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Identification of Pollution in the Lukaya River and Its Tributaries: An Innovative Approach

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Abstract

The study assesses the pollution of the Lukaya River and its tributaries by identifying factors that degrade water quality in order to formulate recommendations for sustainable management of this resource. The analysis uses Principal Component Analysis (PCA), a statistical method that efficiently handles complex water quality data. PCA reduces the dimensionality of the data while preserving variance, facilitating the identification of relationships between key physicochemical parameters such as pH, conductivity, nitrates, and phosphates. The results show that two principal components explain more than 70.23% of the variation in the river data. The sampling sites reveal significant pollution, especially by nutrients, affecting biodiversity and the health of aquatic ecosystems. Agricultural and livestock activities are the main sources of pollution. PCA helps identify these sources and provides a detailed visual analysis. Continuous monitoring and targeted actions are essential to maintain water quality and protect aquatic ecosystems, ensuring their viability for future generations.

1. Introduction

Water quality in aquatic environments is essential to the health of ecosystems and human populations. Factors such as urbanization, intensive agriculture, and industrialization significantly contribute to the degradation of this vital resource, leading to microbiological and chemical pollution of waterways. Poor water quality can have disastrous consequences for biodiversity, drinking water supply, and economic activities. In many regions, particularly in Africa, water quality monitoring and management remain major challenges (Babuji et al., 2023).

The Lukaya River, located in Kinshasa, Democratic Republic of Congo, has been the subject of various studies to assess its water quality and the environmental impacts of pollution. Previous research has revealed high levels of contaminants, posing serious threats to public health and local ecosystems (Musanga et al., 2019). Studies have also indicated significant deterioration in physicochemical parameters, with

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alarming pollutant concentrations exceeding quality standards (Huyen & Lai, 2019). Furthermore, studies on diffuse organic pollution have revealed worrying variations in dissolved oxygen levels without identifying significant organic contamination (Tshibanda et al., 2021). These findings highlight a critical gap in understanding the overall impacts of these pollutants. Furthermore, research has highlighted the negative impact of agricultural activities on water quality, concluding that unsustainable practices exacerbate degradation and threaten community health (Chedadi et al., 2023). These studies underscore the importance of awareness-raising and stakeholder cooperation in natural resource management, emphasizing the urgent need to protect the Lukaya River and its ecosystems (Ustaoğlu et al., 2021). However, a detailed analysis of the interactions between multiple pollutants and their cumulative effects on water quality is lacking.

Previous studies have also focused on applying principal component analysis (PCA) to understand pollution dynamics in aquatic environments better. PCA has proven effective in identifying relationships between various water quality parameters, thus providing valuable information for management strategies (Abba et al., 2021; Arabameri et al., 2025; Belhadj et al., 2011; Emamgholizadeh et al., 2014; Ezzehra Sghiouer et al., 2024; Kun Mei et al., 2025; Laffite et al., 2020; Tabué Youmbi et al., 2013; Xu et al., 2024). Despite its effectiveness, PCA has not been widely applied in studies on the Lukaya River, suggesting a significant opportunity for innovation.

The main objective of this study is to address gaps in the existing literature by using PCA to analyze the pollution dynamics of the Lukaya River and its tributaries. This research aims to identify the main pollution factors and their interactions, thereby providing a better understanding of the water quality challenges in Kinshasa. In doing so, the study aims to formulate concrete recommendations for sustainable water resource management.

To achieve these research objectives, this study will use PCA as a statistical tool to analyze complex water quality data collected at various sampling sites along the Lukaya River and its tributaries. The analysis will focus on key physicochemical parameters, including pH, conductivity, nitrate, and phosphate levels. The data will be processed using R (Nzita et al., 2024) and the Python Anaconda software, enabling efficient manipulation of the dataset and visualization of results to identify significant relationships and patterns.

2. Materials and Methods

2.1. Study Area

The Lukaya watershed is situated between the city of Kinshasa and the province of Kongo-Central in the Democratic Republic of Congo. The Lukaya River originates from the village of Ntampa and flows into the Ndjili River, a tributary of the Congo River, near Ndjili Kilambu. Stretching approximately fifty kilometers, this river features a diverse profile with several tributaries and covers an area of 349.95 km^2, with a perimeter of 133 km^2 and a drainage capacity of 993.46 m^3/km^2. This geographical context is crucial for understanding the river's hydrological dynamics and the pollution challenges it faces (Musanga et al., 2019).

The sampling period ran from November 19 to December 31, 2010, for a total duration of 1 month and 13 days. A total of nine sampling sites were identified, strategically positioned along the Lukaya River and its tributaries just before their confluence. Among these sites, the Regideso Station serves as a key raw water catchment point, significantly influenced by activities upstream. The first site upstream of the Nsaya tributary marks the point of initial discharge for effluent from the Minocongo 1 poultry farm, highlighting its importance in assessing water quality before it mixes with the river. Adjacent to this, the Minocongo 2 poultry farm serves as the second discharge location for effluent, further supporting monitoring efforts in this area. Continuing upstream, the site known as Upstream Bumuna is positioned just before the confluence with the Bumuna tributary, making it the furthest upstream sampling point. This location is crucial for understanding water-quality dynamics prior to any tributary input. The tributaries under study include Nsaya, Malala, Matampa, and Bumuna, each contributing distinct characteristics to the region's overall water quality. To gather comprehensive data, four sampling campaigns were conducted. The first two campaigns took place during the dry season, followed by two additional campaigns in the rainy season. This approach ensures a thorough assessment of how seasonal variations affect the physicochemical parameters of the water across the identified sites. The geographic coordinates of the main sampled sites, collected with a Garmin 60 GPS, are shown in Table 1.

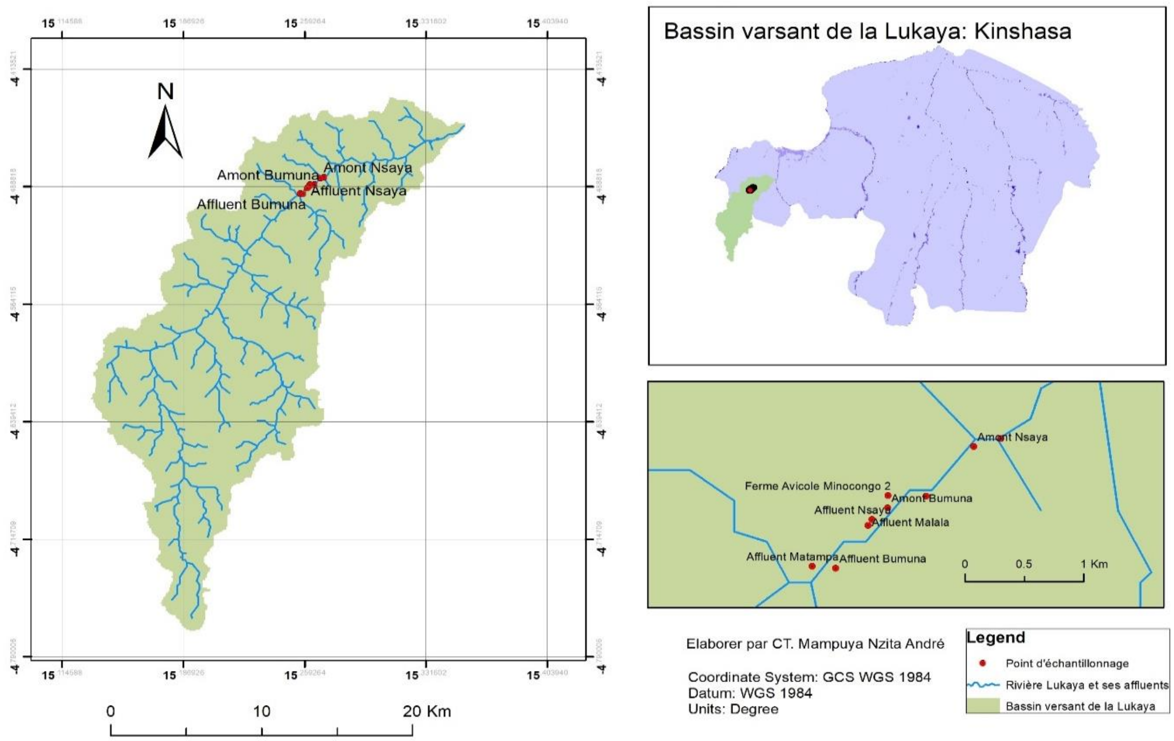

Figure 1. Map of the location of the Lukaya watershed.

Table 1. Geographic coordinates of the sampled points**.**

Station	Altitude(m)	South Latitude (DMS)	East Longitude (DMS)
Regideso	304	4°28’58.3’’	15°16’15’’
Amont Nsaya	310	4°29’0.6’’	15°16’7.6’’
Ferma Avicole Minconga 1	316	4°29’15.2’’	15°15’54.6’’
Amont Bumuna	323	4°29’15.05’’	15°15’44.2’’
Ferme Avicole Minconga 2	317	4°29’18,6’’	15°15’44.1’’
Affluent Nsaya	324	4°29’22’’	15°15’39.8’’
Affluent Malala	327	4°29’23.8’’	15°15’38.7’’
Affluent Matamba	322	4°29’35.7’’	15°15’23.5’’
Affluent Bumuna	320	4°29’36.3’’	15°15’29.9’’

The following physicochemical characteristics were studied: pH, Cond: electrical conductivity (µs/cm), Od: dissolved oxygen (mg/l), Temp: temperature (°C), MES: suspended solids (mg/l), Nit: nitrates (mg/l), NO: nitrites (mg/l), Sul: sulfates (mg/l), and Phos: phosphates (mg/l). Ammonium (mg/l) for water samples from the Lukaya River and its tributaries, presented in Tables 2 and

Table 2. Physicochemical parameters of the Lukaya River.

Parameters	pH	Temp	Cond	Od	MES	Nit	NO	Sul	Phos	Ammonium
Station Regideso	5.87	26.05	23.25	0.84	39.3	3.001	0.006	10.6	2.88	0.24
Amont Nsaya	6.3	27.55	24.25	1.68	28.3	2.9	0,24	11,6	4,77	0.31
Ferme avicol Mincongo 1	6.8	27.1	27.5	1.13	24.93	9	0.036	13.6	0.39	0.29
Ferme avicole Mincongo 2	6.9	28.55	34.25	1.11	38.73	9.37	0.06	10.3	0.79	0.87
Amont Bumuna	6.7	27.25	23.5	1.44	59.73	1.22	0.008	17.1	0.64	0.18

Table 3. Physicochemical parameters of the tributaries of the Lukaya River.

Parameters	pH	Temp	Cond	Od	MES	Nit	NO	Sul	Phos	Ammonium
Affluent Nsaya	5.5	27.37	32	0.55	62.66	2.02	0.22	6.5	0.32	0.42
Affluent Malala	6.1	28.07	46.82	0,88	45.33	2.72	0.015	2.6	0.62	0.48
Affluent Matampa	5.9	28.75	54.5	1.27	29.66	0.69	0.009	11	1	0.35
Affluent Bumuna	6.3	28.3	18	1.45	19.33	0.92	0.013	15	2.31	0.19

To analyze water quality, a portable WTW340i/SET multi-parameter meter was employed. This instrument measures essential parameters, including electrical conductivity, dissolved oxygen, temperature, and pH. Measurements were conducted in the field using specific probes and calibration reagents, requiring careful handling due to their environmental sensitivity. Results were displayed on the meter's digital screen, while chemical analyses were performed in the laboratory using a Hach DR/2400 spectrophotometer, ensuring reliability through strict protocols. Sample transport involved using 500 mL polyethylene bottles, kept cool during transport and refrigerated upon arrival. Analyses were conducted within 48 to 72 hours to minimize degradation, and data were processed using R and Anaconda Python software (Chedadi et al., 2023, Nzita et al., 2024).

2.2. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a vital statistical method for analyzing large, complex datasets, reducing dimensionality while preserving data variance. This technique simplifies data without significant information loss, making it particularly useful in environmental studies, such as those of the Lukaya River, where multiple variables, including water quality and pollution levels, are collected. PCA condenses this information into a limited number of principal components, enhancing interpretability and reducing potential errors (Abba et al., 2021; Arabameri et al., 2025; Belhadj et al., 2011; Emamgholizadeh et al., 2014; Ezzehra Sghiouer et al., 2024; Kun Mei et al., 2025; Laffite et al., 2020; Tabué Youmbi et al., 2013; Xu et al., 2024).

PCA facilitates the identification of relationships among various variables, revealing how environmental factors interact and influence water quality. This understanding is essential for formulating data-driven recommendations. One significant advantage of PCA is its visualization capability, allowing researchers to project data onto principal components to identify patterns, clusters, or anomalies, leading to crucial insights about the ecosystem (Abba et al., 2021; Arabameri et al., 2025; Belhadj et al., 2011; Emamgholizadeh et al., 2014; Ezzehra Sghiouer et al., 2024; Kun Mei et al., 2025; Tabué Youmbi et al., 2013; Xu et al., 2024). For this analysis, R software was used for its powerful, flexible statistical capabilities, including dedicated PCA libraries. This enabled the efficient execution of complex calculations, the visualization of results, and the clear interpretation of data. The integration of R with Anaconda Python further enhanced our ability to apply PCA accurately, yielding actionable results vital to the management and conservation of water resources in the Lukaya River (Belhadj et al., 2011; Xu et al., 2024). This statistical approach is essential for understanding the ecological dynamics of the Lukaya River and its tributaries, facilitating informed decision-making in the management and conservation of these critical water resources.

3. Results and Discussion

3.1 PCA Analysis for the Lukaya River and Its Tributaries

Analysis of the PC1 and PC2 axes reveals that more than 70.23% of the variation in the Lukaya River data is explained (Table 4). Of this variation, PC1 contributes 42.65% and highlights several key parameters, including electrical conductivity, ammonium, nitrate, temperature, pH, phosphate, sulfate, suspended solids, and dissolved oxygen. On the other hand, PC2, which accounts for 27.58% of the variance, provides complementary information on the same parameters, including nitrite, phosphate, sulfate, suspended solids, pH, dissolved oxygen, ammonium, temperature, and electrical conductivity.

Table 4. Absolute values of variable loading coefficients in PCA and the amount of information explained by the main factors of Lukaya River

Variable	PC1	PC2
pH	0.364	0.218
Cond	0.479	0.036
Temp	0.3808	0.105
Od	0.099	0.188
MES	0.117	0.423
Nit	0.434	0.039
NO	0.0389	0.526
Sul	0.155	0.427
Phos	0.258	0.499
Ammonium	0.435	0.130
Standard Deviation	2.0651	1.6608
Proportion of Variance	0.4265	0.2758
Cumulative Proportion	0.4265	0.7023

Regarding the positive correlations on PC1 in Figure 2, the Lukaya River water samples collected upstream of Nsaya indicate possible nutrient pollution, which could promote algae growth, thus affecting water quality and biodiversity. In contrast, the negative correlations with PC1 upstream of Bumuna suggest pollution, which could reduce water clarity and harm aquatic life. Regarding the correlations on PC2 in Figure 2, the results for Mincongo Poultry Farm 2 indicate that livestock and agricultural practices impact water quality. In addition, Mincongo Poultry Farm 1 could negatively affect the health of aquatic ecosystems and soil quality. The negative correlation observed at the Régideso Station indicates the presence of contaminants, underscoring the need to treat this water before use to avoid public health risks. The analysis of the PC1 and PC2 axes highlights water quality problems in the Lukaya River, associated with nutrient and contaminant pollution from agricultural and livestock sources. To preserve public and ecosystem health, it is essential to monitor these parameters and adopt sustainable management practices. Figure 2. PCA on 5 individuals and 10 variables from the Lukaya River.

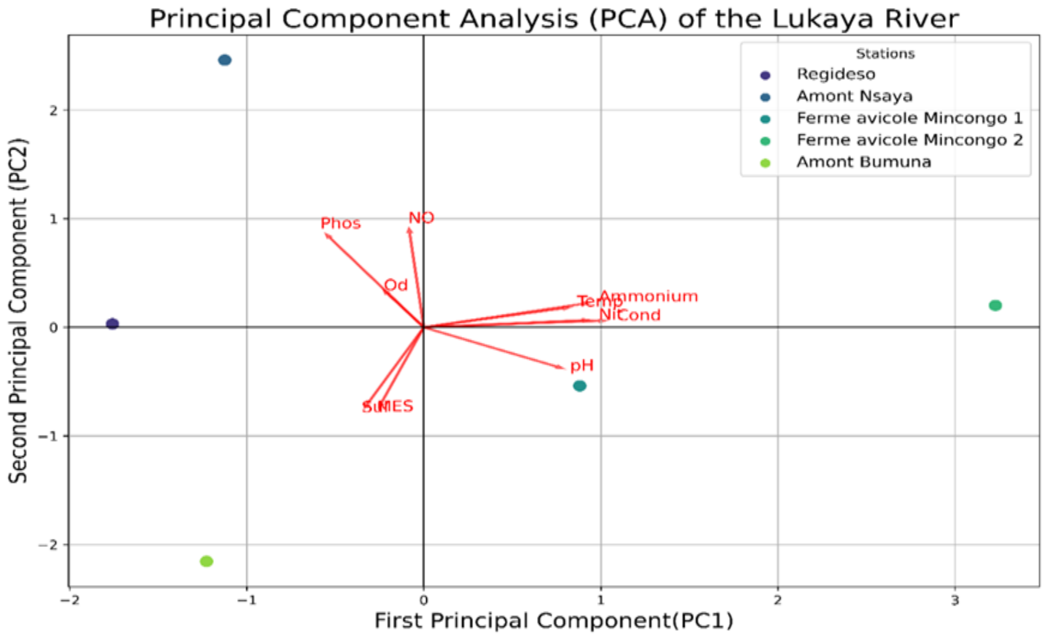

Figure 2. PCA on 5 individuals and 10 variables from the Lukaya River.

The analysis of the PC1 and PC2 axes shows that more than 88.28% of the variance in the Lukaya River tributaries data is explained (Table 5). The PC1 axis accounts for 67.62% of this variance and highlights several key parameters, including dissolved oxygen, suspended solids, phosphates, ammonium, sulfates, nitrates, pH, temperature, nitrites, and electrical conductivity. On the other hand, PC2, which accounts for 21.28%, provides complementary information on the same parameters, including: electrical conductivity, nitrites, temperature, ammonium, sulfates, phosphates, pH, nitrates, suspended solids, and dissolved oxygen.

Table 5. Absolute values of variable loading coefficients in PCA and the amount of information explained by the main factors of the Lukaya River tributaries.

Variable	PC1	PC2
pH	0.299	0.175
Cond	0.110	0.597
Temp	0.296	0.404
Od	0.380	0.101
MES	0.379	0.104
Nit	0.299	0.115
NO	0.282	0.436
Sul	0.330	0.286
Phos	0.359	0.188
Ammonium	0.337	0.328
Standard Deviation	2.6003	1.4587
Proportion of Variance	0.6762	0.2128
Cumulative Proportion	0.6762	0.8889

Analysis of the projection of individuals onto the PC1-PC2 factorial plane allowed us to determine the following characteristics of the Lukaya River tributaries, shown in Figure 3. The analysis of the PC1 and PC2 axes highlights major concerns about water quality in the Lukaya River, including nutrient and other contaminant pollution. The characteristics of its tributaries show potential adverse effects on aquatic fauna and flora. It is crucial to monitor these parameters and adopt sustainable management practices to protect the health of aquatic ecosystems and water quality, ensuring a healthy environment for future generations. Regarding the Malala tributary, the negative correlations on PC1 suggest potential nutrient pollution. This can have adverse consequences on water quality and the health of aquatic ecosystems. For the Bumuna tributary, moderate levels of sulfates and phosphates on PC2 could indicate contamination from agricultural or industrial sources. In addition, the Matampa tributary shows that parameters such as temperature and pH can influence nutrient solubility, affecting aquatic life and water quality. Finally, for the Nsaya tributary, high levels of nitrites and ammonium, combined with suspended solids, also suggest pollution that can affect water clarity and harm aquatic organisms.

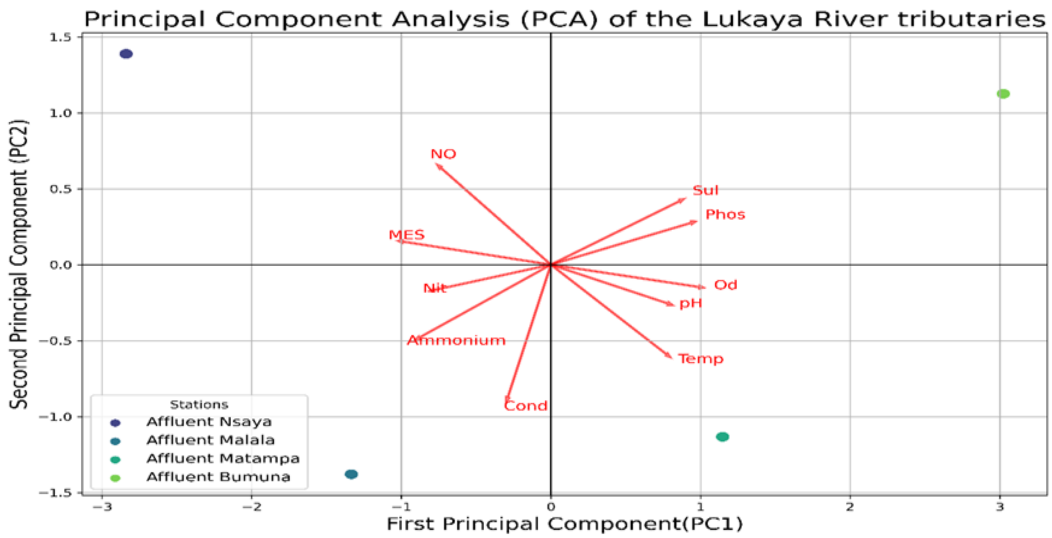

Figure 3. PCA on 4 individuals and 10 variables of the tributaries of the Lukaya River

3.2. Correlation analysis of the Lukaya River and its Tributaries

The correlation values between the physicochemical parameters of the Lukaya River, obtained using Student's t-test, are presented in Table 6. This table includes Pearson correlation coefficients, t-values, degrees of freedom (df), p-values, and confidence intervals.

Table 6. Student t-test and Pearson correlation coefficient of physicochemical parameters of the Lukaya River.

N°	Pearson product-moment correlation	t	df	p-value	Sample estimates	95% confidence interval	
					Pearson Correlation Coefficient	Lower Terminal	Upper limit
1	pH and Temp	2.041	3	0.134	0.762	|0.366|	0.983
2	pH and Cond	1.568	3	0.215	0.671	|0.517|	0.976
3	pH and Od	0.381	3	0.729	0.215	|0.824|	0.922
4	pH and MES	0.137	3	0.899	0.079	|0.864|	0.899
5	pH and Nit	1.289	3	0.288	0.597	|0.603|	0.969
6	pH and NO	|0.213|	3	0.845	|0.122|	|0.907|	0.852
7	pH and Sul	0.675	3	0.548	0.363	|0.764|	0.943
8	pH and Phos	|1.830|	3	0.165	|0.726|	|0.980|	0.434
9	pH and Ammonium	0.962	3	0.407	0.486	|0.694|	0.958
10	Cond and Temp	2.229	3	0.112	0.789	|0.305|	0.985
11	Cond and Od	|0.417|	3	0.705	|0.234|	|0.925|	0.817
12	Cond and MES	|0.388|	3	0.724	|0.219|	|0.923|	0.822
13	Cond and Nit	2.904	3	0.062	0.859	|0.097|	0.991
14	Cond and NO	|0.096|	3	0.929	|0.055|	|0.894|	0.869
15	Cond and Sul	|0.791|	3	0.487	|0.415|	|0.949|	0.737
16	Cond and Phos	|0.889|	3	0.439	|0.456|	0.954	0.713

<table>
<tr><td>17</td><td>Cond and Ammonium</td><td>5.308</td><td>3</td><td>0.013*</td><td>0.951</td><td>0.424</td><td>0.997</td></tr>
<tr><td>18</td><td>Temp and Od</td><td>0.741</td><td>3</td><td>0.513</td><td>0.393</td><td>|0.749|</td><td>0.947</td></tr>
<tr><td>19</td><td>Temp and MES</td><td>|0.057|</td><td>3</td><td>0.958</td><td>|0.033|</td><td>|0.889|</td><td>0.875</td></tr>
<tr><td>20</td><td>Temp and Nit</td><td>0.999</td><td>3</td><td>0.391</td><td>0.499</td><td>|0.684|</td><td>0.959</td></tr>
<tr><td>21</td><td>Temp and NO</td><td>0.629</td><td>3</td><td>0.573</td><td>0.342</td><td>|0.774|</td><td>0.940</td></tr>
<tr><td>22</td><td>Temp and Sul</td><td>|0.181|</td><td>3</td><td>0.868</td><td>|0.104|</td><td>|0.903|</td><td>0.857</td></tr>
<tr><td>23</td><td>Temp and Phos</td><td>|0.400|</td><td>3</td><td>0.716</td><td>|0.225|</td><td>|0.924|</td><td>0.820</td></tr>
<tr><td>24</td><td>Temp and Ammonium</td><td>2.263</td><td>3</td><td>0.109</td><td>0.794</td><td>|0.295|</td><td>0.986</td></tr>
<tr><td>25</td><td>Od and MES</td><td>0.088</td><td>3</td><td>0.935</td><td>0.935</td><td>|0.870|</td><td>0.893</td></tr>
<tr><td>26</td><td>Od and Nit</td><td>|0.717|</td><td>3</td><td>0.525</td><td>|0.382|</td><td>|0.946|</td><td>0.754</td></tr>
<tr><td>27</td><td>Od and NO</td><td>1.868</td><td>3</td><td>0.159</td><td>0.733</td><td>|0.422|</td><td>0.981</td></tr>
<tr><td>28</td><td>Od and Sul</td><td>0.749</td><td>3</td><td>0.508</td><td>0.397</td><td>|0.747|</td><td>0.947</td></tr>
<tr><td>29</td><td>Od and Phos</td><td>0.707</td><td>3</td><td>0.761</td><td>0.378</td><td>|0.757|</td><td>0.945</td></tr>
<tr><td>30</td><td>Od and Ammonium</td><td>|0.333|</td><td>3</td><td>0.761</td><td>|0.189|</td><td>|0.918|</td><td>0.832</td></tr>
<tr><td>31</td><td>MES and Nit</td><td>|1.139|</td><td>3</td><td>0.337</td><td>|0.549|</td><td>|0.964|</td><td>0.646</td></tr>
<tr><td>32</td><td>MES and NO</td><td>|0.995|</td><td>3</td><td>0.393</td><td>|0.498|</td><td>|0.959|</td><td>0.685</td></tr>
<tr><td>33</td><td>MES and Sul</td><td>1.266</td><td>3</td><td>0.295</td><td>0.590</td><td>|0.609|</td><td>0.968</td></tr>
<tr><td>34</td><td>MES and Phos</td><td>|0.627|</td><td>3</td><td>0.575</td><td>|0.341|</td><td>|0.940|</td><td>0.774</td></tr>
<tr><td>35</td><td>MES and Ammonium</td><td>|0.267|</td><td>3</td><td>0.807</td><td>|0.152|</td><td>|0.912|</td><td>0.843</td></tr>
<tr><td>36</td><td>Nit and NO</td><td>|0.205|</td><td>3</td><td>0.851</td><td>|0.118|</td><td>|0.906|</td><td>0.853</td></tr>
<tr><td>37</td><td>Nit and Sul</td><td>|0.751|</td><td>3</td><td>0.507</td><td>|0.398|</td><td>|0.948|</td><td>0.746</td></tr>
<tr><td>38</td><td>Nit and Phos</td><td>|0.977|</td><td>3</td><td>0.401</td><td>|0.491|</td><td>|0.958|</td><td>0.690</td></tr>
<tr><td>39</td><td>Nit and Ammonium</td><td>1.687</td><td>3</td><td>0.190</td><td>0.699</td><td>|0.479|</td><td>0.978</td></tr>
<tr><td>40</td><td>NO and Sul</td><td>|0.551|</td><td>3</td><td>0.620</td><td>|0.303|</td><td>|0.935|</td><td>0.791</td></tr>
<tr><td>41</td><td>NO and Phos</td><td>2.068</td><td>3</td><td>0.131</td><td>0.767</td><td>|0.357|</td><td>0.984</td></tr>
<tr><td>42</td><td>NO and Ammonium</td><td>0.121</td><td>3</td><td>0.911</td><td>0.069</td><td>|0.866|</td><td>0.897</td></tr>
<tr><td>43</td><td>Sul and Phos</td><td>|0.862|</td><td>3</td><td>0.452</td><td>|0.445|</td><td>|0.953|</td><td>0.719</td></tr>
<tr><td>44</td><td>Sul and Ammonium</td><td>|1.179|</td><td>3</td><td>0.324</td><td>|0.563|</td><td>|0.966|</td><td>0.635</td></tr>
<tr><td>45</td><td>Phos and Ammonium</td><td>|0.416|</td><td>3</td><td>0.705</td><td>|0.234|</td><td>|0.925|</td><td>0.817</td></tr>
</table>

In Table 6, the Pearson correlation coefficients indicate the strength and direction of relationships between physicochemical parameters. For instance, the positive correlation between pH and temperature (0.762) suggests that as temperature increases, pH tends to rise, although the p-value (0.134) indicates that this relationship is not statistically significant. Conversely, the significant positive correlation between conductivity and ammonium (r = 0.308, p-value = 0.013) indicates that higher conductivity is associated with higher ammonium levels, suggesting potential contamination sources. Negative correlations, such as between pH and nitrate (|0.213|), may highlight complex interactions affecting water quality.

The correlation values for the tributaries of the Lukaya River are shown in Table 7. This table also includes Pearson correlation coefficients, t-values, degrees of freedom, p-values, and confidence intervals.

Table 7. Student t-test and Pearson correlation coefficient of physicochemical parameters of Lukaya River tributaries.

<table>
<tr><th rowspan="2">N°</th><th rowspan="2">Pearson product-moment correlation</th><th rowspan="2">t</th><th rowspan="2">df</th><th rowspan="2">p-value</th><th>Sample estimates</th><th colspan="2">95% confidence interval</th></tr>
<tr><th>Pearson Correlation Coefficient</th><th>Lower Terminal</th><th>Upper limit</th></tr>
<tr><td>1</td><td>pH and Temp</td><td>1.0967</td><td>2</td><td>0.387</td><td>0.613</td><td>|0.847|</td><td>0.991</td></tr>
<tr><td>2</td><td>pH and Cond</td><td>|0.333|</td><td>2</td><td>0.771</td><td>|0.229|</td><td>|0.975|</td><td>0.939</td></tr>
<tr><td>3</td><td>pH and Od</td><td>1.859</td><td>2</td><td>0.204</td><td>0.796</td><td>|0.703|</td><td>0.996</td></tr>
<tr><td>4</td><td>pH and MES</td><td>|2.115|</td><td>2</td><td>0.169</td><td>|0.831|</td><td>|0.996|</td><td>0.646</td></tr>
<tr><td>5</td><td>pH and Nit</td><td>|0.317|</td><td>2</td><td>0.781</td><td>|0.219|</td><td>|0.975|</td><td>0.939</td></tr>
<tr><td>6</td><td>pH and NO</td><td>|2.502|</td><td>2</td><td>0.129</td><td>|0.871|</td><td>|0.997|</td><td>0.554</td></tr>
<tr><td>7</td><td>pH and Sul</td><td>0.603</td><td>2</td><td>0.608</td><td>0.392</td><td>|0.913|</td><td>0.983</td></tr>
<tr><td>8</td><td>pH and Phos</td><td>1.806</td><td>2</td><td>0.212</td><td>0.787</td><td>|0.714|</td><td>0.995</td></tr>
<tr><td>9</td><td>pH and Ammonium</td><td>|0.884|</td><td>2</td><td>0.469</td><td>|0.530|</td><td>|0.989|</td><td>0.879</td></tr>
<tr><td>10</td><td>Cond and Temp</td><td>0.596</td><td>2</td><td>0.612</td><td>0.388</td><td>|0.914|</td><td>0.983</td></tr>
<tr><td>11</td><td>Cond and Od</td><td>|0.210|</td><td>2</td><td>0.853</td><td>|0.147|</td><td>|0.971|</td><td>0.948</td></tr>
<tr><td>12</td><td>Cond and MES</td><td>0.239</td><td>2</td><td>0.833</td><td>0.167</td><td>|0.946|</td><td>0.972</td></tr>
<tr><td>13</td><td>Cond and Nit</td><td>0.183</td><td>2</td><td>0.872</td><td>0.128</td><td>|0.949|</td><td>0.969</td></tr>
<tr><td>14</td><td>Cond and NO</td><td>|0.364|</td><td>2</td><td>0.751</td><td>|0.249|</td><td>|0.976|</td><td>0.936</td></tr>
<tr><td>15</td><td>Cond and Sul</td><td>|0.799|</td><td>2</td><td>0.508</td><td>|0.492|</td><td>|0.987|</td><td>0.889</td></tr>
<tr><td>16</td><td>Cond and Phos</td><td>|1.053|</td><td>2</td><td>0.403</td><td>|0.597|</td><td>|0.990|</td><td>0.854</td></tr>
<tr><td>17</td><td>Cond and Ammonium</td><td>1.201</td><td>2</td><td>0.353</td><td>0.647</td><td>|0.830|</td><td>0.992</td></tr>
<tr><td>18</td><td>Temp and Od</td><td>2.324</td><td>2</td><td>0.146</td><td>0.854</td><td>|0.597|</td><td>0.997</td></tr>
<tr><td>19</td><td>Temp and MES</td><td>|2.201|</td><td>2</td><td>0.159</td><td>|0.841|</td><td>|0.997|</td><td>0.626</td></tr>
<tr><td>20</td><td>Temp and Nit</td><td>|1.205|</td><td>2</td><td>0.352</td><td>|0.648|</td><td>|0.992|</td><td>0.829</td></tr>
<tr><td>21</td><td>Temp and NO</td><td>|2.659|</td><td>2</td><td>0.117</td><td>|0.883|</td><td>|0.998|</td><td>0.516</td></tr>
<tr><td>22</td><td>Temp and Sul</td><td>0.790</td><td>2</td><td>0.512</td><td>0.4878</td><td>|0.891|</td><td>0.986</td></tr>
<tr><td>23</td><td>Temp and Phos</td><td>0.826</td><td>2</td><td>0.496</td><td>0.505</td><td>|0.886|</td><td>0.987</td></tr>
<tr><td>24</td><td>Temp and Ammonium</td><td>|0.629|</td><td>2</td><td>0.593</td><td>|0.407|</td><td>|0.983|</td><td>0.910</td></tr>
<tr><td>25</td><td>Od and MES</td><td>|22.949|</td><td>2</td><td>0.002**</td><td>|0.998|</td><td>|0.999|</td><td>|0.909|</td></tr>
<tr><td>26</td><td>Od and Nit</td><td>|1.648|</td><td>2</td><td>0.241</td><td>|0.759|</td><td>|0.995|</td><td>0.747</td></tr>
<tr><td>27</td><td>Od and NO</td><td>|1.982|</td><td>2</td><td>0.186</td><td>|0814|</td><td>|0.996|</td><td>0.676</td></tr>
<tr><td>28</td><td>Od and Sul</td><td>1.847</td><td>2</td><td>0.206</td><td>0.794</td><td>|0705|</td><td>0.995</td></tr>
<tr><td>29</td><td>Od and Phos</td><td>2.611</td><td>2</td><td>0.121</td><td>0.879</td><td>|0.528|</td><td>0.997</td></tr>
<tr><td>30</td><td>Od and Ammonium</td><td>|1.869|</td><td>2</td><td>0.203</td><td>|0.797|</td><td>|0.996|</td><td>0.701</td></tr>
<tr><td>31</td><td>MES and Nit</td><td>1.467</td><td>2</td><td>0.28</td><td>0.719</td><td>|0.783|</td><td>0.994</td></tr>
<tr><td>32</td><td>MES and NO</td><td>2.111</td><td>2</td><td>0.169</td><td>0.831</td><td>|0.647|</td><td>0.996</td></tr>
<tr><td>33</td><td>MES and Sul</td><td>|1.721|</td><td>2</td><td>0.227</td><td>|0.773|</td><td>|0.995|</td><td>0.732</td></tr>
<tr><td>34</td><td>MES and Phos</td><td>|2.768|</td><td>2</td><td>0.109</td><td>|0.890|</td><td>|0.998|</td><td>0.489</td></tr>
<tr><td>35</td><td>MES and Ammonium</td><td>1.826</td><td>2</td><td>0.209</td><td>0.791</td><td>|0.709|</td><td>0.995</td></tr>
<tr><td>36</td><td>Nit and NO</td><td>0.480</td><td>2</td><td>0.679</td><td>0.321</td><td>|0.926|</td><td>0.979</td></tr>
<tr><td>37</td><td>Nit and Sul</td><td>|3.281|</td><td>2</td><td>0.082</td><td>|0.918|</td><td>|0.998|</td><td>0.364</td></tr>
<tr><td>38</td><td>Nit and Phos</td><td>|1.172|</td><td>2</td><td>0.362</td><td>|0.638|</td><td>|0.991|</td><td>0.835</td></tr>
<tr><td>39</td><td>Nit and Ammonium</td><td>1.854</td><td>2</td><td>0.205</td><td>0.795</td><td>|0.704|</td><td>0.995</td></tr>
<tr><td>40</td><td>NO and Sul</td><td>|0.434|</td><td>2</td><td>0.707</td><td>|0.293|</td><td>|0.979|</td><td>0.929</td></tr>
<tr><td>41</td><td>NO and Phos</td><td>|0.968|</td><td>2</td><td>0.435</td><td>|0.565|</td><td>|0.989|</td><td>0.867</td></tr>
<tr><td>42</td><td>NO and Ammonium</td><td>0.487</td><td>2</td><td>0.674</td><td>0.326</td><td>|0.925|</td><td>0.980</td></tr>
<tr><td>43</td><td>Sul and Phos</td><td>2.285</td><td>2</td><td>0.149</td><td>0.850</td><td>|0.606|</td><td>0.997</td></tr>
<tr><td>44</td><td>Sul and Ammonium</td><td>|5.477|</td><td>2</td><td>0.032*</td><td>|0.968|</td><td>|0.999|</td><td>|0.103|</td></tr>
<tr><td>45</td><td>Phos and Ammonium</td><td>|3.849|</td><td>2</td><td>0.061</td><td>|0.939|</td><td>|0.999|</td><td>0.229</td></tr>
</table>

In Table 7, the signed loadings reveal both positive and negative correlations between physicochemical parameters in the tributaries. For example, the correlation between pH and dissolved oxygen (0.796) suggests that higher pH levels are associated with higher dissolved oxygen levels, which are beneficial for aquatic life. Conversely, the negative correlation between pH and ammonium (r =- 0.884) indicates that higher ammonium levels may be associated with lower pH, thereby adversely affecting water quality. Significant correlations, such as the negative correlation between conductivity and sulfates (r =- 0.799), suggest that higher conductivity is associated with lower sulfate levels, highlighting the complexity of the interactions between these parameters.

The results for the Lukaya River and its tributaries, as shown in the principal component analysis for other rivers or water sources listed below, are consistent with the assessment requirements reported by several researchers.

The analysis of axes PC1 and PC2 reveals that over 70.23% of the variation in the Lukaya River data is explained, with PC1 accounting for 42.65% and PC2 for 27.58%. The first principal component highlights significant parameters such as electrical conductivity, ammonium, nitrate, temperature, pH, phosphate, sulfate, suspended solids, and dissolved oxygen. In parallel, PC2 provides additional information on similar elements, such as nitrite. Table 4 presents the loading coefficients of the variables in the principal component analysis (PCA), illustrating the influence of each parameter on the principal axes. Notably, conductivity shows a strong loading on PC1, underscoring its crucial role in water quality, while suspended solids show a strong loading on PC2. The positive correlations observed on PC1, particularly upstream of Nsaya, suggest nutrient pollution, potentially promoting algae growth. In contrast, the negative correlations upstream of Bumuna indicate pollution that can reduce water clarity and harm aquatic life. Results from the Mincongo poultry farms indicate that agricultural and livestock practices significantly affect water quality. The Régideso station emphasizes the need to treat this water before use to avoid public health risks. These findings align with previous research, including that of Abba et al. (2021), which highlights the importance of microbial pollution, while Musanga et al. (2019) focus on organic pollution issues. Other studies, such as Chedadi et al. (2023), indicate that the impacts of anthropogenic activities vary greatly by region, contradicting the notion that Abba et al. (2021) apply uniformly.

Further analysis of the PC1 and PC2 axes in the Lukaya River study underscores the importance of physicochemical factors, such as conductivity and nitrate levels. Abba et al. (2021) reported signs of self-purification in the Oum Er Rabia River, but studies such as Chedadi et al. (2023) show that nutrient pollution can hinder this process. Additionally, the tributaries of the Lukaya River reveal that over 88.28% of the variance is explained, with PC1 accounting for 67.62% and PC2 for 21.28%. PC1 highlights major water-quality concerns, while PC2 provides complementary insights. Negative correlations on PC1 for the Malala tributary suggest potential nutrient pollution, and moderate levels of sulfates and phosphates in the Bumuna tributary may indicate contamination from agricultural or industrial sources. The tributary analysis further emphasizes the importance of parameters such as temperature and pH, which influence nutrient solubility. For the Nsaya tributary, high levels of nitrites and ammonium, combined with suspended solids, signal pollution that can affect water clarity. Abba et al. (2021) emphasize microbiological quality indices, it is crucial to recognize that studies by Musanga et al. (2019) and Babuji et al. (2023) expand this perspective by incorporating considerations on pollution sources and the need for treatment to mitigate public health risks. The research by Chedadi et al. (2023) also highlights the importance of assessing the impacts of anthropogenic activities in specific local contexts, enriching discussions on water quality in the region.

The analysis of the physicochemical parameters of the Lukaya River, as shown in Table 6, reveals significant correlations among them. The results indicate that agricultural activity is a major factor in pollution, particularly through elevated levels of ammonium and phosphate. A significant positive correlation is observed between conductivity and ammonium, with a value of 5.308 and a p-value of

0.013, suggesting that agricultural sources contribute to increases in these nutrients in the water. Conversely, a correlation between pH and temperature displays a coefficient of 0.762, but the p-value of 0.134 indicates that this relationship is not statistically significant. Several factors may explain this weak correlation, such as seasonal fluctuations in water temperature that do not directly affect pH. Additionally, the limited sample size (n=4) may not allow for robust relationships, indicating the need for more extensive sampling to clarify these interactions.

The results highlight critical concerns for the health of aquatic ecosystems. Increased nutrient levels, particularly ammonium and phosphates, could lead to eutrophication, thereby reducing aquatic biodiversity. Harmful algal blooms may degrade water quality and harm aquatic species. The analysis of the Lukaya River tributaries, presented in Table 7, also highlights significant correlations that point to agricultural activities as the main sources of pollution. A negative correlation between pH and ammonium, with a coefficient of |0.884|, indicates that high levels of ammonium, often from agricultural fertilizers, can lower water pH, compromising water quality. Correlations between pH and temperature show a trend toward higher pH with increasing temperature, with a coefficient of 0.613 and a p-value of 0.387, indicating no statistical significance. These findings raise questions about the lack of significance of the observed correlations. Seasonal fluctuations could mask stronger relationships, and the limited sample size (n=3) does not allow for robust conclusions. A broader sample, including different seasons and flow conditions, could reveal more significant correlations. Other factors, such as contaminants or unmeasured physical parameters, could also influence pH and temperature, complicating the interactions. The ecological implications of these findings are significant. Increased nutrient levels, particularly ammonium and phosphates, can lead to eutrophication, harming aquatic biodiversity. Previous studies, such as those by Musanga et al. (2019) and Laffite et al. (2020), support these concerns by highlighting the impact of anthropogenic activities on water quality and ecosystem health. The research by Abba et al. (2021) also emphasizes the importance of monitoring microbiological indicators to assess overall ecosystem health. Furthermore, studies by Arabameri et al. (2025), Belhadj et al. (2011), Emamgholizadeh et al. (2014), Ezzehra Sghiouer et al. (2024), Kun Mei et al. (2025), Laffite et al. (2020), Sari Holopainen & Lehikoinen (2022),Tabué Youmbi et al. (2013), Xu et al. (2024) and Zouaoui Guerraiche et al. (2016) provide additional context and support for the findings regarding the impacts of human activities and agricultural practices on water quality.

The study on water quality in the Lukaya River makes a significant contribution to understanding environmental issues in the region. First, it analyzes variations in water quality, revealing that over 70.23% of the variation is explained by the principal axes, highlighting critical parameters such as electrical conductivity and ammonium. The study also identifies sources of pollution, highlighting that agricultural activities, particularly ammonium and phosphate levels, are major factors in water quality degradation. This identification guides the necessary interventions to mitigate these impacts. Correlation analyses reveal worrying trends. For example, high ammonium levels are associated with deteriorating water quality, signaling risks of eutrophication that can harm aquatic biodiversity. This highlights the importance of monitoring these parameters to preserve ecosystems. By comparing its results with those of other research, the study enriches the scientific debate. It highlights the importance of integrating both microbiological and organic pollution into water quality assessments, thus providing a more comprehensive overview of the issues. The results also highlight the need to treat water before use to ensure drinking water safety and protect public health, especially in areas identified as polluted. Regarding sustainable management, the study suggests environmentally friendly agricultural practices and encourages integrated water resource management. It emphasizes raising awareness among local communities about their ecological impact, enabling them to understand better and reduce their contribution to pollution. The recommendations made following this study focus on several key areas. First, it is crucial to implement regular monitoring programs for water quality parameters, expanding sampling to include more collection points and variables. Next, promoting sustainable agricultural practices, such as the use of plant cover and proper fertilizer management, aims to reduce nutrient inputs into rivers. Furthermore, educating local communities about the impact of their activities on water quality is essential to encourage environmentally friendly behavior. Finally, integrated water resource management must be prioritized. This approach aims to harmonize different water uses to protect both public and ecosystem health. The study highlights the urgent need for targeted interventions and a collaborative approach involving stakeholders, including farmers, policymakers, and researchers. This is essential to ensure the sustainability of water resources and the protection of aquatic ecosystems for future generations. This research offers concrete recommendations and a solid foundation for future actions to improve water quality in the region, highlighting the urgency of preserving aquatic biodiversity and strengthening ecosystem health.

Bank erosion in alluvial rivers is mainly caused by weak hydraulic and geotechnical forces acting on the bed and bank surfaces. These phenomena result in property damage along the river reach. The study investigates the detection and monitoring of river bank instability using HEC-RAS and BSTEM models in the lower reaches of the Shelie River. It primarily focuses on analyzing riverbank erosion, assessing bank stability, and predicting lateral bank migration rates. According to the model results, the upper, middle, and lower reaches had factors of safety of 4.41, 0.0, and 3.46, respectively. Naturally, the middle reach has shallow bank heights and channel slopes, a failed plane angle, and less vegetation coverage. This is why the lower reach has a lower factor of safety than the upper reach. In addition, in the lower reaches, sand mining and irrigation trench excavation are carried out continuously throughout the dry season. In addition, irrigation water and household liquid waste return to the Shelie River as seepage through cracks in the soil, thereby wetting the stream bank materials.

This could exacerbate stream bank instability and mass bank failures. As elderly people claim that flood risk and river bank collapse in the upper reaches are not as serious as those in the downstream reaches, this is due to the shallow channel depth, which allows water to escape and inundate its surroundings easily. Mostly, stream banks fail due to excessive toe erosion by streams, weak hydraulic and geotechnical forces, flow undercutting, bank sloughing, and the development of high water pressure. From soil lab studies, the dominant materials are fine sand and silt throughout the reach. These materials have less cohesive resistance and can be easily eroded by flowing water. External interventions, such as sand mining, household discharge, and vegetation clearance, are the main factors that have accelerated bank instability in the Shelie River.

For bank stability and toe-erosion model calibration, the analysis requires parameters such as stratigraphy, cohesion, angle of friction, and critical shear. Bed material type, flow depth, and longitudinal slopes are additional data collected from soil lab results and field work. For this study, default soil parameters were used as input for the BSTEM model. To avoid uncertainty, more representative soil samples with accurate geotechnical values should be used for extended reach.

4. Conclusions

The study of the Lukaya River revealed several types of pollution, highlighting significant correlations among physicochemical parameters. The results show that pollution by pH, high conductivity, temperature, suspended solids, as well as nitrates and ammonium, directly affects water quality and the health of aquatic ecosystems. In particular, high conductivity associated with elevated ammonium levels indicates contamination potentially toxic to aquatic life, while uncontrolled pH fluctuations can harm biodiversity. These findings highlight the importance of increased monitoring of water quality in the Lukaya River. To ensure a healthy aquatic environment and protect local communities that depend on this resource, it is imperative to implement rigorous, appropriate water management protocols. Particular attention must be paid to the management of nitrates and phosphates to prevent eutrophication phenomena, which can aggravate pollution. The innovative approach based on principal component analysis (PCA) enabled us to identify and visualize the complex relationships among the parameters, facilitating understanding of pollution dynamics. The use of advanced statistical tools, such as R and Python via Anaconda, demonstrates that scientific innovation is crucial to solving contemporary environmental problems. It is essential to intensify research efforts to understand better the specific sources of pollution and their long-term impacts. The development of new technologies and treatment methods could also improve water quality in the Lukaya River, thereby ensuring the sustainability of aquatic ecosystems and the safety of the populations that depend on them. An integrated approach that combines awareness-raising, research, and concrete actions is necessary to protect this vital resource for future generations.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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