Assessment of heavy metal pollution in groundwater using a multivariate analysis approach

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Abstract: The current study aims to assess underground water pollution using an integrated approach that combines statistical methods such as principal component analysis (PCA) and water quality diagrams (Piper diagram, Schoeller–Berkalov diagram). A total of twenty water samples were collected from the Tiflet region in the Sebou basin and analysed for various physicochemical parameters, including temperature, pH, and heavy metal concentrations (Cu^{2+}, Zn^{2+}, Fe^{2+} and Pb^{2+}). The average concentrations of Pb^{2+}, Zn^{2+}, Cu^{2+}, and Fe^{2+} in the water samples were found to be 41.9, 14.8, 20.1, and 8.1 mg·dm^{-3}, respectively. These concentrations indicate a significant presence of heavy metals in the groundwater samples. Therefore, it can be concluded that the groundwater in this area is heavily polluted with heavy metals and other pollutants. This finding raises concerns regarding the use of this water for irrigation and agricultural activities in the region. This suggests that these four components play a crucial role in determining the overall water quality. The distribution patterns of the metals Pb^{2+}, Zn^{2+}, Cu^{2+}, and Fe^{2+} in the well water within the study area are of particular environmental concern. It is recommended to establish a monitoring network to ensure the sustainable management of water resources in order to address this issue effectively.

Keywords: groundwater, heavy metals, pollution, principal component analysis (PCA), Tiflet region, water quality

INTRODUCTION

Water, a fundamental element for human survival, holds profound importance due to its indispensable role in sustaining life. In recent decades, mounting concern has arisen regarding the quality of water sources, exacerbated by the escalating proximity of human activities to rivers and groundwater reservoirs, resulting in the infiltration of hazardous substances (El Khoumsi *et al.*, 2017; Lawani *et al.*, 2017). Notably, the assurance of groundwater quality, especially in the context of agricultural applications, assumes pivotal significance in every geographical setting. Pertinently, a contemporary study accentuates the gravity of "widespread contamination", asserting that it poses a graver peril to the sustainable abundance of groundwater compared to mere depletion (Bouchahm, Hecini and Kherifi, 2016).

Several recent studies underscore the imperativeness of safeguarding groundwater quality, underpinning the cause of

sustainability (Bhadra *et al.*, 2016; Bouchahm, Hecini and Kherifi, 2016). Beyond mere suitability assessment, the evaluation of groundwater quality assumes a dual purpose: facilitating its judicious use and devising strategies for its enduring management to cater to both present and future demands encompassing drinking water and crop irrigation. Moreover, the unpredictable precipitation patterns in the Tiflet region introduce another layer of complexity by impacting the chemistry and quality of groundwater.

Nevertheless, the unbridled extraction of groundwater, coupled with human-driven activities, has instigated a perilous trend marked by its over-exploitation and consequential deterioration in quality, inflicting profound socio-economic ramifications upon various Moroccan regions (Chakraborti *et al.*, 2017). This worrisome pattern, mirrored in disparate corners of the globe, underscores the far-reaching consequences of neglecting responsible groundwater management (Chakraborti *et al.*, 2017).

Compounding this issue are geological attributes that wield considerable influence on groundwater quality. The intricate interplay between geological formations and water dynamics, encompassing processes such as dissolution, evaporation, and rock-water interactions, collectively define the primary geogenic forces that shape the quality of groundwater in this specific region.

The contamination of groundwater by heavy metals constitutes a profound and pressing concern with far-reaching implications for human well-being. This insidious pollution not only gives rise to substantial and urgent health challenges but also disrupts ecosystems by unsettling the delicate balance of biodiversity. This unsettling of equilibrium within the natural order subsequently triggers disturbances in the environment itself, as highlighted by Wagh *et al.* (2018).

Given these stark realities, the precise evaluation and continuous monitoring of water pollution emerge as imperative tasks. This is primarily due to the undeniable and immediate impacts such pollution wields over both aquatic life and human health. Mercury (Hg) and lead (Pb), two heavy metals of great concern, possess toxic properties that persist even in low concentrations. Adding to the gravity of the situation, these elements display an alarming trait: their inability to degrade over time. Consequently, they accumulate and proliferate across the entire spectrum of the food chain, intensifying their detrimental influence.

The roster of concerning elements extends further, encompassing iron (Fe), copper (Cu), and zinc (Zn). Being essential micronutrients, these elements become a cause for concern when their concentrations escalate to high levels. Recent research, exemplified by Szabo, Bodolea, and Mocan (2021), has unveiled that their presence at elevated concentrations can severely compromise the physiological well-being of living organisms.

To better grasp the intricacies of water quality, researchers resort to an array of parameters that serve as invaluable mathematical tools. These parameters amalgamate data related to both the physicochemical composition and metal content of water, enabling a comprehensive overview of its quality. The culmination of these efforts is an enhanced understanding of the intricate web of pollution caused by heavy metals and physicochemical pollutants.

The endeavour to comprehend and mitigate this challenge spans the globe, as researchers worldwide engage in extensive investigations to assess the degree of water resource contamination by heavy metals. Unsurprisingly, this escalating concern has catalysed a corresponding surge in the demand for robust water quality monitoring systems. To address this pressing need, there has been a burgeoning interest in the formulation and implementation of indicative methods tailored to gauge the extent of metal pollution. Noteworthy contributions in this domain include studies by Keddari *et al.* (2019) and Talhaoui *et al.* (2020).

In short, the gravity of heavy metal contamination in groundwater necessitates a holistic approach encompassing not only the elucidation of its ramifications but also the development of effective strategies for its assessment and control.

Several studies have extensively examined the quality of the Tiflet groundwater and investigated the relationship between its constituent elements using data mining approaches. Integrated methods, such as principal component analysis (PCA) (Sadat *et al.*, 2011; Zouagui *et al.*, 2018), along with quality assessment charts, were employed to explore the extent and sources of metal pollution.

Heavy metals, which are metallic elements with high density and toxicity at low concentrations, pose a significant environmental and public health concern at both regional and national levels. Their presence in groundwater, including lead, cadmium, zinc, iron, and others, can have detrimental effects on human health, including the development of cancer (Su, 2015). The accumulation of toxic metals in the natural environment is primarily caused by human activities, with soil leaching and chemical inputs being the main sources of heavy metal contamination in water (Dijkstra, Meeussen and Comans, 2004).

Heavy metals can enter water sources through natural processes, such as chemical weathering of bedrock and water catchments, as well as through human activities. Anthropogenic sources of heavy metal contamination include industrial waste disposal, pesticide application, vehicle emissions, and emissions from coal-fired power plants. The extent of pollution is assessed by studying chemical characteristics of water bodies. Numerous studies in the literature have focused on the pollution of water resources by heavy metals worldwide (Khamar, Bouya and Ronneau, 2000; Adjagodo *et al.*, 2016; Lawani *et al.*, 2017; Kpiagou *et al.*, 2022).

The primary objective of this research is to evaluate pollution in surface waters. This involves initially identifying the aquatic facies of the samples under study, followed by quantifying pollution levels. Subsequently, multivariate statistical techniques are applied to determine the sources and potential risks of pollution in underground waters. The findings of this assessment could offer valuable insights for managing the contaminated area situated near agricultural perimeters characterised by a Mediterranean climate and varying rainfall patterns in recent years.

MATERIALS AND METHODS

STUDY AREA

Tiflet is a city in Morocco situated within the eponymous administrative circle, which falls under the province of Khémisset in the Rabat-Salé-Kénitra region. It occupies a strategic position at the regional level, located on the periphery of the Gharb plain, approximately 56 km east of Rabat, the national capital, and the Atlantic coast. The city spans an area of around 10 km^2 and is surrounded by four rural communes: Aït Bou Yahya El Hajjama to the north, Khémis Sidi Yahya to the south, Aït Belkacem to the southwest, and Aïn Johra to the west.

The water supply for the Tiflet area is sourced from the Ganzra dam, which belongs to the Sebou hydrological basin. This dam is situated southwest of the operational zone of the Sebou Hydraulic Basin Agency, west of the Fes-Meknes groundwater table, and northwest of the Maâmora groundwater table. The geological characteristics of the Sebou watershed, to which the Tiflet groundwater table belongs, consist of clay and limestone formations originating from the Middle Atlas Mountains.

SAMPLING

To gain a comprehensive understanding of groundwater quality, a sampling network was established to obtain representative data regarding the spatial variability of the studied elements. This network encompasses the entire study area, extending from

upstream to downstream, and consists of a series of wells. The sampling of water took place between January 2022 and February 2022, with the selection of water points aimed at obtaining a comprehensive overview of the groundwater table across the study area. A total of twenty water samples were collected for analysis of physico-chemical properties and metallic trace elements. During the sampling process, each water point was targeted, and a 500 ml polyethylene bottle, previously rinsed and sealed tightly, was used to collect water samples. This method ensured the preservation of major elements in the water. The bottles were placed in coolers to maintain a suitable temperature and were then transported to the laboratory. Upon arrival, the samples were stored in a refrigerator for further analysis and evaluation (Fig. 1).

SPATIAL PARAMETERS

Geology

The Khémisset-Tiflet zone is situated between the Meseta, which underwent structural changes during the Hercynian phase, and the ridges formed as a result of the Rif orogeny during the Mio-Pliocene period. This region encompasses the geological provinces of the Sehoul Block in its western portion (Tiflet region), while the majority of it lies to the south of the Pre-Rifian ridges.

Hydrogeology

The Tiflet area is located within a well-studied hydrogeological context with significant water resource potential. Its western boundary is defined by the Maâmora and Rharb groundwater tables, while the Fes-Meknes corridor groundwater table marks its eastern limit (ABHS, 2020). Previous studies indicate that the study area shares litho-stratigraphic facies similarities with neighbouring hydrogeological units, such as Maâmora to the north and northwest, Rharb to the northeast, and the Meknes basin to the east.

Hydrology

The area contains two groundwater tables: the shallow water table, which circulates within alluvial formations comprising sands, sandstones, and limestones, and the deep water table, composed of Lias limestones. Geophysical studies have identified the presence of a groundwater table in the region of Oued Beht, which corresponds to the basal part of Sinemurian limestones (lower Lias) and the sandstone limestones of the Burdigalian in its upper part. The roof of the water table dips eastward toward the Sais basin, while the lenticular Lias limestones are found to the west. Marly formations of Miocene age separate the deep aquifer from the shallow one. Underground flow occurs from south to north, and the piezometric level of the shallow water table ranges from 50 m in the northern area near the El Kansera dam to 400 m in the eastern and southern parts of the region (Sfassif and Khémisset communes).

The flow direction of the shallow groundwater is from the higher elevation zones towards the north of the El Kansera dam. This flow appears to converge on both sides of the Beht River, indicating a hydraulic relationship between the river and the groundwater table. While the shallow groundwater table may benefit from infiltration of precipitation, the recharge of the deep groundwater table is limited to a few outcrop areas of the Lias formation in the western part of the Tiflet region (ABH, 2020).

METHODS

Physico-chemical analysis

The physico-chemical parameters (temperature, pH, Cd) were measured using a multiple probe (Probe Holder, Standard, Portable hach) that was calibrated before each sampling campaign (Rodier, 2009). Major elements (Mg^{2+}, Ca^{2+}, HCO_3^-, Na^+, K^+, Cl^-, SO_4^{2-}, CO_3^-, Cd^{2+}, Pb^{2+}, Zn^{2+}, Cu^{2+}, Mn^{2+}, Fe^{2+}) were analysed through ion chromatography (ICS 1100 from Dionex) at the chemical analysis centre of the scientific institute in Rabat. The concentrations were reported in $meq \cdot dm^{-3}$.

Elemental toxic metals (ETM) analysis

The concentration of metallic trace elements was measured using an Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES) with argon plasma. The X-ray diffractometer employed was the X'Pert Pro, equipped with an ultrafast X'Celerator scintillation detector.
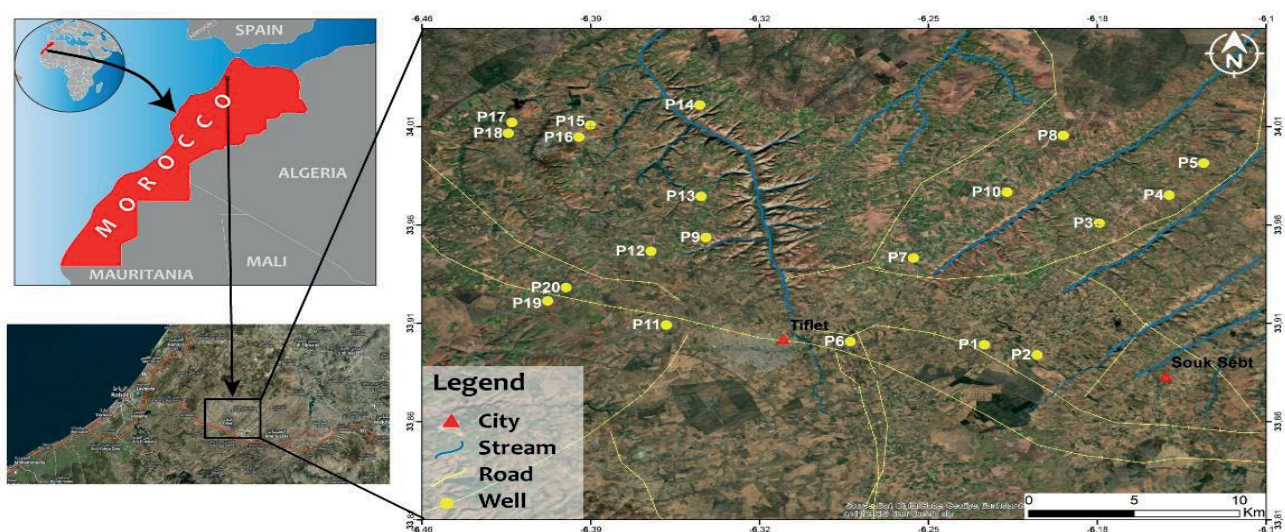

Fig. 1. Location of wells (P1–P20) studied in the Khemisset Tiflet region; source: own elaboration

Piper diagram

Piper diagram is utilised to represent the chemical facies of a collection of water samples. It consists of two triangles representing the cationic and anionic facies, respectively, and a diamond that synthesises the overall facies.

Schoeller–Berkalov diagram

Schoeller–Berkalov diagram is employed to depict the chemical facies of multiple waters. Each sample is represented by a broken line, while the concentration of each chemical element is indicated by a vertical line on a logarithmic scale. The broken lines connect the points representing different chemical elements, and intersections of the lines highlight changes in chemical facies.

Principal component analysis (PCA)

The principal component analysis (PCA) is a statistical technique used to analyse and visualise datasets containing quantitative variables and multiple individuals. It is particularly useful in capturing the variance present in large datasets with numerous variables, making it an efficient tool for pattern recognition (Zouagui *et al.*, 2018). The PCA helps to identify the most significant data components or patterns, allowing for a more comprehensive understanding of its structure and relationships.

RESULTS AND DISCUSSION

GROUNDWATER QUALITY

The evaluation of groundwater quality involves the examination of pollution parameters (Mehdaoui and Mahboub, 2019) and the interpretation of overall quality using a simplified grid (Nouayti,

Khattach and Hilali, 2015) that includes pollution indicators (Dimane *et al.*, 2017) such as physicochemical properties and ETM (elemental trace metal) concentrations.

Table 1 presents results of the physico-chemical analysis and the concentrations of heavy metals. The pH parameter exhibited values ranging from 7.9 to 7.4, with 7.6 and 0.4 being the maximum, minimum, mean, and standard deviation, respectively. The electrical conductivity (EC) varied from 0 to 2.3 mS·cm^{-1}, with an average of approximately 1.09 mS·cm^{-1}. These elevated values appear to be attributed to the leaching from the rock formations accumulating water. The higher EC levels may also be linked to the Triassic salt deposits coming into contact with the groundwater reservoir through significant fault lines that dominate the structure of the Sebou basin, as well as the utilisation of fertilisers.

The concentrations of Mg^{2+} and Ca^{2+} in the well water samples ranged from 9.5 to 25.82 mg·dm^{-3} and from 32 to 140.80 mg·dm^{-3}, respectively. The mean concentration of Na^+ ranged from 32.31 to 69.23 mg·dm^{-3}. The concentration of K^+ in the water was determined to be between 0 and 3.92 mg·dm^{-3}. The HCO_3^- concentrations varied from 141.52 to 288.23 mg·dm^{-3}, while CO_3^{2-} concentrations ranged from 6 to 30 mg·dm^{-3}. Bicarbonate was found to be present in higher concentrations compared to carbonate ions. The Cl^- concentrations in the water samples ranged from 84 to 623 mg·dm^{-3}, while the SO_4^{2-} concentration ranged from 4.14 to 84 mg·dm^{-3}.

Additionally, Table 1 displays the Moroccan groundwater pollution limit standards for ETM. The average concentration of Cu^{2+} was found to be 29.65 μg·dm^{-3}, Fe^{2+} approximately 13.65, 2.54 for Pb^{2+} and 9.20 μg·dm^{-3} for Zn^{2+}, all within the Moroccan control standards. According to the Moroccan standards, Cd^{2+} and Mn^{2+} levels in the well water samples from the study area

Table 1. Basic statistics of metals in the samples studied compared to Moroccan standards

Parameter	Min.	Median	Max.	Avg.	SD	Moroccan control standard[1]
pH	7.30	7.49	7.65	7.48	0.11	6.5–8.5
EC (mS·cm^{-1})	0	1.10	2.30	1.09	0.57	<1300
Ca^{2+} (mg·dm^{-3})	32.00	76.80	140.80	75.52	25.50	<200
Na^+ (mg·dm^{-3})	32.31	41.54	69.23	46.38	12.72	<20
K^+ (mg·dm^{-3})	0	3.92	3.92	3.72	0.88	10–15
Mg^{2+} (mg·dm^{-3})	9.51	17.29	25.82	17.26	4.55	<50
HCO_3^- (mg·dm^{-3})	141.52	171.87	288.23	187.10	40.94	<518
CO (mg·dm^{-3})	6	12	30	13.40	6.06	–
SO_4^{2-} (mg·dm^{-3})	4.14	17.88	84	26.63	20.12	<250
Cl (mg·dm^{-3})	84	227.50	623	272.13	168.24	<300
Zn (μg·dm^{-3})	2	8.50	19	9.20	5	<1
Cu (μg·dm^{-3})	3	31	64	29.65	17.94	<0.05
Fe (μg·dm^{-3})	8	12	33	13.65	5.52	<1
Mn (μg·dm^{-3})	0	1.50	19	3.70	4.90	<13
Cd (μg·dm^{-3})	0.20	0.70	0.80	0.59	0.19	<3
Pb (μg·dm^{-3})	0.80	2.40	4.30	2.54	1.01	<10

[1] Arrêté (2002).
Source: own study.

were below the detection limits, registering values of 0.59 and 3.70 $\mu g \cdot dm^{-3}$, respectively.

The analysis of Piper diagram (Fig. 2) reveals that the samples obtained from the study area exhibit diverse facies. Specifically, samples P2, P3, P10, P13, P17, P18, P19 and P20 indicate a chloride-dominant facies with sulphated calcium and magnesium. Samples P1, P8, P9, P14, P15, and P17 display a facies characterised by chloride, sodium, and potassium. Lastly, samples P18, P19, and P20 exhibit a facies consisting of bicarbonate, calcium, and magnesium (Fig. 3).
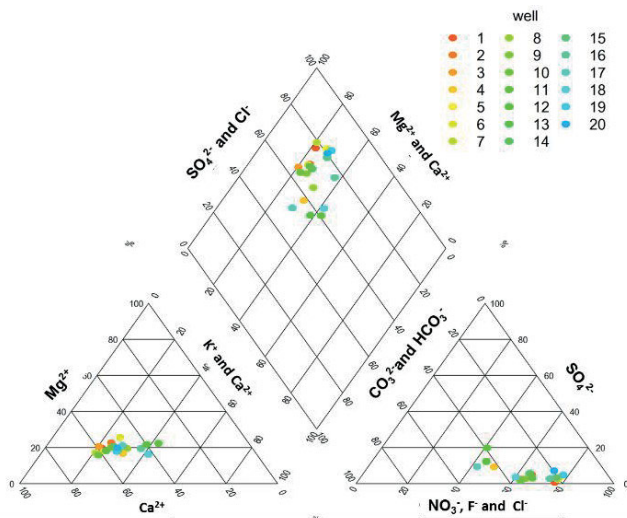

Fig. 2. Piper diagrams representing all water categories in the study area; source: own study

The presence of elevated salt content in the water can be attributed to the intensive use of fertilisers and pesticides during the agricultural season, which is characterised by irregular rainfall and high temperatures (Manaouch, Zouagui and Fenjiro, 2020).

The Schoeller–Berkalov diagram was employed to analyse the chemical composition of each sample. The results of the chemical analysis indicate that the majority of the samples exhibit a similar chemical profile for ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-},
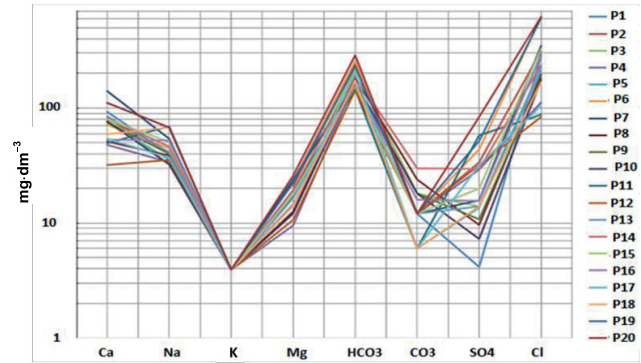

Fig. 3. Identification of well water facies by Schoeller–Berkalov diagrams; source: own study

HCO_3^-, and CO_3^-. However, wells P2, P19, and P6 display higher concentrations of chloride (>100 mg·dm^{-3}) compared to the other samples. In terms of cation concentrations, the 20 samples demonstrate elevated levels of Na^+, while approximately half of the samples (including samples P5, P6, P7, P8 and P9) exhibit medium concentrations of Mg^{2+} exceeding 10 mg·dm^{-3}. However, the remaining samples show lower concentrations of K^+ (<10 mg·dm^{-3}) – Figure 4.

STATISTICAL APPROACHES TO RESULTS

To analyse the extent of metal and chemical pollution and identify its source, a principal component analysis (PCA) was conducted. The findings of the PCA, carried out using R software, are presented in Figure 4 and Table 2.

Table 2 indicates that it is recommended to select factors that account for more than 64% of the cumulative variation. In this study, five factors, Dim1 to Dim5 were identified, which collectively explain 64% of the total variance. Specifically, Dim1, Dim2, Dim3, Dim4, and Dim5 account for 23%, 17%, 9%, 8%, and 6% of the variance, respectively.

Component (1) exhibits a high loading for Na^+, Fe^{2+}, Cl^-, Mg^+, HCO_3^-, Ca^{2+} and SO_4^{2-} (Fig. 4a). The elevated dissolved concentrations of these ions directly contribute to the high values
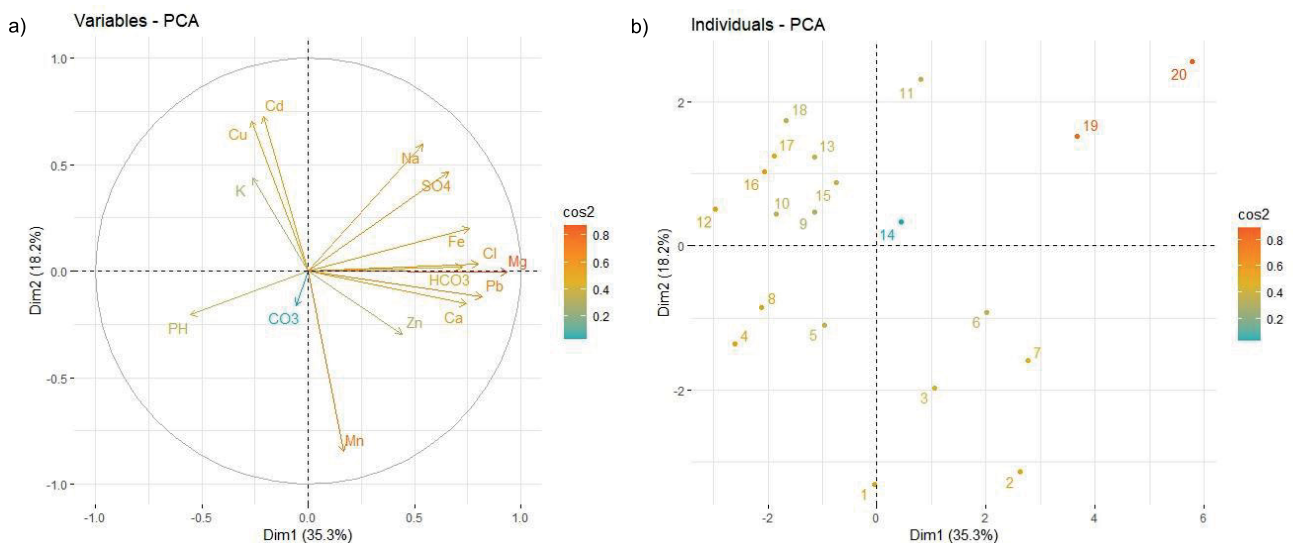

Fig. 4. Findings of principal component analysis (PCA): a) projection of the statistical variables in the factorial plan Dim1–Dim, b) representation of the water points of the factorial plan Dim1×Dim5

Table 2. Variables of principal component analysis (PCA)

Specification	Dim1	Dim2	Dim3	Dim4	Dim5
Zn^{2+}	0.443604	−0.29592	0.564038	−0.31139	0.085675
Cu^{2+}	−0.26724	0.704626	0.197073	0.003074	−0.06564
Fe^{2+}	0.759733	0.202078	−0.20034	−0.00296	0.071475
Mn^{2+}	0.165093	−0.84712	0.008455	−0.28038	−0.09207
Cd^{2+}	−0.20985	0.72484	−0.00505	0.042619	−0.19812
Pb^{2+}	0.820067	−0.12038	−0.1056	0.291617	−0.33803
pH	−0.55281	−0.20646	−0.242	−0.28335	0.540332
Ca^{2+}	0.744759	−0.15504	0.517336	0.172021	−0.03475
Na^+	0.540491	0.593945	0.176694	−0.3034	−0.0478
K^+	−0.26235	0.43552	0.489343	0.093297	0.478241
Mg^{2+}	0.935149	−0.00551	0.105698	0.020564	0.006799
HCO_3^-	0.724863	0.019511	−0.36716	0.016801	0.321206
CO_3^-	−0.05529	−0.16203	−0.01831	0.872862	0.250968
SO_4^{2-}	0.661098	0.463122	−0.46997	−0.1675	0.06016
Cl^-	0.800251	0.033972	0.036976	−0.01426	0.439583
Variance (%)	23	17	9	8	6
Cumulative (%)	23	40	49	58	64

Source: own study.

of Cl^-. These parameters are widely distributed in samples 20, 19, and 14 (Fig. 4B). Chloride displays a moderate positive charge, which can be attributed to significant hydrothermal water circulation in the study area (Hafiane *et al.*, 2020b).

Component (2) is characterised by high loadings of Mn^{2+}, CO_3^-, K^+, Cu^{2+}, and Cd^{2+}, which are notably distributed in wells 18, 13, 17, 10, 12, 13, 15, and 16. The high positive charge of Cu^{2+} and Cd^{2+} may result from the oxidation of sulphides present in geological deposits. The presence of potassium can be attributed to the use of fertilisers, pesticides, and wastewater discharges in the area. The positive charge of Cu^{2+} is likely associated with the leaching of chemical inputs present in the study area.

The negative pH distribution observed at wells 4, 5 and 8 can be attributed to sulphide oxidation, which generates an acidic environment along with the presence of sulphate (Singh *et al.*, 2016; Amar *et al.*, 2021). Component (1) is strongly associated with HCO_3^-, Pb^{2+}, Zn^{2+}, and pH. It exhibits high scores in well samples 3, 6, 7, and 2. The elevated positive charge of Zn^{2+} may originate from anthropogenic sources such as domestic sewage and intensive agricultural activities. The presence of HCO_3^- and Mn^{2+} is linked to the dissolution of carbonate formations encountered in the area (Laghzal and Nouayti, 2018).

DISCUSSION

The concentrations of heavy metals in the water samples are found to be influenced by certain physicochemical parameters such as conductivity, pH, and alkalinity. It is widely recognised that the solubility of heavy metals increases as the pH decreases, shifting from alkaline to acidic conditions. Moreover, the levels of elemental toxic metals (ETM) are found to be directly associated

with other pollutants present in the water. Chemical analyses reveal that the overall contamination of water tends to increase progressively in the direction of water flow (Vuppala and Reddy, 2007). The lowest contamination values are typically observed in the central region of the underground water, which is sourced from depths >30 m and mainly comprises superficial infiltration from the rivers descending from Sebou. Conversely, the most vulnerable zone is characterised by a lower piezometric level and intensified agricultural activities, which contribute to increased contamination risks. The identification of pollution sources is conducted through basic statistical analysis of extreme values and the use of Piper and Schoeller–Berkalov diagrams to identify facies. The well waters in the study area generally exhibit homogeneous characteristics of mixed bicarbonate type, as discussed earlier. However, it is enriched with certain concentrations of chlorides and carbonates. Over the years, there has been an increase in conductivity and the concentrations of chlorides, sodium, calcium, sulphates, and magnesium. The main sources of sulphates in the study area include atmospheric deposition, oxidation of sulphide minerals, application of sulphate-based fertilisers in agricultural lands, and human influences such as domestic sewage (Sidle *et al.*, 2000; Wayland *et al.*, 2003; Khadija *et al.*, 2021). Elevated levels of sodium (Na^+) and potassium (K^+) can be attributed to the presence of rock minerals containing these elements, which are naturally abundant and highly soluble in water. The elevated concentrations of metals (such as Pb^{2+}, Cu^{2+}, and Zn^{2+}) in the well waters, exceeding the established standards, are associated with natural processes resulting from water-rock interactions of geological origin. The pollution is linked to the contact of water with the Zn-Pb deposit in abandoned mining sites, and the release of these metals is facilitated by the erosion of volcanic rocks due to wind and

precipitation (Nouayti *et al.*, 2020). As indicated by Manaouch, Zouagui and Fenjiro (2020), water erosion significantly contributes to soil redistribution in the study area. These heavy metals (Zn^{2+} and Pb^{2+}) can be dispersed in the area following rainfall events.

CONCLUSIONS

The analysis of heavy metal concentrations in water samples highlights the influence of various physicochemical parameters, including conductivity, pH, and alkalinity. The inverse relationship between heavy metal solubility and pH underscores the impact of shifting from alkaline to acidic conditions. The presence of elemental toxic metals (ETM) is directly correlated with other pollutants present in water bodies. The study reveals a progressive increase in water contamination along the direction of water flow, with central underground water areas sourced from deeper depths displaying lower contamination levels. In contrast, areas with lower piezometric levels and intensive agricultural activities exhibit higher contamination risks. Pollution source identification employs statistical analysis of extreme values and the utilisation of diagrams like Piper and Schoeller–Berkalov to discern facies.

The uniform chemical profile of well waters in the study area predominantly falls under the mixed bicarbonate type, albeit with elevated chloride and carbonate concentrations. The passing years have witnessed rising levels of conductivity, chlorides, sodium, calcium, sulphates, and magnesium. The presence of sulphates can be attributed to atmospheric deposition, sulphide mineral oxidation, fertiliser application, and anthropogenic inputs. Similarly, high sodium and potassium levels are naturally attributed to rock minerals rich in these elements. However, the excessive concentrations of metals such as Pb^{2+}, Cu^{2+}, and Zn^{2+} exceeding set standards stem from natural water-rock interactions, especially with the Zn-Pb deposit in abandoned mining sites. Wind and precipitation-induced erosion of volcanic rocks exacerbate the release of these metals into the water, as highlighted by past studies. Notably, water erosion plays a substantial role in soil redistribution within the study area, contributing to the dispersion of heavy metals like Zn^{2+} and Pb^{2+} following rainfall events.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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