Journal of Water Resource and Protection, 2025, 17(2), 108-143
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Assessment of Spatial Water Quality Variations in Shallow Wells Using Principal Component Analysis in Half London Ward, Tanzania

Matungwa William[1], Zacharia Katambara[2]

[1]Department of Earth Sciences, College of Science and Technical Education, Mbeya University of Science and Technology, Mbeya, Tanzania
[2]Department of Civil Engineering, College of Engineering and Technology, Mbeya University of Science and Technology, Mbeya, Tanzania
Email: matungwa.william@must.ac.tz, matungwa.william@mail.huji.ac.il, zacharia.katambara@must.ac.tz, zkatambara1@gmail.com

How to cite this paper: William, M. and Katambara, Z. (2025) Assessment of Spatial Water Quality Variations in Shallow Wells Using Principal Component Analysis in Half London Ward, Tanzania. *Journal of Water Resource and Protection*, **17**, 108-143.
https://doi.org/10.4236/jwarp.2025.172007

Received: December 27, 2024
Accepted: February 18, 2025
Published: February 21, 2025

Abstract

Groundwater is a crucial water source for urban areas in Africa, particularly where surface water is insufficient to meet demand. This study analyses the water quality of five shallow wells (WW1-WW5) in Half-London Ward, Tunduma Town, Tanzania, using Principal Component Analysis (PCA) to identify the primary factors influencing groundwater contamination. Monthly samples were collected over 12 months and analysed for physical, chemical, and biological parameters. The PCA revealed between four and six principal components (PCs) for each well, explaining between 84.61% and 92.55% of the total variance in water quality data. In WW1, five PCs captured 87.53% of the variability, with PC1 (33.05%) dominated by pH, EC, TDS, and microbial contamination, suggesting significant influences from surface runoff and pit latrines. In WW2, six PCs explained 92.55% of the variance, with PC1 (36.17%) highlighting the effects of salinity, TDS, and agricultural runoff. WW3 had four PCs explaining 84.61% of the variance, with PC1 (39.63%) showing high contributions from pH, hardness, and salinity, indicating geological influences and contamination from human activities. Similarly, in WW4, six PCs explained 90.83% of the variance, where PC1 (43.53%) revealed contamination from pit latrines and fertilizers. WW5 also had six PCs, accounting for 92.51% of the variance, with PC1 (42.73%) indicating significant contamination from agricultural runoff and pit latrines. The study concludes that groundwater quality in Half-London Ward is primarily affected by a combination of surface runoff, pit latrine contamination, agricultural inputs, and geological factors. The presence of microbial contaminants and elevated nitrate and phosphate levels underscores the need for improved sanitation and sustainable agricultural practices. Recommendations include strengthening sanitation infrastructure, promoting responsible farming techniques, and implementing regular groundwater monitoring to safeguard water resources and public health in the region.

Keywords

Groundwater Contamination, Principal Component Analysis (PCA), Shallow Well Water Quality, Anthropogenic Pollution, Hydrogeological Processes

1. Introduction

1.1. Background

Growing urban areas in Africa increasingly depend on groundwater as a primary source for domestic and commercial water use [1]. Groundwater is typically accessed via shallow or deep wells [2]. In regions where surface water supply systems are insufficient to meet demand, urban populations often turn to shallow wells due to their affordability and accessibility [3] and [4]. Approximately 85% of public water consumption in these areas comes from groundwater sources [5], which is generally perceived as clean and safe, particularly when drawn from deep, confined aquifers [6] and [7]. Groundwater's slower response to climate change, compared to surface water, further enhances its appeal. However, shallow wells often face contamination risks due to their proximity to sources like pit latrines, small farms, and solid waste dumps, introducing pollutants from physical, chemical, and microbial origins [2] and [8]. Studies in various African towns have consistently reported microbial contamination in shallow wells near pit latrines, especially in densely populated areas where wells are located downslope of sanitation facilities ([9], [10] and [11]). As a result, managing the quality of groundwater from shallow wells remains a critical challenge. Groundwater quality is often degraded by factors such as small-scale agriculture, urbanization, and industrial activities [12] and [13], while climate change and natural stream movement further impact groundwater chemistry and flow dynamics [14] and [15]. Therefore, regular assessment of groundwater quality is crucial for sustainable water resource management [16] [17].

Water quality assessment involves considering multiple parameters, making it a multidimensional process that requires a robust analytical approach. Principal Component Analysis (PCA) has become an effective tool for this purpose, reducing data complexity while preserving essential information. PCA identifies patterns and correlations among water quality parameters, simplifying multivariate datasets and aiding in better management and decision-making. [18] applied PCA and Cluster Analysis to groundwater data from 20 boreholes, identifying five principal factors that explained 78.69% of the total variance. Significant factors included total hardness, total dissolved solids, and electrical conductivity, which were linked to anthropogenic activities and natural processes. PCA revealed the significant contribution of human actions, such as waste disposal, to groundwater quality degradation. Similarly, [19] used PCA to analyse water samples from a tropical Ramsar wetland near seafood processing facilities. Six principal components were identified, accounting for 65.79% of the variance, with parameters like alkalinity, BOD, and COD indicating organic pollution from seafood waste. This demonstrates the utility of PCA in isolating major pollution contributors in complex ecosystems. Furthermore, [20] used PCA to reduce the dimensionality of water quality data, identifying six significant components that explained 65.40% of the variance. These components were subsequently used as inputs for Artificial Neural Network (ANN) models, which accurately predicted the Water Quality Index (WQI) with a high coefficient of determination ($R^2 = 0.9999$). These studies exemplify the effectiveness of PCA in groundwater quality analysis, making it an essential tool for assessing water quality in areas like Half London, Tunduma Town, Tanzania.

1.2. Description of the Study Area

Tunduma Town, located in the Southern Highlands of Songwe Region at the border of Tanzania and Zambia, spans an area of 87.5 km^2 and supports a population of 219,309, with a rapid annual growth rate of 13% [21]. The town's elevation varies from just below 1500 meters to above 1600 meters above mean sea level, reflecting a varied topography (**Figure 1**). The study area, Half-London Ward, experiences a unimodal rainy season, which lasts from November to mid-May, with the heaviest rainfall typically occurring in January and February. The region receives an annual average of 1006 mm of rainfall. The average temperature is 20.5˚C, with extremes recorded as low as 6.5˚C in October and as high as 29.0˚C in July. These climatic conditions, along with the town's geographic and demographic characteristics, make it an ideal setting for water resource studies, particularly related to groundwater from shallow wells.

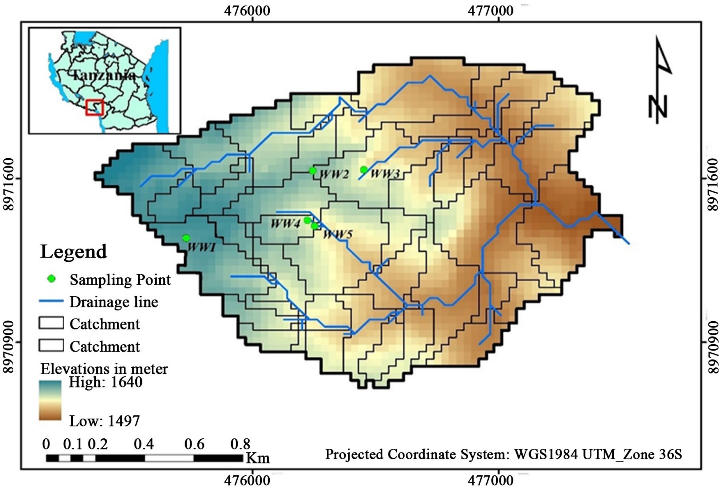


Figure 1. Location map of the study area (Half-London Ward) in Tunduma Town, Tanzania.

2. Methods

2.1. Study Design and Data Sampling

Water quality sampling was conducted by randomly selecting five commonly used shallow wells from the Half-London Ward in Tunduma, Tanzania. These wells were coded as WW1, WW2, WW3, WW4, and WW5. The selection followed the guidelines provided by the Environmental Protection Agency (EPA) as revealed by [22], which recommend a minimum sample size of five to ten shallow wells when studying groundwater within a specific community. Considering the temporal variation in rainfall patterns, water sampling was carried out monthly over 12 months, from June to May, to capture seasonal changes. Water was collected from the designated points of the five shallow wells, as shown in **Figure 1**. The position and elevation of the wells were measured using a Global Positioning System (GPS), as detailed in **Table 1**, and the depth of each well was recorded.

Water analysis was performed for biological (faecal coliform and total coliform), selected physical (pH, electrical conductivity, turbidity, total suspended solids, total dissolved solids, and colour), and chemical (nitrate, phosphate, total iron, and BOD) parameters. The parameters were selected based on their public health importance [23] and their relevance to public water consumption [24]. Samples for microbial tests were collected in sterilized glass bottles, which were rinsed three times with the source water to minimize the risk of external contamination. Since all the shallow wells were open, the sample bottle was held by a bottle holder and submerged to a depth of 0.4 m below the water level to avoid collecting floating debris. For bacterial counts (total coliforms and faecal coliforms), the membrane filtration technique was applied, with results expressed as counts per 100 ml for each sample. All procedures for water sample collection and analysis followed the methods prescribed by the American Public Health Association [25], and the results were compared against the World Health Organization [26] and [27] for water quality to determine the suitability of the water for domestic use.

2.2. Application of Principal Component Analysis

In addition to traditional water quality assessments, Principal Component Analysis (PCA) was employed as a robust statistical tool to manage and interpret the multidimensional water quality data collected over the year. PCA helps in reducing the complexity of the dataset by identifying key variables that contribute most to the variance in water quality. This method was used to transform the original water quality parameters into a set of principal components, which simplified the data while preserving essential information. The PCA was perceived to be capable of revealing the most significant factors affecting water quality, including biological contamination and chemical pollutants, thus providing clearer insights into the primary sources of contamination. Principal Component Analysis (PCA) was conducted using the Jamovi software [28], following the method outlined by [29].

3. Results and Discussion

In this study all water quality parameters which include physical, chemical and biological parameters that were tested are considered in the analysis in order to create an insight of the water quality issues in Half London Ward in Tunduma Tanzania. The descriptive statistics follows next.

3.1. Descriptive Statistics

In spite of the water quality from shallow wells being site specific, it also depends on the various parameters. The pollution parameters of the 5 shallow wells have been summarized by the calculation of minimum and maximum, mean (average), median, standard deviation, skewness, kurtosis, and Shapiro-Wilk as shown in **Tables 1-5**. When the skewness is considered for all the wells, the values ranged from −2.2 to 11.8 with no zero-value suggesting that the data are skewed. The Kurtosis values for all the wells suggest that the colour for WW1, total dissolved salts for WW2, total dissolved salts and Salinity for WW4 and total dissolved salts for WW5 have their values greater than 3 suggesting that the data are from distribution that has sharper peak and fatter tails compared to a normal distribution [30].

Table 1. Descriptive statistics for analytical measurements of pollution parameters for WW1.

	Mean	Minimum	Maximum	Median	SD	Skewness	Kurtosis	Shapiro-Wilk (p)
pH	6.35	6.20	6.70	6.30	0.16	1.15	0.72	0.03
EC	264.48	240.94	283.88	265.01	14.21	−0.31	−1.20	0.48
Temp	23.67	22.30	25.20	23.90	1.00	0.07	−0.85	0.30
Col	1.36	0.95	2.50	1.34	0.40	2.32	6.90	0.00
Turb.	7.65	5.50	10.50	7.24	1.27	0.74	1.54	0.53
TSS	0.49	0.12	1.80	0.23	0.53	1.78	2.68	0.00
TDS	61.89	52.00	69.20	60.77	5.62	−0.50	−0.40	0.20
Hd	177.33	160.00	194.10	177.50	12.24	−0.13	−1.55	0.28
Alk	180.04	165.02	194.10	183.17	8.75	−0.27	−0.88	0.61
Sal	0.15	0.01	0.35	0.17	0.12	0.17	−1.12	0.17
Cl^-	11.99	8.10	14.50	12.27	1.92	−0.68	−0.07	0.66
PO_4^-	0.10	0.02	0.22	0.07	0.07	0.81	−0.94	0.03
SO_4^{2-}	7.55	4.20	9.64	7.88	1.47	−1.01	1.27	0.33
NO_3^-	2.32	0.48	4.25	2.22	1.07	−0.01	−0.17	0.86
BOD	2.93	0.89	4.78	3.01	1.22	−0.19	−0.78	0.92
Ca^{2+}	12.92	9.60	15.00	13.25	1.60	−0.73	−0.08	0.39
Mg^{2+}	29.09	24.90	32.30	29.75	2.08	−0.82	0.38	0.21
Fe^{2+}	0.46	0.02	1.20	0.09	0.52	0.51	−1.95	0.00
FC	1.25	0.00	3.00	1.00	1.06	0.52	−0.64	0.07
TC	5.08	2.00	9.00	5.00	2.35	0.28	−1.45	0.16

Table 2. Descriptive statistics for analytical measurements of pollution parameters for WW2.

	Mean	Minimum	Maximum	Median	SD	Skewness	Kurtosis	Shapiro-Wilk (p)
pH	6.60	6.30	6.80	6.70	0.17	−0.53	−1.20	0.06

Continued

EC	182.75	165.30	195.80	185.35	8.67	−0.69	0.20	0.57
Temp	22.51	20.40	23.90	22.88	1.19	−0.54	−1.20	0.14
Col	0.87	0.32	2.30	0.57	0.59	1.47	2.05	0.02
Turb.	11.97	9.00	19.20	10.97	3.18	1.30	1.22	0.05
TSS	0.24	0.00	2.26	0.05	0.64	3.43	11.82	<0.001
TDS	298.33	240.90	350.30	297.73	31.16	−0.13	−0.41	0.98
Hd	193.24	182.30	209.40	191.04	8.56	0.77	−0.47	0.23
Alk	181.45	160.70	196.75	181.60	9.23	−0.66	1.47	0.55
Sal	0.39	0.11	1.50	0.25	0.37	2.83	8.72	<0.001
Cl^-	17.85	12.33	24.56	17.38	3.13	0.50	1.26	0.74
PO_4^-	0.38	0.09	0.60	0.41	0.17	−0.52	−0.77	0.33
SO_4^{2-}	5.04	2.60	7.22	5.38	1.73	−0.38	−1.47	0.11
NO_3^-	1.83	0.47	4.20	1.33	1.09	1.09	0.47	0.07
BOD	2.25	1.07	3.20	2.25	0.66	−0.24	−0.96	0.74
Ca^{2+}	24.05	19.50	28.82	23.60	2.32	0.17	1.43	0.83
Mg^{2+}	19.49	13.75	23.55	19.89	2.69	−0.80	1.04	0.23
Fe^{2+}	0.16	0.03	0.45	0.11	0.13	0.99	0.40	0.06
FC	0.58	0.00	2.00	0.00	0.79	0.99	−0.46	0.00
TC	1.83	0.00	6.00	1.00	2.12	0.67	−0.81	0.01

Table 3. Descriptive statistics for analytical measurements of pollution parameters for WW3.

	Mean	Minimum	Maximum	Median	SD	Skewness	Kurtosis	Shapiro-Wilk (p)
pH	6.57	6.30	6.80	6.55	0.17	−0.21	−0.64	0.28
EC	261.25	240.00	274.65	265.00	12.76	−0.65	−0.87	0.10
Temp	22.58	21.30	23.80	22.50	0.65	−0.03	0.67	0.65
Col	1.32	0.55	3.00	0.86	0.84	1.09	−0.16	0.02
Turb.	7.61	4.20	12.70	7.58	2.11	0.96	2.69	0.26
TSS	0.47	0.18	1.30	0.27	0.39	1.23	0.16	0.00
TDS	203.34	163.69	245.50	200.30	18.98	0.17	2.93	0.13
Hd	222.28	190.25	250.00	222.65	20.83	−0.23	−1.51	0.24
Alk	191.43	179.40	203.25	190.70	8.76	−0.07	−1.42	0.26
Sal	0.58	0.23	0.99	0.57	0.19	0.45	1.54	0.78
Cl^-	18.40	10.78	24.55	18.57	3.85	−0.52	0.47	0.62
PO_4^-	0.95	0.33	1.80	1.04	0.44	0.31	−0.53	0.60
SO_4^{2-}	5.38	3.00	8.50	5.64	1.58	0.16	0.12	0.68
NO_3^-	1.14	0.49	2.54	0.99	0.61	1.08	1.18	0.13
BOD	2.77	1.20	5.00	2.93	1.01	0.61	0.99	0.54
Ca^{2+}	30.18	27.50	36.82	30.25	2.59	1.55	3.37	0.02
Mg^{2+}	27.08	16.90	31.83	27.55	4.61	−1.39	1.40	0.02
Fe^{2+}	0.04	0.02	0.09	0.04	0.02	1.10	2.33	0.05
FC	2.25	1.00	5.00	2.00	1.29	0.98	0.37	0.06
TC	12.75	8.00	18.00	12.00	3.60	0.19	−1.77	0.08

Table 4. Descriptive statistics for analytical measurements of pollution parameters for WW4.

	Mean	Minimum	Maximum	Median	SD	Skewness	Kurtosis	Shapiro-Wilk (p)
pH	6.53	6.20	6.90	6.40	0.27	0.29	−1.78	0.05

Continued

EC	419.96	368.53	442.00	425.40	21.56	−1.28	1.78	0.08
Temp	23.09	20.50	24.10	23.23	1.04	−1.46	2.54	0.04
Col	2.03	0.50	4.20	1.85	1.08	0.41	−0.04	0.80
Turb.	11.28	7.56	18.70	10.21	3.30	1.38	1.26	0.03
TSS	0.85	0.10	7.20	0.20	2.01	3.40	11.68	<0.001
TDS	237.21	200.55	266.50	243.99	23.62	−0.28	−1.65	0.14
Hd	121.17	16.50	201.30	185.00	87.69	−0.38	−2.24	<0.001
Alk	178.11	155.00	189.40	179.58	8.71	−1.78	4.48	0.02
Sal	0.39	0.03	0.76	0.38	0.20	0.22	0.10	0.97
Cl^-	31.90	25.66	37.93	31.90	3.65	0.04	−0.40	0.96
PO_4^-	1.29	0.48	2.51	1.22	0.53	0.87	1.38	0.52
SO_4^{2-}	4.91	3.90	6.94	4.68	0.91	1.09	0.75	0.15
NO_3^-	2.18	1.20	3.20	2.04	0.62	0.30	−0.63	0.70
BOD	2.86	0.97	4.69	2.84	1.22	0.01	−1.08	0.83
Ca^{2+}	22.32	16.30	26.81	22.98	2.81	−0.54	0.73	0.57
Mg^{2+}	30.01	25.46	34.66	30.29	2.53	−0.12	0.17	0.86
Fe^{2+}	1.37	0.95	1.85	1.33	0.32	0.31	−1.55	0.12
FC	0.67	0.00	2.00	0.00	0.89	0.80	−1.27	0.00
TC	4.58	2.00	6.00	5.00	1.38	−0.58	−0.83	0.10

Table 5. Descriptive statistics for analytical measurements of pollution parameter for WW5.

	Mean	Minimum	Maximum	Median	SD	Skewness	Kurtosis	Shapiro-Wilk (p)
pH	6.51	6.10	6.80	6.55	0.24	−0.34	−1.35	0.25
EC	302.51	274.25	325.80	308.27	18.73	−0.28	−1.41	0.20
Temp	21.95	20.50	23.90	21.70	1.08	0.83	−0.12	0.18
Col	1.10	0.23	3.86	0.58	1.11	1.74	2.54	0.00
Turb.	12.00	7.50	18.50	11.68	3.48	0.41	−0.59	0.65
TSS	0.52	0.00	4.25	0.10	1.22	3.08	9.76	<0.001
TDS	366.33	320.89	390.16	369.53	20.43	−0.98	0.77	0.31
Hd	235.01	209.20	253.55	233.00	15.16	−0.47	−0.76	0.22
Alk	214.57	168.30	245.00	216.76	19.41	−1.01	2.38	0.31
Sal	0.08	0.03	0.17	0.08	0.04	0.63	−0.28	0.34
Cl^-	25.97	18.60	29.50	26.75	3.44	−1.23	0.80	0.06
PO_4^-	1.10	0.12	2.30	1.24	0.67	0.18	−0.97	0.46
SO_4^{2-}	3.61	1.59	5.48	3.51	1.18	−0.12	−0.80	0.96
NO_3^-	0.77	0.09	1.50	0.75	0.48	0.15	−1.13	0.56
BOD	2.41	0.59	3.90	2.51	1.06	−0.21	−0.68	0.60
Ca^{2+}	19.65	17.50	21.89	19.80	1.30	−0.08	−0.68	0.86
Mg^{2+}	24.17	17.52	27.57	24.63	2.99	−1.10	0.82	0.12
Fe^{2+}	0.39	0.09	0.69	0.39	0.24	0.09	−1.71	0.10
FC	0.17	0.00	1.00	0.00	0.39	2.06	2.64	<0.001
TC	1.00	0.00	5.00	0.00	1.65	1.60	1.94	<0.001

3.2. Correlation Matrix for Different Shallow Wells Water Quality

The correlation matrices for various water quality parameters were analysed using Pearson's correlation coefficients, as detailed in Tables 6-10. Pearson's correlation coefficient (r) values were used to assess the strength and direction of the relationships between variables. According to [25] and [28] correlation values are interpreted as follows: $|r| \geq 0.5$ is considered a strong correlation, $0.3 \leq |r| < 0.5$ is moderate, $0.1 \leq |r| < 0.3$ is weak, and 0 indicates no correlation. A positive r indicates that as one variable increases, the other also increases, while a negative r suggests an inverse relationship between the variables.

In WW1 (**Table 6**), pH showed strong correlations with temperature (Temp), total suspended solids (TSS), nitrate (NO_3^-), and faecal coliforms (FC). Electrical conductivity (EC) correlated with NO_3^- and biochemical oxygen demand (BOD). Total dissolved solids (TDS) showed strong correlations with NO_3^-, iron (Fe^{2+}), FC, and total coliforms (TC), highlighting the connection between runoff and microbial contamination. Salinity (Sal) correlated with phosphate (PO_4^{3-}), BOD, and magnesium (Mg^{2+}). Chloride (Cl^-) was negatively correlated with TC, suggesting reduced microbial contamination with higher Cl^- concentrations. Other significant correlations included sulphate (SO_4^{2-}) with calcium (Ca^{2+}), and NO_3^- with Fe^{2+}, FC, and TC, pointing to potential contamination from fertilizers and human waste sources [14] [31].

For WW2 (**Table 7**), EC was negatively correlated with coliforms (Col), while temperature (Temp) was positively correlated with Col and Ca^{2+} but negatively correlated with BOD. TDS showed significant correlations with hardness (Hd), NO_3^-, Mg^{2+}, Fe^{2+}, and TC. Alkali (Alk) was correlated with SO_4^{2-}, NO_3^-, BOD, and Mg^{2+}, reflecting the geological influence on water chemistry. Similar patterns were observed for Cl^-, which was positively correlated with PO_4^{3-}, BOD, and Mg^{2+}. These relationships indicate that both geological strata and human activities, such as pit latrine use and agricultural runoff, significantly influence groundwater quality [32] [33].

In WW3 (**Table 8**), pH correlated with hardness (Hd), while EC correlated with Alk, reflecting mineral dissolution. Col was positively correlated with turbidity (Turb) and Alk. Strong correlations were found between TSS, Cl^-, and Fe^{2+}, indicating contamination from runoff and potential industrial activities. Additionally, PO_4^{3-} and NO_3^- were strongly correlated with Ca^{2+}, Mg^{2+}, FC, and TC, pointing to contamination from fertilizers and human waste sources. These findings align with studies highlighting the role of agricultural runoff and sanitation practices in groundwater contamination [7] [34] and [35].

For WW4 (**Table 9**), EC was negatively correlated with Col and positively correlated with Alk. Temperature was negatively correlated with TSS and Hd but positively correlated with Sal and Fe^{2+}, indicating a complex relationship between water temperature and chemical composition. Turb was correlated with NO_3^-, PO_4^{3-}, and other dissolved solids, indicating pollution from both agricultural and geological sources. The correlation between SO_4^{2-}, BOD, and Mg^{2+} further supported the role of mineral dissolution and organic pollution in influencing water quality [35] [37].

In WW5 (**Table 10**), pH was significantly correlated with several variables, including Turb, TDS, Hd, Alk, Sal, PO_4^{3-}, SO_4^{2-}, NO_3^-, BOD, and Mg^{2+}. Negative correlations were observed between EC and Col, while temperature was correlated with Col but negatively correlated with Hd, Mg^{2+}, and BOD. TDS, Hd, and Alk were positively correlated with PO_4^{3-}, SO_4^{2-}, and NO_3^-, indicating pollution from fertilizers and waste sources. These results demonstrate the influence of human activities and natural processes on groundwater quality in WW5 [29].

Table 6. Correlation matrix for different water quality parameters in WW1.

	pH	EC	Temp	Col	Turb	TSS	TDS	Hd	Alk	Sal	Cl^-	PO_4^-	SO_4^{2-}	NO_3^-	BOD	Ca^{2+}	Mg^{2+}	Fe^{2+}	FC	TC
pH	1.00																			
EC	0.20	1.00																		
Temp	0.50	0.07	1.00																	
Col	0.32	−0.23	0.04	1.00																
Turb.	0.37	−0.36	0.14	0.87***	1.00															
TSS	0.60*	−0.06	0.64*	0.679*	0.714**	1.00														
TDS	0.26	0.32	0.51	−0.18	−0.03	0.32	1.00													
Hd	0.22	0.16	0.27	0.31	0.34	0.43	0.44	1.00												
Alk	0.03	0.39	−0.25	0.17	0.34	−0.03	0.07	0.31	1.00											
Sal	−0.30	0.09	−0.35	0.48	0.49	0.19	0.05	0.36	0.672*	1.00										
Cl^-	−0.18	−0.26	−0.08	0.37	0.53	0.01	−0.32	−0.08	0.52	0.34	1.00									
PO_4^-	0.23	0.41	0.31	−0.60	−0.63	−0.15	0.42	−0.44	−0.43	−0.645*	−0.56	1.00								
SO_4^{2-}	0.36	−0.31	0.33	0.14	0.38	0.28	0.14	0.605*	0.09	−0.09	0.07	−0.40	1.00							
NO_3^-	0.58	0.53	0.47	−0.05	0.02	0.51	0.773*	0.47	0.10	0.03	−0.55	0.43	0.09	1.00						
BOD	0.01	0.54	−0.03	0.29	0.34	0.26	0.30	0.580*	0.83**	0.80**	0.25	−0.40	0.05	0.37	1.00					
Ca^{2+}	0.14	0.07	−0.01	0.36	0.39	0.25	0.20	0.762**	0.43	0.53	−0.01	−0.59	0.67*	0.19	0.57*	1.00				
Mg^{2+}	0.01	0.35	0.04	0.17	0.18	0.20	0.35	0.51	0.56	0.689*	−0.07	−0.33	0.21	0.35	0.76**	0.76**	1.00			
Fe^{2+}	0.45	0.18	0.77**	0.13	0.15	0.75**	0.66*	0.34	−0.24	−0.01	−0.46	0.33	0.11	0.769**	0.17	0.12	0.34	1.00		
FC	0.56	0.38	0.61*	0.10	0.29	0.69*	0.647*	0.44	0.25	0.15	−0.24	0.21	0.22	0.86***	0.48	0.22	0.40	0.79**	1.00	
TC	0.49	0.10	0.48	−0.14	−0.02	0.41	0.77**	0.41	−0.20	−0.22	−0.58	0.44	0.22	0.84***	−0.02	0.05	0.08	0.69*	0.68*	1.00

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7. Correlation matrix for different water quality parameters in WW2.

	pH	EC	Temp	Col	Turb	TSS	TDS	Hd	Alk	Sal	Cl^-	PO_4^-	SO_4^{2-}	NO_3^-	BOD	Ca^{2+}	Mg^{2+}	Fe^{2+}	FC	TC
pH	1																			
EC	−0.08	1.00																		
Temp	−0.24	−0.30	1.00																	
Col	−0.13	−0.65*	0.63*	1.00																
Turb.	−0.39	−0.35	0.50	0.66*	1.00															
TSS	0.18	0.09	−0.37	−0.21	−0.23	1.00														
TDS	0.07	0.11	0.35	0.05	0.50	−0.03	1.00													
Hd	−0.06	−0.11	0.36	0.42	0.85***	−0.22	0.63*	1.00												
Alk	−0.19	0.06	−0.14	−0.04	0.637*	0.07	0.48	0.68*	1.00											
Sal	0.36	0.18	−0.45	−0.01	0.00	−0.11	0.03	0.22	0.05	1.00										
Cl^-	0.30	0.12	−0.43	−0.08	0.27	−0.01	0.34	0.54	0.48	0.85***	1.00									
PO_4^-	0.27	−0.01	−0.56	−0.17	0.06	−0.01	−0.17	0.36	0.39	0.50	0.65*	1.00								
SO_4^{2-}	−0.10	−0.26	−0.16	0.00	0.39	0.28	0.10	0.46	0.701*	−0.24	0.20	0.58*	1.00							
NO_3^-	−0.02	−0.06	0.39	0.35	0.77**	−0.15	0.65*	0.97***	0.64*	0.17	0.51	0.36	0.50	1.00						
BOD	−0.03	0.43	−0.76**	−0.45	−0.01	0.36	−0.07	0.09	0.583*	0.50	0.61*	0.51	0.30	0.05	1.00					
Ca^{2+}	0.04	−0.45	0.58*	0.42	0.60*	−0.05	0.35	0.648*	0.42	−0.38	−0.04	0.11	0.58*	0.70*	−0.31	1.00				
Mg^{2+}	0.28	−0.01	−0.11	−0.12	0.45	0.11	0.73**	0.73**	0.74**	0.26	0.69*	0.48	0.58	0.75**	0.33	0.47	1.00			
Fe^{2+}	−0.39	0.04	0.54	0.22	0.60*	−0.19	0.719**	0.51	0.34	−0.05	0.16	−0.45	−0.11	0.49	−0.10	0.28	0.33	1.00		
FC	−0.07	−0.28	0.44	0.27	0.62*	−0.21	0.52	0.76**	0.44	0.04	0.39	0.26	0.48	0.83***	−0.13	0.75**	0.64*	0.55	1.00	
TC	0.00	−0.14	0.46	−0.01	0.30	−0.25	0.72**	0.43	0.15	−0.13	0.17	−0.14	0.10	0.51	−0.38	0.45	0.54	0.67*	0.76**	1

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8. Correlation matrix for different water quality parameters in WW3.

	pH	EC	Temp	Col	Turb	TSS	TDS	Hd	Alk	Sal	Cl^-	PO_4^-	SO_4^{2-}	NO_3^-	BOD	Ca^{2+}	Mg^{2+}	Fe^{2+}	FC	TC
pH	1.00																			
EC	−0.25	1.00																		
Temp	−0.28	0.00	1.00																	
Col	−0.10	−0.51	0.39	1.00																
Turb.	−0.06	−0.17	0.30	0.601*	1.00															
TSS	−0.08	−0.23	0.24	0.44	0.772**	1.00														
TDS	0.11	−0.04	0.02	−0.49	−0.34	0.13	1.00													
Hd	0.67*	−0.38	−0.23	0.03	0.10	0.30	0.48	1.00												
Alk	0.03	0.80**	−0.24	−0.612*	0.06	−0.06	0.04	−0.12	1.00											
Sal	0.34	−0.17	−0.32	0.38	0.68*	0.54	−0.24	0.54	0.19	1.00										
Cl^-	0.50	−0.26	−0.24	−0.07	0.43	0.62*	0.43	0.79**	0.21	0.68*	1.00									
PO_4^-	0.50	−0.43	−0.04	0.12	0.20	0.49	0.52	0.74**	−0.11	0.42	0.78**	1.00								
SO_4^{2-}	−0.10	−0.05	−0.32	0.49	0.29	0.03	−0.69*	−0.17	−0.09	0.49	−0.21	−0.41	1.00							
NO_3^-	0.45	−0.50	−0.28	0.44	0.22	0.38	0.10	0.76**	−0.31	0.69*	0.58*	0.70**	0.24	1.00						
BOD	0.02	0.12	−0.19	−0.36	0.32	0.26	0.19	−0.01	0.58*	0.26	0.50	0.36	−0.35	−0.12	1.00					
Ca^{2+}	0.27	−0.16	−0.44	0.20	0.45	0.46	0.06	0.603*	0.19	0.90***	0.69*	0.47	0.44	0.75**	0.24	1.00				
Mg^{2+}	0.43	−0.30	−0.30	−0.30	0.17	0.44	0.68*	0.76**	0.14	0.40	0.90***	0.72**	−0.41	0.41	0.51	0.52	1.00			
Fe^{2+}	−0.09	−0.47	0.29	0.44	0.71**	0.54	0.04	0.34	−0.23	0.49	0.47	0.32	−0.01	0.31	0.25	0.42	0.40	1.00		
FC	0.42	−0.37	−0.37	0.21	0.23	0.44	0.33	0.83***	−0.10	0.66*	0.75**	0.83***	−0.02	0.87***	0.18	0.72**	0.67*	0.32	1.00	
TC	0.50	−0.47	−0.32	0.06	−0.11	0.23	0.52	0.90***	−0.36	0.36	0.61*	0.66*	−0.11	0.80**	−0.23	0.52	0.64*	0.22	0.80**	1.00

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9. Correlation matrix for different water quality parameters in WW4.

	pH	EC	Temp	Col	Turb	TSS	TDS	Hd	Alk	Sal	Cl^-	PO_4^-	SO_4^{2-}	NO_3^-	BOD	Ca^{2+}	Mg^{2+}	Fe^{2+}	FC	TC
pH	1.00																			
EC	0.26	1.00																		
Temp	−0.19	−0.02	1.00																	
Col	0.03	−0.57	0.08	1.00																
Turb.	0.26	−0.19	0.32	0.80**	1.00															
TSS	0.23	0.04	−0.75**	−0.03	−0.13	1.00														
TDS	0.36	0.27	0.30	−0.30	0.20	0.05	1.00													
Hd	−0.40	−0.33	−0.58*	0.16	−0.32	0.22	−0.75**	1.00												
Alk	−0.07	0.53	−0.03	−0.24	0.08	0.41	0.53	−0.20	1.00											
Sal	−0.01	0.00	0.61*	0.08	0.50	−0.17	0.78**	−0.75**	0.45	1.00										
Cl^-	−0.16	0.05	0.37	0.20	0.52	−0.17	0.47	−0.14	0.55	0.57	1.00									
PO_4^-	0.22	0.40	0.45	0.07	0.60*	−0.22	0.66*	−0.71**	0.42	0.71**	0.61*	1.00								
SO_4^{2-}	−0.02	−0.15	0.14	0.40	0.67*	0.18	0.56	−0.25	0.53	0.70*	0.79**	0.65*	1.00							
NO_3^-	0.11	−0.10	0.25	0.52	0.79**	0.11	0.38	−0.23	0.45	0.58*	0.81**	0.61*	0.88***	1.00						
BOD	−0.17	0.09	−0.24	0.15	0.34	0.29	0.33	0.17	0.672*	0.33	0.73**	0.41	0.79**	0.62*	1.00					
Ca^{2+}	−0.07	0.22	0.02	0.09	0.41	0.18	0.53	−0.07	0.80**	0.53	0.83***	0.55	0.82***	0.70*	0.93***	1.00				
Mg^{2+}	0.21	0.17	−0.06	0.20	0.52	0.20	0.58*	−0.15	0.64*	0.49	0.72**	0.61*	0.83***	0.694*	0.86***	0.92***	1.00			
Fe^{2+}	0.28	0.37	0.63*	−0.20	0.22	−0.14	0.70*	−0.82**	0.39	0.670*	0.30	0.67*	0.30	0.34	−0.09	0.22	0.26	1.00		
FC	0.00	0.22	0.50	−0.13	0.36	−0.22	0.64*	−0.70**	0.29	0.73**	0.57	0.80**	0.55	0.52	0.25	0.34	0.28	0.57*	1.00	
TC	0.05	0.28	0.46	−0.46	0.02	−0.13	0.86***	−0.75**	0.48	0.83***	0.36	0.57	0.40	0.22	0.21	0.40	0.34	0.64*	0.69*	1.00

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

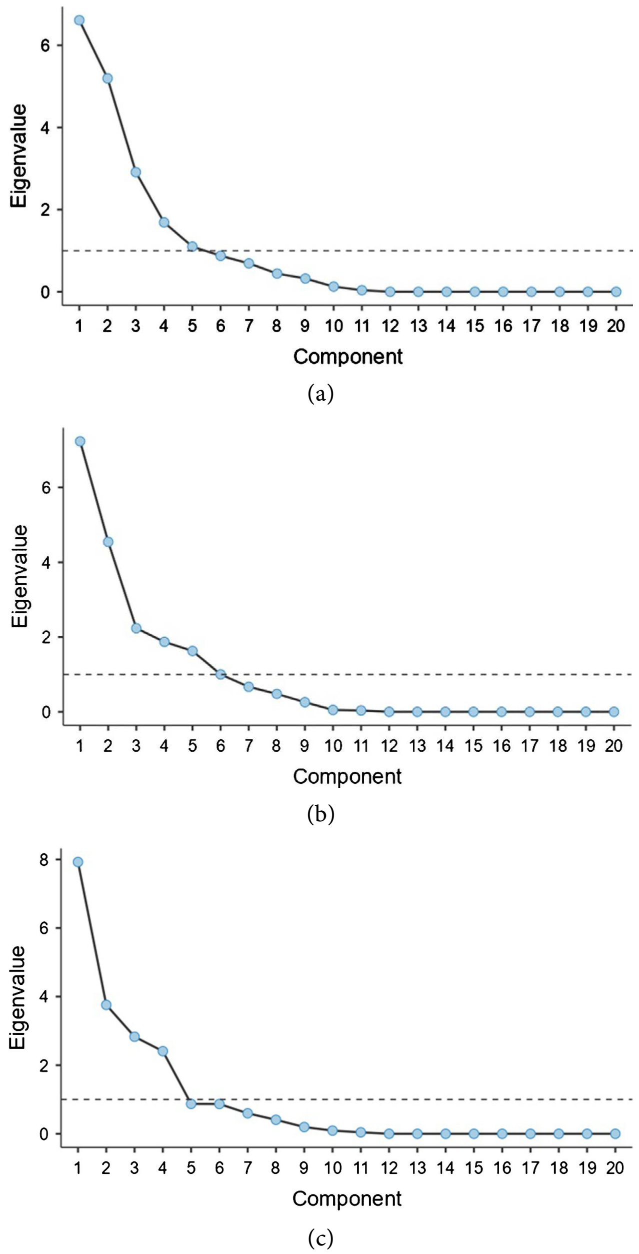
Table 10. Correlation matrix for different water quality parameters in WW5.

	pH	EC	Temp	Col	Turb	TSS	TDS	Hd	Alk	Sal	Cl^-	PO_4^-	SO_4^{2-}	NO_3^-	BOD	Ca^{2+}	Mg^{2+}	Fe^{2+}	FC	TC
pH	1.00																			
EC	−0.04	1.00																		
Temp	−0.35	−0.28	1.00																	
Col	−0.08	−0.65*	0.76**	1.00																
Turb.	0.57	−0.31	0.05	0.37	1.00															
TSS	−0.31	−0.01	−0.06	0.03	0.16	1.00														
TDS	0.61*	0.25	−0.46	−0.28	0.15	−0.02	1.00													
Hd	0.76**	0.19	−0.57	−0.21	0.62*	0.01	0.59*	1.00												
Alk	0.78**	0.35	−0.45	−0.37	0.58*	−0.05	0.60*	0.86***	1.00											
Sal	0.60*	0.31	−0.23	−0.10	0.20	−0.23	0.72**	0.57	0.63*	1.00										
Cl^-	−0.15	−0.23	−0.02	0.08	0.45	0.19	−0.49	0.03	−0.08	−0.50	1.00									
PO_4^-	0.77**	0.11	−0.26	0.04	0.48	−0.15	0.73**	0.80**	0.75**	0.89***	−0.35	1.00								
SO_4^{2-}	0.57	−0.14	−0.42	0.06	0.67*	0.23	0.63*	0.761**	0.54	0.38	0.27	0.629*	1.00							
NO_3^-	0.68*	0.09	−0.27	0.09	0.41	−0.03	0.82***	0.76**	0.65*	0.84***	−0.45	0.95***	0.67*	1.00						
BOD	0.65*	0.08	−0.62*	−0.29	0.72**	0.15	0.40	0.89***	0.83***	0.36	0.35	0.58	0.741**	0.50	1.00					
Ca^{2+}	−0.18	−0.11	−0.40	−0.19	−0.20	0.21	0.20	−0.11	−0.16	0.19	−0.06	−0.06	0.12	0.06	0.04	1.00				
Mg^{2+}	0.73**	0.01	−0.51	−0.19	0.62*	0.33	0.71**	0.76**	0.73**	0.43	0.02	0.60*	0.81**	0.64*	0.77**	0.14	1.00			
Fe^{2+}	−0.18	0.15	0.14	−0.01	0.41	0.27	−0.40	−0.06	0.05	−0.33	0.72**	−0.38	0.03	−0.42	0.25	0.05	0.08	1.00		
FC	0.37	0.14	−0.41	−0.07	0.08	−0.12	0.54	0.48	0.24	0.62*	−0.02	0.61*	0.61*	0.59*	0.32	0.26	0.33	−0.27	1.00	
TC	0.30	0.44	−0.38	−0.25	−0.27	−0.20	0.65*	0.37	0.23	0.71**	−0.47	0.60*	0.33	0.63*	0.06	0.14	0.19	−0.54	0.84***	1.00

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

3.3. Component Numbers and Eigenvalue Relations

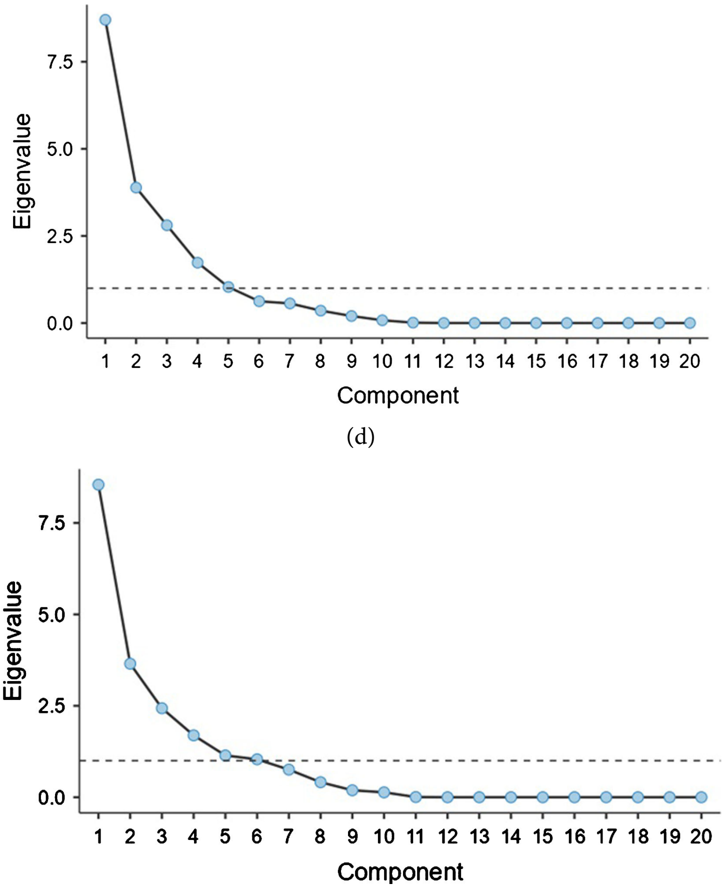
The selection of the component numbers in the analysis was based on the Kaiser criterion, where only eigenvalues greater than 1 were considered significant [38]. Consequently, wells WW1, WW2, WW3, WW4, and WW5 had 5, 6, 4, 5, and 6 principal components (PCs), respectively, in the principal component analysis (PCA) as indicated in **Figure 2**. These PCs were deemed sufficient to capture the essential variation in the original water quality variables from the shallow wells. The analysis allowed for a comprehensive representation of the water quality characteristics, with a detailed explanation of the significant PCs for each well provided to ensure a clear understanding of the underlying factors influencing water quality [39].



(a)

(b)

(c)



(d)

(e)

Figure 2. Scree plot of the eigenvalue for each component for the 5 shallow wells.

3.3.1. WW1

The water quality from WW1 can be effectively described by five principal components (PC1, PC2, PC3, PC4, and PC5), accounting for 87.53% of the total variability in the dataset (Table 11). The variance contributions for each component are: 33.05% for PC1, 25.97% for PC2, 14.56% for PC3, 8.44% for PC4, and 5.50% for PC5, indicating PC1 and PC2 are the most influential. The Sum of Squared Loadings (SS Loadings) also explain 87.53% of the variability, with PC1, PC2, PC3, PC4, and PC5 contributing 29.47%, 18.47%, 17.96%, 14.15%, and 7.47%, respectively. These results indicate that the first two components capture the majority of the water quality variability, consistent with findings in similar environmental studies [15] [40].

Table 11. Percentage variances and cumulative variance of the first 5 PCs' eigenvalues and SS loadings.

PC No.	Eigenvalue	% of Variance	Cumulative %	SS Loadings	% of Variance	Cumulative %
1	6.61	33.05	33.05	5.89	29.47	29.47
2	5.19	25.97	59.03	3.69	18.47	47.95
3	2.91	14.56	73.59	3.59	17.96	65.91
4	1.69	8.44	82.03	2.83	14.15	80.05
5	1.10	5.50	87.53	1.49	7.47	87.53

Figure 3 presents the factor scores for the five principal components (PCs) that explain 87.53% of the total variance in the water quality data from WW1. These scores indicate the contribution of each variable to the variance explained by each component, providing insight into the underlying factors driving water quality variations.

PC1 (33.05%) is strongly influenced by pH, electrical conductivity (EC), temperature, total suspended solids (TSS), total dissolved solids (TDS), hardness (Hd), phosphate (PO_4^{3-}), nitrate (NO_3^-), iron (Fe^{2+}), faecal coliforms (FC), and total coliforms (TC). This suggests that surface runoff is a major factor, contributing to increased EC, Temp, TSS, and TDS, while contamination from pit latrines is indicated by high FC and TC levels. The presence of agrochemical fertilizers is highlighted by the elevated levels of PO_4^{3-} and NO_3^-. Interestingly, chloride (Cl^-) has a negative effect, implying an inverse relationship with the contaminants driving PC1. Variables such as alkalinity (Alk), biochemical oxygen demand (BOD), calcium (Ca^{2+}), coliforms (Col), magnesium (Mg^{2+}), salinity (Sal), sulphate (SO_4^{2-}), and turbidity (Turb) do not significantly influence PC1. This aligns with studies showing that microbial and chemical contaminants are frequently associated with surface runoff and poor sanitation practices [14] and [41].

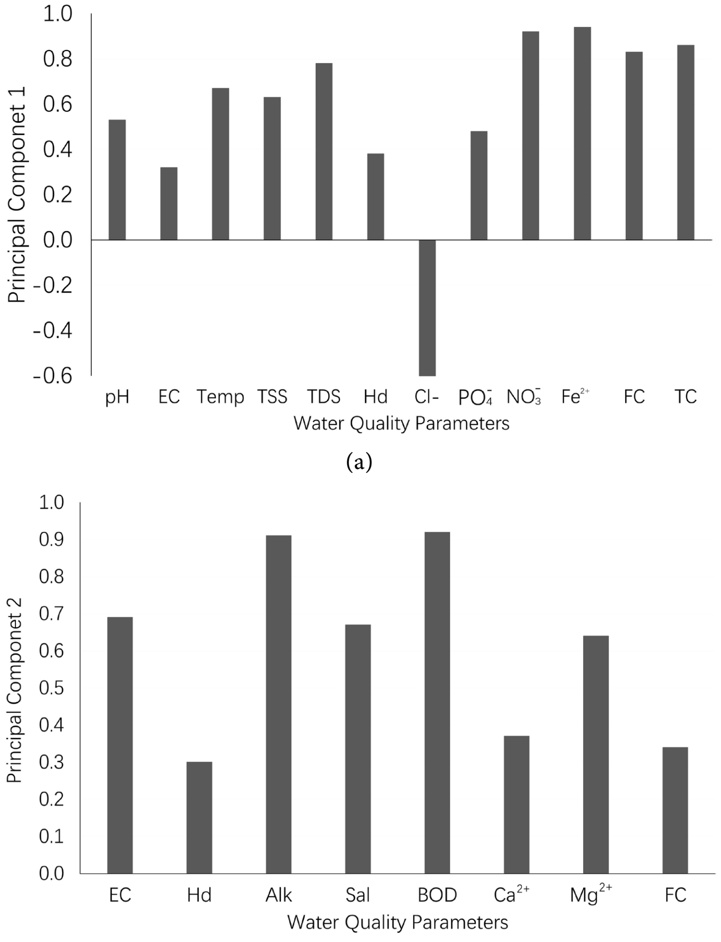
PC2 (25.97%) is characterized by the positive contribution of EC, hardness (Hd), Alk, Sal, BOD, Ca^{2+}, Mg^{2+}, and FC, pointing to the influence of geological formations and pit latrine contamination. High alkalinity, hardness, and salinity often result from water interacting with geological strata, such as limestone or dolomite, which release calcium and magnesium ions into the water [42]. The presence of faecal coliforms further suggests the proximity of contamination sources like pit latrines. Variables such as Cl^-, Col, Fe^{2+}, NO_3^-, pH, PO_4^{3-}, SO_4^{2-}, TC, TDS, Temp, TSS, and Turb do not significantly contribute to PC2, reinforcing the idea that geological processes dominate in this component [43].

PC3 (14.56%) is dominated by coliforms (Col), turbidity (Turb), TSS, Sal, and Cl^-, suggesting that surface runoff and microbial contamination play a key role. The positive loadings of TSS and Turb indicate the presence of suspended particles typically carried by runoff from urban or agricultural lands. The strong association between salinity and chloride further suggests influence from both surface runoff and geological sources, as these ions can enter the water through the dissolution of rock salts or human activities like road de-icing [41]. The negative contribution of EC and PO_4^{3-} may suggest areas where high microbial contamination correlates with lower concentrations of these chemicals, potentially due to dilution or other local environmental factors.

PC4 (8.44%) is defined by the positive loadings of hardness (Hd), PO_4^{3-}, SO_4^{2-}, Ca^{2+}, and Mg^{2+}, which are indicative of mineral dissolution from geological sources. The significant presence of sulphate and phosphate suggests the influence of sulphate-bearing minerals like gypsum or anthropogenic sources such as agricultural fertilizers. The negative effect of PO_4^{3-} points to the possibility of competing interactions between geological sources and human activities for phosphorus levels in the water. These findings align with studies indicating that areas with high sulphate and hardness often reflect regions where groundwater interacts with mineral-rich bedrock [42].

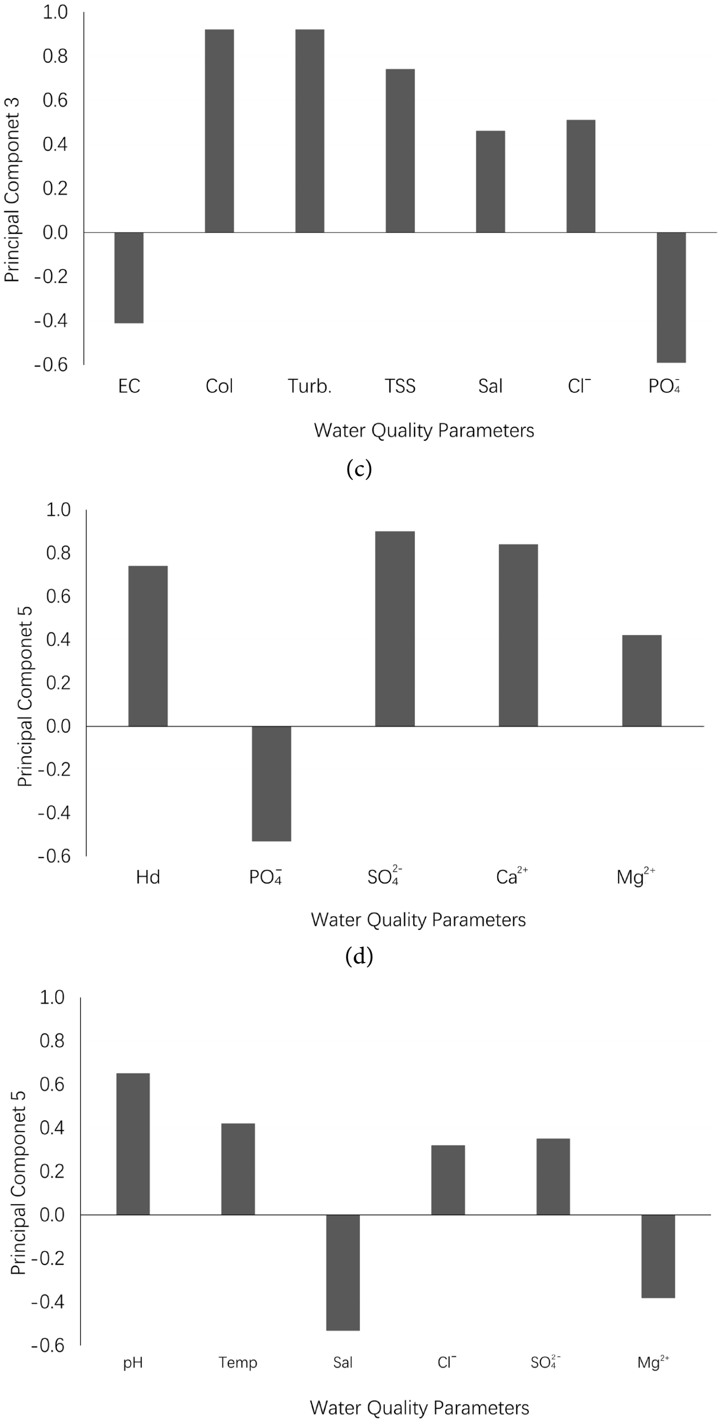
PC5 (5.50%) reflects the influence of pH, temperature (Temp), Cl⁻, and SO_4^{2-}, suggesting a combination of geological and human influences. Human activities such as water treatment or industrial discharges can impact pH and temperature, while the presence of sulphate and chloride may indicate inputs from both natural sources (e.g., mineral dissolution) and urban activities. The negative contributions of salinity and Mg^{2+} suggest that these factors are less influenced by surface interactions and may reflect deeper groundwater characteristics. This component aligns with findings from studies where industrial or urban activities have a significant impact on water temperature and chemical composition [14].

The factor scores reveal a complex interplay between surface runoff, agricultural practices, pit latrine contamination, and geological processes. PC1 emphasizes the impact of surface runoff and microbial contamination, PC2 and PC4 highlight the role of geological formations, while PC3 and PC5 show the combined effects of human activities and natural processes. These findings are consistent with previous research that demonstrates the significant contributions of both natural and anthropogenic factors to water quality variability [41] and [42].



(a)

(b)



(c)

(d)

(e)

Figure 3. Factor score coefficient for different water quality parameter for WW1 for PCs.

3.3.2. WW2

The water quality from WW2 can be effectively described by six principal components (PCs): PC1, PC2, PC3, PC4, PC5, and PC6, which together account for 92.55% of the total variability in the original dataset (**Table 12**). The contribution of each PC to the variance is as follows: 36.17% for PC1, 22.72% for PC2, 11.17%

for PC3, 9.35% for PC4, 8.13% for PC5, and 5.00% for PC6. Additionally, the Sum of Squared Loadings (SS Loadings) for these PCs explain 92.55% of the total variance, with each PC contributing 25.97%, 18.08%, 17.19%, 14.85%, 9.13%, and 7.34%, respectively. These results indicate that the first two components, PC1 and PC2, capture the majority of the variability, highlighting their importance in explaining the water quality variation in WW2 [29].

Table 12. Percentage variances and cumulative variance of the first 5 PCs' eigenvalues and SS loadings.

PC No.	Eigenvalue	% of Variance	Cumulative %	SS Loadings	% of Variance	Cumulative %
1	7.23	36.17	36.17	5.19	25.97	25.97
2	4.54	22.72	58.89	3.62	18.08	44.04
3	2.23	11.17	70.06	3.44	17.19	61.23
4	1.87	9.35	79.41	2.97	14.85	76.08
5	1.63	8.13	87.55	1.83	9.13	85.21
6	1.00	5.00	92.55	1.47	7.34	92.55

Figure 4 illustrates the factor scores for the six principal components (PCs) that explain 92.55% of the total variability in water quality data. These PCs highlight the dominant variables influencing water quality, providing insight into both natural processes and anthropogenic activities that impact the study area.

PC1, accounting for 36.17% of the total variance, is driven by pH, electrical conductivity (EC), temperature (Temp), coliforms (Col), turbidity (Turb), total suspended solids (TSS), total dissolved solids (TDS), salinity (Sal), chloride (Cl^-), sulphate (SO_4^{2-}), magnesium (Mg^{2+}), and iron (Fe^{2+}). These variables indicate the influence of surface runoff (EC, Temp, Col, TSS, TDS), which contributes to elevated suspended solids and microbial contamination, and geological formations (pH, Sal, Cl^-, SO_4^{2-} , Mg^{2+}, Fe^{2+}), which affect water chemistry through mineral dissolution. Variables such as hardness (Hd), alkalinity (Alk), phosphate (PO_4^{3-}), nitrate (NO_3^-), and faecal coliforms (FC) show no significant effect on PC1, aligning with studies that link surface runoff and geological strata as major drivers of water quality variation [42].

PC2, contributing 22.72% of the variance, is influenced by Col, Turb, TSS, TDS, Hd, Alk, Sal, Cl^-, and Mg^{2+}. This reflects surface runoff (Col, Turb, TSS, TDS) and geological processes (Hd, Alk, Sal, Cl^-, Mg^{2+}). Runoff from urban or agricultural areas increases suspended solids, while mineral dissolution contributes to hardness and alkalinity in the groundwater. Variables such as pH, EC, Temp, PO_4^{3-} , and NO_3^- show no effect. These patterns are consistent with studies of water quality where runoff and mineral dissolution affect the chemical composition of water sources [41].

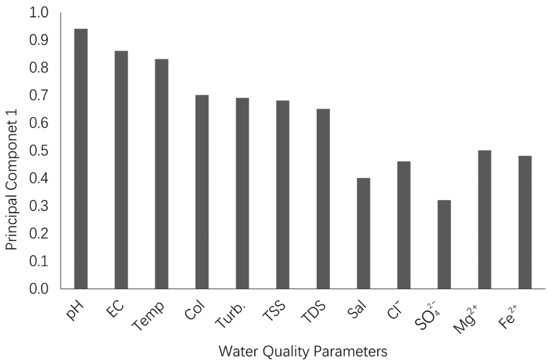
PC3, explaining 11.17% of the variance, is dominated by TSS, TDS, Alk, PO_4^{3-} , SO_4^{2-} , and NO_3^-, indicating surface runoff (TSS, TDS), agrochemical influences (PO_4^{3-} , NO_3^-), and geological factors (Alk, SO_4^{2-}). The presence of phosphates and nitrates suggests contamination from agricultural fertilizers, while alkalinity and sulphates point to mineral dissolution. Chloride (Cl^-) and Fe^{2+} contribute negatively, possibly indicating dilution or lower concentrations of these ions in areas dominated by agricultural inputs. These results are in line with research showing the impact of fertilizers on water quality in regions with high agricultural activity [43].

PC4, which accounts for 9.35% of the total variance, is influenced by Turb, TDS, Cl^-, BOD, Mg^{2+}, and Fe^{2+}. Surface runoff (Turb, TDS) and contamination from pit latrines (BOD) are key factors, while Mg^{2+} and Fe^{2+} suggest mineral dissolution from geological strata. The negative contributions from Ca^{2+} and NO_3^- imply less influence from these variables in this component, which may be explained by their absence in areas of higher pit latrine contamination or geological settings less rich in these minerals. Such findings are consistent with studies in regions where sanitation and runoff significantly affect water quality [14].

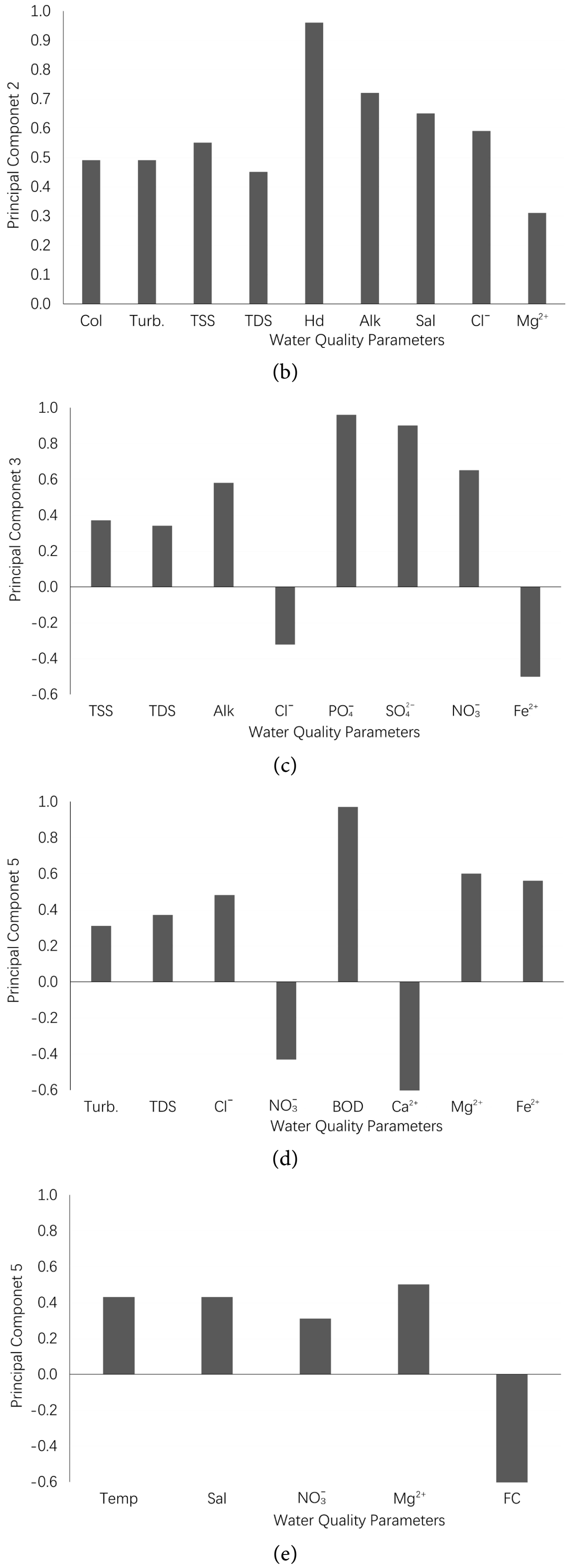
PC5 contributes 8.13% of the variance and is dominated by Temp, Sal, NO_3^-, and Mg^{2+}, indicating a combination of agrochemical (NO_3^-) and geological influences (Mg^{2+}, Sal). The presence of NO_3^- suggests contamination from agricultural sources or pit latrines, while the influence of salinity and magnesium reflects interactions with geological formations. The negative contribution of FC implies lower microbial contamination in areas influenced by geological and agrochemical sources, potentially due to deeper groundwater sources being less exposed to surface contamination [41].

PC6, explaining 5.00% of the variance, is primarily driven by NO_3^- and FC, indicating contamination from both agrochemical runoff and pit latrines. The strong presence of nitrates and faecal coliforms in this component suggests areas where agricultural and sanitation practices significantly affect water quality. Other variables have minimal influence, consistent with studies that highlight nitrate and microbial contamination as major issues in regions affected by human and agricultural waste [14].

The six principal components reflect a complex interplay of surface runoff, geological factors, agrochemical pollution, and sanitation-related contamination. PC1 and PC2 highlight the dominant roles of surface runoff and geological strata, while PC3 and PC5 emphasize the contributions of agrochemicals and sanitation practices. These results align with previous studies, confirming that both natural processes and human activities significantly impact water quality in the study area [42].



(a)

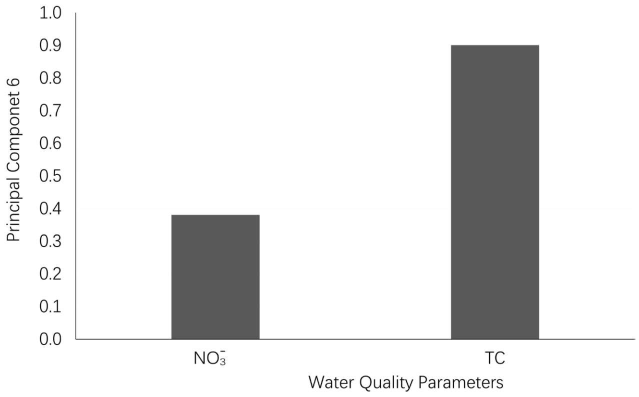

Principal Componet 2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Col
Turb.
TSS
TDS
Hd
Alk
Sal
Cl⁻
Mg²⁺
Water Quality Parameters
Principal Componet 3
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
TSS
TDS
Alk
Cl⁻
PO₄⁻
SO₄²⁻
NO₃⁻
Fe²⁺
Water Quality Parameters
Principal Componet 5
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Turb.
TDS
Cl⁻
NO₃⁻
BOD
Ca²⁺
Mg²⁺
Fe²⁺
Water Quality Parameters
Principal Componet 5
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Temp
Sal
NO₃⁻
Mg²⁺
FC
Water Quality Parameters

(b)

(c)

(d)

(e)



(f)

Figure 4. Factor score coefficient for different water quality parameter for WW2 for PCs.

3.3.3. WW3

The quality of the water from the WW2 can be sufficiently described by 4 PCs namely PC1, PC2, PC3 and PC4. These PCs contribute 84.61% of the variability of the original results (**Table 13**). The variances of the PCs are 39.63%, 18.79%, 14.15% and 12.04% for PC1, PC2, PC3 and PC4 respectively. On the other hand, the sum of the square loading (SS Loading) for the PCs are shown and the variance contribute to 84.61% of the variability of the SS loading. The variances of the PCs are 34.27%, 19.84%, 15.4% and 15.09% for PC1, PC2, PC3 and PC4 respectively.

Table 13. Percentage variances and cumulative variance of the first 5 PCs' eigenvalues and SS loadings.

PC No.	Eigenvalue	% of Variance	Cumulative %	SS Loadings	% of Variance	Cumulative %
1	7.93	39.63	39.63	6.85	34.27	34.27
2	3.76	18.79	58.42	3.97	19.84	54.11
3	2.83	14.15	72.57	3.08	15.4	69.52
4	2.41	12.04	84.61	3.02	15.09	84.61

Figure 5 provides the factor scores for the five principal components (PCs) that explain water quality variability. Each component reflects a combination of factors such as surface runoff, geological formations, sanitation, and agrochemical use. The higher the score value of a variable, the greater its contribution to the variability of the corresponding component.

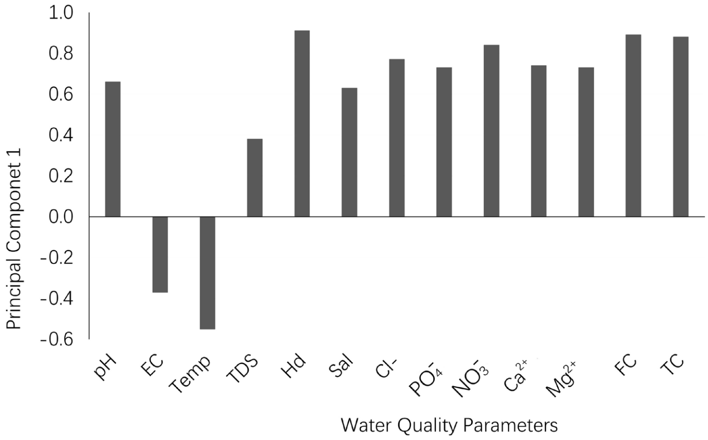
PC1 contributes 36.17% of the variance and is driven by pH, electrical conductivity (EC), temperature (Temp), total dissolved solids (TDS), hardness (Hd), salinity (Sal), chloride (Cl^-), phosphate (PO_4^{3-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), faecal coliforms (FC) and total coliforms (TC). This component indicates a blend of influences: Geological strata (pH, Hd, Sal, Cl^-, Ca^{2+}, Mg^{2+}). These parameters are typically associated with natural mineral dissolution as groundwater interacts with subsurface formations. Elevated hardness and salinity often reflect regions rich in minerals like limestone or gypsum, contributing to higher concentrations of calcium, magnesium, and salts in water [43]. Surface runoff (TDS, Cl^-): Runoff from urban or agricultural areas can introduce dissolved solids and chloride, often due to fertilizers. This results in elevated levels of TDS and chloride in surface and shallow groundwater. Sanitation-related contamination (FC, TC). The presence of faecal coliforms and total coliforms suggests contamination from pit latrines or poorly maintained sanitation systems, which can leach into groundwater. This is consistent with studies showing microbial contamination in areas with inadequate waste management [32]. Agrochemical influence (PO_4^{3-} , NO_3^-). Phosphates and nitrates are commonly associated with fertilizer runoff, highlighting the impact of agricultural activities on water quality. Interestingly, EC and Temp have negative effects on PC1, suggesting that in areas with high contributions from other variables (e.g., TDS and coliforms), conductivity and temperature may have less of an impact. Variables such as coliforms (Col), turbidity (Turb), TSS, alkalinity (Alk), sulphate (SO_4^{2-}), BOD, and Iron (Fe^{2+}) do not contribute significantly to PC1.

PC2 explains 22.72% of the total variance and is influenced by Temp, Col, Turb, TSS, Sal, Cl^-, PO_4^{3-} , BOD, Ca^{2+} and Fe^{2+}. This component suggests a mix of surface and subsurface influences: Surface runoff (Temp, Col, Turb, TSS): Runoff from urban areas or agricultural lands can introduce suspended solids, turbidity, and coliform bacteria into the water, increasing contamination. High temperature often indicates surface water interaction or shallow groundwater exposed to climatic variations [15]. Geological influence (Sal, Cl^-, Ca^{2+}, Fe^{2+}): These variables point to mineral dissolution processes, particularly in groundwater rich in iron and calcium due to the presence of minerals such as calcite or dolomite. Agrochemical contamination (PO_4^{3-}). Elevated phosphate levels suggest fertilizer runoff, indicating agricultural activities as a major influence on water quality. Phosphates in groundwater are often linked to excessive use of chemical fertilizers, leading to nutrient pollution. Variables such as pH, EC, TDS, Hd, Alk, SO_4^{2-} , NO_3^-, Mg^{2+}, FC, and TC show no significant effect, highlighting that PC2 is primarily dominated by runoff and specific geological interactions.

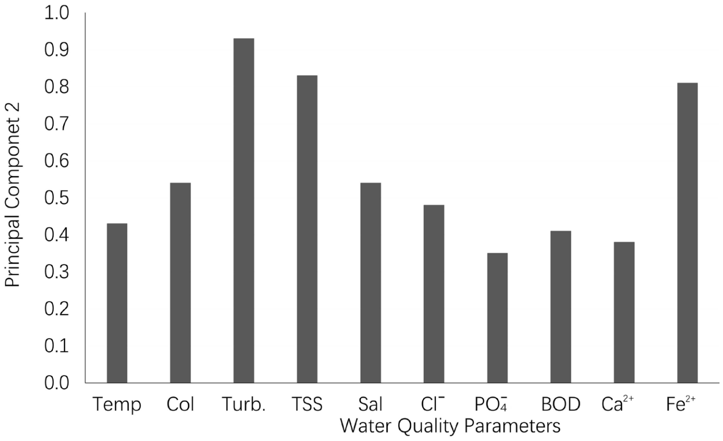
PC3, accounting for 11.17% of the variance, is driven by Temp, TDS, PO_4^{3-} , and Mg^{2+}, while Col, Sal, SO_4^{2-} , and Ca^{2+} show negative effects: Surface runoff (TDS, Temp): This highlights the influence of dissolved solids from runoff, where temperature plays a role in the rate of contamination. Geological strata (Mg^{2+}): The presence of magnesium reflects mineral interactions within groundwater aquifers, pointing to natural sources of contamination. Agrochemical inputs (PO_4^{3-}): Again, phosphates are a strong indicator of agricultural runoff, emphasizing the impact of farming activities on groundwater quality. Negative contributions from Col, Sal, SO_4^{2-} , and Ca^{2+} may suggest that in regions with high phosphate or magnesium concentrations, these variables are less influential. Other variables such as pH, EC, Turb, TSS, Hd, Alk, NO_3^-, BOD, Fe^{2+}, FC, TC, and Cl^- do not show a significant impact, implying a more localized influence of surface runoff and geological features in PC3.

PC4 explains 9.35% of the variance, with positive contributions from EC, Alk, and BOD, and negative contributions from Temp, Col, NO_3^-, and TC: Geological influence (EC, Alk): The presence of alkalinity and conductivity suggests mineral dissolution, particularly in regions where groundwater interacts with calcareous formations, contributing to higher alkalinity. Pit latrine contamination (BOD): Elevated BOD indicates organic pollution, typically associated with human waste leaching into water sources, often from pit latrines. Negative contributions from temperature, coliform bacteria, and nitrates suggest that microbial contamination may be less impactful in areas dominated by mineral dissolution or deeper groundwater sources. This finding reflects regions where organic pollution from pit latrines is more significant than surface contamination. Variables such as pH, Turb, TSS, TDS, Hd, Sal, Cl^-, PO_4^{3-}, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Fe^{2+}, and FC do not show significant influence, emphasizing geological and sanitation-related processes as dominant in this component.

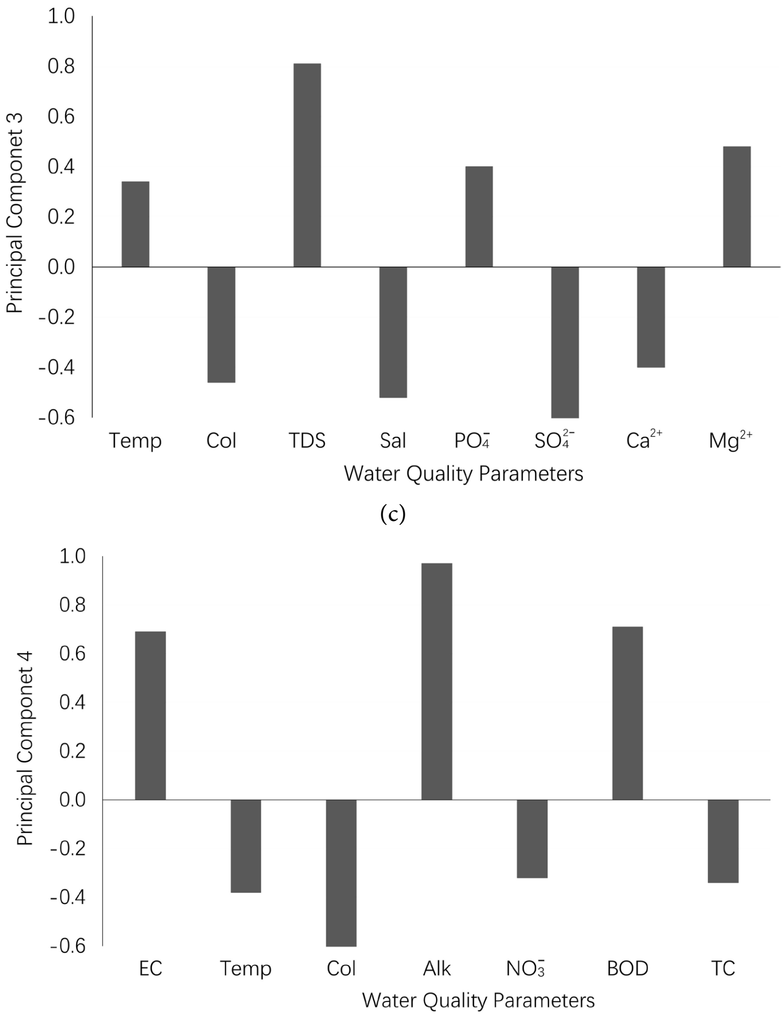
The four principal components reveal critical influences on water quality, including surface runoff, geological interactions, agricultural activities, and sanitation-related contamination. PC1 highlights the role of runoff and geology, while PC2 and PC3 emphasize the impact of agrochemical runoff and geological processes. PC4 points to contamination from pit latrines. The analysis underscores the complex interaction between natural processes and human activities in shaping groundwater quality [42].



(a)



(b)



(c)

(d)

Figure 5. Factor score coefficient for different water quality parameter for WW3 for PCs.

3.3.4. WW4

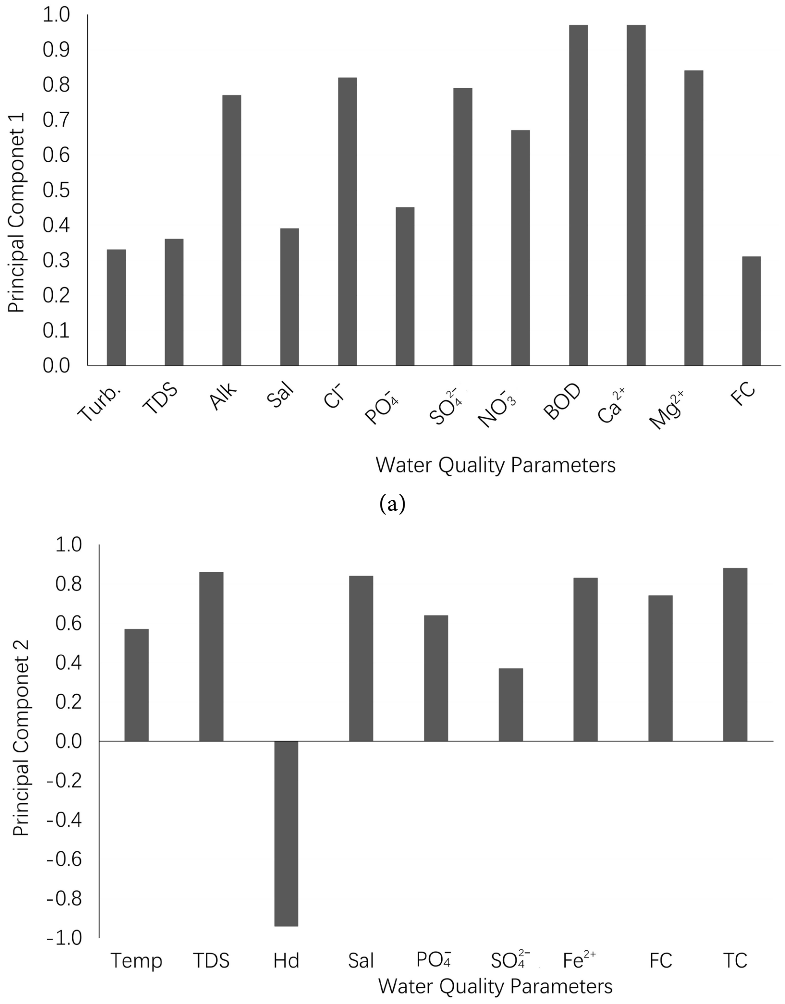
The water quality of WW4 can be adequately described by six principal components (PC1-PC6), which together explain 90.83% of the total variability in the original dataset (**Figure 6**). The variance contributions for each PC are 36.17% for PC1, 22.72% for PC2, 11.17% for PC3, 9.35% for PC4, 8.13% for PC5, and 5.00% for PC6, making them sufficient to represent the underlying water quality patterns. The Sum of Squared Loadings (SS Loadings) for these PCs explain 92.55% of the total variance, with each PC contributing 25.97%, 18.08%, 17.19%, 14.85%, 9.13%, and 7.34%, respectively, indicating a substantial representation of the original data [29] (**Table 14**).

As shown in **Table 12**, PC1 has an eigenvalue of 8.71, accounting for 43.53% of the variance, followed by PC2 at 3.89 (19.44%), PC3 at 2.81 (14.04%), PC4 at 1.73 (8.66%), and PC5 at 1.03 (5.17%). These components cumulatively explain 90.83% of the variance, indicating that the majority of the variability in water quality across WW4 can be captured by these five components [44].

Table 14. Percentage variances and cumulative variance of the first 5 PCs' eigenvalues and SS loadings.

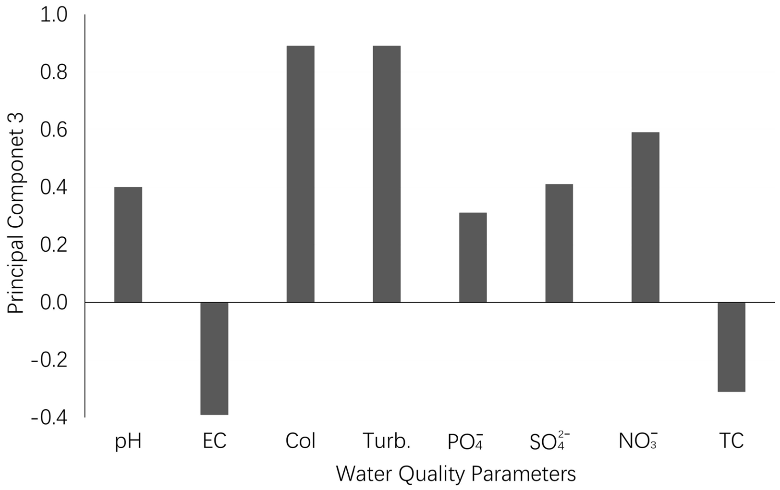
PC No.	Eigenvalue	% of Variance	Cumulative %	SS Loadings	% of Variance	Cumulative %
1	8.71	43.53	43.53	5.86	29.32	29.32
2	3.89	19.44	62.96	5.72	28.61	57.93
3	2.81	14.04	77.00	2.9	14.51	72.44
4	1.73	8.66	85.66	2.09	10.46	82.9
5	1.03	5.17	90.83	1.59	7.93	90.83

Figure 6 shows the factor scores for the five PCs. The higher the score value of the variable, the more the variable contributes to the variability of the particular PC. PC1 (43.53% variance). 12 variables contribute positively, including Turb, TDS, Alk, Sal, Cl^-, PO_4^{3-}, SO_4^{2-}, NO_3^-, BOD, Ca^{2+}, Mg^{2+} and FC. This indicates influences from surface runoff (Turb, TDS), pit latrines (PO_4^{3-}, NO_3^-, BOD, FC), and geological strata (Alk, Sal, Cl^-, Ca^{2+}, Mg^{2+}), as well as agrochemical fertilizers (PO_4^{3-}, NO_3^-). Variables such as pH, EC, Temp, Col, TSS, Hd, Fe^{2+}, and TC do not contribute significantly [42].

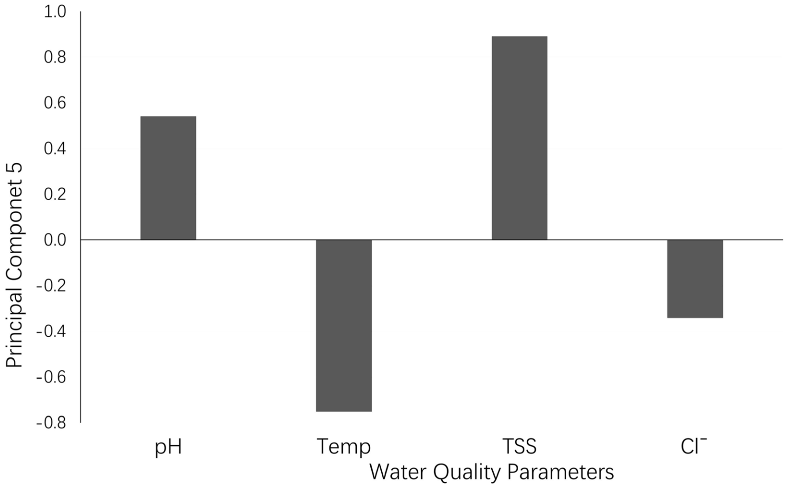


(a)

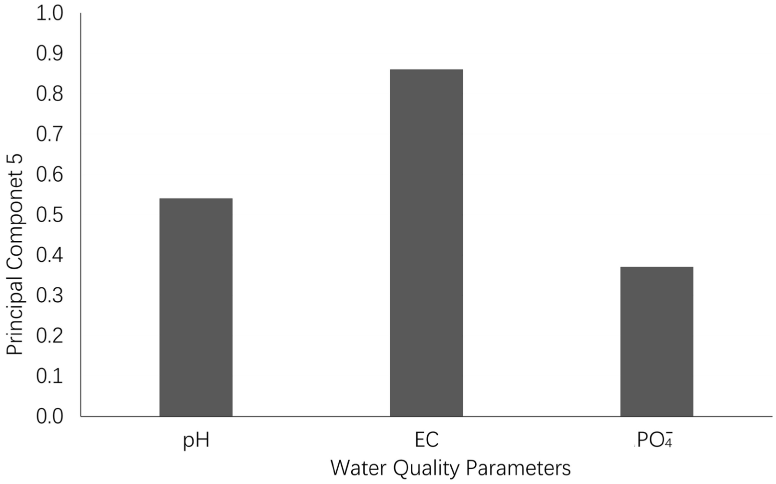
(b)



(c)



(d)



(e)

Figure 6. Factor score coefficient for different water quality parameter for WW4 for PCs.

PC2 (19.44% variance): Positive contributors include Temp, TDS, Sal, PO_4^{3-} ,

SO_4^{2-}, Fe^{2+}, FC, and TC, while Hd has a negative effect. This suggests that surface runoff (Temp, TDS), pit latrine contamination (FC, TC), and geological factors (Sal, Fe^{2+}) are key drivers, along with agrochemical inputs (PO_4^{3-}, NO_3^-) [36].

PC3 (14.04% variance): Positive contributions from pH, Col, Turb, PO_4^{3-}, SO_4^{2-}, and NO_3^- suggest influences from surface runoff (Col, Turb), pit latrines (PO_4^{3-}, NO_3^-), geological factors (pH), and agrochemical use. Negative effects from EC and TC indicate areas where these variables are less influential [14].

PC4 (8.66% variance): Only pH and TSS contribute positively, while Temp and Cl^- have negative effects. This suggests the role of surface runoff (TSS) and geological influence (pH), with other variables showing minimal impact.

PC5 (5.17% variance): pH, EC, and PO_4^{3-} contribute positively, indicating influences from surface runoff (PO_4^{3-}), geological strata (pH, EC), and agricultural fertilizers. Other variables, including Temp, Col, Turb, TSS, Hd, Sal, and Fe^{2+}, have no significant contribution.

The principal component analysis reveals that water quality in WW4 is strongly influenced by surface runoff, geological factors, pit latrine contamination, and agrochemical inputs. The first three components capture the majority of variability, with PC1 highlighting the combined effect of geological and human influences, particularly from sanitation and agricultural practices [36] [45].

3.3.5. WW5

The water quality of WW2 can be effectively described by six principal components (PC1-PC6), accounting for 92.51% of the total variability in the original dataset (**Figure 7**). The variance contributions of each PC are 42.73% for PC1, 18.26% for PC2, 12.17% for PC3, 8.46% for PC4, 5.71% for PC5, and 5.18% for PC6, making these components sufficient to capture the underlying water quality variation. The Sum of Squared Loadings (SS Loadings) further explain 92.55% of the variance, with contributions of 35.21%, 15.04%, 14.92%, 11.06%, 8.79%, and 7.50% for the respective PCs (**Table 15**) [29].

As presented in **Table 15**, PC1 has the highest eigenvalue of 8.55, explaining 42.73% of the variance, followed by PC2 at 3.65 (18.26%), PC3 at 2.43 (12.17%), PC4 at 1.69 (8.46%), PC5 at 1.14 (5.71%), and PC6 at 1.04 (5.18%). The cumulative variance explained by these components is 92.51%, indicating that the six PCs sufficiently capture the essential patterns in the water quality data [44].

Table 15. Percentage variances and cumulative variance of the first 5 PCs' eigenvalues and SS loadings.

PC No.	Eigenvalue	% of Variance	Cumulative %	SS Loadings	% of Variance	Cumulative %
1	8.55	42.73	42.73	7.04	35.21	35.21
2	3.65	18.26	60.98	3.01	15.04	50.26
3	2.43	12.17	73.15	2.98	14.92	65.17
4	1.69	8.46	81.62	2.21	11.06	76.23
5	1.14	5.71	87.33	1.76	8.79	85.02
6	1.04	5.18	92.51	1.50	7.50	92.51

PC1 (42.73% variance): 11 variables contribute positively, including pH, turbidity (Turb), total dissolved solids (TDS), hardness (Hd), alkalinity (Alk), salinity (Sal), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), nitrate (NO_3^-), biochemical oxygen demand (BOD), and magnesium (Mg^{2+}). Temperature (Temp) has a negative effect. This indicates influences from surface runoff (Turb, TDS), pit latrines (PO_4^{3-} , NO_3^- , BOD), geological strata (pH, Hd, Alk, Sal), and agrochemical fertilizers (PO_4^{3-} , SO_4^{2-} , NO_3^-). EC, Col, TSS, Cl^-, Ca^{2+}, Fe^{2+}, FC, and TC show no significant effect [42].

PC2 (18.26% variance): Positive contributors include TDS, Sal, PO_4^{3-} , SO_4^{2-} , NO_3^- , Ca^{2+}, FC, and TC, suggesting influences from surface runoff (TDS), pit latrines (PO_4^{3-} , NO_3^- , FC, TC), geological strata (Ca^{2+}, Sal), and agrochemical fertilizers (PO_4^{3-} , SO_4^{2-} , NO_3^-). Variables such as pH, EC, Temp, Col, Turb, TSS, Hd, Alk, and BOD have no significant effect [41].

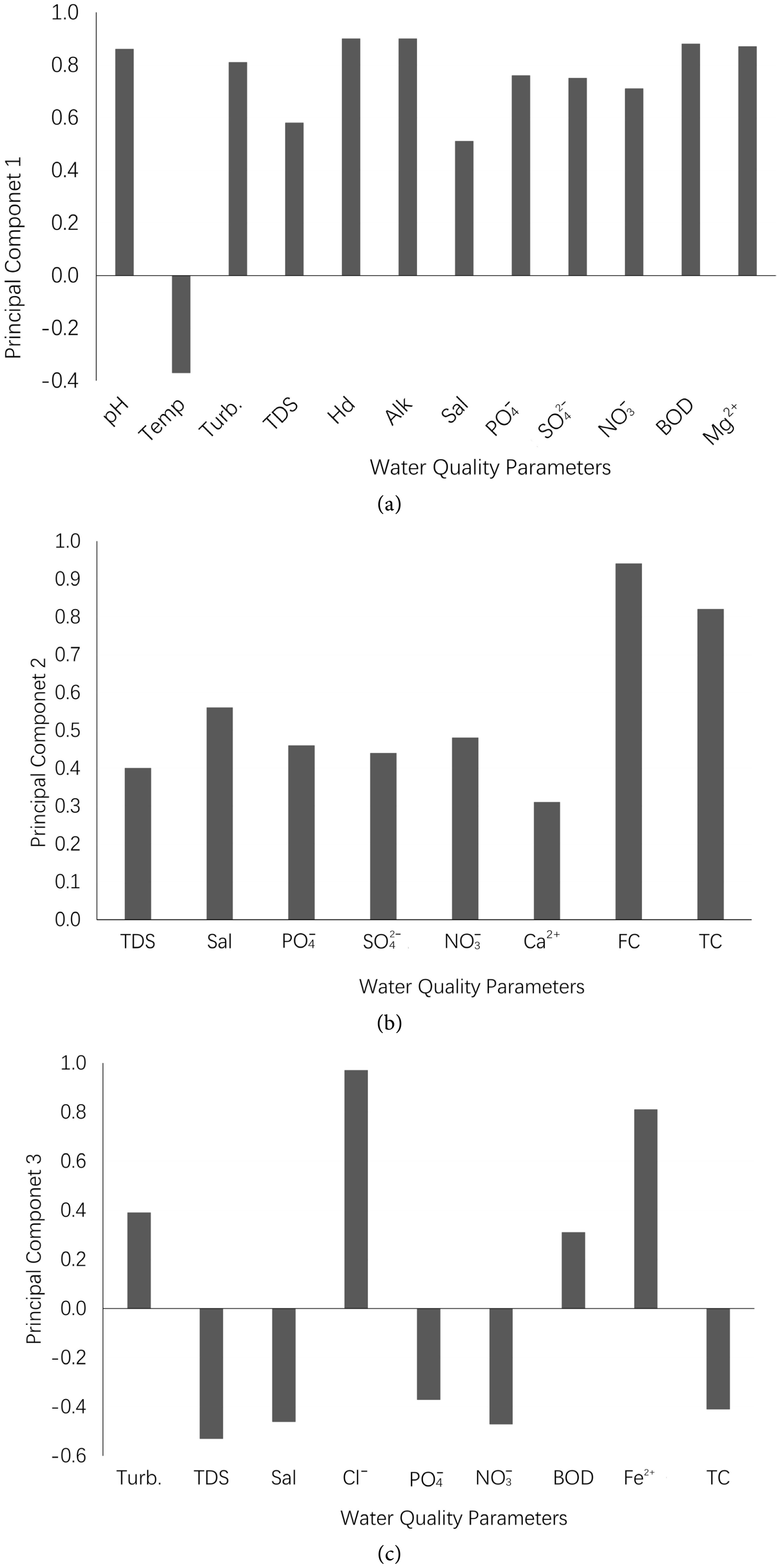
PC3 (12.17% variance): Four variables—Turb, Cl^-, BOD, and Fe^{2+}—contribute positively, while TDS, Sal, PO_4^{3-} , NO_3^- , and TC negatively affect this component. This suggests the influence of surface runoff (Turb), pit latrine connections (BOD), and geological strata (Cl^-, Fe^{2+}) [14].

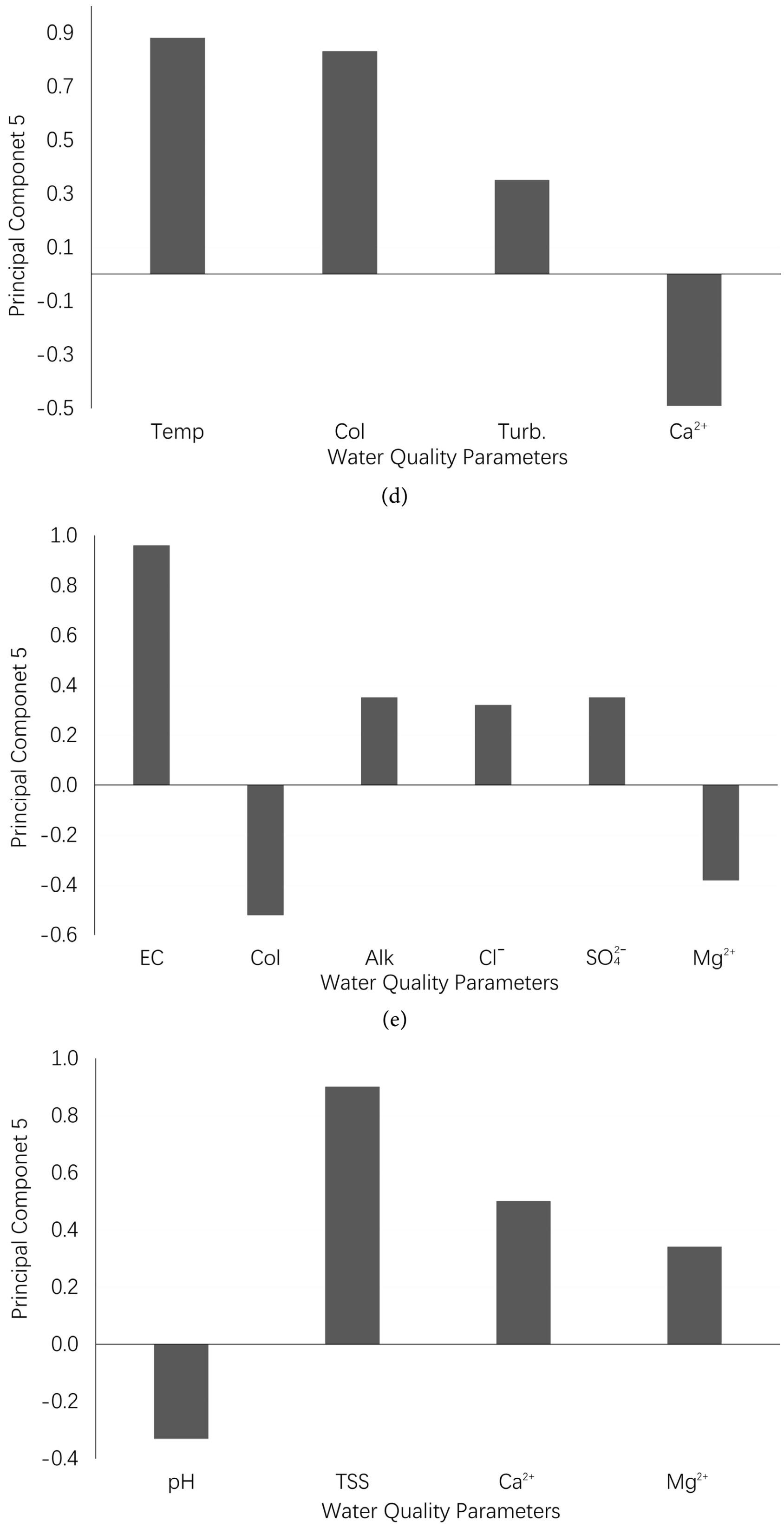
PC4 (8.46% variance): Positive contributions from Turb, Col, and Temp suggest the impact of surface runoff (Turb, Col, Temp). Ca^{2+} has a negative effect, with no significant influence from other variables [15].

PC5 (5.71% variance): EC, Alk, Cl^-, and SO_4^{2-} contribute positively, while Col and Mg^{2+} have negative effects. This suggests influences from geological strata (EC, Alk, Cl^-, SO_4^{2-}) and surface runoff (Turb, Col) [42].

PC6 (5.18% variance): Positive contributors are TSS, Ca^{2+}, and Mg^{2+}, suggesting influences from surface runoff (TSS) and geological strata (Ca^{2+}, Mg^{2+}). pH negatively affects this component.

The analysis of the six principal components (PCs) highlights the complex interactions among natural and human factors influencing the water quality of WW2. The first three PCs explain the majority of the variance, underscoring the significant role of surface runoff, pit latrines, geological strata, and agro-chemical usage. Surface runoff acts as a key vector for transporting natural sediments and anthropogenic pollutants, while pit latrines contribute to microbial and nutrient contamination, especially in proximity to water sources [46] and [47]. Geological formations regulate water quality through mineral leaching and filtration, mediating the impacts of agricultural and human activities [38] and [48]. Agro-chemical application further exacerbates nutrient loading, contributing to water quality degradation. These findings align with predictive models demonstrating the long-term effects of runoff and leaching on water systems, emphasizing the need for comprehensive land-use and sanitation management [42]. Together, these components reveal the necessity of integrating natural geological characteristics with mitigation strategies to address anthropogenic impacts sustainably.


Principal Componet 1
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
pH
Temp
Turb.
TDS
Hd
Alk
Sal
PO_4^-
SO_4^{2-}
NO_3^-
BOD
Mg^{2+}
Water Quality Parameters
(a)
Principal Componet 2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
TDS
Sal
PO_4^-
SO_4^{2-}
NO_3^-
Ca^{2+}
FC
TC
Water Quality Parameters
(b)
Principal Componet 3
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Turb.
TDS
Sal
Cl^-
PO_4^-
NO_3^-
BOD
Fe^{2+}
TC
Water Quality Parameters
(c)



(d)

(e)

(f)

Figure 7. Factor score coefficient for different water quality parameter for WW5 for PCs.

4. Conclusion and Recommendation

The water quality of shallow wells in Half London Ward, Tunduma, Tanzania, reveals significant variability across the five wells (WW1 to WW5), with principal component analysis (PCA) demonstrating the dominant roles of surface runoff, pit latrine contamination, agrochemical inputs, and geological factors. In all wells, surface runoff, particularly after rainfall, contributes significantly to microbial contamination, with faecal and total coliforms indicating poor sanitation practices. Contamination from agricultural fertilizers, notably nitrates (NO_3^-) and phosphates (PO_4^{3-}), further degrades water quality, highlighting the impact of small-scale farming on groundwater. Geological processes, including the dissolution of minerals like magnesium, calcium, and sulphates, contribute to the water's hardness and salinity. The study reveals that both human activities (such as sanitation and agricultural practices) and natural processes (like mineral dissolution) significantly influence the water quality, underscoring the vulnerability of shallow wells to contamination in densely populated and agriculturally active regions. The study recommends on implementation of improved sanitation practices, proper use of agrochemicals, regular monitoring of Water Quality, Safe Well Construction public awareness campaigns enforcement of regulations on safe distances between wells and latrines, as well as agricultural fields.

Acknowledgements

The authors extend their heartfelt gratitude to the Management of Mbeya University of Science and Technology, particularly Prof. Aloys Mvuma, for their invaluable support and granting permission to pursue this research. We deeply appreciate their unwavering guidance and encouragement throughout the preparation of this research article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Lapworth, D.J., MacDonald, A.M., Tijani, M.N., Darling, W.G., Gooddy, D.C., Bonsor, H.C., *et al.* (2012) Residence Times of Shallow Groundwater in West Africa: Implications for Hydrogeology and Resilience to Future Changes in Climate. *Hydrogeology Journal*, **21**, 673-686. https://doi.org/10.1007/s10040-012-0925-4

[2] Mbaka, P.K. (2017) Influence of Iso 9001: 2008 Quality Management System on The Reliability of Services Offered in Public Universities in Kenya. *European Journal of Research and Reflection in Educational Sciences*, **5**, 22-31.

[3] Graham, J.P. and Polizzotto, M.L. (2013) Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review. *Environmental Health Perspectives*, **121**, 521-530. https://doi.org/10.1289/ehp.1206028

[4] Kimani-Murage, E.W. and Ngindu, A.M. (2007) Quality of Water the Slum Dwellers Use: The Case of a Kenyan Slum. *Journal of Urban Health*, **84**, 829-838. https://doi.org/10.1007/s11524-007-9199-x

[5] Ufoegbune, G., *et al.* (2009) Hydro-Geological Characteristics and Groundwater Quality Assessment in Some Selected Communities of Abeokuta, Southwest Nigeria. *Journal of Environmental Chemistry and Ecotoxicology*, **1**, 10-22.

[6] Pandey, P.K., Kass, P.H., Soupir, M.L., Biswas, S. and Singh, V.P. (2014) Contamination of Water Resources by Pathogenic Bacteria. *AMB Express*, **4**, Article No. 51. https://doi.org/10.1186/s13568-014-0051-x

[7] Foster, S. and Chilton, J. (2021) Policy Experience with Groundwater Protection from Diffuse Pollution—A Review. *Current Opinion in Environmental Science & Health*, **23**, Article 100288. https://doi.org/10.1016/j.coesh.2021.100288

[8] Sorensen, J.P.R., Lapworth, D.J., Marchant, B.P., Nkhuwa, D.C.W., Pedley, S., Stuart, M.E., *et al.* (2015) In-situ Tryptophan-Like Fluorescence: A Real-Time Indicator of Faecal Contamination in Drinking Water Supplies. *Water Research*, **81**, 38-46. https://doi.org/10.1016/j.watres.2015.05.035

[9] Kanyerere, T., Levy, J., Xu, Y. and Saka, J. (2012) Assessment of Microbial Contamination of Groundwater in Upper Limphasa River Catchment, Located in a Rural Area of Northern Malawi. *Water SA*, **38**, 581-596. https://doi.org/10.4314/wsa.v38i4.14

[10] Dzwairo, B., Hoko, Z., Love, D. and Guzha, E. (2006) Assessment of the Impacts of Pit Latrines on Groundwater Quality in Rural Areas: A Case Study from Marondera District, Zimbabwe. *Physics and Chemistry of the Earth*, *Parts A/B/C*, **31**, 779-788. https://doi.org/10.1016/j.pce.2006.08.031

[11] Hoko, Z. and Toto, T.N. (2020) Integration of Water Hyacinth Plants into Waste Stabilization Ponds: A Case Study of Donnybrook 4 Sewage Ponds in Mabvuku-Tafara, Harare, Zimbabwe. *Environmental Monitoring and Assessment*, **192**, Article No. 625. https://doi.org/10.1007/s10661-020-08579-6

[12] Zolkefli, N., Sharuddin, S.S., Yusoff, M.Z.M., Hassan, M.A., Maeda, T. and Ramli, N. (2020) A Review of Current and Emerging Approaches for Water Pollution Monitoring. *Water*, **12**, Article 3417. https://doi.org/10.3390/w12123417

[13] Akana, T., George, G. and Oki, O. (2016) Aquifer Vulnerability Assessment in Some Towns of Yenagoa, South-South Nigeria. *Science and Technology*, **6**, 15-23.

[14] Postolache, O., Silva, P. and Dias Pereir, J.M. (2012) Water Quality Monitoring and Associated Distributed Measurement Systems: An Overview. In: Voudouris, K. and Voutsa, D., Eds., *Water Quality Monitoring and Assessment*, InTech, 25-64. https://doi.org/10.5772/32159

[15] Howard, G., Calow, R., Macdonald, A. and Bartram, J. (2016) Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. *Annual Review of Environment and Resources*, **41**, 253-276. https://doi.org/10.1146/annurev-environ-110615-085856

[16] Kawo, N.S. and Karuppannan, S. (2018) Groundwater Quality Assessment Using Water Quality Index and GIS Technique in Modjo River Basin, Central Ethiopia. *Journal of African Earth Sciences*, **147**, 300-311. https://doi.org/10.1016/j.jafrearsci.2018.06.034

[17] Danert, K. and Healy, A. (2021) Monitoring Groundwater Use as a Domestic Water Source by Urban Households: Analysis of Data from Lagos State, Nigeria and Sub-Saharan Africa with Implications for Policy and Practice. *Water*, **13**, Article 568. https://doi.org/10.3390/w13040568

[18] Weller, P. and Parastar, H. (2023) Unsupervised and Supervised Chemometrics in Flavoromics. In: Nollet, L. and Bordiga, M., Eds., *Flavoromics*, CRC Press, 123-161. https://doi.org/10.1201/9781003268758-9

[19] Vidya, V. and Prasad, G. () Interpretation of Water Quality Using Principal Component Analysis—A Case Study from a Tropical Ramsar Wetland Site Adjacent to the Seafood Processing Facilities. *Ecology, Environment and Conservation*, **30**, S305-S311. https://doi.org/10.53550/EEC.2024.v30i03s.053

[20] Ibrahim, A., Ismail, A., Juahir, H., Iliyasu, A.B., Wailare, B.T., Mukhtar, M., *et al.* (2023) Water Quality Modelling Using Principal Component Analysis and Artificial Neural Network. *Marine Pollution Bulletin*, **187**, Article 114493. https://doi.org/10.1016/j.marpolbul.2022.114493

[21] Rugeiyamu, R. (2022) The Tanzania Housing and Population Census 2022: A Panacea for Local Service Delivery and Development Drawbacks. *Local Administration Journal*, **15**, 1-13.

[22] Foran, J.A. and Griggs, A. (2017) Water Contamination. In: Levy, B.S., *et al.*, Eds., *Occupational and Environmental Health* (7th ed., pp. 365-380). Oxford University Press. https://doi.org/10.1093/oso/9780190662677.003.0019

[23] Sangani, K., Ujjania, N.C., Bengani, R. and Patel, S. (2021) Selected Hydrological Parameters and Water Quality Index Analysis of Ambica River, Gujarat (India). *Environment and Ecology*, **39**, 691-696.

[24] Zhao, Q., Liu, S., Deng, L., Yang, Z., Dong, S., Wang, C., *et al.* (2011) Spatio-Temporal Variation of Heavy Metals in Fresh Water after Dam Construction: A Case Study of the Manwan Reservoir, Lancang River. *Environmental Monitoring and Assessment*, **184**, 4253-4266. https://doi.org/10.1007/s10661-011-2260-y

[25] American Public Health Association (1926) Standard Methods for the Examination of Water and Wastewater. Vol. 6. American Public Health Association.

[26] Howard, G., Bartram, J., Williams, A., *et al.* (2020) Domestic Water Quantity, Service Level and Health. World Health Organization.

[27] Abaasa, C.N., Ayesiga, S., Lejju, J.B., Andama, M., Tamwesigire, I.K., Bazira, J., *et al.* (2024) Assessing the Quality of Drinking Water from Selected Water Sources in Mbarara City, South-Western Uganda. *PLOS ONE*, **19**, e0297794. https://doi.org/10.1371/journal.pone.0297794

[28] Caldwell, A.R. (2022) Simplyagree: An R Package and Jamovi Module for Simplifying Agreement and Reliability Analyses. *Journal of Open Source Software*, **7**, Article 4148. https://doi.org/10.21105/joss.04148

[29] Jolliffe, I.T. and Cadima, J. (2016) Principal Component Analysis: A Review and Recent Developments. *Philosophical Transactions of the Royal Society A*: *Mathematical, Physical and Engineering Sciences*, **374**, Article 20150202. https://doi.org/10.1098/rsta.2015.0202

[30] Baek, H.J., Kim, H.S., Kim, N., Choi, Y.J. and Kim, Y.J. (2012) Percent Change of Perfusion Skewness and Kurtosis: A Potential Imaging Biomarker for Early Treatment Response in Patients with Newly Diagnosed Glioblastomas. *Radiology*, **264**, 834-843. https://doi.org/10.1148/radiol.12112120

[31] Khan, M.N., Mobin, M., Abbas, Z.K. and Alamri, S.A. (2018) Fertilizers and Their Contaminants in Soils, Surface and Groundwater. *Encyclopedia of the Anthropocene*, **5**, 225-240. https://doi.org/10.1016/b978-0-12-809665-9.09888-8

[32] Zhang, Q., Xu, P. and Qian, H. (2020) Groundwater Quality Assessment Using Improved Water Quality Index (WQI) and Human Health Risk (HHR) Evaluation in a Semi-Arid Region of Northwest China. *Exposure and Health*, **12**, 487-500. https://doi.org/10.1007/s12403-020-00345-w

[33] Egboka, B.C., Nwankwor, G.I., Orajaka, I.P. and Ejiofor, A.O. (1989) Principles and

Problems of Environmental Pollution of Groundwater Resources with Case Examples from Developing Countries. *Environmental Health Perspectives*, **83**, 39-68. https://doi.org/10.1289/ehp.898339

[34] Atemoagbo, O.P. (2024) Investigating the Impact of Sanitation Infrastructure on Groundwater Quality and Human Health in Peri-Urban Areas. *International Journal of Medical Science and Clinical Invention*, **11**, 7260-7273. https://doi.org/10.18535/ijmsci/v11i.1.07

[35] Shaikh, M. and Birajdar, F. (2023) Groundwater Management and Sustainable Farming Practices: A Socioeconomic Analysis of Their Interplay in Rural Agriculture—A Case Study of Solapur, Maharashtra. *International Journal for Innovative Science Research Trends and Innovation*, **8**, 1543-1551. https://doi.org/10.5281/zenodo.8402903

[36] Ullah, R., Muhammad, S., Ali, W., Amin, S., Khan, S., Rasool, A., *et al.* (2024) Evaluation of Irrigation, Drinking, and Risk Indices for Water Quality Parameters of Alpine Lakes. *Environmental Geochemistry and Health*, **46**, Article No. 175. https://doi.org/10.1007/s10653-024-01950-3

[37] Ahmad, T., Muhammad, S., Umar, M., Azhar, M.U., Ahmed, A., Ahmad, A., *et al.* (2024) Spatial Distribution of Physicochemical Parameters and Drinking and Irrigation Water Quality Indices in the Jhelum River. *Environmental Geochemistry and Health*, **46**, Article No. 263. https://doi.org/10.1007/s10653-024-02026-y

[38] Gudda, F., Odinga, E.S., Tang, L., Waigi, M.G., Wang, J., Abdalmegeed, D., *et al.* (2023) Tetracyclines Uptake from Irrigation Water by Vegetables: Accumulation and Antimicrobial Resistance Risks. *Environmental Pollution*, **338**, Article 122696. https://doi.org/10.1016/j.envpol.2023.122696

[39] Nombuyiselo, M., Taiwo, A.O., Abdultaofeek, A. and Ikudayisi, A. (2023) Evaluation of Surface Water Quality Indices in Mthatha River Using Multivariate Statistical Techniques. *Indonesian Journal of Environmental Management and Sustainability*, **7**, 1-12. https://doi.org/10.26554/ijems.2023.7.1.1-12

[40] Zhang, J., Li, S., Dong, R., Jiang, C. and Ni, M. (2019) Influences of Land Use Metrics at Multi-Spatial Scales on Seasonal Water Quality: A Case Study of River Systems in the Three Gorges Reservoir Area, China. *Journal of Cleaner Production*, **206**, 76-85. https://doi.org/10.1016/j.jclepro.2018.09.179

[41] Fida, M., Li, P., Wang, Y., Alam, S.M.K. and Nsabimana, A. (2022) Water Contamination and Human Health Risks in Pakistan: A Review. *Exposure and Health*, **15**, 619-639. https://doi.org/10.1007/s12403-022-00512-1

[42] Yu, C., Huang, X., Chen, H., Godfray, H.C.J., Wright, J.S., Hall, J.W., *et al.* (2019) Managing Nitrogen to Restore Water Quality in China. *Nature*, **567**, 516-520. https://doi.org/10.1038/s41586-019-1001-1

[43] Foster, S. and Chilton, J. (2021) Institutional Issues around Agricultural Land-Use Control for Groundwater Conservation—A Long-Term Perspective. *Water*, **13**, Article 2417. https://doi.org/10.3390/w13172417

[44] Kaiser, H.F. (1960) The Application of Electronic Computers to Factor Analysis. *Educational and Psychological Measurement*, **20**, 141-151. https://doi.org/10.1177/001316446002000116

[45] Auddy, N., Kumar Rai, A., Chatterjee, S., Pobi, K., Dutta, S. and Nayek, S. (2023) Trophic Classification and Assessment of Lake Health Using Indexing Approach and Geostatistical Methods for Sustainable Management of Water Resources. *Water Practice & Technology*, **18**, 967-980. https://doi.org/10.2166/wpt.2023.039

[46] Rahman, M.A. and Hasegawa, H. (2011) High Levels of Inorganic Arsenic in Rice in

Areas Where Arsenic-Contaminated Water Is Used for Irrigation and Cooking. *Science of the Total Environment*, **409**, 4645-4655. https://doi.org/10.1016/j.scitotenv.2011.07.068

[47] Abulude, F., Ndamitso, M.M. and Abdulkadir, A. (2018) Rainfall Water Quality Assessment in Atmospheric Deposition of an Urban Area: A Case Study of Akure in Nigeria. *Anthropogenic Pollution*, **2**, 1-9.

[48] Kusuma, H.S., Nida, R.A., Listiawati, V., Rahayu, D.E., Febryola, L.A., Darmokoesoemo, H., *et al*. (2024) Trends on Adsorption of Lead (Pb) Using Water Hyacinth: Bibliometric Evaluation of Scopus Database. *Environmental Research*, **244**, Article 117917. https://doi.org/10.1016/j.envres.2023.117917