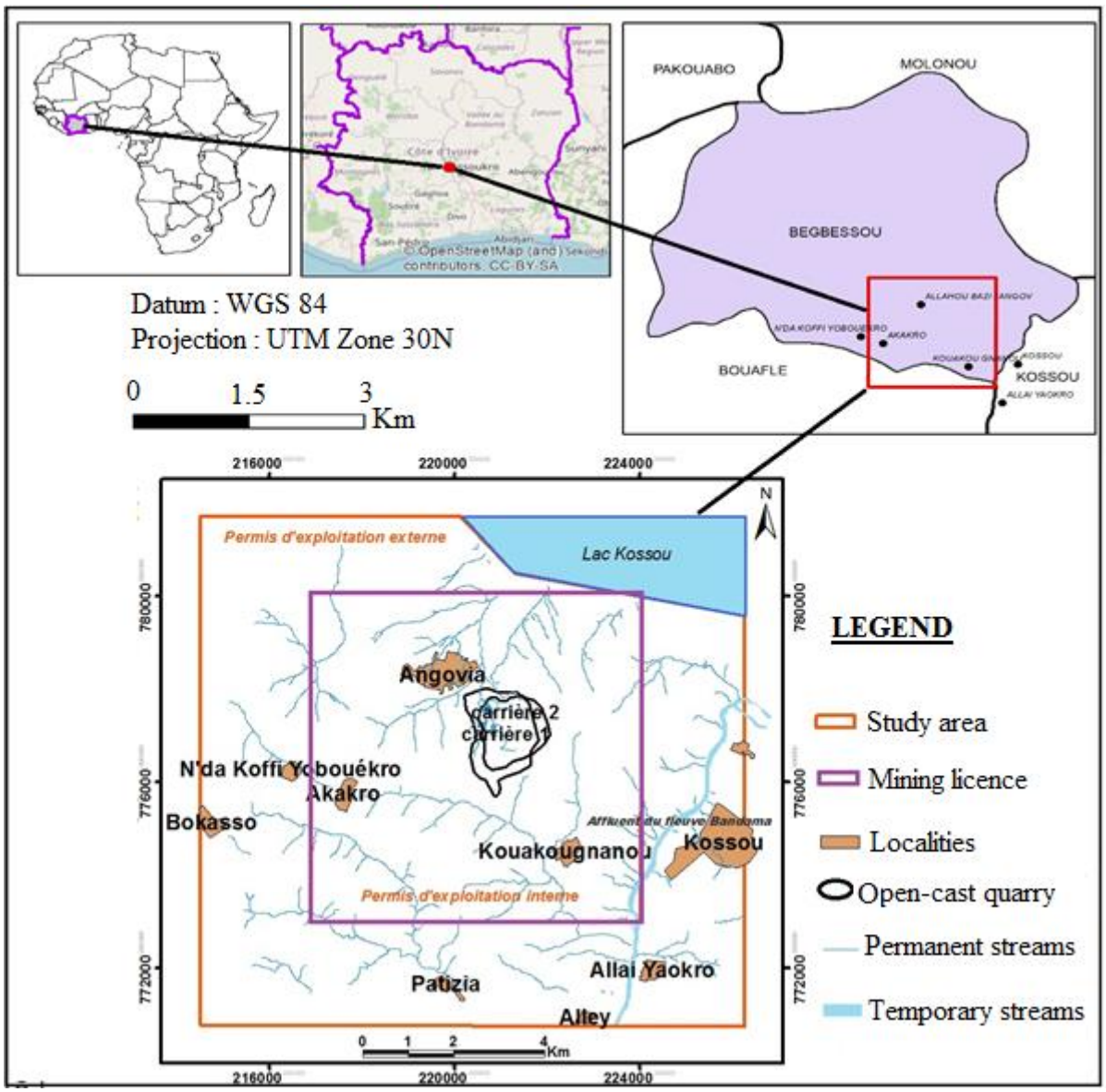


Figure 1*:* Scope of Angovia's operating licence

2.2 Materials and data

The study aims to assess groundwater pollution in the Angovia gold mine area by analysing six heavy metals and cyanide. Fifteen (15) water points were sampled for their physico-chemical parameters. The hydrogeological data were obtained from six boreholes and nine piezometers located within the study area. This information was provided by the Bouaflé Regional Water Authority (DTH) and the mining company Perseus Yaouré. Cartographic data, including DTM images (30 m × 30 m), were used to produce maps of slopes, the hydrographic network and drainage density. Furthermore, LANDSAT 7 ETM+ satellite data were used to identify fractures. Statistical analysis of heavy metal and cyanide concentrations was carried out using STATISTICA 7.0 software. Vulnerability to pollution was assessed using a thematic overlay of geospatial indicators. 5 km × 5 km grids were generated using MapInfo, after which fracture and drainage densities were calculated using Linwin 2.2. Finally, ArcGIS 10.4.1 was used to produce the final thematic maps.

2.3 Methodology

2.3.1 Statistical analysis using the Generalised Linear Model (GLM)

In order to characterise the spatio-temporal variability of heavy metal concentrations (Cu, Cd, As, Pb, Hg) and cyanide (CN^-) in the groundwater at the Angovia gold mine, a rigorous statistical approach was implemented using STATISTICA 7.0 software. This method is based on the application of a Generalised Linear Model (GLM), combining three complementary statistical tests: Wilks' Lambda test, analysis of variance (ANOVA), and Tukey's HSD post-hoc test, used where significance is found.

- *Wilks' Lambda test*

Wilks' Lambda test is used to assess whether the concentrations of toxic elements differ significantly between the various sampling points. It is based on the p-value (significance) [14]:

- If $p < 0.05$, it is concluded that there is a significant difference in concentrations between the water points.

If $p > 0.05$, this indicates that there is no significant difference; therefore, the water points have similar concentrations for all pollutants.

- *ANOVA test (Analysis of Variance)*

The ANOVA (Analysis of Variance) test is used to compare the mean concentrations across several groups in order to detect significant differences. It is based on the formulation of statistical hypotheses [14].

Null hypothesis (H_0): there is no significant difference between the means of the different water points (e.g. Measurement 1 = Measurement 2 = Measurement 3);

Alternative hypothesis (H_1): at least one mean differs (e.g. Measurement 1 ≠ Measurement 2 ≠ Measurement 3).

- The p-value obtained allows us to conclude:
- If $p > 0.05$, H_0 is accepted, indicating the absence of a significant difference.
- If $p < 0.05$, H_0 is rejected, meaning that there is a significant difference in concentration.
- It then becomes necessary to carry out a post-hoc comparison.

- Post-hoc test (Tukey HSD)

The post-hoc test, and more specifically Tukey's HSD (Honestly Significant Difference) method, enables the identification of which pairs of water points show significant differences in concentration for a given pollutant [14]. This test provides a comparison matrix that distinguishes between water points with similar concentrations of the same pollutant and those with a statistically significant difference. This approach makes it possible to identify significant differences between water points and to determine the sources or geographical areas potentially most affected by the pollutants. The flowchart in Figure 2 illustrates the methodology for applying the Generalised Linear Model (GLM), combining the three complementary statistical tests.

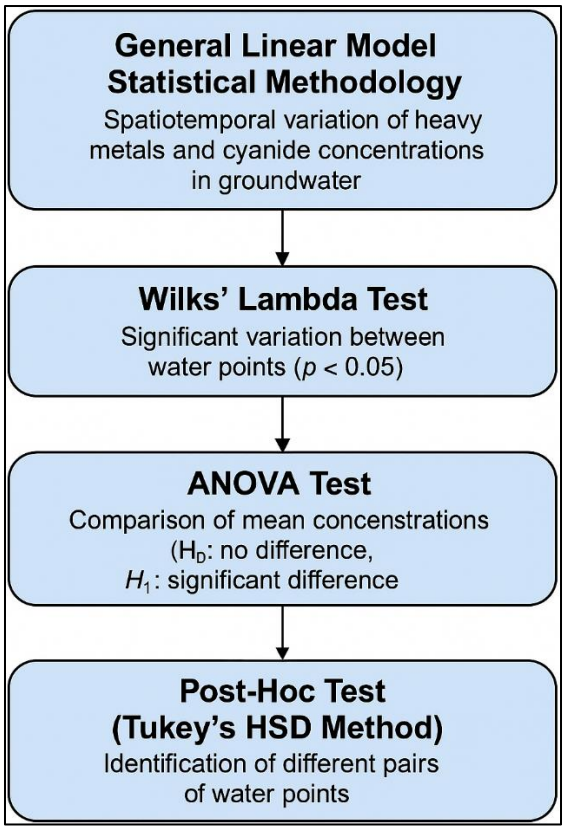


Figure 2*:* Methodology for applying the Generalised Linear Model (GLM), combining the three complementary statistical tests

2.4 PaPRI method

The PaPRI method is derived from the PaPRIKa method, which is applied in karst environments. The latter utilises protection parameters (P), reservoir rock characteristics (R) and infiltration (I). The absence of epikarst means that the number of parameters is limited to three (3), compared with four (4) for PaPRIKa [15]. The choice of this method meets three requirements: the method must be cost-effective; it must be technically feasible for hydrogeologists and other water-related organisations; and, finally, it must utilise available data [16].

- *Criterion P*

Criterion P represents all the factors contributing to the protection of groundwater against infiltration. It characterises the ability to reduce the movement of pollutants and their rate of transfer from the surface to the groundwater. It depends mainly on the nature and thickness of the soil (S), but also on weathered material (A) and the unsaturated zone (NSA), as well as its fracturing [15], [17], [18].

- *Criterion R*

Criterion R represents the geological nature of the aquifer, characterised by its lithology and fracturing [19]. It is spatialised using geological maps, field observations, data on lithological characteristics and borehole data.

- Criterion I

Criterion I relates to infiltration conditions. This infiltration is influenced by various parameters which, depending on their nature, may either accelerate or delay it. Infiltration is determined by two significant criteria: slope and drainage density [17], [18].

The various criteria presented here contribute to the development of the final vulnerability map by successively combining these criteria using ArcGIS software via inverse distance weighting (IDW) interpolation (Fig 3).

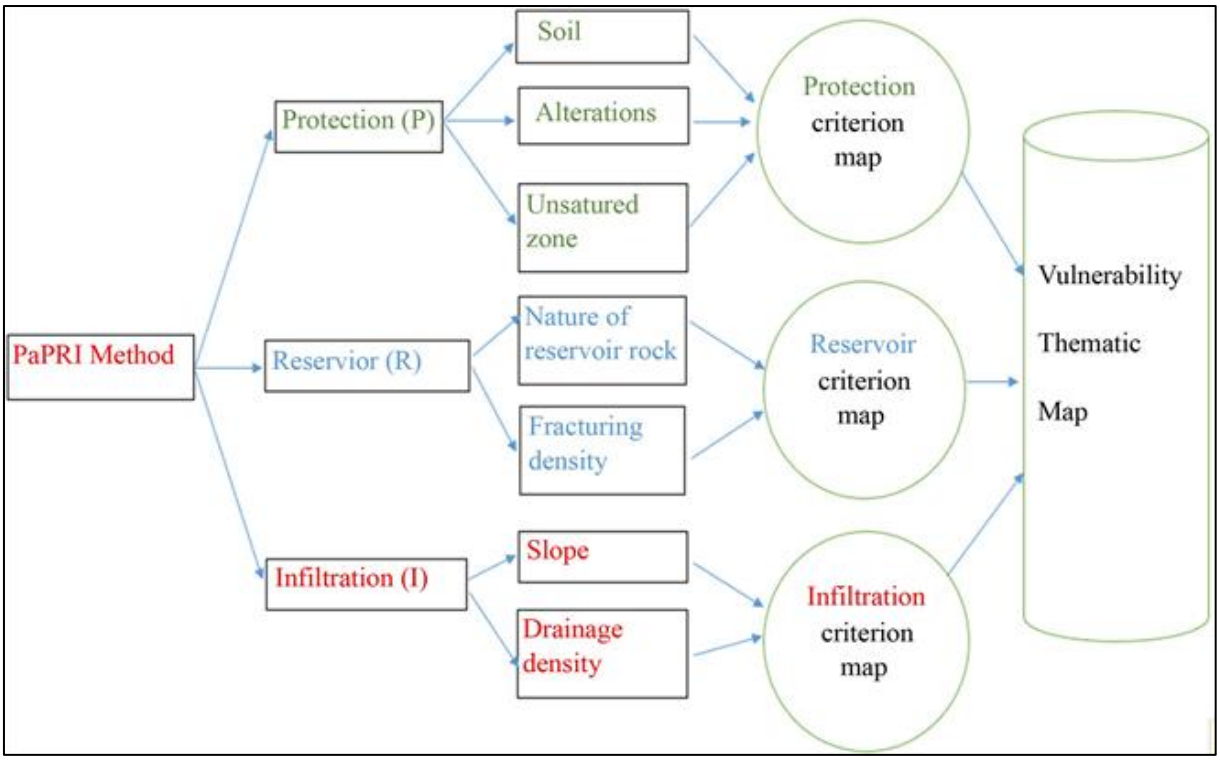


Figure 3: A conceptual model illustrating the stages involved in developing the vulnerability map [18].

- *Weighting calculation*

The calculation of weights or weighting coefficients is based on Saaty's pair-wise comparison method [20] (Table 1).

Table 1: Verbal and numerical expression of the relative importance of a pair of factors

Expression of a criterion compared to another	Note
Less important	1/3
Slightly less important	1/2
Same importance	1
Slightly more important	2
More important	3

The values resulting from this comparison were then incorporated into a calculation of the eigenvector (Equation (1)) and the weighting coefficient (Equation (2)) for each parameter [21].

$$V_{p_i} = \sqrt[n]{\prod_{i=1}^{n} N_i} \qquad (1)$$

V_{pi} = Eigenvector of each factor; Ni = Value of each factor.

$$W_i = \frac{V_{p_i}}{\sum_{i=1}^{n} V_{p_i}} \qquad (2)$$

W_i: Weighting coefficient for each factor

On this basis, correlation matrices were drawn up for each sub-criterion in order to determine, for each cell in the grid, the value of the criterion in question (Table 2).

Table 2: Pair comparison matrix and weighting coefficient of the reservoir, infiltration and protection factors

Protection factor (P)					
	NSA	Alterites	Soil	Eigen-Vector	weighting coefficient
NSA	1	1/3	2	1.49	0.32
Alterities	3	1	3	1.91	0.42
Soil	1/2	1/3	1	1.22	0.26
Roche factor (R)					
	Fracture	Nature of Rock	Eigen-Vector	weighting coefficient	
Fracture	1	3	2	0.63	
Nature of Rock	1/3	1	1.15	0.37	
Infiltration factor (I)					
	Slope	Drainage density	Eigen-Vector	weighting coefficient	
Slope	1	3	2	0.63	
Drainage density	1/3	1	1.15	0.37	

2.4.1 Aggregation of factors by weighting

For this study, the method of complete aggregation by coding was adopted [22]. The scoring system used is that of an arithmetic progression, so that the 'points' obtained can be added to those from the classifications relating to the other factors. The final result (S), representing the value of the indicator, is:

$$\boldsymbol{S = \sum_{i=2}^{n} Wi.Xi} \qquad \textbf{(3)}$$

Where:

S: the value of the indicator;

W_i: the weight of criterion i;

Xi: the standardised value of criterion i.

Determination of the vulnerability index

Calculating the overall vulnerability index makes it possible to assess the intrinsic vulnerability of groundwater and to delineate areas with different levels of aquifer protection. In this study, the vulnerability assessment was carried out using the PaPRI approach, adapted from the PaPRIKa method developed for fissured aquifers [10]. This approach is based on the analysis of several factors governing groundwater vulnerability, notably aquifer protection conditions, reservoir characteristics and infiltration conditions. The vulnerability index is therefore determined using the following equation:

$$\mathbf{Vg = iI + pP + rR} \qquad \textbf{(4)}$$

Where I, P and R represent the criteria relating to infiltration, protection and the aquifer, respectively, whilst i, p and r correspond to the weights assigned to each of these criteria. The weighted combination of these parameters yields a composite vulnerability value for each sector studied. The values obtained are then classified according to different levels of vulnerability in order to produce the overall vulnerability map and to identify the sectors where groundwater is most likely to be affected by contamination from the surface.

2.4.2 Method for validating the vulnerability map

Deterioration in groundwater quality can be assessed by analysing physico-chemical and bacteriological parameters. The validation of vulnerability maps involves comparing the vulnerability levels obtained through modelling with the actual characteristics of groundwater quality. Several studies have shown that hydrochemical data can be used to assess the relevance of vulnerability maps and verify their ability to identify areas that are actually exposed to contamination [23], [22.

In this study, the validation of the intrinsic vulnerability map is based on a comparison between the vulnerability classes obtained using the PaPRI method and the spatial distribution of concentrations of chemical elements likely to be associated with mining activities, notably As, Pb, Cd, Hg, Cu and CN^-. The validation principle is based on the assumption that areas with the highest vulnerability indices should also have a greater probability of contamination. Thus, a correlation between areas of high to very high vulnerability and high concentrations of contaminating elements serves as an indicator of the relevance of the vulnerability map produced.

3 RESULTS

3.1 Characterisation of trends in heavy metals and cyanide in groundwater using statistical analysis

3.1.1 Alpha Wilk Test

Statistical analyses carried out on the groundwater quality data from Angovia show distinct trends depending on the parameters measured. The Wilk's alpha multivariate test reveals a significant overall difference ($p = 0.0006 < 0.05$) between the sampling points, indicating spatial heterogeneity in the chemical composition (Table 3).

Table 3: Wilk's Alpha Test Table

Effect	**Multivariate significance tests (data arrangements) Sigma-restricted parameterisation Efficient decomposition of the hypothesis**					
	Test	Valeur	F	Effet dl	Erreur dl	p
Water sources	Wilk	0,281160	1,863480	56	270,568600	0,000601

3.1.2 ANOVA test

In order to understand the trends in the chemical components, we carried out an ANOVA test using the mean values for these various chemical pollutants. The results are set out in Table 4:

Table 4: Results of the ANOVA test at the water point level

Chemical elements	**Average (mg/L)**	**Ddl**	**F**	**p**
Cuivre	0,008000	14	1,137279	0,329795
Cyanure	0,016000	11	4,305900	0,360685
Cadmium	0,000420	6	0,106003	0,985954
Arsenic	0,006000	14	0,999808	0,456614
Plomb	0,054800	14	2,308908	0,007492
Mercure	0,089000	8	252,745900	0,000001

The ANOVA test yields $p > 0.05$ for copper, cadmium, cyanide and arsenic; hypothesis H0 is therefore confirmed. This means that the concentrations of copper, cadmium, cyanide and arsenic vary little and uniformly across the 15 water points in the study area. We can therefore conclude that the quality of the groundwater in our study area is less at risk from these various chemical elements.

As for hypothesis H1, it is supported for mercury and lead, as the ANOVA test yields $p < 0.05$. This means that the concentrations of lead and mercury vary significantly across certain water points at the Angovia gold mine.

Given that the concentrations of mercury and lead vary from one water point to another, a post-hoc test was carried out using Tukey's HSD method to identify where the differences lie across the water points.

3.2 Post-hoc Test

3.2.1 Analysis of the results of the post-hoc tests for lead

When the wells ESIA/G1, ESIA/G2, ESIA/G3, ESIA/G4, ESIA/G5, ESIA/G7, GW1, GW2, GW3B, GW4, GW6 and GW9 are compared with one another (Table 5), the p-value is greater than 0.05. This means that the lead concentration in these wells varies little from one well to another.

A comparison of wells ESIA/G5 and ESIA/G8, ESIA/G8 and PZ01, and ESIA/G8 and PZ03 yields a p-value of $p < 0.05$. This means that the ESIA/G8 well, when compared with these three (3) water sources, shows a significant variation in lead concentration compared with the others, as the other wells (ESIA/G5, PZ01 and PZ03), when compared with one another, yield p-values greater than 0.05, indicating that lead levels vary little and are consistent across these water sources.

3.3 Analysis of the results of the post-hoc mercury tests

With regard to mercury, the ESIA/G7, PZ03, GW1, GW3B, GW4 and GW9 wells showed mercury levels well below the standard (0.0001 mg/L) within the study area. The post-hoc tests for mercury content therefore cover nine (9) water points (Table 6). These tests reveal variations in mercury concentrations across the different wells within the Angovia mine's operational perimeter.

When the wells ESIA/G1, ESIA/G2, ESIA/G3, ESIA/G4, ESIA/G5 and GW2 are compared with one another, the p-value is > 0.05. This means that the mercury concentration at these wells varies little from one well to another.

A comparison of wells ESIA/G1, ESIA/G2, ESIA/G4 and ESIA/G5 with wells ESIA/G8, PZO1 and GW6 yields a significance level of $p < 0.05$. This means that the ESIA/G8, PZO1 and GW6 wells show a significant variation in mercury content compared with the others, as the pair-wise comparison of the ESIA/G1, ESIA/G2, ESIA/G4 and ESIA/G5 wells yields $p > 0.05$.

When the water points ESIA/G3 and GW2 are compared with the wells PZO1 and GW6, the p-value is < 0.05. This means that PZO1 and GW6 show a significant variation in mercury content compared with the others, as the pairwise comparison of the wells ESIA/G3 and GW2 yields a p-value > 0.05.

A comparison of the ESIA/G8, PZO1 and GW6 wells also yields a significance level of $p < 0.05$. This result indicates that one of the two wells being compared shows a greater variation in mercury concentration than the other.

Table 5: Results of the post-hoc tests on changes in lead concentration at the various water points

Approximate probabilities for post-hoc tests of the lead concentration variable (mg/L)															
Puits	ESIA/G1	ESIA/G2	ESIA/G3	ESIA/G4	ESIA/G5	ESIA/G7	ESIA/G8	PZ01	PZ03	GW1	GW2	GW3B	GW4	GW6	GW9
ESIA/G1	---	0,97	1,00	1,00	1,00	1,00	0,69	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ESIA/G2	0,97	---	1,00	0,98	0,40	0,66	1,00	0,46	0,35	0,61	0,95	0,87	0,53	0,61	1,00
ESIA/G3	1,00	1,00	---	1,00	0,86	0,97	0,96	0,90	0,82	0,92	1,00	0,98	0,90	0,93	1,00
ESIA/G4	1,00	0,98	1,00	---	1,00	1,00	0,50	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ESIA/G5	1,00	0,40	0,86	1,00	---	1,00	0,03	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ESIA/G7	1,00	0,66	0,97	1,00	1,00	---	0,09	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
ESIA/G8	0,69	1,00	0,96	0,50	0,03	0,09	---	0,04	0,02	0,12	0,64	0,41	0,07	0,12	0,99
PZ01	1,00	0,46	0,90	1,00	1,00	1,00	0,04	---	1,00	1,00	1,00	1,00	1,00	1,00	1,00
PZ03	1,00	0,35	0,82	1,00	1,00	1,00	0,02	1,00	---	1,00	1,00	1,00	1,00	1,00	1,00
GW1	1,00	0,61	0,92	1,00	1,00	1,00	0,12	1,00	1,00	---	1,00	1,00	1,00	1,00	1,00
GW2	1,00	0,95	1,00	1,00	1,00	1,00	0,64	1,00	1,00	1,00	---	1,00	1,00	1,00	1,00
GW3B	1,00	0,87	0,98	1,00	1,00	1,00	0,41	1,00	1,00	1,00	1,00	---	1,00	1,00	1,00
GW4	1,00	0,53	0,90	1,00	1,00	1,00	0,07	1,00	1,00	1,00	1,00	1,00	---	1,00	1,00
GW6	1,00	0,61	0,93	1,00	1,00	1,00	0,12	1,00	1,00	1,00	1,00	1,00	1,00	---	1,00
GW9	1,00	1,00	1,00	1,00	1,00	1,00	0,99	1,00	1,00	1,00	1,00	1,00	1,00	1,00	---

Table 6: Results of the post-hoc tests on changes in mercury levels at the various water points

Approximate probabilities for post-hoc tests of the variable 'mercury concentration' (mg/l)									
Points d'eau	ESIA/G1	ESIA/G2	ESIA/G3	ESIA/G4	ESIA/G5	ESIA/G8	PZ01	GW6	GW2
ESIA/G1	---	1,0000	1,0000	0,9966	0,9994	0,0455	0,0002	0,0004	0,3178
ESIA/G2	1,0000	---	1,0000	0,9912	0,9974	0,0499	0,0002	0,0004	0,495
ESIA/G3	1,0000	1,0000	---	1,0000	1,0000	0,0708	0,0002	0,0007	0,3844
ESIA/G4	0,9966	0,9912	1,0000	---	1,0000	0,0266	0,0002	0,0004	0,1763
ESIA/G5	0,9994	0,9974	1,0000	1,0000	---	0,0207	0,0002	0,0003	0,1587
ESIA/G8	0,0455	0,0499	0,0708	0,0266	0,0207	---	0,0002	0,0079	0,7584
PZ01	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	---	0,0002	0,0002
GW6	0,0004	0,0004	0,0007	0,0004	0,0003	0,0079	0,0002	---	0,0025
GW2	0,3178	0,3495	0,3844	0,1763	0,1587	0,7584	0,0002	0,0025	---

3.4 Assessment of vulnerability to groundwater pollution using the PaPRI method

3.4.1 Thematic map of the protection factor

The thematic map of the protection factor (P) highlights two index classes: moderate protection and high protection (Fig.4). The moderate protection class is predominant and covers approximately 60 per cent of the study area's surface area. It is mainly distributed across the central, north-central and east-central sectors, as well as in the far north-west and certain southern parts of the study area. The high protection class accounts for approximately 40 per cent of the total surface area and is mainly concentrated in the northern, southern and western parts. It generally corresponds to areas characterised by granitic formations, whose lithological characteristics and cover conditions contribute to better groundwater protection. Thus, the spatial distribution of the P factor reflects moderate to high protection of the aquifer, with moderate protection predominating in the central areas and high protection mainly associated with the peripheral granitic zones.

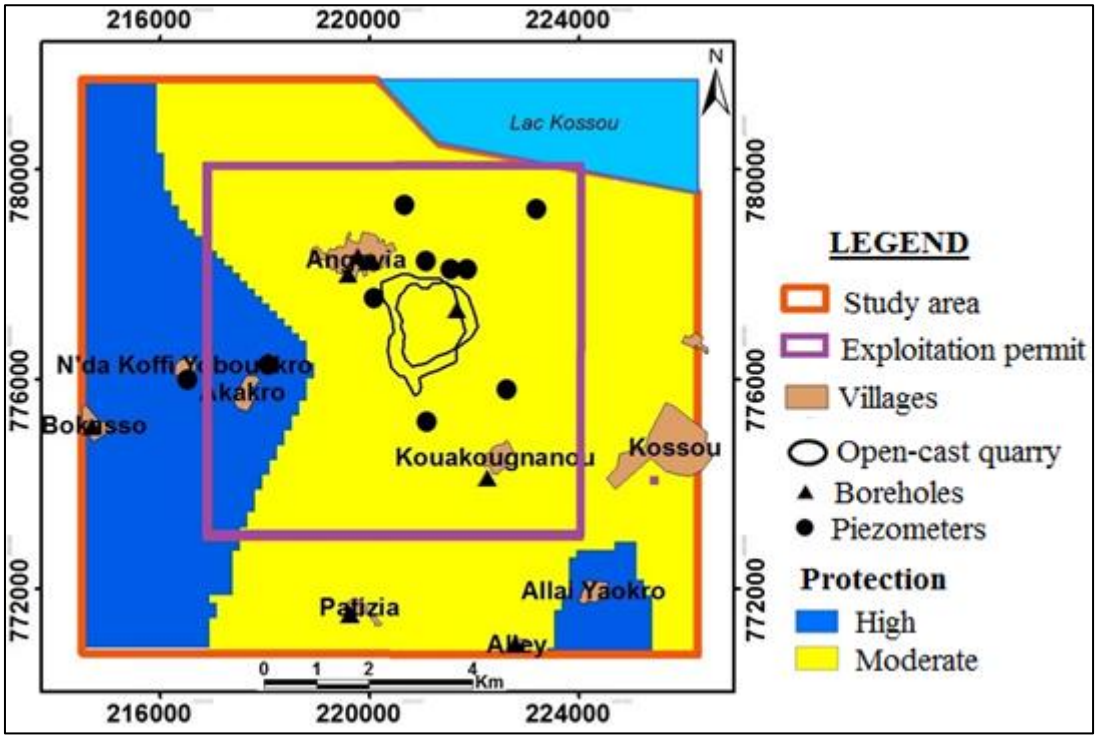


Figure 4: Thematic map of the protection factor

3.5 Thematic map of the reservoir factor

Analysis of the reservoir criterion (R) map reveals four porosity classes: low, moderate, high and very high. In the context of vulnerability assessment, higher porosity indicates a greater capacity for the movement and transfer of contaminants within the aquifer and thus corresponds to a lower level of protection for the aquifer. The reservoir criterion map (Fig 5) shows a predominance of the moderate porosity class, which covers approximately 60 per cent of the study area's surface area. It is mainly distributed across the central, north-central and east-central sectors, as well as in the far north-west and in certain southern sections. This class is primarily associated with the shaly formations that constitute the aquifer rocks. The high and very high porosity classes together account for more than 38 per cent of the study area and are mainly concentrated in the central-western part. These sectors therefore present conditions that are more favourable to groundwater flow and the potential transport of contaminants. Conversely, the low porosity class, located mainly in the south-east, accounts for only around 2 per cent of the total area. Overall, the distribution of the R criterion reflects a spatial heterogeneity in the properties of the aquifer, which is likely to influence the vulnerability of groundwater in the study area.

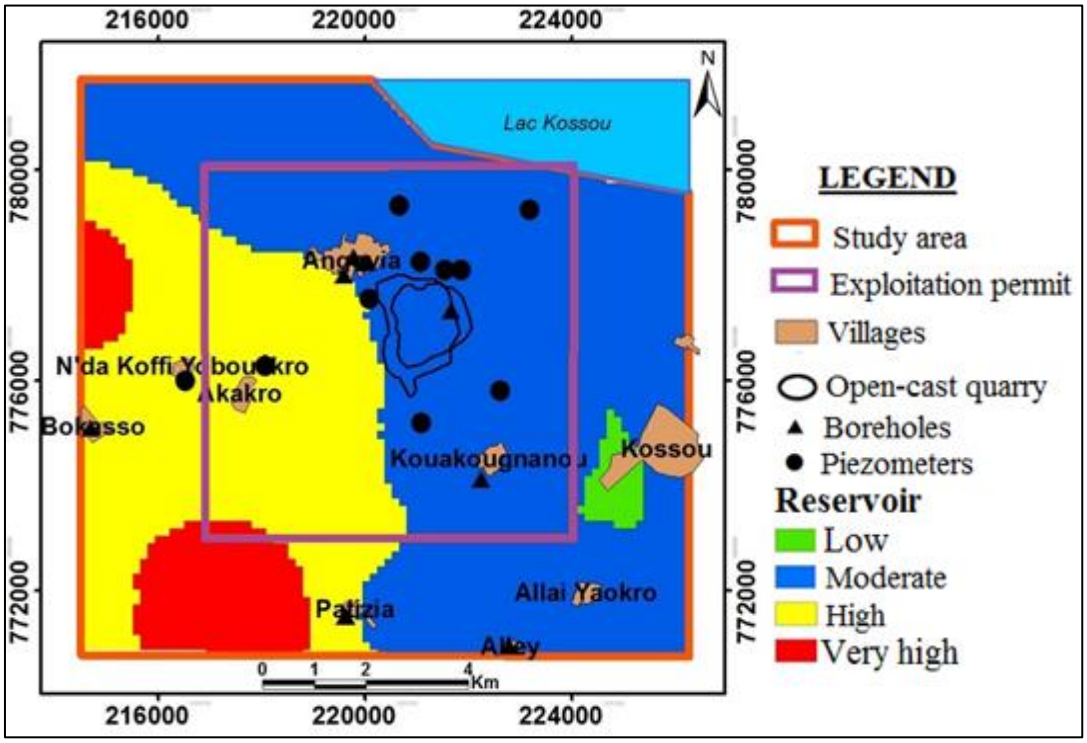


Figure 5*:* Thematic map of the reservoir factor

3.6 Thematic map of the infiltration factor

The infiltration criterion (I) reflects the environment's capacity to facilitate or limit the penetration of surface water into aquifers. Analysis of the infiltration map (Fig 6) shows a clear predominance of the 'high' and 'very high' infiltration classes, which together cover approximately 85 per cent of the study area's surface area, with 55 per cent for the 'high' class and 30 per cent for the 'very high' class respectively. These classes are widely distributed across the entire area, particularly in sectors characterised by a sparse or absent river network. They are generally associated with areas of gentle slope, which are conducive to the infiltration of rainwater into the subsoil. The moderate infiltration class accounts for approximately 13 per cent of the total area. It is mainly concentrated in the central, central-western and southern parts of the study area, with a few isolated occurrences in the eastern part. The low infiltration class remains marginal and covers only around 2 per cent of the territory. It corresponds to areas where topographical and hydrological conditions are less favourable to water penetration into the ground. Overall, the predominance of high and very high infiltration classes indicates a high infiltration capacity of the environment, which is likely to promote aquifer recharge but also to increase their exposure to the vertical transfer of any contaminants originating from the surface.

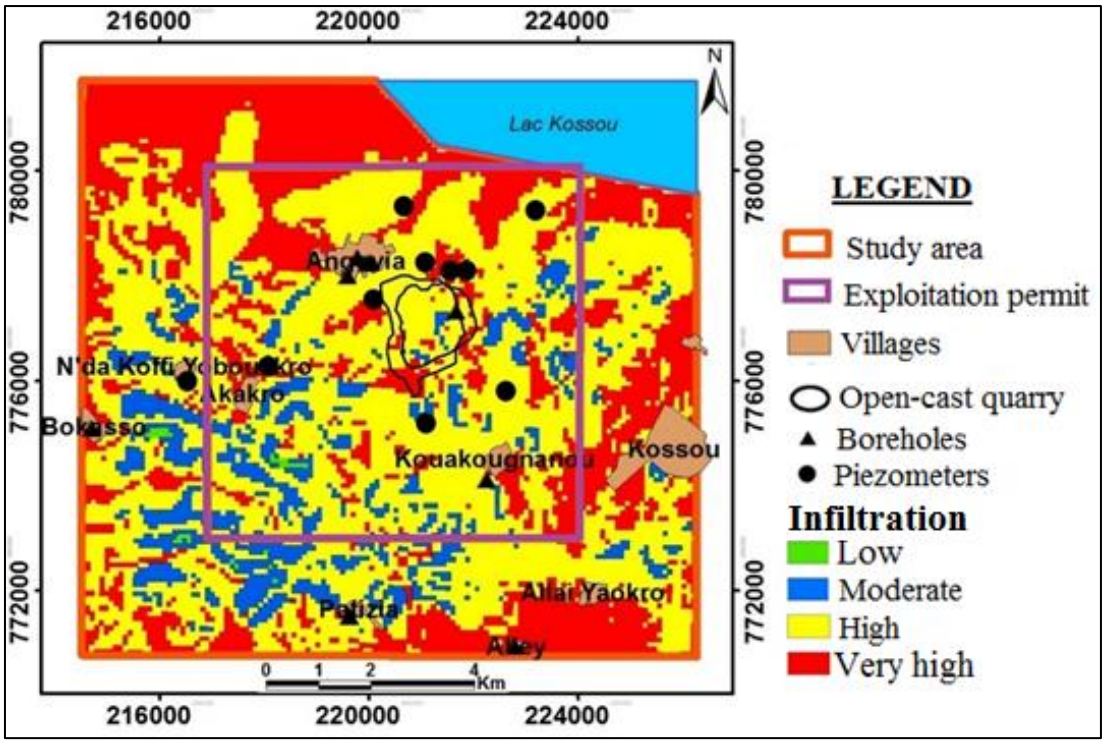


Figure 6:Thematic map of the infiltration factor

3.7 Vulnerability map

Analysis of the overall vulnerability (Vg) map (Fig 7) reveals three classes: moderate, high and very high vulnerability. The moderate vulnerability class covers approximately 10 per cent of the total area of the study area. It occurs exclusively on schist formations and is gene rally associated with areas characterised by moderate slopes. It is mainly located in the central-western and southern parts, with a few isolated occurrences in the eastern part.

The high vulnerability class is by far the most prevalent and accounts for nearly 80 per cent of the study area. It extends across most of the territory and corresponds mainly to areas characterised by moderate slopes and by the coexistence of the area's two main lithological formations, namely schist and granite. This predominance reflects a combination of protective conditions, reservoir characteristics and infiltration patterns that favour the potential transfer of contaminants into groundwater.

The 'very high' vulnerability class accounts for around 10 per cent of the total area. It is distributed sporadically across the entire study area, with a more pronounced concentration in the northern and eastern sectors. These areas correspond to sectors where the combination of protective factors, reservoir characteristics and infiltration is most conducive to the penetration and transfer of potentially contaminating substances into the aquifer. Overall, the predominance of the high and very high vulnerability classes, which together cover around 90 per cent of the study area, reflects the groundwater's high intrinsic susceptibility to contamination from the surface.

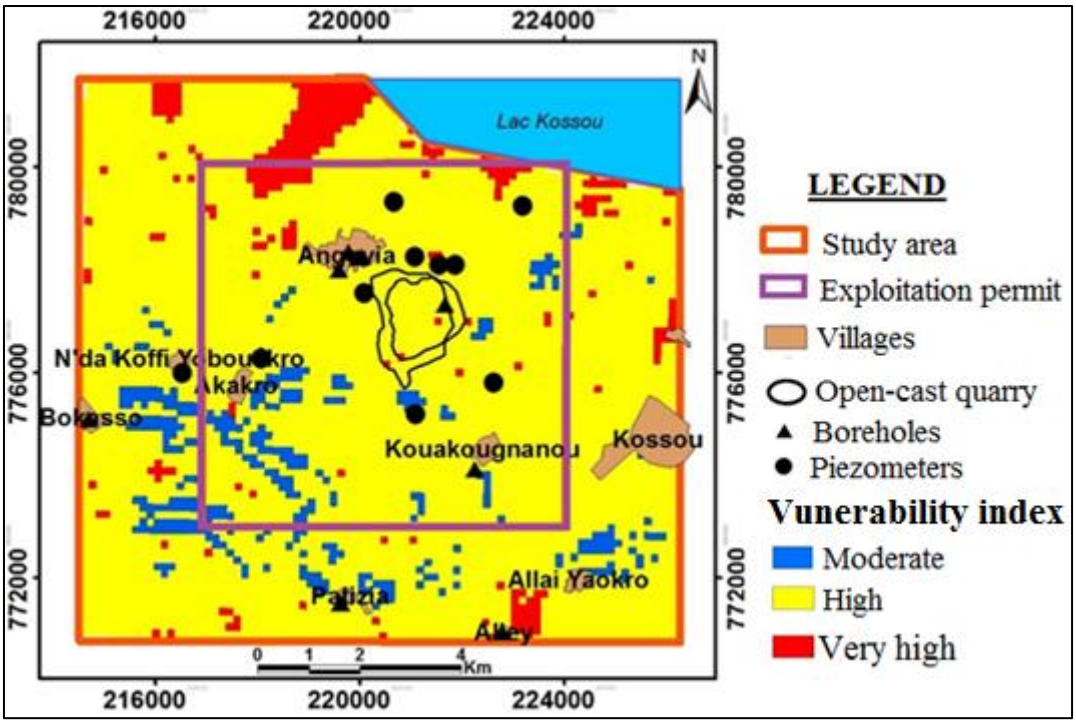


Figure 7: Map of the vulnerability index for the Angovia gold mine

3.8 Validation of the vulnerability map

The validation of the aquifer vulnerability map for the Angovia mine was based on a comparison of the vulnerability classes obtained using the PaPRI method with the results of chemical analyses carried out on groundwater. Several potentially toxic elements were considered, notably copper (Cu), cyanide (CN^-), cadmium (Cd), arsenic (As), lead (Pb) and mercury (Hg). This approach enables an assessment of the spatial consistency between areas identified as highly vulnerable and those exhibiting groundwater quality anomalies.

Statistical analyses highlighted, in particular, a more pronounced spatial variability in lead and mercury concentrations at certain water points, particularly at the ESIA/G8, PZ01 and GW6 wells. These points are located near former quarries or in areas that have experienced significant mining activity and are situated in zones classified as highly vulnerable (Fig 8). This spatial correlation between highly vulnerable areas and the points with the highest Pb and Hg concentrations supports the validity of the map produced using the PaPRI method.

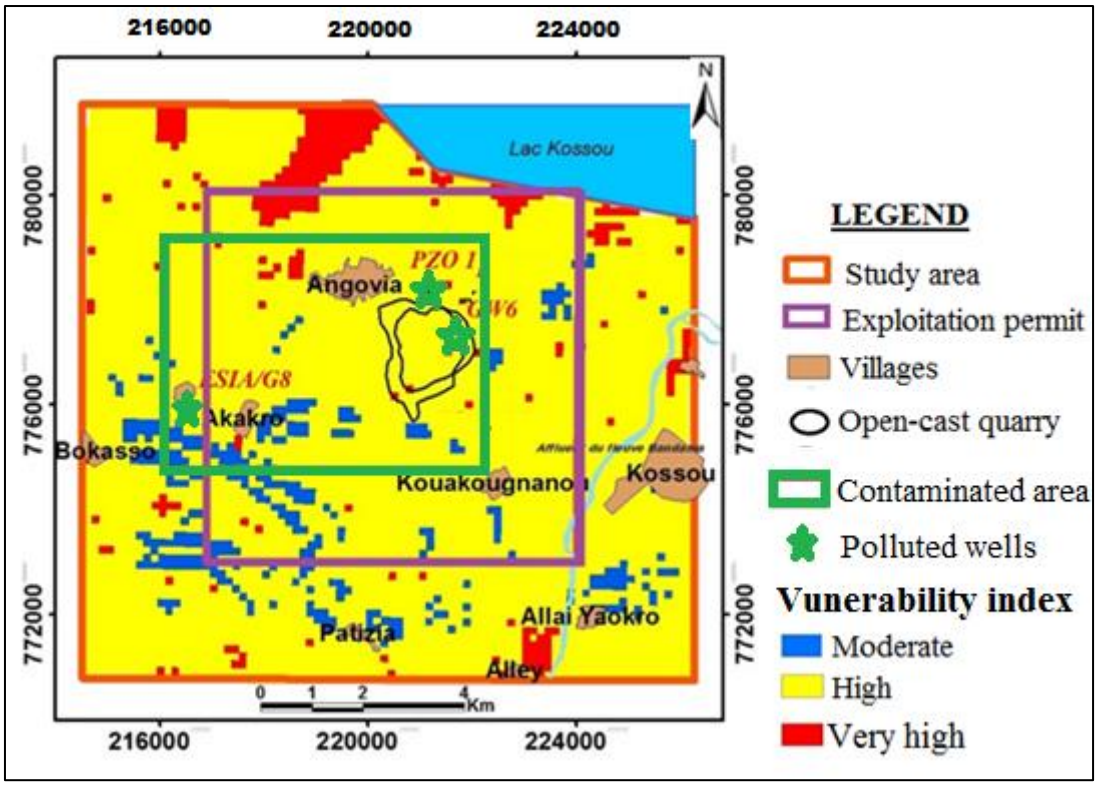


Figure 8*:* Spatial representation of the various contaminated water sources

4 DISCUSSION

The results obtained in the Angovia mining area show spatial heterogeneity in the chemical quality of groundwater, as confirmed by statistical analyses. This variability may result from the interaction between the lithology, weathering and fracturing of the bedrock, recharge conditions and anthropogenic pressures associated with mining activities. Recent studies in various gold-bearing contexts have indeed shown that the composition of groundwater is controlled by a combination of geogenic and anthropogenic processes [24–26], [13], [3], [27].

The relatively low concentrations and low variability of Cu, Cd, CN^- and As ($p > 0.05$) indicate a relatively homogeneous distribution of these elements in the waters studied. This situation may be linked to dilution by recharge water, water–rock interactions and various natural attenuation mechanisms. However, it does not necessarily imply the absence of mining-related influence. The behaviour of cyanide depends in particular on its speciation and on conditions relating to pH, redox potential, biological activity and interactions with metals [28], [29]. Similarly, the mobility of arsenic is strongly controlled by redox conditions and by interactions with Fe and Mn oxides [30], [31]. In the Ivorian context, [26] also demonstrated that groundwater in mining environments can exhibit relatively low mineralisation despite the presence of certain metallic elements.

By contrast, Pb and Hg exhibit significant spatial variability ($p < 0.05$), with particularly marked differences between certain points, notably ESIA/G8, PZ01 and GW6. This heterogeneous distribution may reflect the influence of localised sources, but also that of the hydrodynamic and geochemical conditions specific to each sector. In gold-bearing environments, Hg is a cause for particular concern due to its use in certain extraction processes and its ability to be transferred to various environmental compartments. Variable concentrations of Hg and Pb have been reported in mining areas of West Africa and other gold-bearing regions [32–36]. In Côte d'Ivoire, [37] also demonstrated a differentiated spatial distribution of several trace elements, notably Pb and Hg, around gold mining areas. The results from Angovia are thus consistent with this heterogeneity, although they do not allow these elements to be attributed exclusively to mining activities. Further characterisation of the sources would be necessary to distinguish between geogenic and anthropogenic contributions.

However, the situation observed in Angovia differs from that at certain mining sites where much higher levels of contamination have been reported. In the Tongon area, for example, [38] observed arsenic concentrations exceeding the guideline value in several groundwater samples. Similarly, [36] found concerning concentrations of Cd and Hg in water sources located in a gold-mining area in Ghana. These differences show that the severity of contamination depends heavily on local mining conditions, geology, hydrodynamics and proximity to sources of pollution. Recent work

by [39] and [2] further confirms the diversity of environmental signatures associated with gold mining in sub-Saharan Africa.

The intrinsic vulnerability derived from the PaPRI approach highlights the significant sensitivity of the Angovia aquifer. The 'high' and 'very high' vulnerability classes cover approximately 90 per cent of the study area, whilst 'moderate' vulnerability accounts for only around 10 per cent. This pattern results mainly from the combination of protective conditions, the characteristics of the fractured reservoir and infiltration conditions. In particular, the high proportion of areas with high to very high infiltration rates is a factor that favours recharge, but also the potential transfer of dissolved substances from the surface into the aquifer.

These results are consistent with those obtained by [12] in a fractured aquifer in south-eastern Côte d'Ivoire, which demonstrate the value of incorporating protection conditions, reservoir characteristics and infiltration into vulnerability assessments. In bedrock aquifers, fracturing can increase hydraulic connectivity and facilitate the rapid transfer of contaminants when protection measures are inadequate. The use of the PaPRI method therefore appears appropriate for identifying areas requiring priority monitoring.

Comparing the vulnerability map with hydrochemical data is an important factor in assessing the model's consistency. Areas of high to very high vulnerability represent sectors where the aquifer is naturally more susceptible to contamination from the surface. However, intrinsic vulnerability should not be equated with actual contamination. High vulnerability indicates greater susceptibility of the aquifer system, whilst contamination also depends on the existence, intensity and nature of pollution sources. Thus, the correlation between highly vulnerable areas and the points with the highest concentrations of Pb and Hg supports the consistency of the PaPRI map, but is not sufficient on its own to establish that these elements originate from mining activities.

Recent research confirms the value of an integrated approach combining vulnerability, hydrochemistry and potential sources of contamination. [40] show, in particular, that integrating geochemical and geostatistical analyses enables better identification of pollution signatures in aquifers affected by mining activities. Similarly, the work of [41] and [42] highlights the importance of monitoring water resources in gold-bearing regions subject to increasing pressures.

Overall, the results obtained at Angovia therefore indicate a high intrinsic vulnerability of the aquifer, coupled with spatial heterogeneity in certain trace elements, particularly Pb and Hg. Monitoring of these elements should be stepped up in areas of high and very high vulnerability, particularly around mining, processing and tailings storage sites. Seasonal monitoring and improved characterisation of sources would help to clarify the temporal evolution of contaminants and to distinguish more effectively between natural and anthropogenic contributions. This approach would contribute to the sustainable management of groundwater resources in the Angovia mining area.

5 CONCLUSION

This study assessed the chemical quality and intrinsic vulnerability of groundwater in the Angovia mining area, in central-western Côte d'Ivoire. The results highlight spatial heterogeneity in water quality, as confirmed by statistical analyses. Cu, Cd, CN^- and As generally exhibit low concentrations and low spatial variability, whilst Pb and Hg show significant variations between sampling points. This differentiated distribution likely reflects the combined influence of the aquifer's geological and hydrodynamic characteristics and the anthropogenic pressures associated with mining activities.

The assessment using the PaPRI approach indicates a generally high intrinsic vulnerability of the aquifer, with approximately 90 per cent of the area classified as having high to very high vulnerability. This situation is mainly due to a combination of protection conditions, the characteristics of the fissured reservoir and generally high infiltration rates. The highly vulnerable sectors therefore constitute priority areas for groundwater quality monitoring.

A comparison of the hydrochemical results with the vulnerability map shows that areas classified as highly or very highly vulnerable may facilitate the potential transfer of contaminants from the surface to the aquifer. However, intrinsic vulnerability does not directly indicate actual contamination. Regular water monitoring, particularly for Pb and Hg, is therefore necessary in mining areas and areas of high vulnerability.

Finally, these results highlight the value of combining chemical quality assessment with vulnerability mapping to improve the protection of Angovia's groundwater resources. The introduction of seasonal monitoring, combined with a more precise characterisation of contamination sources and hydrogeochemical conditions, would help to strengthen the sustainable management of water resources in this mining context.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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The authors declare that they have no conflict of interest**.**

Credit authorship contribution statement

Gningnéri Souleymane OUATTARA: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jean-Jacques Hervé KOKOBOU:** Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing**. Jean Michel KOUASSI:** Supervision, Validation, Writing – review & editing. **Oi Mangoua Jules MANGOUA:** Conceptualization, Methodology, Validation, Writing – review & editing. **Yao Emile Desmond KONAN:** Writing – review & editing. **Brou DIBI:** Validation, Writing – review & editing.

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