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Research Article

Geological and Anthropogenic Sources of Tin, Zinc, Cadmium, and Vanadium in Western Sokoto Basin Using Multivariate Statistical Analysis

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Abstract

This study investigates the geological and anthropogenic sources of Tin, zinc, cadmium, and vanadium in the western Sokoto Basin, employing multivariate statistical analysis to understand their distribution, interactions, and implications for groundwater quality and environmental management. In Western Sokoto, Nigeria, this research investigates water quality in terms of temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity (TUR), and concentration of some heavy metals such as zinc (Zn), cadmium (Cd), vanadium (V), and Tin (Sn). The study employed both in-situ and laboratory analysis. The physical parameters were analysed in situ using hand-held meters. Heavy metals were analysed using an MP-AES machine (Model 4200). The study further applied Principal Component Analysis to analyse the data. Based on Principal Component Analysis (PCA) among the parameters, the results showed that EC, TDS, Zn, and V can be described as highly correlated. The combination of these parameters explains 33.042% of the total variance in water quality. In addition, Sn independently accounts for 21.863% of independent information, thus giving a total explanation of 55% overall variability of the dataset. Spatial examination shows different effects of these pollution sources, industrial and agricultural activities, on contamination levels in water quality. The unmitigated concentrations of Cd and Sn's incidences pose high environmental and public health threats**.** The findings highlight the important role of dissolved ions and heavy metal concentrations on water quality effects that significantly affect regional water resources management. Amongst the significant recommendations are continuous monitoring of water quality to identify pollution hotspots, enforcement of pollution control measures, and targeted remediation in areas with high levels of Cd and Sn. Awareness of water contamination risks and strengthened environmental policies on waste management and water protection are also necessary for sustainable water quality management. The study, therefore, emphasises localized strategies to mitigate contamination and protect water resources concerning the western part of the Sokoto basin.

Keywords

Heavy Metals, Correlation Analysis, Principal Component Analysis, Shallow Groundwater, Sokoto Basin

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1. Introduction

Groundwater contamination is growing worldwide, especially where natural hydrogeology meets anthropogenic activity [1, 2]. Tin (Sn), zinc (Zn), cadmium (Cd), and vanadium (V) are some of the most immediate pollutants as they are toxins, persistent and bioaccumulative. Groundwater availability for drinking water, food production and industrial processes is critically important, but heavy metal contamination is catastrophically health and environmental. Globally, groundwater pollution with heavy metals has come from many directions: from industrial discharges and mining to agricultural runoff and mineral-poor rocks [2, 3]. Geological and human influences usually reinforce them and create tricky water quality problems.

The Western Sokoto Basin in Nigeria is a clear example of such integration of geology, people and activities. This region has climate is mainly arid to semi-arid water and resources; therefore, such relies on groundwater for water supply for domestic and agricultural uses [4, 5]. The basin has a geology complex, which has been further compounded by increasing anthropic activities, thus making the water quality a significant concern [6, 7]. The issues of heavy metals contamination of the shallow groundwater in the basin cannot but provoke important sources, questions and movement of these metals. It is important to determine the effects of geology and human activities in this region to manage and control heavy metal pollution properly.

Geologically, the Western Sokoto Basin is underlain by varied lithologies, including sedimentary sequences hosting metallic minerals. The dissolution and oxidation of these mineral-rich rocks through natural weathering may release heavy metals into the groundwater system [8, 9]. For instance, Tin and zinc could be derived from the decomposition of sulfide minerals such as casseterite and sphalerite, common in sedimentary and igneous rocks [10, 11]. It works with zinc minerals and will be mobilized in some geochemical conditions. Most of the vanadium also undergoes association with shales and other organic-rich sedimentary deposits [12-14]. The pH, redox-potential, and/or organic matter content determines its geochemical behavior, ensuring mobility and bioavailability or not in groundwater.

In addition to these natural processes, anthropogenic activities significantly amplify the heavy metal burden in the Western Sokoto Basin. Artisanal mining, one of Nigeria's standard practices, is pivotal in mobilizing heavy metals [14]. Mining operations disturb the geological strata, exposing mineral deposits to oxidation and leaching. The use of chemicals in mining processes further contributes to metal pollution, often exacerbating groundwater contamination. Agricultural addition to the basin also accounts for heavy metal loading, such as fertilizers and pesticides, which may contain trace metals, including cadmium and zinc [15, 16]. These metals leach through the groundwater over time through shallow water tables and permeable soils.

Other sources include urbanization and industrial activity. In addition, waste disposal in the Western Sokoto Basin typically occurs without adequate waste treatment [17]. This results in untreated or poorly treated effluents being released directly into the environment. It is further in position to contain very high concentrations of heavy metals, percolating down through the groundwater body. Another emerging environmental issue is fossil fuel and electronic waste-burning; metals such as vanadium and cadmium have been reported to be associated with such activities [18]. These anthropogenic factors, in combination with the limited regional capacity for waste management and pollution control, may pose severe threats to groundwater quality.

Aquifer heavy metal pollution has been widely reported as an outcome of different human activities [19, 20]. Chronic intakes of some metals, such as cadmium and vanadium, may cause health disorders, including kidney dysfunction, bone demineralization, and cancer risks. While zinc is essential in trace quantities, it is toxic at higher concentrations and may cause damage to the nervous and immune systems [21]. Though less commonly considered an environmental pollutant, Tin has been implicated in neurological and reproductive disorders. The global relevance of these findings underlines the urgency with which heavy metal contamination needs to be addressed, especially in regions like the Western Sokoto Basin, where groundwater is a key resource. Such geological and anthropogenic factors interplay in the Sokoto Basin gives rise to unique challenges. While the basin's geology is a natural source of heavy metals, their mobilization and distribution have been escalated through human activities [22, 23]. The semi-arid climate complicates this with limited groundwater recharge that might contaminate contaminants in the aquifer. Challenges like these require understanding heavy metal pollution's sources, pathways, and controls [24].

Multivariate statistical analysis is an effective tool to unravel the contribution of geologic and anthropogenic sources to groundwater contamination [25, 26]. From patterns and correlations in hydrochemical data, this approach can identify the dominant source of heavy metals and their spatial distribution within the basin. This insight is key to proposing targeted interventions and improvements in mining practices, strict waste management regulation, or increased monitoring of agricultural inputs. Ultimately, protecting the groundwater quality in the Western Sokoto Basin is a multidisciplinary effort involving hydrogeology, Environmental Science, and policy-making to address both natural and human-induced challenges.

2. The Study Area

2.1. Location and Climate

Western Sokoto basin is part of the larger Iullemmeden basin, which is one of the largest inland basins in West Africa. It occupies more significant portions of Northwestern Nigeria and lies in the Sudan belt of Africa, usually classified as semi-arid in the Savannah zone. Sokoto basin covers an estimated land area of 65,00 sqkm. It is located between Longitude. 3° and 7°E and Latitude. 10° and 14, as shown in Figure 1. The study area has dry and wet seasons, and the climate is semi-arid and hot tropical [5, 27, 28]. Generally, temperatures are high, with significant disparities between seasons. The mean maximum temperature is highest in April (40°C), and the mean minimum temperature is lowest in December (25°C), as shown in Figure 2a.

Annual rainfall varies significantly and increases southwards. Annual rainfall varied from 500mm to 900m from the eastern parts of the basin (Figure 2b). In the extreme south, annual rainfall is above 1200mm. The relative humidity is highest in July and August (>60%), as Figure 2c indicates. The evaporation rate is generally high, and potential annual evaporation exceeds 2500 mm [29]. The River Rima-Sokoto network drains the study area, creating the key drainage system. The critical tributaries of the River Rima-Sokoto system are Gayan Gulbe, Zamfara, Gulbin Ka, Kware, Gajere, and Bunsuru [30].

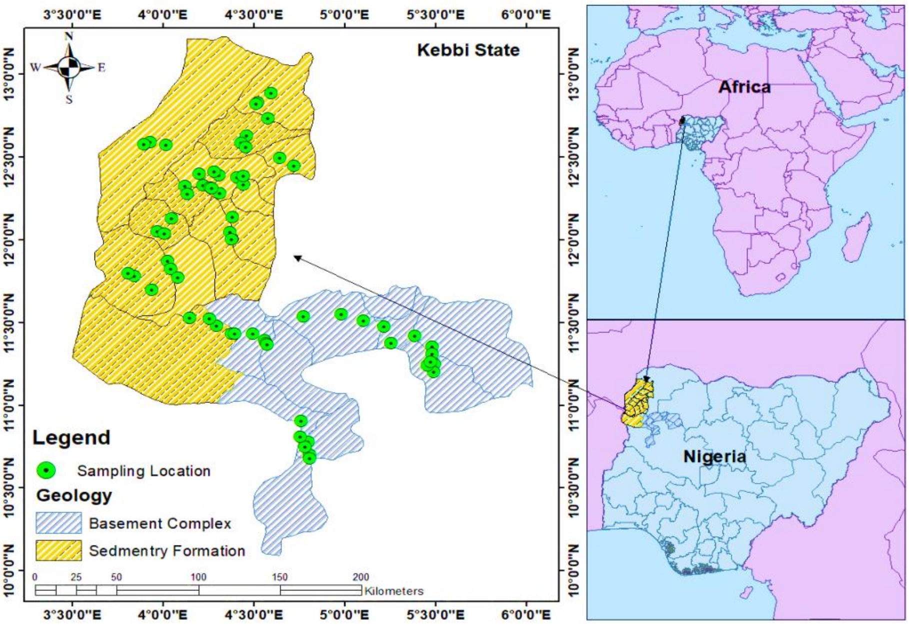

Figure 1. *Map of Nigeria Showing Kebbi State.*

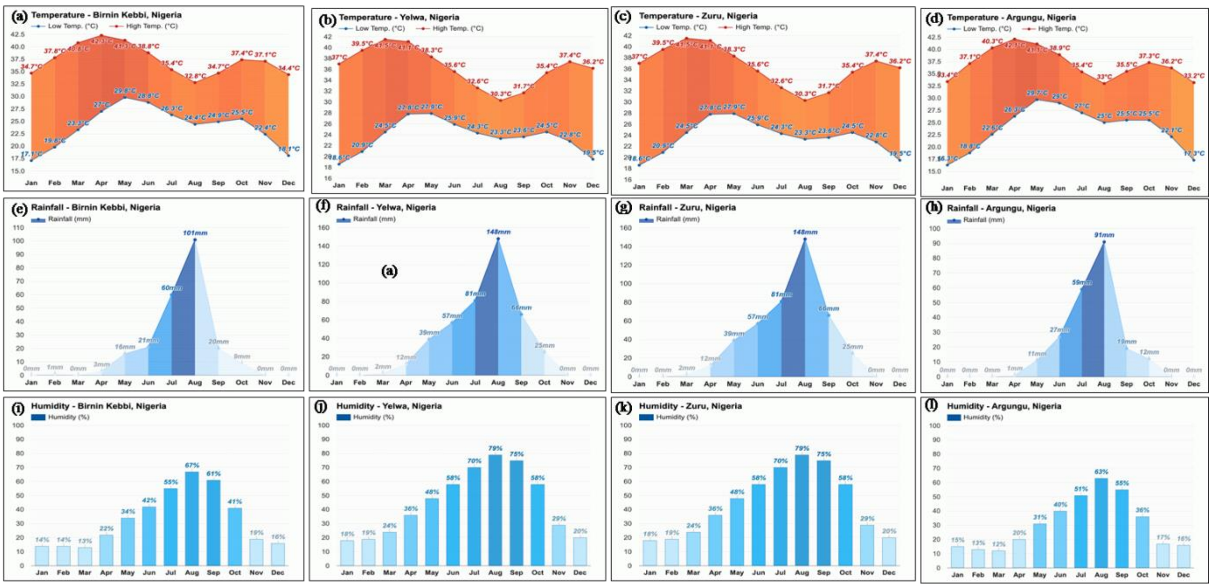

Figure 2. *Variability of Climatic variables (a) Temperature, (b) Rainfall, and (c) Humidity.*

2.2. Geology and Hydrogeology

The Sokoto basin's sediments were deposited over three phases (Figure 3). These are Continental Tertiary, Paleocene Marine Maastrichtian, and Mesozoic deposits [31]. The geological and stratigraphical depiction of the Sokoto basin has been analysed extensively in the literature [30, 32-34]. Gwandu Formation is the best-known aquifer in the Sokoto basin, and it is recharged primarily from overflow and infiltration over the outcropped area.

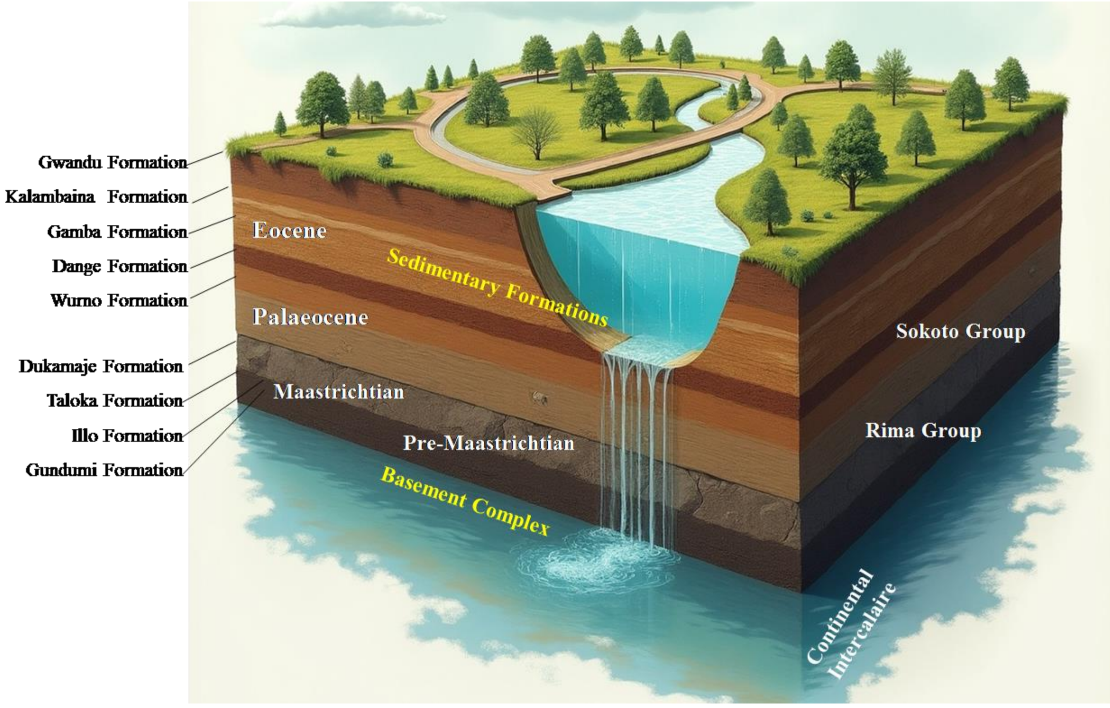

Figure 3. *Hydrogeological cross-section of Sokoto Basin.*

Shallow groundwater abstraction is mainly from shallow wells, increasing due to irrigation, urbanisation, and industrialisation [30, 35]. Although prolific aquifers are in the study area, many settlements still lack access to good-quality drinking water [36-38]. The soil types in the Sokoto basin are mainly sandy and acidic, with a pH level varying from 4.6. to 5.4. the soils are made up of limestone, clay and sand. The dominant mineral is quartz, with traces of kaolinite [39]. The soils are classified as Ustic Quartzipsamment and Typic Ustipsamment. The soil may not be appropriate for irrigated agriculture due to its coarse texture [39]. The study area has phosphate deposits in the shales of the Dukamaje and Dange formations and limestone from the Kalambaina Formation.

The Crystalline Rocks of the pre-Cretaceous age underlie the sedimentary formations [40]. The outcrops of these formations formed the highlands areas in the east and west of the basin. The Crystalline Rocks comprised plutonic granite of igneous derivation and weathered metamorphic rocks, primarily schist, gneiss, quartzite, and phyllites [41]. Groundwater potential is generally low, and water is obtained from tabular partings, fissures, and regoliths. The fissures of the Crystalline Rocks are generally above a depth of 91.44 meters(m). However, the borehole yields are generally low and are associated with high drawdowns [35]. Hydrogeologically, the Gundumi and Illo Formations contain aquiferous layers. The Gundumi and Illo formations' outcrop area constitutes about 30% of the Sokoto basin's total area. The most comprehensive discussion on the groundwater condition of the Gundumi Formation was provided by Anderson and Ogilbee [35].

2.3. Land Use

Various human activities, comprising livestock, extensively graze in the fallow and uncultivated lands. Shifting cultivation is widely practised in the highland areas, though it is reducing because of rising population and urbanisation. In areas where surface water is accessible easily, irrigation farming is widely practised, especially along floodplains during the dry season [42, 43]. Other human activities, including agriculture, imply more grab for land, which increases deforestation, shallow groundwater extraction, and waste generation [44]. Significant drivers of shallow groundwater extraction in the Sokoto basin include the pressing need for housing, economic development, and irrigation farming. Thus, the risk of shallow groundwater pollution by phosphate and heavy metals pollution of shallow aquifers from human activities is expected in the Western Sokoto basin.

The western Sokoto Basin's land use/land cover (LULC) is characterized by a mix of agricultural fields, sparse vegetation, and settlements, reflecting semi-arid climatic conditions and anthropogenic activities. Predominantly rain-fed agriculture dominates, with millet, sorghum, and cowpea as primary crops. Overgrazing and deforestation, driven by livestock rearing and fuelwood demand, exacerbate soil erosion and land degradation. Urbanization and expanding settlements further alter natural landscapes. Limited vegetation cover reduces soil stability, while seasonal rivers influence land use patterns. Understanding LULC dynamics is crucial for sustainable resource management, mitigating environmental degradation, and promoting climate-resilient livelihoods in the region.

3. Materials and Methods

3.1. Selection of Sampling Sites

The sampling sites cover the entire Western Sokoto Basin (i.e., Kebbi State). However, three representative shallow groundwater samples were collected from three communities in 21 local government areas (LGAs) or clusters during the dry (April), wet (September), and intermediate (December) seasons. All sample bottles were acidified during the sample collection by directly adding a small amount of concentrated nitric acid to the sample bottles upon collection of water samples to maintain low pH and preserve metal ions in the solution. Samples were collected from public wells (Dud wells, Hand pumps, and Motorised boreholes) presently in use [45]. Sample bottles were entirely filled with water samples to remove air foams and carbon-based particulate matter captured in the bottles [46]. This technique will prevent the incidence of biochemical and surface reactions in the water samples, which tend to experience a reduction process during storage and transportation. Water samples were stored below 5°C [47]. Water analysis was performed within seven days. The method's accuracy was assured by triplicate analysis for quality control procedures. Repetitive duplicates from each sampling station were collected at all sampling periods to raise analysis power.

3.2. Collection of Samples and Laboratory Analysis

Shallow groundwater samples were collected using sterilised 1-litre polyethene bottles from sixty-three sampling locations. Sampling was performed following standard protocols, ensuring minimal contamination [48]. Groundwater samples (heavy metals and phosphate) were acidified for laboratory analysis and preserved below 5°C. Physical parameters, including pH, turbidity (Tur), temperature (°C), and electrical conductivity (EC), were measured in situ [49]. Groundwater samples were collected in 1-litre polyethene (PE) bottles for laboratory analysis. After filling the sampling bottles with water, the bottles were capped tightly, labelled, and stored in a box. Groundwater samples were filtered through WHATMAN 0.45lm membrane cellulose nitrate filter paper using a glass filtration unit [50]. All analyses were conducted in triplicates for quality control, and values are found with ±5 error limits.

The samples were acidified with concentrated Analar HNO_3 to pH < 2 to prevent adsorption onto the container surface retard biological activity while avoiding hydrolysis and precipitation of cations within the matrix [51]. The PO_4 concentration was analysed using the MP-AES machine (Model 4200). Typical detection limits for the MP AES vary from low µg/l to ng/l levels for various elements. The superb detection capabilities, joined with a wide linear dynamic, vary from 4 to 6 orders of magnitude, allowing for precise heavy metal analysis in a single measurement. The MP-AES (model 4200) offers low detection limits for heavy metals, mainly in the ppb range, ensuring sensitivity to water quality analysis [52, 53]. The calibration standards are prepared using certified reference materials for accuracy. Table 1 presents the geographical and hydrochemical data. All the analyses were performed in triplicate, and results were found to be within ±5 error limits.

Table 1. Physicochemical parameters of water quality.

LGA	Sampling location	LAT	LON	ALT	Tem	PH	EC	TDS	DO	TUR	Zn	Cd	V	Tin
	B.Yauri	10.70	4.81	230.74	36.90	9.00	442.00	208.00	6.51	81.40	5.85	0.02	12.91	20.23
Ngaski	Macrin	10.68	4.80	230.74	39.60	8.80	1212.00	570.00	5.16	96.30	8.32	-0.01	13.58	14.81
	Yadi	10.78	4.80	230.74	36.30	8.50	163.00	77.00	4.40	0.00	4.22	0.02	1.69	9.53
	Tondi Tsamiya	10.91	4.76	230.74	36.70	0.00	759.00	357.00	5.10	10.30	3.02	0.03	6.82	9.29
Yauri	MB. Yauri	10.75	4.78	230.74	35.00	0.00	1357.00	635.00	6.30	0.00	3.00	0.03	2.31	11.12
	Baha	10.81	4.74	191.62	39.40	0.00	1376.00	653.00	7.10	8.30	0.86	0.04	4.75	9.18

LGA	Sampling location	LAT	LON	ALT	Tem	PH	EC	TDS	DO	TUR	Zn	Cd	V	Tin
Fakai	Fakai 1	11.54	4.77	284.70	36.90	9.00	442.00	208.00	6.51	81.40	5.85	0.02	12.91	20.23
	Fakai 2	11.55	4.98	300.00	39.60	8.80	1212.00	570.00	5.16	96.30	8.32	-0.01	13.58	14.81
	Fakai 3	11.51	5.10	327.40	36.30	8.50	163.00	77.00	4.40	0.00	4.22	0.02	1.69	9.53
Suru	Kwakware	11.87	4.02	251.93	34.40	0.00	34.00	16.00	2.80	0.00	3.55	0.06	4.30	15.20
	Dole Kwandage	11.83	4.04	334.44	39.60	0.00	14.00	7.00	2.30	0.00	3.54	0.02	1.48	8.53
	Kaykiriya	11.77	4.08	231.35	37.70	0.00	21.00	10.00	1.30	0.00	-0.19	-0.03	-5.35	-44.95
Bunza	Balu	12.05	3.97	259.07	37.50	0.00	817.00	391.00	5.40	0.00	0.03	-0.04	-2.96	-41.14
	Maidahini	12.13	4.04	210.09	39.00	0.00	104.00	49.00	3.30	74.50	0.10	-0.04	-9.38	-41.75
	T. Riskuwa	12.04	4.01	216.17	34.10	0.00	376.00	177.00	4.20	3.10	0.09	-0.04	-9.13	-41.72
Argungu	Kaiwa	12.73	4.57	246.70	39.00	8.40	470.00	221.00	7.30	0.00	0.06	-0.01	-9.75	-41.51
	Bere	12.63	4.46	253.99	34.90	7.90	42.00	20.00	2.00	0.00	0.07	-0.05	-7.50	-39.73
	G. Hammani	12.59	4.43	233.72	32.80	9.00	2472.00	1162.00	5.50	0.00	0.54	-0.04	-8.73	-41.95
Kalgo	U. Dikko	12.33	4.22	228.42	45.50	9.40	412.00	194.00	3.40	55.20	0.13	-0.02	-3.19	-11.86
	Gayi	12.33	4.12	241.49	93.80	9.00	276.00	131.00	3.70	8.00	0.08	-0.03	-8.58	-36.75
	Sabon G. Asarara	12.28	4.13	224.64	38.80	8.50	34.00	16.00	1.70	0.00	0.07	-0.03	-6.94	-15.08
Shanga	Shanga Keri	11.39	4.56	225.36	37.50	0.00	668.00	314.00	2.80	0.00	0.06	-0.02	-9.12	-37.10
	S. Garin Bala	11.38	4.57	212.59	38.10	0.00	544.00	255.00	3.00	0.00	0.04	-0.03	-8.55	-43.02
	Jajjaye	11.37	4.57	210.65	37.40	0.00	768.00	361.00	2.00	42.50	0.35	-0.16	-3.01	14.19
Zuru	T. Kobal Near Bedi	11.42	5.38	420.40	36.50	9.40	370.00	175.00	4.90	0.00	0.30	-0.04	-8.89	-44.10
	S. Garin Dabai	11.48	5.21	442.70	35.70	9.30	187.00	88.00	1.70	0.00	0.14	-0.05	-6.39	-44.82
	Amanawa	11.38	5.25	399.20	0.00	9.20	997.00	469.00	26.80	2.00	0.11	-0.04	-8.59	-44.22
K/Besa	K/Bese Tungar. A	11.43	4.49	240.34	38.40	0.00	331.00	160.00	4.70	18.60	0.27	-0.03	-8.66	-45.27
	Matsinkai	11.43	4.38	272.79	36.00	0.00	644.00	304.00	5.60	6.20	0.21	-0.03	-8.43	-45.17
	Damba	11.43	4.39	205.63	35.40	0.00	68.00	32.00	3.60	73.90	0.03	-0.03	-8.36	-44.94
Gwandu	Gwandu K. kalambaina	12.49	4.64	264.69	40.40	8.80	648.00	303.00	4.30	0.00	0.09	-0.01	-8.98	-45.39
	Gwabare	12.56	4.46	277.78	42.60	8.90	85.00	40.00	3.50	57.80	0.11	-0.03	-8.06	-46.05
	Malisa	12.45	4.72	271.76	39.10	9.10	280.00	132.00	5.30	0.00	0.13	-0.03	-8.61	-44.69
Maiyama	Mayama Giwa Tazo	12.14	4.38	262.50	39.30	0.00	65.00	31.00	3.28	0.00	2.35	-0.08	-11.10	-3.62
	Rafin Guzuma	12.05	4.37	288.15	37.40	0.00	119.00	56.00	3.30	0.00	1.72	-0.02	-13.27	-137.52
	Sarandosa	12.01	4.38	285.44	37.10	0.00	38.00	18.00	2.80	0.00	1.46	-0.04	-12.41	8.39
D. Wasagu	Danko Wasagu Gilanko	11.36	5.48	416.60	36.10	8.70	163.00	77.00	4.16	0.00	0.90	-0.05	-14.04	0.22
	Dan Masallaci	11.31	5.48	375.90	36.90	9.10	525.00	247.00	6.17	0.00	5.28	0.05	-11.33	-0.24
	Biki	11.25	5.49	380.40	36.80	8.40	278.00	131.00	2.90	0.00	1.19	-0.04	-11.27	5.53
Dandi	Dandi Shiko	11.78	3.84	215.59	34.20	0.00	425.00	200.00	2.60	29.00	0.80	-0.04	-7.55	-133.14
	Fana	11.70	3.94	185.66	35.20	0.00	48.00	23.00	3.10	0.00	0.99	-0.05	-3.67	3.52

LGA	Sampling location	LAT	LON	ALT	Tem	PH	EC	TDS	DO	TUR	Zn	Cd	V	Tin
	Rijiyar Maikabi	11.80	3.81	225.86	34.10	0.00	395.00	185.00	3.60	4.10	0.46	-0.06	-3.84	-0.76
	Jega Basaura	12.32	4.26	251.77	33.00	0.00	31.00	15.00	2.50	0.00	4.90	-0.04	-12.91	1.38
Jega	Sabon garin zarya	12.28	4.31	280.44	37.50	0.00	408.00	191.00	4.11	0.00	1.32	-0.06	-11.59	-2.52
	Langido	12.31	4.27	243.36	36.50	0.00	78.00	35.00	3.27	0.00	1.40	-0.04	-12.67	4.46
	B. Kebbi Huda	12.39	4.30	244.75	40.20	8.30	44.00	21.00	1.60	79.20	0.99	-0.03	-12.18	6.18
B. Kebbi	Sabon Garin Goru	12.40	4.20	231.73	36.90	8.40	53.00	25.00	2.00	80.50	0.07	-0.03	-6.94	-15.08
	Kardi	12.41	4.28	231.73	36.90	7.60	87.00	41.00	0.01	65.30	0.94	-0.04	-12.33	-0.42
	Bagudo k/maje	11.48	4.29	213.84	34.20	0.00	61.00	29.00	2.50	2.00	0.70	-0.04	-10.82	1.37
Bagudo	Kende	11.53	4.26	213.84	34.20	0.00	61.00	29.00	3.40	0.00	0.43	-0.05	-9.65	-1.33
	Kwasara	11.53	4.15	213.84	32.80	0.00	123.00	58.00	4.10	0.00	1.59	-0.03	-9.47	1.57
	Augie Yola	12.83	4.52	253.18	35.50	7.90	225.00	106.00	4.10	6.20	2.22	0.00	-9.37	4.18
Augie	Gobirawa	12.82	4.51	239.94	35.20	8.70	59.00	28.00	2.30	0.00	0.95	-0.04	-9.44	-3.73
	Augie	12.89	4.59	267.13	40.00	8.70	255.00	120.00	4,2	0.00	0.57	-0.03	-9.15	0.65
	Arewa Tila	12.57	4.01	234.76	37.50	9.20	129.00	59.00	2.60	65.30	0.68	-0.01	-9.05	3.23
Arewa	Kwalaye (company)	12.59	3.93	270.92	43.30	8.60	42.00	21.00	3.20	14.50	1.30	-0.03	-2.86	-1.54
	Kwalaye (Arewa)	12.58	3.89	244.16	44.70	7.50	372.00	176.00	3.40	0.01	0.53	-0.01	-8.75	2.31
	Aliero Dakala	12.38	4.41	266.63	40.90	8.50	27.00	13.00	1.80	4.20	0.41	-0.01	-7.67	-1.25
Aliero	Gumbulu	12.34	4.44	277.91	37.10	8.90	40.00	27.00	2.10	6.20	0.90	0.01	-7.55	3.18
	Sabiel	12.39	4.44	255.59	46.80	9.20	85.00	40.00	2.20	0.00	0.48	0.01	-1.87	1.32
	Sakaba Yombe	11.20	5.49	370.90	35.30	8.90	225.00	106.00	1.10	0.00	0.24	-0.01	-7.55	1.40
Sakaba	Hayin boka	11.24	5.46	344.80	35.30	9.20	457.00	212.00	1.80	2.00	0.42	0.00	-6.07	0.60
	Dirin daji	11.26	5.47	368.70	35.30	8.80	219.00	103.00	5.50	0.00	0.74	0.00	-1.73	1.01

3.3. Statistical Analysis

Data acquired were summarised and standardised using basic statistics [(i.e., mean, minimum, maximum, and Standard Error(SE)] to evaluate phosphate concentrations concerning the World Health Organization and Nigerian Standard for Drinking Water Quality reference guidelines. Accordingly, data on physical parameters and heavy metals (Zn, Cd, V, and Tin) were analysed using correlation and principal components. Analysis was performed using the PAST 4 Statistical Package.

3.3.1. Correlation Analysis

The correlation analysis was used to study the relationship between physical parameters and heavy metals [54, 55]. The Pearson correlation is defined in Eq. 1:

$$r = \frac{\sum(x-m_x)(y-m_y)}{\sqrt{\sum(x-m_x)^2\sum(y-m_y)^2}} \tag{1}$$

where the dual vectors are x and y of the n, $m_z and\ m_y$ size equivalents of the average value of x and y. The correlation coefficient expresses the relationship (or p-value) ion's significance level, typically a matrix table for the degrees of freedom: $df = n - 2$, where n is the sum of the reflection in the x and y variables. It can be measured by calculating the t value as follows:

$$t = \frac{r}{\sqrt{1-r^2}}\sqrt{n-2} \tag{2}$$

In Eq. 4, the subsequent *p-value* is explained by the t distribution table for $df = n - 2$. The relationship between hydrochemical elements is substantial if the *p-value* is less than 0.50 [47].

3.3.2. Principal Component Analysis

Hydrogeochemical analysis of shallow groundwater aquifers is a multivariate problem. The PCA's significance relates to reducing hydrochemical data [56, 57]. Although some analogous hydrochemical data can be lost in the transformation process, the system's explanation is considerably abridged. The bilinear PCA model can be rearranged vis the matrix decomposition equation, thus:

$$X = TP^T + E \quad (3)$$

X represents the data matrix, abridged to T (scores of the matrices), and PT represents matrix loadings, plus the E (residual of the matrix). This study uses PCA to study the study area's phosphate concentration variability. Even though there might not be much to realise after statistical application, PCA is a transforming data method that eases hydrochemical data interpretation [58, 59]. After this process, the new axes, called principal components (PCs), are chosen based on a linear model. Therefore, PC1 defines the most crucial variance in the data set, followed by PC2, which describes the second most crucial variance in the data set, though it is built orthogonally to PC1 and consequently is independent from PC2. It is measured using the equation below:

$$PC_{jk} = a_{j1}x_{k2} + \cdots + a_{jn}x_{kn} \quad (4)$$

where PC_{jk} is the PC value *j* for variable *k* (the score for object *j* on component *k*), *aj*1 is the scoring of variable 1 on component *j*, *xk*1 is the length of the score for variable 1 on item *k*, and *n* is the sum of variables observed. This process can be repetitive until the number of PCs corresponds to the initial variables' sum. The advantage of the technique is that the variance in the hydrochemical data is restricted to the first few PCs; thus, the magnitude or size of the multivariate matrix [58, 60-63].

4. Results and Discussion

4.1. Physical Parameters

Physical parameters of analyzed groundwater are presented in Table 2, forming a resultant effect of complex interactions between geological factors and the environment on the quality of water within the Western Sokoto Basin. The pH is highly variable with a range from 0 to 9.4, having a mean of 4.98, which is far below the limits recommended by WHO and NSDWQ of 6.5-8.5. The acidity of the groundwater could be attributed to weathering of sulfide minerals, which releases acidic elements into the water. Anthropogenic activities, such as agricultural runoff containing acidic fertilizers, could exacerbate low pH levels.

Electrical conductivity (EC), with a mean of 390.94 \u03bcS/cm and a maximum of 2472 uS/cm, suggests variable mineralization. High EC values point to the dissolution of geologic materials like evaporites or the influence of anthropogenic sources such as wastewater discharge [64, 65]. Total dissolved solids follow this trend, averaging 184.22 mg/L, indicating moderate salinity and contribution of minerals from geological formations. DO averages 4.28 mg/L and is mainly below the WHO guidelines of 6.5-8 mg/L in most cases. This deficiency may result from the organic matter decomposition or reduced conditions in aquifers, potentially linked to limited recharge and anthropogenic pollution [66, 67].

Table 2. *Physical Parameters.*

Parameters	Min	Max	Mean	SE	WHO (2011)	NSDWQ (2007)
Tem	30.01	93.8	38.94	0.97	Ambient	Ambient
PH	0	9.4	4.98	0.55	6.5-8.5	6.5-8.5
EC	14	2472	390.94	54.58	500 (uS/cm)	1000
TDS	7	1162	184.22	25.67	1000	1000
DO	0.01	26.8	4.28	0.41	6.5-8	
TUR	0	96.3	18.01	3.75	5 NTU	5 NTU

Turbidity values (mean 18.01 NTU) exceed the WHO and NSDWQ threshold of 5 NTU, indicating the presence of suspended particles. This turbidity could arise from geological erosion processes or anthropogenic inputs such as runoff from unregulated mining and agricultural activities [68, 69]. General inferences from the data include that natural and human factors strongly influence regional-scale groundwater quality. The variability of physical parameters is further illustrated in Figure 4.

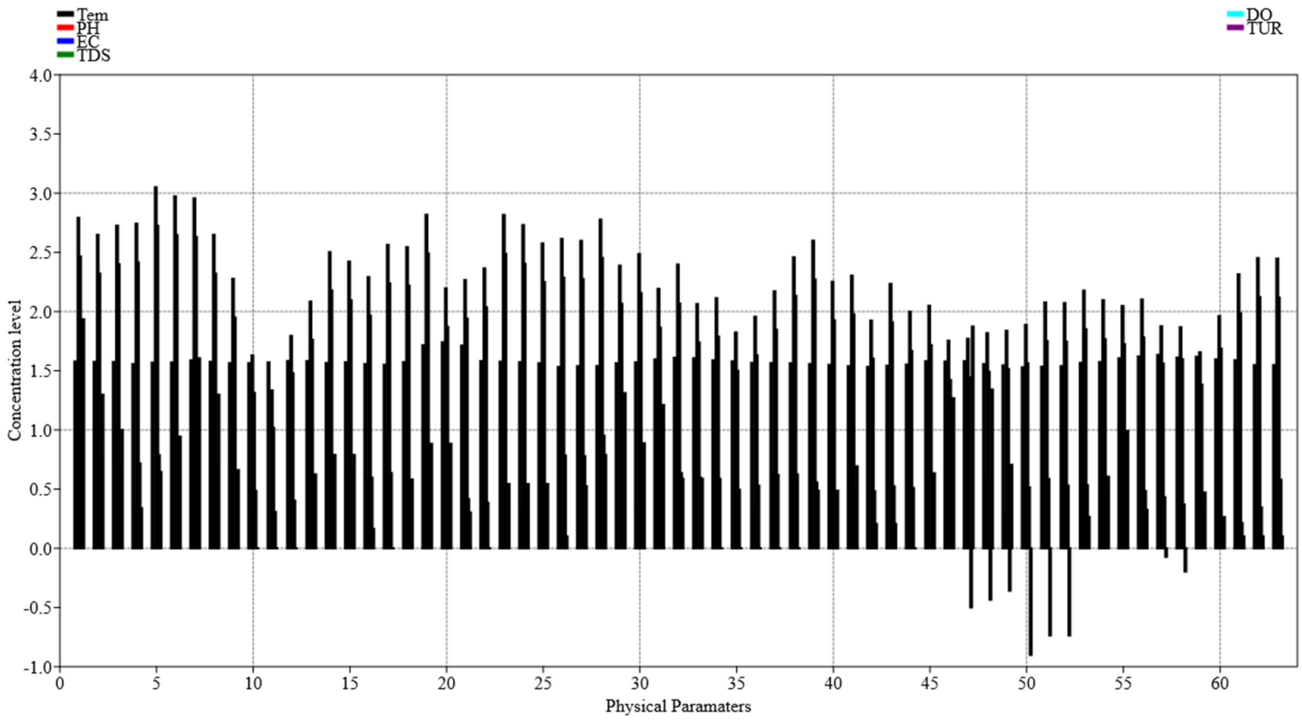

Figure 4. *Physical Parameters.*

4.2. Heavy Metals Concentration

Distribution of zinc (Zn), cadmium (Cd), vanadium (V) and Tin (Sn) in shallow groundwater of Sokoto Basin exhibiting interactions between geological formation and groundwater quality. The concentrations of zinc (average: 1.52 mg/L) marginally exceed the permissible limit set by WHO and NSDWQ standards (0.3 mg/L); possible sources could be the weathering of mineral deposits, notably sphalerite and anthropogenic input from agriculture runoff [70, 71]. Its relatively low standard error indicates the spatial homogeneity of its distribution (Table 3).

Table 3. *Heavy Metals Concentrations.*

Parameters	Min	Max	Mean	SE	WHO (2011)	NSDWQ (2007)
Zn	-0.19	8.32	1.517451	0	0.3	0.3
Cd	-0.16	0.06	0.02312	0	0.3	0.3
V	-14.04	13.58	0.5.53379	0	0.51	
Tin	-137.52	20.23	0.16.1924	0		

Cadmium levels (0.023 mg/L mean) are below regulatory limits (0.3 mg/L). However, its limited presence could be due to the dissolution of cadmium-bearing minerals, such as greenockite, or leaching from fertilizers [72, 73]. The extreme geochemical sensitivity of cadmium emphasizes its ultimate potential for bioaccumulation and toxicity at low levels. Vanadium has a mean (5.53 mg/L) with very positive/negative extremes, which indicates that a good level occurs naturally from silicate minerals present in the basement intrusive and metamorphic rocks of the Precambrian [74, 75]. However, the lousy level may also come from anthropogenic activities such as mining and industrial emissions [76]. The geochemical mobility of vanadium in oxidizing environments might be responsible for macerating concentrations in semi-arid areas such as the Sokoto Basin. Figure 5 shows the spatial variation of heavy metals in the Western Sokoto Basin.

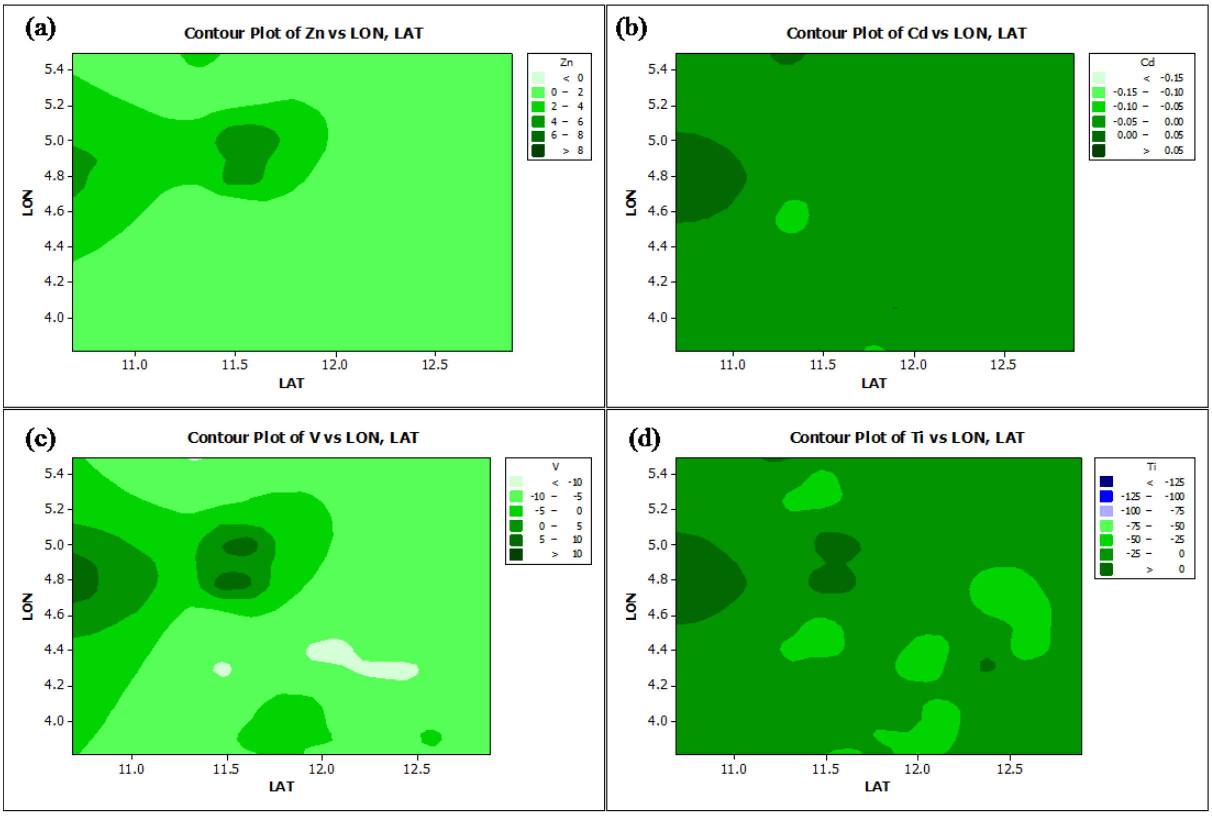

Figure 5. Spatial distribution of heavy metals in western Sokoto Basin.

Tin (mean: 16.19 mg/L) displays peculiar variation, potentially related to granitic intrusions and the weathering of cassiterite-bearing deposits. The minimum is significantly greater than 0, implying potential groundwater (or anthropogenic, e.g., tin alloys) contribution from deep weathering zones [77, 78]. The sedimentary environment of the Sokoto Basin, which consists of typical alluvial deposits and weathered basement rocks, contributes to the distribution and variation in the concentration of these metals. The joint interactions underscore the importance of ongoing monitoring to constrain potential impacts from both natural and anthropogenic sources in the groundwater system.

In the Western Sokoto Basin, heavy metals such as Tin, zinc, cadmium, and vanadium in groundwater are influenced by geological and anthropogenic factors. Geological sources include the natural weathering of metal-bearing rocks and sediments, while anthropogenic activities such as mining, agricultural runoff, and industrial discharge exacerbate contamination. The local governing bodies have implemented various policies aimed at managing water quality and controlling pollution. However, there are gaps in their enforcement and monitoring systems, particularly in remote rural areas. For instance, although there are guidelines for wastewater disposal and industrial emissions, there is limited surveillance of groundwater quality at the local level, which makes it difficult to assess the true extent of contamination. Additionally, local awareness campaigns on the risks of heavy metals in drinking water are minimal, which hinders public participation in water quality monitoring and protection efforts.

The existing precautionary methods, such as the occasional closure of mining sites suspected of heavy metal pollution, are often reactive rather than preventive. While some communities have adopted basic filtration techniques, these do not effectively remove heavy metals, especially in areas with high concentrations of cadmium or vanadium. To mitigate the risk of contamination, local authorities must invest in more robust and systematic water quality monitoring programs, allowing for early detection of pollution hotspots. Strengthening regulations on industrial discharge and mining practices is essential, and public education initiatives should be expanded to raise awareness about the long-term health effects of heavy metal exposure. Additionally, promoting more sustainable agricultural practices could help reduce the inflow of contaminants into groundwater systems.

4.3. Statistical Application

4.3.1. Correlation Analysis

Heavy metals (Zn, Cd, V, and Tin) and their relationship with environmental variables in the western Sokoto Basin are either geogenic or anthropogenic. For example, Zn has a weak positive correlation with pH (0.095), suggesting potential mobilization under alkaline conditions due to weathering processes of sphalerite or other Zn-rich minerals [79, 80]. The low correlation with EC and TDS indicates the low saturation of the groundwater basin. Cadmium (Cd) showed a significant positive correlation with pH (r = 0.217), which corroborates the enhanced mobility of cadmium in slightly alkaline groundwater [79, 80]. This association may be related to the dissolution of cadmium-bearing phosphates, typical for the sedimentary geology of Sokoto Basin [81].

Table 4. *Correlation analysis.*

PARAMETERS	LAT	LON	ALT	Tem	PH	EC	TDS	DO	TUR	Zn	Cd	V	Tin
LAT		2E-05	2E-01	7E-02	7E-02	2E-02	2E-02	6E-02	6E-01	2E-03	6E-02	4E-05	2E-01
LON	-0.509		0.000	0.071	0.000	0.081	0.083	0.018	0.505	0.081	0.097	0.315	0.179
ALT	-0.181	0.742		0.116	0.000	0.658	0.656	0.046	0.063	0.632	0.503	0.413	1.000
Tem	0.228	-0.229	-0.200		0.307	0.271	0.273	0.000	0.574	0.736	0.719	0.852	0.930
PH	0.228	0.471	0.452	0.131		0.860	0.864	0.371	0.112	0.456	0.087	0.435	0.181
EC	-0.299	0.221	-0.057	-0.141	0.023		0.000	0.001	0.555	0.111	0.480	0.005	0.777
TDS	-0.299	0.220	-0.057	-0.140	0.022	1.000		0.001	0.558	0.112	0.477	0.005	0.775
DO	-0.239	0.298	0.252	-0.472	0.115	0.423	0.423		0.735	0.454	0.382	0.252	0.492
TUR	-0.063	-0.086	-0.235	0.072	0.202	0.076	0.075	-0.043		0.003	0.986	0.001	0.341
Zn	-0.379	0.222	0.062	-0.043	0.096	0.203	0.202	0.096	0.367		0.000	0.000	0.000
Cd	-0.236	0.211	0.086	0.046	0.217	0.091	0.091	0.112	-0.002	0.436		0.000	0.066
V	-0.491	0.129	-0.105	0.024	0.100	0.352	0.353	0.146	0.409	0.671	0.473		0.002
Tin	-0.176	0.171	0.000	0.011	0.171	-0.036	-0.037	-0.088	0.122	0.432	0.233	0.387	

The low degree of association of the alkali and alkaline earth metals with EC and TDS indicates that human activities have not influenced the input and are predominantly of geogenic origin [82]. There is a moderate positive relationship between vanadium and EC (0.352) and TDS (0.353); this shows that vanadium occurs in proportion to water salinity level [83]. In the case of pH, the coefficient is 0.100, which shows that while weakly positive that is vanadium mobility increases in the oxidization environment [84, 85]. The weathering of vanadium-bearing silicates in the sedimentary and basement rock profiles is probably associated with it. Tin (Sn) shows relatively low but generally negative and weak associations with most analysed variables and a strongly negative correlation with EC (- 0.036), indicating Tin's low solubility under the basin's hydrochemical conditions.

However, its vanadium content of 0.386 suggests a lithogenic affinity with the potential source rocks of granite or pegmatite [86, 87]. These metals' geochemical behavior is closely tied to the basin geology with the sedimentary sequence intercalated by a weathered crystalline basement. This correlation, therefore, calls for constant observation because the natural decay process and other human activities that may arise in the future may shift the nature of the groundwater qualities of the western Sokoto Basin.

4.3.2. Principal Component Analysis

Table 5 presents the results of principal component analysis (PCA). The parameters assessed in the study comprised PH, EC, TDS, DO, TUR, Zn, Cd, V, and Tin. Based on the PCA results, component 1 explained 33.042% of the total variance. Component 2 explained 21.863% of the total variance. The first component has positive loadings (≥0.4) on EC, TDS, Zn, and Vanadium. Component 2 has high positive loadings (≥0.4) on Tin only. These components joint together explained about 55% of the total variance. Figure 6a further shows the variability and component loadings. This component has the highest Eigenvalue, as indicated by Figure 6b. Figure 7 shows Biplots of components 1 and 2, respectively.

Table 5. *Principal component analysis.*

Parameters	PC 1	PC 2	PC 3	PC 4	PC 5
PH	0.14331	0.16151	0.44977	0.7626	0.2104

Parameters	PC 1	PC 2	PC 3	PC 4	PC 5
EC	0.40434	-0.47068	-0.09672	-0.01799	0.2007
TDS	0.40429	-0.47093	-0.0962	-0.01869	0.19996
DO	0.23932	-0.34962	0.35668	0.1439	-0.22699
TUR	0.23061	0.22938	-0.58136	0.51217	-0.25437
Zn	0.42087	0.30403	-0.11161	-0.17373	-0.12649
Cd	0.29939	0.24202	0.52694	-0.23814	-0.40198
V	0.47554	0.20775	-0.13598	-0.13578	-0.15011
Tin	0.22174	0.40196	0.072732	-0.17151	0.74775
Eigenvalue	2.97376	1.9678	1.04831	1.01043	0.737654
% variance	33.042	21.864	11.648	11.227	8.1962

Principal Component Analysis (PCA) was used to reduce the complexity of the dataset and identify the key factors that explain the variability in the water quality parameters [88, 89]. Based on the PCA results, Component 1 explained 33.042% of the total variance. Component 2 explained 21.863% of the total variance. Together, these two components accounted for 55% of the total variance in the dataset. The first component has positive loadings (≥0.4) for EC, TDS, zinc (Zn), and vanadium (V), indicating that these parameters are strongly correlated with each other and contribute most significantly to the variance captured by Component 1.

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) are typically associated with the salinity and mineral content of water [90, 91]. Higher EC and TDS values indicate greater ionic concentrations, suggesting potential pollution from dissolved salts or metals. Zinc (Zn) and Vanadium (V) are trace metals, and their positive loadings in this component suggest that their concentrations may be influenced by factors related to EC and TDS, such as industrial discharges, runoff, or natural geochemical processes [92, 93]. These parameters collectively indicate that Component 1 likely represents the influence of dissolved mineral content and metals in the water. High values of EC, TDS, Zn, and vanadium in water could be associated with industrial pollution, metal leaching from natural deposits, or agricultural runoff [94, 95]. This component is critical in understanding the water system's overall ionic load and metal contamination.

The second component has a high positive loading (≥0.4) for Tin (Sn) only, meaning that tin concentrations are the primary contributors to the variance explained by Component 2. Unlike Component 1, which groups several variables, Component 2 seems to be dominated by Tin, suggesting that Tin behaves independently of the other parameters. Tin (Sn) may enter water systems through industrial activities such as metal plating, soldering, or organotin compounds' breakdown in agricultural and marine applications [96]. Its isolated loading in Component 2 implies that tin contamination might stem from a specific, localized source rather than broader water quality factors like EC and TDS. This suggests that Component 2 reflects the influence of tin contamination, which could arise from specific industrial or agricultural activities. The fact that Tin does not cluster with other metals or water quality parameters in Component 1 indicates that its presence in the water may be due to different sources or processes.

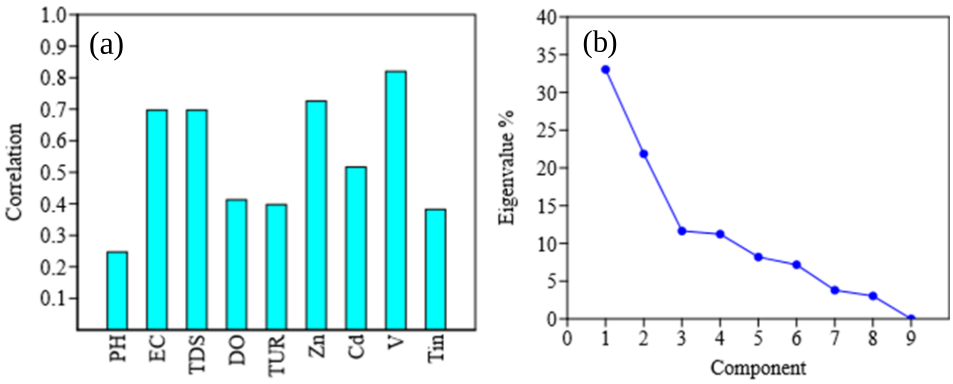

Figure 6. *(a) Component ladings and (b) Eigenvalue.*

Component 1 and Component 2 explain about 55% of the total variance in the dataset. Although this is a substantial portion, 45% of the variance is still unaccounted for, indicating that other factors or combinations of parameters not captured by these two components may also play a significant role in water quality variation. Component 1 (33.042% variance) represents the overall dissolved ionic and metal content, suggesting that EC, TDS, zinc, and vanadium are the key drivers of this variation [92, 97]. These parameters likely indicate industrial or agricultural pollution, where salts and metals contribute to water quality degradation. Component 2 (21.863% variance) is strongly associated with Tin, indicating its independent behavior in the system. The fact that Tin is the only significant parameter in this component suggests a localized contamination source, which could be linked to specific industrial or environmental processes [98, 99]. The correlation (Figure 6a) highlights significant relationships among physicochemical parameters and heavy metals, suggesting potential anthropogenic and geogenic sources. High correlations of Zn, Cd, and V with conductivity and TDS indicate industrial and agricultural runoff contamination. The principal component analysis (Figure 6b) shows key components explaining variance, with the first two capturing over 50%, emphasizing contributions from natural rock weathering and human activities. Elevated tin (Sn) levels could indicate localized mining or industrial residues. These findings underscore the need for integrated monitoring to mitigate groundwater contamination risks in the western Sokoto Basin.

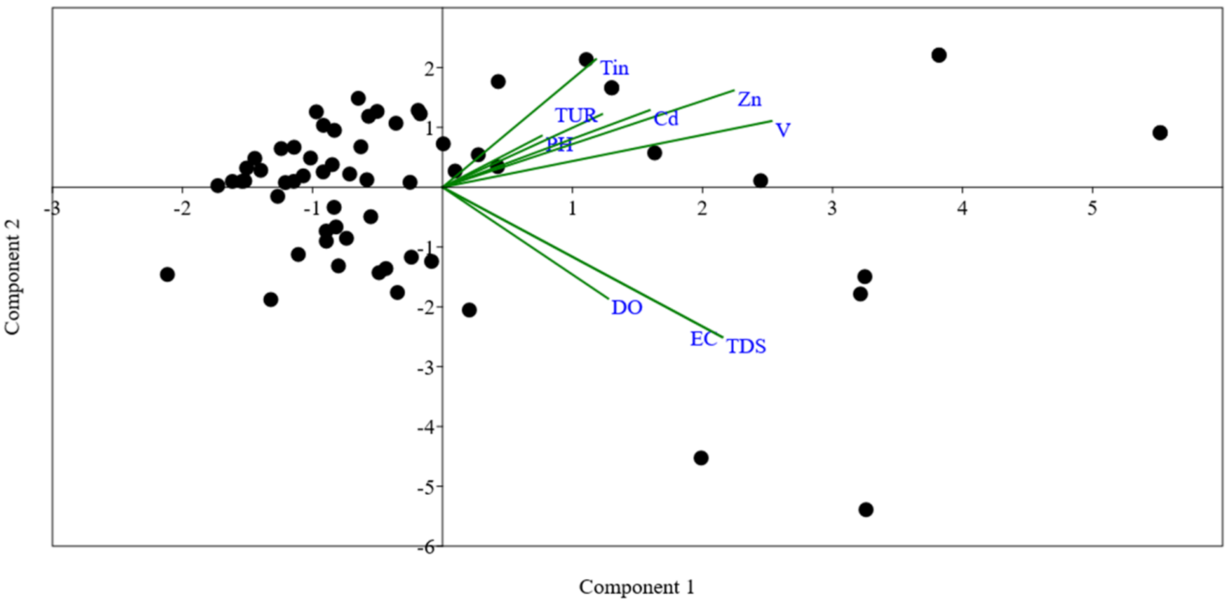

Figure 7. *Biplots of component 1 and component 2.*

4.4. Implications for Water Quality Management

High Loadings in Component 1: The association of EC, TDS, Zn, and V implies that measures should be taken to monitor and control industrial and agricultural runoff, which may contribute to elevated metal concentrations and overall ionic content in the water. Tin's Independent Role (Component 2): Since Tin has a strong, isolated loading, it may require separate investigation, focusing on industries or specific regions that could release Tin into the water system. The PCA results highlight the importance of dissolved salts and trace metals, especially zinc and vanadium, as key contributors to water quality variation [92, 100] groundwater. This could be the same in the western Sokoto basin. Tin's independent contribution suggests localized contamination. Together, these components explain over half of the variability in the water quality, underscoring the need for targeted water quality monitoring and pollution control strategies tailored to these key parameters. Further investigation may be required to understand the remaining variance and the influence of other potential contaminants or environmental factors not captured in these two components.

5. Conclusion

This study investigated the water quality in western Sokoto Basin by assessing key parameters such as temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity (TUR), and concentrations of heavy metals including zinc (Zn), cadmium (Cd), vanadium (V), and Tin (Sn). Using Principal Component Analysis (PCA), it was found that EC, TDS, Zn, and vanadium were strongly correlated, explaining 33.042% of the total variance in water quality. Tin, acting independently, contributed 21.863% to the total variance. Together, these components explained 55% of the overall variability in the dataset.

Additionally, the ANOVA results revealed significant differences in water quality parameters across the sampling sites, indicating varying contamination levels, likely due to differing local pollution sources and environmental conditions. The findings indicate that water quality in the western Sokoto basin is significantly influenced by dissolved ions and heavy metal concentrations, particularly zinc, cadmium, vanadium, and Tin. The variability in these parameters across different locations suggests that certain areas are more polluted than others, potentially due to industrial or agricultural activities. These pollutants, especially cadmium and Tin, pose health and environmental risks if not addressed. The significant differences in water quality parameters highlight the need for localized approaches to managing water pollution. Based on these results, this study recommends the following:

1) *Regular Water Quality Monitoring:* Continuous water quality monitoring across multiple locations should be conducted to track pollutant levels and identify pollution hotspots, focusing mainly on heavy metals like cadmium, zinc, vanadium, and Tin.
2) *Strengthening Pollution Control:* Authorities should enforce stricter regulations on industrial and agricultural discharges, especially in areas with high metal contamination, to prevent further water quality degradation.
3) *Targeted Remediation Efforts:* Immediate remediation should be implemented in areas with high concentrations of cadmium and Tin to reduce their environmental and health impact. This can involve both physical and biological treatment of contaminated water sources.
4) *Public Health Awareness:* Local communities should be informed about the risks of contaminated water and encouraged to use alternative or treated water sources in regions with high pollution levels.
5) *Policy Enforcement and Improvement:* Local and regional governments should strengthen environmental policies on waste management, industrial regulation, and water resource protection, ensuring stricter compliance through regular inspections and penalties for non-compliance.

Abbreviations

ANOVA	Analysis of Variance
Cd	Cadmium
DO	Dissolved Oxygen
EC	Total Dissolved Solids
LGAs	Local government areas
LULC	Land use/land cover
m	Meters
Max	Maximum
mg/L	Milligram per Litre
Min	Minimum
NSDWQ	Nigerian Standard for Drinking Water Quality
PC	Principal Component
PCA	Principal Component Analysis
pH	Redox Potential
PO_4	Phosphate
SE	Standard Error
Sn	Tin
TUR	Turbidity
uS/cm	Micro Siemens per Centimetre
V	Vanadium
WHO	World Health Organisation
Zn	Zinc

Author Contributions

Saadu Umar Wali: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing

Salma Aliyu: Data curation, Formal Analysis, Investigation, Resources

Hussaini Muhammad Usman: Data curation, Formal Analysis, Investigation, Resources

Peter Danladi: Data curation, Formal Analysis, Investigation, Resources

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Conflicts of Interest

The authors declare that there is no conflict of interest. Associated with this research.

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