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RESEARCH ARTICLE

THE ROLE OF ANTHROPOGENIC ACTIVITIES ON WATER QUALITY AND RIVER RESTORATION. A CASE OF MONIK RIVER, ARUSHA-TANZANIA

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Abstract

This study assessed seasonal and spatial variations in physicochemical water-quality parameters in the Monik River and evaluated the influence of anthropogenic activities on river health. Water samples were collected from upstream, midstream, and downstream locations during dry and rainy seasons and analyzed for temperature, dissolved oxygen (DO), electrical conductivity (EC), nitrate (NO_3^-), phosphate (PO_4^{3-}), pH, total dissolved solids (TDS), turbidity, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Results indicated significant seasonal variation in most parameters ($p < 0.05$), with higher turbidity, nutrient concentrations, BOD, and COD observed during the rainy season, primarily due to surface runoff from agricultur al and livestock activities. However, most measured parameters remained within WHO and TBS permissible limits, suggesting generall y acceptable water quality with moderate pollution levels. Cluster and heatmap analyses further revealed distinct seasonal groupings, identifying potential pollution hotspots associated with nutrient loading and organic matter inputs. The findings highlight the influence of land-use activities on river water quality and emphasize the need for riparian buffer restoration, improved agricultural practices, livestock control, and continuous monitoring to protect and sustain the ecological integrity of the Monik River.

Introduction: -

Anthropogenic activities, driven by increasing human needs and socio-economic demands, exert significant pressure on ecosystems, biodiversity, and the overall health of the planet. These activities encompass various human actions that directly or indirectly alter the natural environment. When conducted near or along water sources, anthropogenic activities become major drivers of environmental degradation (Glibert, 2020). Activities such as agriculture, deforestation, urbanization, and livestock keeping exert considerable pressure on the ecological integrity and sustainability of aquatic ecosystems. These processes not only increase nutrient concentrations in the environment but also alter their chemical forms and proportions, resulting in detrimental impacts on water quality (Doggart et al., 2020).Globally, numerous studies have demonstrated a strong correlation between the intensification of

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anthropogenic activities and the deterioration of water quality in receiving water bodies (Akhtar et al., 2021; Sidabutar et al., 2017). For instance, Liu et al. (2014) reported that industrial activities significantly altered the physicochemical characteristics of urban stream water in China. Similarly, Anh et al. (2023) identified key factors influencing river water quality in both urban and rural environments, highlighting the accelerating role of anthropogenic activities. In the African context, similar trends have been observed. A review conducted in Ethiopia revealed that urban streams are more severely degraded compared to agricultural streams, while forested streams tend to maintain relatively better water quality (Bakure et al., 2020). Likewise, Chisanga et al. (2022) reported that livestock keeping activities along the Zambezi River in Zambia have caused substantial impacts on riparian ecosystems and water chemistry. These findings highlight the growing necessity for continuous river health assessments to monitor environmental changes and support sustainable water resource management.

Rivers represent one of the most vital freshwater resources for both ecological systems and human livelihoods. However, the impacts of unsustainable anthropogenic activities on river systems have become increasingly pronounced across the East African region. In Kenya, for example, growing demand for agricultural land and human settlements has led to the encroachment of water catchment areas, thereby threatening river ecosystems (Nyasulu et al., 2024). Similarly, several studies in Tanzania have reported that industrial activities, small-scale agriculture, and settlements located near riverbanks contribute to the discharge of heavy metals, chemicals, and organic wastes—including effluents from pit latrines—into rivers such as the Msimbazi River in Dar es Salaam, the Ngerengere River in Morogoro, and the Pangani River in Tanga City (Mbonaga et al., 2024). Consequently, regular monitoring of water resources, together with effective management and conservation strategies, is essential for assessing and mitigating the impacts of anthropogenic activities on river water quality.

Monik River (MR), located in northern Tanzania, discharges its water into the Lake Natron Ramsar Site (LNRS). MR is among the rivers reported to be experiencing increasing levels of water pollution, which consequently threatens the ecosystem services it provides. Human activities occurring within the LNRS catchment include agricultural practices, deforestation, and overgrazing, which contribute to eutrophication, acidification, and increased sediment inflow containing organic matter and trace metals (Yona et al., 2023). As a result, the ecological integrity of the Monik River has been progressively deteriorating, leading to a decline in its ecosystem services. Lake Natron Ramsar Site (LNRS), located in East Africa, receives inflows from several rivers, including Monik, Pinyinyi, Ewaso Ngiro, and Ngare Sero (Rajabu et al., 2024). Anthropogenic activities within the LNRS catchment contribute to water pollution, reduced water availability, decreased dissolved oxygen levels for aquatic organisms, and alterations in pH levels. Additionally, increased soil erosion within the catchment accelerates watershed degradation and disrupts the breeding cycles of several species, including the globally significant flamingo populations inhabiting the area (Sadikiel E. Kaale et al., 2024). Although previous studies have provided important scientific insights for the conservation and management of the LNRS, there remains a significant knowledge gap regarding the specific impacts of anthropogenic activities occurring within its catchment areas on the water quality of the Monik River. Therefore, the present study aims to analyze the physicochemical water quality parameters of water influenced by anthropogenic activities within the Lake Natron Ramsar Site.

Materials and Methods:-

This study employed a cross-sectional research design, utilizing quantitative methods for both data collection and analysis. The research was conducted along the Monik River (MR) located in Monik Ward, Ngorongoro District, Arusha Region, Tanzania. The study area lies within the catchment of the Lake Natron Ramsar Site (LNRS), which covers an estimated area of approximately 7,600 km² (Rajabu et al., 2024). The LNRS watershed is composed of four major rivers, namely the Ewaso Ngiro River, Pinyinyi River, Ngaresero River, and Monik River, all of which contribute to the hydrological system of Lake Natron (Mgimwa et al., 2021). The spatial distribution of these rivers within the watershed is illustrated in Figure 1.

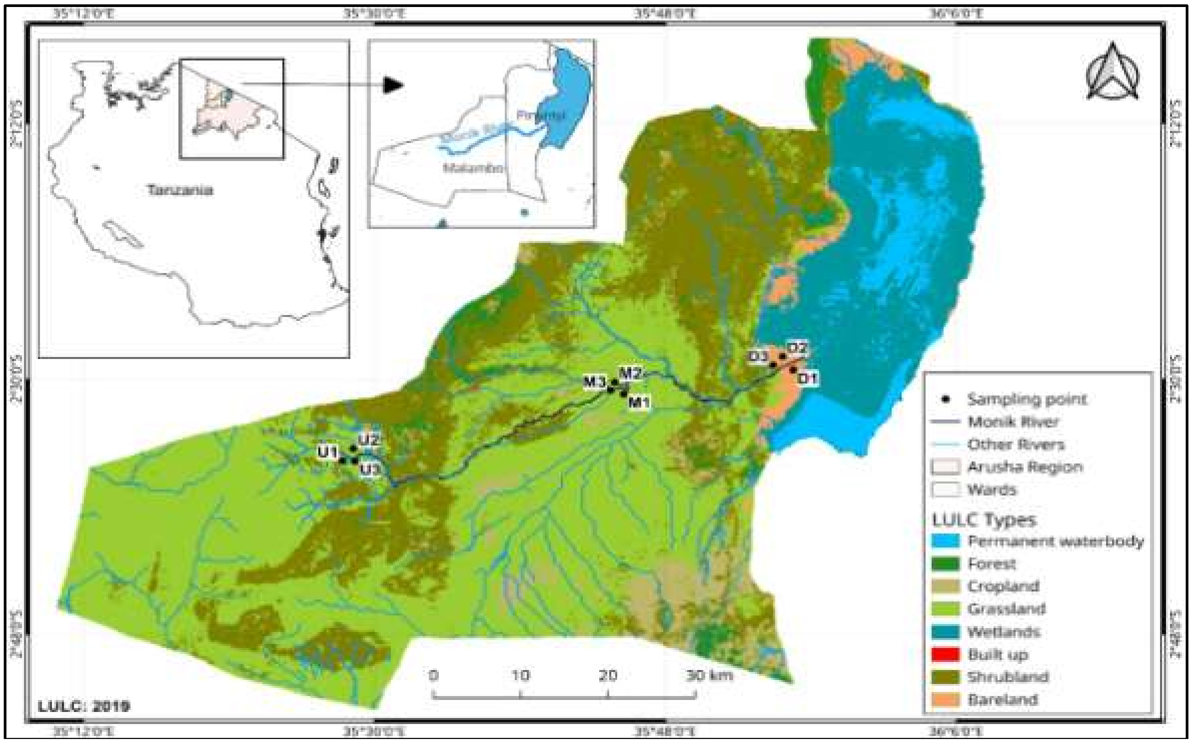

Figure 1.A map of study area showing sampling points along the Monik River

As illustrated in Figure 1, the upstream sampling points (U1, U2, and U3) are located farthest from the river mouth and represent areas with minimal human disturbance. These sites were therefore considered reference points, reflecting relatively natural water quality conditions.The midstream section of the river includes sampling points M1, M2, and M3, which are characterized by intensive anthropogenic activities. These activities include agriculture, livestock grazing, bathing, washing, sand mining, and water diversion for irrigation purposes. Due to the high level of human interference, these sites were categorized as agricultural points and represent areas with the highest level of disturbance to the river ecosystem.

The downstream sampling points (D1, D2, and D3) are located near the river mouth. Although these areas experience relatively lower levels of agricultural activities compared to the midstream section, they remain susceptible to organic pollution. Organic materials, particularly animal fecal matter, are often transported into the river through surface runoff during irrigation and rainfall events. This process contributes to the accumulation of organic matter in the water and can lead to a reduction in dissolved oxygen levels, thereby affecting the ecological health of the river system.

Data collection methods:-

Anthropogenic Activities performed along Lake Natron Ramsar Site:-

Secondary data obtained from the government documents and a parallel, similar study previously conducted in the Lake Natron Ramsar site catchment area, and reported byRajabu et al., (2024). In this study, observation was used to analyze the anthropogenic activities, which were descriptively presented.

Water sampling:-

Water sampling was conducted at predetermined sampling locations categorized as upstream (U), midstream (M), and downstream (D) sections of the river. The geographical coordinates of all sampling sites were recorded using a Global Positioning System (GPS) device to ensure accurate spatial referencing. A total of nine (9) sampling sites were selected, comprising three sites within each river section. Sampling was performed during both the dry season (September–October 2024) and the wet season (March–April 2024) to capture seasonal variations in water quality.At each site, water samples were collected weekly for three consecutive weeks during the dry season, and the same sampling procedure was repeated during the wet season, resulting in a total of 54 water samples (9 sites × 3 weeks × 2 seasons). A composite sampling technique was employed to obtain representative samples from each site, following the recommendations of Golnick et al. (2016).Water samples were collected in pre-labeled 1-L plastic bottles that had been previously rinsed with distilled water to minimize contamination. Immediately after collection, the samples were placed in a cool box maintained at approximately 4 °C to preserve their physicochemical integrity. The samples were then transported promptly to the laboratory at Arusha Technical College (ATC) for analysis of key water quality parameters, including nitrate (NO_3^-), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and phosphate (PO_4^{3-}).

Analysis of Physicochemical Parameters:-
Water quality parameters that are highly sensitive to temporal changes were measured in situ to ensure data accuracy (APHA, 2022). Accordingly, pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, temperature, and dissolved oxygen (DO) were measured directly at the sampling sites using a multiparameter probe meter (HACH HQ40D), while turbidity was additionally verified using a turbidity meter (Wag-WT3020). Upon arrival at the Arusha Technical College (ATC) laboratory, water samples were filtered through a 0.45 µm membrane filter to remove suspended particles before chemical analysis. The filtered samples were then stored at 4 °C to preserve their chemical stability until analysis was conducted.

Alkalinity was determined from unfiltered water samples using the titrimetric method with 0.1 N hydrochloric acid (HCl), and the results were expressed as bicarbonate (HCO_3^-) in mg/L, following the procedures described by APHA et al. (2022). The concentrations of nitrate (NO_3^-) and phosphate (PO_4^{3-}) were determined from filtered water samples using the photometric method with a HACH DR/2700 spectrophotometer, in accordance with standard analytical methods.

Statistical Analysis:-
Prior to statistical analysis, the datasets were tested for normality using the Shapiro–Wilk test, where the null hypothesis that the data follow a normal distribution was rejected when $p < 0.05$. Descriptive statistical analysis was then employed to summarize the basic characteristics of the dataset and to describe the variation in physicochemical water quality parameters across the different sampling sites.To evaluate seasonal variations in water quality, an independent sample t-test was applied to determine whether there were statistically significant differences between the mean values of parameters measured during the dry and wet seasons, using a 95% confidence level ($p < 0.05$).Furthermore, Hierarchical Cluster Analysis (HCA) was performed to classify the sampling locations based on similarities in their water quality characteristics. This multivariate technique was used to assess spatial patterns among the sampling sites and to identify clusters that may represent areas with similar pollution levels, thereby helping to determine the most impacted sections of the river based on the measured parameters.All statistical analyses were conducted using PAST statistical software (Version 4.03) unless otherwise specified. The measured water quality parameter values were subsequently compared with the Tanzania Drinking Water Quality Standards (2018) and the World Health Organization (WHO) Guidelines for Drinking Water Quality (2018) in order to evaluate their compliance with both national and international standards. These guideline values were also used to assess the overall water quality status of the Monik River and to determine whether the measured parameters fall within the permissible limits for safe water use.

Results:-

Activities performed along the Monik River: -
Livestock keeping and deforestation were identified as the dominant anthropogenic activities occurring at the upstream sampling points. Runoff from these activities facilitates the transport of herbicides, pesticides, inorganic fertilizers, and animal wastes into the river system, thereby contributing to alterations in the physicochemical characteristics and overall water quality of the river (Figure 2).

Figure 2: Anthropogenic activities along Monic River

Seasonal Variation of Physicochemical Water Parameters: -

The concentrations of the measured physicochemical parameters generally exhibited an increasing trend from the upstream to the midstream sections, followed by a decline toward the downstream section of the river during both seasons, as summarized in Table 1.

Table 1. Concentration, mean, and Standard Deviation values for measured physicochemical characteristics from three sampling points along the Monik River during the dry and rainy seasons

	Dry season (n=27)			**Rainy season (n=27)**			**WHO**	**TBS**
	Upstream (Means±SD)	Midstream (Means±SD)	Downstream (Means±SD)	Upstream (Means±SD)	Midstream (Means±SD)	Downstream (Means±SD)		
Temp (°C)	20.24±0.22	20.36±0.26	20.29±0.24	18.91±0.26	19.04±0.26	18.93±0.30	20-25	20-25
DO (mg/L)	6.93±0.23	7.04±0.24	6.96±0.26	6.32±0.20	6.21±0.15	6.23±0.14	8-10	5-7
EC (µS/cm)	328.89±9.60	335.33±10.	329.89±11.74	293.89±6.21	297.33±8.4	295.11±7.85	2500	2500
NO_3^- (mg/L)	1.46±0.31	1.63±0.29	1.48±0.37	2.67±0.20	2.78±0.26	2.66±0.34	50	30
PO_4^{3-} (mg/L)	0.12±0.02	0.14±0.02	0.12±0.03	0.26±0.02	0.27±0.03	0.26±0.03	6	6
pH	7.14±0.11	7.20±0.11	7.16±0.13	6.66±0.11	6.63±0.16	6.62±0.14	6.5-8.5	6.5-8.5
TDS (mg/L)	209.22±9.77	215.44±11.	210.00±13.25	188.56±6.00	191.56±8.6	190.44±7.67	500	1000
Turbidity (NTU)	17.11±2.42	18.89±2.37	18.11±3.06	50.11±4.01	51.89±5.30	51.56±4.39	5	<25
BOD (mg/L)	2.67±0.21	2.81±0.24	2.71±0.29	4.39±0.28	4.56±0.38	4.53±0.33	10	2-6
COD (mg/L)	13.67±1.41	14.67±1.41	13.78±1.92	25.67±.00	26.44±2.88	26.11±2.37	60	60

Clustering of the river's sampling points: -

A two-way hierarchical cluster analysis (HCA) of the measured water quality parameters was performed to illustrate the similarities and relationships among sampling sites along the river during both the rainy and dry seasons. The clustering results are presented in Figures 3 and 4.

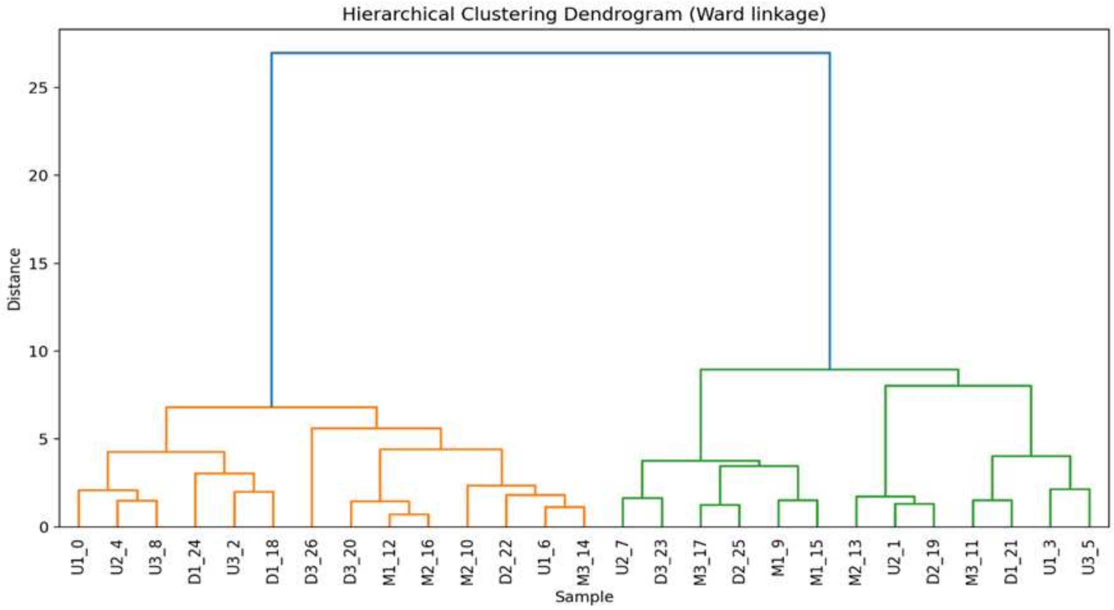

Figure 3: The dendrogram showing overall similarities (Ward linkage, Euclidean distance on z-scored variables)

Figure 3 presents the dendrogram obtained from hierarchical cluster analysis using Ward's linkage method and Euclidean distance on z-score standardized variables, which groups the 27 water quality observations based on their overall similarity. The heatmap presents the standardized mean values (z-scores) for each cluster across all variables, showing deviations from the overall grand average. Red indicates values above the mean, while blue represents values below the mean. The intensity of color reflects the magnitude of deviation, highlighting patterns and differences clearly, as shown in Figure 4 below

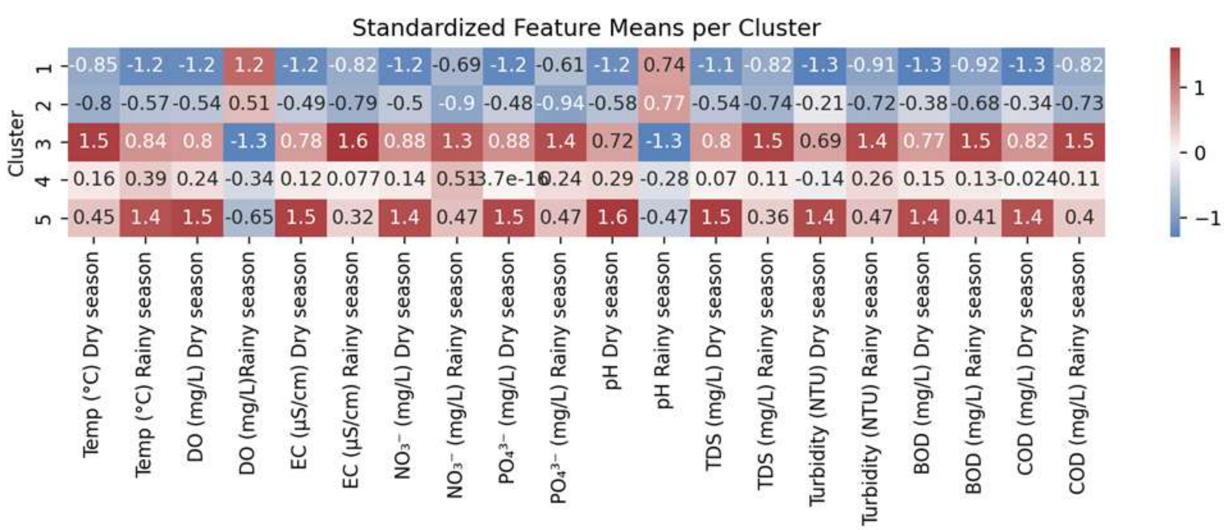

Figure 4. The heatmap shows, how far each cluster's mean (z-score) for every variable, sits above (red) or below (blue) the grand average.

Discussion: -

In the present study, water temperature in the Monik River ranged from 18.5 to 20.7 °C, with higher values recorded during the dry season and lower values during the rainy season. Independent sample t-test analysis revealed a statistically significant seasonal variation in temperature between the dry and rainy seasons ($t = 19.47$, $p = 1.54 \times 10^{-25}$). Temperature variations influence water density, metabolic activity of aquatic organisms, and oxygen solubility, whereby higher temperatures reduce dissolved oxygen availability and may threaten aquatic life. Water temperature plays a critical role in regulating river health by affecting dissolved oxygen levels, biological metabolism, and chemical reaction rates in aquatic systems. The recommended temperature range for healthy water ecosystems is 20–25 °C (WHO, 2018; TBS, 2018). All values recorded in this study fall within or close to the acceptable range, suggesting that temperature conditions in the Monik River remain generally suitable for aquatic organisms.

Dissolved Oxygen (DO): -

Adequate DO levels are necessary for maintaining aerobic biological processes in aquatic ecosystems. In this study, DO concentrations ranged from 6.6 to 7.4 mg/L, with the highest values recorded at upstream sites during the rainy season. These values indicate favorable aerobic conditions within the river system. Dissolved oxygen plays a vital role in regulating aquatic ecosystem functions, influencing nutrient solubility and biological productivity (Katonge & Gayo, 2025). Seasonal comparison showed a statistically significant difference between rainy and dry seasons ($t = 12.92$, $p = 7.33 \times 10^{-18}$). Typically, DO levels decrease with increasing water temperature and microbial activity, particularly during warmer periods (Yona et al., 2022). The measured DO concentrations in this study fall within acceptable environmental standards. The minimum acceptable DO concentration for aquatic life ranges from approximately 6 mg/L in warm waters to 9.5 mg/L in colder environments (WHO, 2018). The permissible limits for drinking water sources are 5–7 mg/L (TBS, 2018) and 8–10 mg/L (WHO, 2008). Previous studies in tropical environments report similar DO ranges (Rajesh & Rehana, 2022). Dissolved oxygen acts as an important indicator of the trophic status and ecological health of water bodies. Reduced DO levels often indicate ecosystem degradation and may threaten organisms requiring aerobic conditions (Mbaruku, 2016).

Electrical Conductivity (EC): -

In the Monik River, EC values ranged between 285 and 352 µS/cm, with lower values observed during the rainy season and higher values during the dry season. Statistical analysis indicated a significant seasonal variation ($t = 14.39$, $p = 8.9 \times 10^{-20}$). The observed EC values suggest that the river water can be categorized as moderately fresh with moderate mineral content. The measured EC values were well within the permissible limits of 1000 µS/cm (TBS, 2018) and 1500 µS/cm (WHO, 2008). Elevated EC values may indicate the presence of dissolved salts, which can negatively affect aquatic organisms, particularly macroinvertebrates that are sensitive to salinity changes (Mbaruku, 2016).

Nitrate (NO_3^-): -

Nitrate concentrations ranged between 1.0 and 3.1 mg/L, with the lowest values recorded during the dry season downstream and the highest values during the rainy season at midstream locations. Statistical analysis confirmed significant seasonal variation ($t = 14.57$, $p = 5.35 \times 10^{-20}$). The observed nitrate concentrations were well below the permissible limits of 50 mg/L (WHO, 2018) and 30 mg/L (TBS, 2018). The presence of nitrate in the river may be attributed to background natural levels and minor nutrient inputs, possibly from agricultural activities and livestock keeping. Increased nitrate concentrations in rivers are commonly associated with agricultural runoff, fertilizer application, and livestock waste, particularly during rainfall events that facilitate nutrient transport into water bodies (Lalika et al., 2015; Mbaruku, 2016). Elevated nitrate levels can stimulate excessive algal growth, which upon decomposition, may reduce dissolved oxygen levels and create hypoxic conditions that threaten aquatic organisms (Mbaruku, 2016).

Phosphate (PO_4^{3-}): -

Phosphate concentrations recorded in this study ranged from 0.1 to 0.3 mg/L, with higher values observed during the rainy season. Statistical analysis showed a significant seasonal variation between dry and rainy seasons. The observed concentrations are far below the permissible limit of 6 mg/L set by both WHO (2018) and TBS (2018). Although the detected levels were low, they may indicate minor agricultural runoff and domestic activities, including bathing, washing, and the use of detergents containing phosphates (Mgimwa et al., 2021). Fertilizer application in agricultural fields may also contribute phosphorus inputs into nearby water bodies (Bwalya, 2015).

Lower phosphate concentrations observed during the dry season may be associated with adsorption onto suspended particles followed by sedimentation (Melaku et al., 2007).

pH: -

The pH values recorded in this study ranged from 6.4 to 7.4, indicating neutral to slightly alkaline conditions. Statistical analysis revealed significant seasonal variation between rainy and dry seasons ($t = 15.47$, $p = 4.23 \times 10^{-21}$), with higher values observed during the dry season. Rainfall events often dilute river water and introduce runoff containing hydrogen ions, resulting in slightly lower pH values during the rainy season. Similar observations have been reported in other studies examining river water quality during rainfall events (Mhande et al., 2022). The recorded pH values fall within the recommended range of 6.5–8.5 for drinking water (WHO, 2018; TBS, 2018). Monitoring pH is important because extreme pH levels can affect aquatic organisms and influence the solubility and availability of nutrients and metals in water (Mbaruku, 2016). The slightly higher pH values observed at upstream sites may be associated with carbonate and bicarbonate compounds derived from livestock activities and natural geological processes (Suthar et al., 2010).

Total Dissolved Solids (TDS): -

TDS values in the Monik River ranged from 180 to 235 mg/L, with the lowest values observed during the rainy season and the highest values during the dry season, particularly at midstream locations. These variations may be attributed to evaporation, water diversion, deforestation, weathering of rocks, and agricultural inputs such as pesticides. Statistical analysis confirmed significant seasonal variation ($t = 8.19$, $p = 6.17 \times 10^{-11}$). The recorded values are well below the permissible limits of 500 mg/L (WHO, 2018) and 1000 mg/L (TBS, 2018), indicating acceptable water quality conditions.

Turbidity: -

Turbidity levels in the Monik River ranged between 14 and 59 NTU, with the lowest values observed during the dry season and the highest values during the rainy season. The elevated turbidity during the rainy season can be attributed to surface runoff carrying sediments and other materials into the river. Statistical analysis revealed a significant seasonal difference ($t = 33.07$, $p = 1.34 \times 10^{-36}$). The WHO guideline value for turbidity in drinking water is 5 NTU, while the TBS standard allows values of less than 25 NTU. Therefore, turbidity levels recorded in this study partially comply with national standards during the dry season but exceed recommended limits during the rainy season. High turbidity reduces light penetration in water, thereby limiting photosynthesis and primary productivity (Mbaruku, 2016). Anthropogenic activities such as sand mining, deforestation, agriculture, and brick making may further contribute to increased turbidity levels (Khatri & Tyagi, 2014; Mezgebe et al., 2015).

Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD_5): -

In the present study, COD values ranged from 11 to 31 mg/L, while BOD_5 values ranged from 2.3 to 5.1 mg/L. Minimum values were recorded during the dry season, whereas higher values occurred during the rainy season, likely due to increased transport of organic materials into the river via runoff. Statistical analysis confirmed significant seasonal differences for both COD ($t = 21.86$, $p = 7.07 \times 10^{-28}$) and BOD_5 ($t = 22.4$, $p = 2.08 \times 10^{-28}$). Similar findings have been reported in previous studies where organic pollutants from domestic waste and agricultural activities contributed to elevated oxygen demand in water bodies (Muniz et al., 2011; Mustapha et al., 2013). The measured COD values fall below the permissible limit of 60 mg/L set by both WHO (2018) and TBS (2018). Similarly, BOD_5 values fall within the acceptable range of 2–6 mg/L (TBS, 2018) and 10 mg/L (WHO, 2018), indicating relatively low organic pollution levels in the Monik River.

Biological Oxygen Demand (BOD): -

In this study, BOD concentrations during the dry season ranged from 2.67 ± 0.21 mg/L at the upstream, 2.81 ± 0.24 mg/L at the midstream, and 2.71 ± 0.29 mg/L at the downstream. These values fall within the Tanzania Bureau of Standards (TBS) permissible range of 2–6 mg/L and are below the World Health Organization (WHO) guideline limit of 10 mg/L, indicating relatively low organic pollution during the dry season. During the rainy season, BOD values increased to 4.39 ± 0.28 mg/L (upstream), 4.56 ± 0.38 mg/L (midstream), and 4.53 ± 0.33 mg/L (downstream). The increase may be attributed to surface runoff during rainfall, which transports organic materials such as agricultural residues, animal waste, and domestic pollutants into the river. Similar seasonal increases in BOD have been reported in recent studies, where higher BOD levels during rainy periods were associated with increased runoff and anthropogenic inputs into surface waters (Ali et al., 2022; Zhang et al., 2023).Overall, although

BOD values were higher during the rainy season, they remained within WHO and TBS permissible limits, suggesting moderate organic pollution and relatively acceptable water quality in the river during the study period.
Figure 3 presents the dendrogram obtained from hierarchical cluster analysis using Ward's linkage method and Euclidean distance on z-score standardized variables, which groups the 27 water quality observations based on their overall similarity. In the dendrogram, shorter horizontal linkage distances indicate higher similarity between samples, while longer linkage distances represent greater dissimilarity and the formation of distinct clusters. The dendrogram indicates that both seasonal variation (dry and rainy seasons) and sampling location (upstream, midstream, and downstream) influence the physicochemical characteristics of the water.

However, some upstream samples collected during the dry season cluster with downstream samples from the rainy season, suggesting possible mixing effects or similarities in water chemistry under certain conditions. Cluster 1, the largest group, contains most of the baseline observations characterized by moderate temperature, electrical conductivity, and nutrient concentrations. These samples generally represent low contaminant levels and fall within acceptable ranges for agricultural irrigation, indicating minimal salinity or nutrient-related risks. Cluster 2 groups samples with slightly elevated turbidity and total dissolved solids (TDS) accompanied by relatively lower dissolved oxygen levels, which may reflect moderate organic inputs or suspended materials. Cluster 3 is characterized by higher turbidity, BOD, and COD values during the rainy season, suggesting the influence of stormwater runoff and increased transport of organic matter and suspended particles into the river. Cluster 4 shows higher nitrate, phosphate, and electrical conductivity (EC) values, indicating stronger nutrient enrichment and increased ionic content, which may be associated with agricultural runoff or localized pollution sources. Finally, Cluster 5 contains samples with relatively higher temperatures, elevated dissolved oxygen, and increased organic demand during the dry season, suggesting a distinct hydro chemical regime that may represent less mixed upstream conditions. Overall, the clustering pattern highlights Clusters 4 and 5 as potential areas of concern, as they exhibit higher nutrient loading and organic pollution indicators.

These clusters may represent localized pollution hotspots, and therefore targeted monitoring and management strategies should focus on these areas to mitigate potential environmental impacts. In addition to sampling site similarities, the heatmap (Figure 4) illustrates five clusters of water quality parameters based on seasonal patterns. Cluster 1 represents a baseline organic signal during the dry season, characterized by relatively higher turbidity, BOD, and COD, suggesting increased particulate and organic matter while other parameters remain near average levels. Cluster 2 reflects nutrient enrichment during the rainy season, with elevated phosphate (PO_4^{3-}) and nitrate (NO_3^-) concentrations, likely associated with runoff from surrounding land.Cluster 3 shows higher electrical conductivity (EC) and total dissolved solids (TDS) along with warmer temperatures in the dry season, indicating increased ionic strength and dissolved solids. Cluster 4 is characterized by lower temperature, high nitrate levels, and reduced dissolved oxygen, suggesting the influence of cool inflows rich in oxidized nitrogen, possibly from groundwater seepage or fertilizer runoff. Finally, Cluster 5 exhibits higher pH, EC, and TDS during the dry season, which may reflect a mineral-rich and relatively less disturbed upstream water source.Overall, the heatmap highlights key parameters influencing seasonal water quality variations and suggests that Cluster 2 should be prioritized during the rainy season for nutrient management, while Cluster 4 requires attention due to potential low-oxygen conditions.

Restoration Plans: -
The Monik River provides important ecosystem services, including habitat provision, sediment and nutrient regulation, and water supply for domestic use, wildlife, and agriculture. However, many rivers in Tanzania have been degraded due to unsustainable land-use practices such as agriculture and livestock keeping (Mgimwa et al., 2021). Similarly, the present study found that the Monik River is affected by deforestation, water diversion, agricultural activities, livestock grazing, sand harvesting, and burnt-brick production along the riverbanks. Although rivers have a natural capacity for self-restoration (Yahaya et al., 2024), the recovery process is often slower than the rate of pollution, highlighting the need for active restoration measures. Several river restoration strategies have been proposed to improve degraded river systems. These include re-vegetation, establishment of riparian buffer zones, livestock exclusion, fencing of riverbanks, weed removal, bank stabilization, and adoption of agricultural best management practices (Bell et al., 2025). In the case of the Monik River, creating riparian buffer zones or fencing sensitive areas could be particularly effective, as vegetation along riverbanks helps filter pollutants and reduce sediment and nutrient runoff (Collins et al., 2013; Yahaya et al., 2024). Additionally, restricting livestock access to riverbanks can reduce sediment disturbance and fecal contamination (Kilgariff et al., 2020). This measure should be accompanied by community awareness programs and the development of alternative water sources, such as wells, to

minimize direct dependence on river water. Implementing these strategies, together with improved agricultural management, would help restore the lost ecosystem services and improve the ecological health of the Monik River.

Conclusion and Recommendation: -

Conclusion: -

This study assessed the seasonal and spatial variations of physicochemical parameters in the Monik River and evaluated the influence of anthropogenic activities on water quality. The results indicate that livestock keeping, deforestation, agriculture, and other human activities occurring mainly in the upstream areas contribute to the transport of nutrients, sediments, and organic matter into the river through surface runoff. Most physicochemical parameters showed slight spatial variation, generally increasing from upstream to midstream and declining downstream, while seasonal variation was evident between the dry and rainy seasons. Higher values of turbidity, nutrients, BOD, and COD during the rainy season suggest the influence of runoff transporting sediments, fertilizers, and organic wastes into the river. Despite these variations, most parameters remained within the permissible limits of WHO and TBS standards, indicating that the river water is generally of acceptable quality with moderate levels of pollution. Cluster analysis further revealed distinct seasonal and spatial groupings of water quality parameters, highlighting areas with relatively higher nutrient loading and organic pollution that may represent potential pollution hotspots. These findings emphasize the need for sustainable land management practices and targeted river restoration strategies, including riparian buffer establishment, livestock control, and improved agricultural practices, to protect the ecological health and ecosystem services of the Monik River.

Recommendation: -

To improve and protect the water quality of the Monik River, several management measures are recommended. First, the establishment of riparian buffer zones through re-vegetation along riverbanks can help reduce sediment, nutrient runoff, and other pollutants entering the river. Controlling livestock access to the riverbanks by fencing sensitive areas and providing alternative watering points can also reduce bank erosion and fecal contamination.

In addition, the adoption of sustainable agricultural practices, such as proper fertilizer application and soil conservation techniques, is necessary to minimize nutrient runoff into the river. Increasing community awareness about the impacts of deforestation, sand harvesting, and other activities near the riverbanks is also important for promoting responsible land use. Finally, regular water quality monitoring and the development of alternative water sources such as wells or boreholes, are recommended to reduce direct dependence on river water and support long-term river ecosystem protection.

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Data availability: -

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Authors' Contributions: -

M, P.: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing of the original draft, and review and editing of the manuscript. T, M.: Supervision, methodology, software, validation, visualization, and review and editing of the manuscript. H, M.: Review and editing of the manuscript. I, T, M.: Review and editing of the manuscript.

Declarations: -

The authors have no competing interests. The AI-assisted tool Quill Bot was used solely for grammar checking during the preparation of this manuscript. Ethical clearance for this study was obtained from the Open University of Tanzania. Permission to conduct the research in the study area was also granted by the Ngorongoro District authorities in Arusha, Tanzania.

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