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Land-Use–Land Cover Changes in the Urban River's Buffer Zone and Variability of Discharge, Water, and Sediment Quality—A Case of Urban Catchment of the Ngerengere River in Tanzania

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Abstract: The physical integrity of the Ngerengere River and its three tributaries drains within Morogoro Municipality were evaluated by assessing the variations in land-use–land cover (LULC) in the river's buffer zone, the discharge, and the contamination of river water and sediment from nutrients and heavy metals. Integrated geospatial techniques were used to classify the LULC in the river's buffer zone. In contrast, the velocity area method and monitoring data from the Wami-Ruvu Basin were used for the discharge measurements. Furthermore, atomic absorption spectrophotometry was used during the laboratory analysis to determine the level of nutrients and heavy metals in the water and river sediment across the 13 sampling locations. The LULC assessment in the river's buffer during the sampling year of 2023 showed that bare land and built-up areas dominate the river's buffer, with a coverage of 28% and 38% of the area distribution. The higher discharge across the sampling stations was in the upstream reaches at 3.73 m^3/s and 2.36 m^3/s at the confluences. The highest concentrations of heavy metals in the water for the dry and wet seasons were 0.09 ± 0.01, 0.25 ± 0.01, 0.03 ± 0.02, 0.73 ± 0.04, 4.07 ± 0.08, and 3.07 ± 0.04 mg/L, respectively, for Pb, Cr, Cd, Cu, Zn, and Ni. The order of magnitude of the heavy metal concentration in the sediments was Zn > Ni > Cr > Cu > Cd > Pb, while the highest NO_2^-, NO_3^-, NH_3, and PO_4^{3-} in the water and sediment were 2.05 ± 0.01, 0.394 ± 0.527, 0.66 ± 0.05, and 0.63 ± 0.01 mg/L, and 2.64 ± 0.03, 0.63 ± 0.01, 2.36 ± 0.01, and 48.16 ± 0.01 mg/kg, respectively, across all sampling seasons. This study highlights the significant impact of urbanization on river integrity, revealing elevated levels of heavy metal contamination in both water and sediment, the variability of discharge, and alterations in the LULC in the rivers' buffer. This study recommends the continuous monitoring of the river water quality and quantity of the urban rivers, and the overall land-use plans for conserving river ecosystems.

Keywords: discharge; tributaries; sediment; Ngerengere River; Tanzania; heavy metals

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1. Introduction

The physical integrity of rivers, i.e., the flow, quality, and healthy riparian zone of the water, is of vital importance in shaping their ecological state and functioning [1]. However, in numerous countries, the prominent environmental challenges are regarded as the surplus of contaminants, particularly organics, nutrients, and heavy metals, in their rivers [2–4]. Rivers face a notable challenge from disturbances to riparian vegetation, which can have far-reaching impacts on the ecohydrological dynamics. In some regions, the significance of this issue may not be fully acknowledged, resulting in the human-induced degradation of riparian zones. This degradation exacerbates riverbank erosion and sediment buildup, and diminishes the ecosystem's ability to filter surface runoff effectively [4].

The concept of "urban rivers" is described as rivers that flow through or are situated within urban areas, which is characterized by human and infrastructure development that has a significant impact on their ecosystems, water quality, and overall management [5]. Urban rivers are subjected to various environmental challenges, including point and non-point sources of pollution, habitat degradation, altered flow patterns, and flooding urbanization [6]. Urban rivers have undergone significant changes in utility and status, primarily due to urbanization and various human activities [7]. The overall river health and functionality have been affected by increased pollution, reduced water quality, and altered ecosystems [3]. Consequently, the once vital sources of water supply, recreation, and aesthetic value have been compromised, negatively impacting both the environment and human well-being [8].

In rural parts of Tanzania, water pollution primarily arises from agrochemicals used in agricultural areas, while, in urban areas, the primary sources of pollution include industries, on-site sanitation systems, and the discharge of stormwater runoff into sewers [9]. These challenges arise from inadequate pollution control measures, resulting in a higher degree of indiscriminate pollution. Poorly executed urban planning and the weak enforcement of land-use regulations lead to encroachment on watersheds by unplanned settlements, agricultural practices, and industrial facilities. Additionally, there is a distinct source of environmental pollution in developing nations like Tanzania stemming from the informal sector [8].

As far as the pollution of urban rivers is concerned, the contamination of the river's water with heavy metals is a widespread issue due to the persistent nature of these metals and their potential to harm living organisms when their concentrations exceed certain levels [10,11] and Tanzania is not spared from this. Heavy metals generated through diverse processes like chemical production, mining, municipal waste, and other human-induced activities eventually find their way into the aquatic ecosystem [12]. Ordinarily, river sediment serves as a significant absorptive repository for heavy metals, and the elevated levels found in this sediment can result in elevated concentrations in living organisms along the food chain due to their persistence and resistance to degradation [13]. In addition to their accumulation within the food chain, heavy metals that infiltrate into sediment can pose a risk by contaminating drinking water wells and potentially causing harm to those who consume the water [14]. Heavy metals cannot undergo biological or chemical degradation, making it possible for them to be transported over extended distances. Given their enduring nature and ability to be transported, it is possible to conduct a distribution analysis of heavy metals in sediment to assess the human-induced effects on heavy metal pollution and perform an analysis starting from the upstream sediment and moving downstream, because downstream areas typically exhibit more consistent pollutant levels compared to the upstream regions and the water column [15]. The literature has shown that the contamination of water and sediment with heavy metals can significantly harm aquatic ecosystems, and their concentrations are commonly regarded as dependable indicators of the overall health of these ecosystems [16].

On the other hand, the accumulation of nutrients in urban rivers has accelerated the problem of eutrophication. Eutrophication, identified by the overabundant proliferation of algae and other aquatic vegetation, frequently results from an increase in nitrogen (N) and phosphorus [P] levels in rivers and streams [17]. This phenomenon can lead to a range of ecological issues, including a decline in aquatic biodiversity, the loss of benthic communities, and the mortality of fish [18]. The elevated transport of nutrients in rivers has been identified as a significant danger to aquatic organisms and human health [19]. The issue of nitrogen (N) and phosphorus (P) pollution has grown into a predominant environmental concern in various countries, and is expected to escalate as a result of the extensive utilization of inorganic fertilizers and fossil fuels [12]. Over the past years, Tanzania's economic progress and population expansion have led to the introduction of nutrients and heavy metals into rivers, attributed to anthropogenic activities [20]. Recent research suggests that the threat of detrimental algal blooms in some rivers could grow in the coming decades as a consequence of eutrophication [3,4]. Nutrients and heavy metals infiltrate river waters from various sources, both human-induced and natural, within the catchment areas. These sources include industrial discharges, residential sewage, and agricultural runoff [5,6]. These sources encompass industrial waste, household sewage, and agricultural runoff [21–23]. The identification of these potential origins is crucial for devising precise measures aimed at mitigating the adverse impacts of contaminants on ecosystems and living organisms [24,25]. Another component in evaluating the physical integrity of a river is the river discharge/flow rate. The quantity of water in rivers is a vital indicator of river health, with a healthy system characterized by a dynamic flow supporting diverse ecosystems; adequate water sustains ecological processes, while altered quantity can signal stress, impacting biodiversity. Monitoring river flow is crucial for assessing health, guiding conservation efforts, and ensuring the sustainability of ecosystems, linking directly to water quality and various utilities [26]. Therefore, alterations in the status of urban rivers have compromised their associated ecological services over the past years, which have affected human livelihood and have posed severe health implications [26–28].

In various urban areas of Morogoro, there is a growing problem of increased water demand due to the rising population and limited water sources. For Morogoro Municipality in particular, most of the residents rely on the Mindu Dam as its primary source of water supply for both domestic and industrial needs [27]. Growth in urbanization and population, coupled with climate change effects, have posed threats to major urban rivers, with the Ngerengere River not being spared. The catchment area of the Ngerengere River that drains in urban centers of Morogoro Municipality encompasses an array of pollution sources, including on-site sanitation systems, industrial effluent sewer outfall, crude solid waste disposal sites, petrol stations, car washing facilities, and urban agricultural fields. Being flanked by human settlements and industrial establishments contributes to the river's potential to be polluted. Notably, major portions of the river and its tributaries are inhabited or built up through the expansion of unplanned settlements and industrial or commercial establishments.

Various methodologies have been employed to quantify the alterations in water quality, runoff, and sediment fluctuations. In studying sediment and water quality, different pollution indices have been utilized to study the extent of pollution and associated health and ecological risks [12–14]. Multivariate statistics have also been used to study the water and sediment status in the urban river basins [28–30]. These methods have been considered efficient in the study and appointment of pollution sources. The assessment of river discharge is crucial, offering essential insights for both scientific understanding and societal needs. Traditional techniques, such as the velocity area method and the use of a current meter, have been used over the years to compute the river discharge [31]. While these methods are generally dependable and straightforward in many scenarios, challenges may arise during periods of exceptionally high discharge. Modern techniques, such as modeling/simulation and the use of geospatial techniques, have also been reported to be efficient in estimating the river discharge, but suffer from economic and technical prerequisites [32].

Previous research efforts have been performed in urban rivers within Morogoro Municipality with a focus on assessing the water quality and pollution extent [33–36]; however, these studies did not establish an in-depth status regarding the existing physical integrity of that urban river, including the existing LU/LC status in the river's buffer, the variability of river discharge, the surface water and sediment quality along with their associated health and ecological risks, as well as the implications to riverine ecosystem services. Therefore, building on the previous studies [37], the present research seeks to characterize the existing LU/LC status in the river's buffer. Furthermore, this study intends to assess the existing spatial and seasonal variability in the quantity and quality of the surface water and sediments in Morogoro urban rivers, specifically the Ngerengere River and its three tributaries, namely, Morogoro, Bigwa, and Kikundi. This study proposes a hypothesis suggesting that the current status of the LU/LC in the river's buffer is dominated by built-up areas and agricultural areas, and variations in the quantity and water quality within rivers could be notably influenced by diverse catchment features such as urbanization and industrial development. Additionally, this study theorizes that the concentrations of nutrients and heavy metals might display significant differences between the wet and dry seasons due to the dilution effect caused by rainfall and flooding. The objectives of this investigation encompass the following three key aspects: firstly, assessing the LU/LC in the riparian zone of the urban catchment; secondly, evaluating the discharge (quantity) in the examined river and its tributaries; thirdly, analyzing the seasonal and spatial patterns of nutrients (phosphate, nitrate, nitrite, and ammonia) and heavy metals (Cr, Cd, Pb, Ni, Cu, and Zn) in the water and sediments within the urban catchment of the Ngerengere River and employing multivariate statistical analyses to investigate the potential sources of these pollutants.

The novelty of this study lies in its comprehensive approach to assessing the physical integrity of urban rivers within Morogoro Municipality, focusing on previously unexplored aspects such as the detailed characterization of the land-use/land cover status in river buffers, spatial and seasonal variability in water and sediment quality, and implications for the riverine ecosystem.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Drainage Patterns and Hydrology

This study was conducted within the urban rivers of Morogoro Municipality in Tanzania, namely, the Ngerengere River and its three tributaries, namely, the Morogoro, Kikundi, and Bigwa Rivers. However, for the discussion and interpretation of this study's findings, information from other rivers that are not within the municipality, namely, Mzinga, Likulunge, and Mlali, but might have hydrological implications to the study literature, was consulted. These selected rivers in this study are within the Ngerengere sub-catchment of the Wami-Ruvu Basin and originate as fast-flowing streams in the Uluguru Mountain. The Ngerengere sub-catchment has been dammed to create the Mindu reservoir to supply water to Morogoro [36]. Morogoro Municipality is one of the nine districts in Morogoro Region. Large urban centers of Morogoro Municipality are drained by streams and tributaries that drain from the Ngerengere River as a tributary of the Ruvu sub-basin of the Wami-Ruvu Basin. The rivers in this basin play a crucial role in providing water for domestic use, irrigation, industrial activities, and livestock, especially for Ngerengere Maasai. Morogoro Municipality, located 190 km southwest of Dar es Salaam, covers a total area of 290.02 km^2 [38,39].

Major Plant Species Observed in the Riparian Zone

The ecosystem of the Ngerengere River comprises seven primary riparian vegetation species, including phragmites, elephant grasses, Reeds, Sesbania, Sedges, Ficus, and Bulrush. These vegetation types encompass a variety of plant forms, ranging from grasses and shrubs to some taller tree species. The dominance of phragmites along the Ngerengere River is primarily due to their robust ability to regenerate compared to other plant species. These plants typically form dense thickets with coarse hairs on their surfaces. Similarly, elephant grasses possess stiff and upright hairs, serving as a defensive mechanism akin to phragmites [35].

2.1.2. LU/LC in the Riparian Zone of Ngerengere River and Its Tributaries

Characterization of LULC during the Study Year 2023

The LULC assessment in the river's buffer (60 m away from the river) was conducted. The Environmental Management Act, 2004, of the United Republic of Tanzania provides for the restriction of human activities within 60 m of the water bodies. High-resolution satellite imagery was acquired to facilitate the accurate classification of land cover types (Table 1). Landsat 8 Operational Land Imager with Thermal Infrared Sensor (OLI-TRIS) imagery was selected for its suitability in capturing detailed land surface characteristics. The specific path/row for the study area was identified as 167/065 to ensure comprehensive coverage. The imagery acquisition occurred on 1 July 2023, chosen strategically to coincide with the dry season, when land cover features are more distinct and less obscured by seasonal variations. The Landsat 8 imagery provided a spatial resolution of 30 m, allowing for a detailed analysis of the land cover features within the buffer zone. Importantly, the selected imagery exhibited a minimal cloud cover of 2%, ensuring clarity and reliability in the classification process [37].

Table 1. Downloaded satellite imagery for the LULC classification detection from the source from 2001 to 2021.

Satellite	Sensor	Path/Row	Acquisition	Resolution	Season	Cloud Cover
Landsat 5	TM	167/065	1 July 2001	30 m	dry	2%
Landsat 7	ETM	167/065	1 July 2011	30 m	dry	3%
Landsat 8	OLI-TRIS	167/065	1 July 2021	30 m	dry	2%

Characterization of Previous LULC in the River's Buffer (2001–2021)

Characterization of the land-use–land cover change (LULCC) in the river buffer from 2001 to 2021 involved the acquisition of satellite imagery for the LULCC detection. The Landsat 5 TM, Landsat 7 ETM, and Landsat 8 OLI-TRIS data for the years 2001, 2011, and 2021 were downloaded from the United States Geological Survey (USGS) Earth Explorer and DIVA GIS (Table 1). The satellite images were classified into distinct land cover classes using appropriate algorithms [40,41]. Mathematical formulae were employed to calculate area changes, percentage area changes, and annual rate changes, with β representing the specific land cover and land-use classes. The accuracy of the procedure was assessed through Procedure Accuracy (PA) and User Accuracy (UA) for each LULC class in 2001, 2011, and 2021. Landsat bands utilized for classification in each year were documented. Overall accuracy and Kappa statistics were computed to evaluate the classification's reliability.

The following formulae were used to calculate the Area change (ha), % Area changes, and Annual rate change (ha/year):

$$\text{i}\quad Area\ change = Area\ of\ \beta\ in\ Year\ 2 - Area\ of\ \beta\ in\ Year\ 1 \tag{1}$$

$$\text{ii}\quad \%\ Area\ change = (Area\ of\ \beta\ in\ Year\ 2 - Area\ of\ \beta\ in\ Year\ 1) \div (Total\ area\ in\ the\ study\ Area) \times 100\% \tag{2}$$

$$\text{iii}\quad Annual\ rate\ of\ change = \frac{(Area\ of\ \beta\ in\ Year\ 2 - Area\ of\ \beta\ in\ Year\ 1)}{(Years\ between\ year\ 1\ and\ year\ 2)} \tag{3}$$

where β is the land cover and land-use class in the study area.

- **Validation and Ground-Truth Data**

To ensure the reliability of our study results, rigorous validation procedures were employed by using ground-truth data. Integrated field surveys and high-resolution imagery were utilized to verify the accuracy of our analysis within the 60 m buffer zone, providing confidence in the reliability of our findings.

2.1.3. Population

Sumari et al. [38] investigated the impact of population growth and spatial expansion in Morogoro Municipality, Tanzania, from 2000 to 2016. The study found that, while the population increased by 1.7% on average, the built-up area expanded by 4.5% on average during this period, suggesting rapid urban expansion beyond population growth and highlighting the potential implications for urban sustainability. Per the 2012 Population and Housing Census report, the Morogoro Municipal Council had a population of 117,601 in the year 1988, 227,921 in the year 2002, and 315,866 in the year 2012. It is indicated further in the report that the annual growth rate of Morogoro Municipal Council's population in

2012 was 3.3% [39]. According to the National Bureau of Statistics 2022 population and household census, the recorded population in Morogoro was 471,409, distributed among 133,809 households. These data reveal an average household size of 3.5 individuals. The municipality has 29 administrative wards.

2.1.4. Climatological Conditions

According to the Tanzania Metrological Authority, 2024, the study area is found in a bimodal rainfall regime that receives both Vuli and Masika rains (Swahili words meaning short rain seasons). Climatologically, Vuli rains normally occur during October–December, followed by the dry season during January and February. However, due to climate change, extended rains (off-season rains) have been observed even during January and February. Masika rains normally occur from March to May. Therefore, wet conditions usually dominate many areas of the Morogoro District, since this is the time of the main rainfall season (Masika season). Otherwise, the period from June to September is mainly the dry season. However, variability is sometimes obvious due to climate change. In the year 2023, based on the meteorological data obtained from the Tanzania Metrological Authority, the climatological conditions in the catchment area exhibited a notable variation throughout the year. November emerges as the peak period for rainfall, with a substantial measurement of 198 mm, possibly indicating the influence of seasonal patterns or localized weather phenomena. Conversely, September experiences the lowest rainfall among the months, recording a minimal value of 2.3 mm. Temperature fluctuations also demonstrate distinct patterns, with December marking the highest temperature of 27.1 °C, while June records the lowest temperature of 22.75 °C. Moreover, examining the evaporation rates reveals September as the month with the highest evaporation level, reaching 161.1 mm, whereas June exhibits the lowest evaporation rate, registering 78.7 mm.

2.1.5. Human Activities

Based on the last inventory of the existing industries performed by the Morogoro Municipal Council, the municipality had ten (10) large industries, including textile, plastics, tobacco processing, leather and agricultural, and processing machinery and fabrics, as well as seven (7) medium industries dealing with food processing, gypsum, packaging materials, and engineering activities. The municipality recorded a significant number of small industries, including 159 milling machines and 34 formal garages. Another group of small-scale industries includes block fabrication and processing industries. Field observation revealed that other socio-economic activities such as urban agriculture, livestock keeping, and fishing activities are dominant in the municipality. Despite having the potential to foster socio-economic development in the municipality [39], the rapid expansion of the aforementioned human activities in the urban catchment is associated with the occurrence of the hydrological response of the urban rivers, including the Ngerengere and Morogoro tributaries; this scenario has been amplified by the current encroachment by human activities in the upstream areas such as the Uluguru mountain and Mindu, while industries, on-site sanitation systems, and urban farming in amplify this scenario in the downstream areas. Those activities are directly associated with the potential alterations in the quantity and quality of the water [40].

2.1.6. Geology

Morogoro Municipality comprises the Usagaran unit, a Precambrian basement complex featuring high-grade metamorphic rocks like amphibolite, gneiss, and granulites. Additionally, there is a Neogene formation marked by a substantial accumulation of red soil, “mbuga” soil, and alluvium. Mkumbo et al. [41] reported that a significant portion of Morogoro Municipality, especially its central parts, is characterized by silty clay soil and loamy sand in the peripheral areas [41].

2.2. Data Collection Methods

2.2.1. Sampling and Water Quality Analysis

Thirteen (13) sampling locations strategically positioned along the Ngerengere River and its tributaries (Figure 1) were established. Each sampling location was characterized by varying degrees of urbanization, human activities (point and non-point pollution sources), and riparian vegetation. Notably, some of these sampling sites were situated within the vicinity of bridges, as recommended by the WHO [42], namely, the Msamvu, Kingo, Nguzo, Kasanga, Kitungwa, and Kihonda bridges, while others were located near major residential areas, agricultural areas, industrial zones, car washes and petrol stations, and forested areas. This also applied in the previous studies of [43,44] and the WHO guidelines [42].

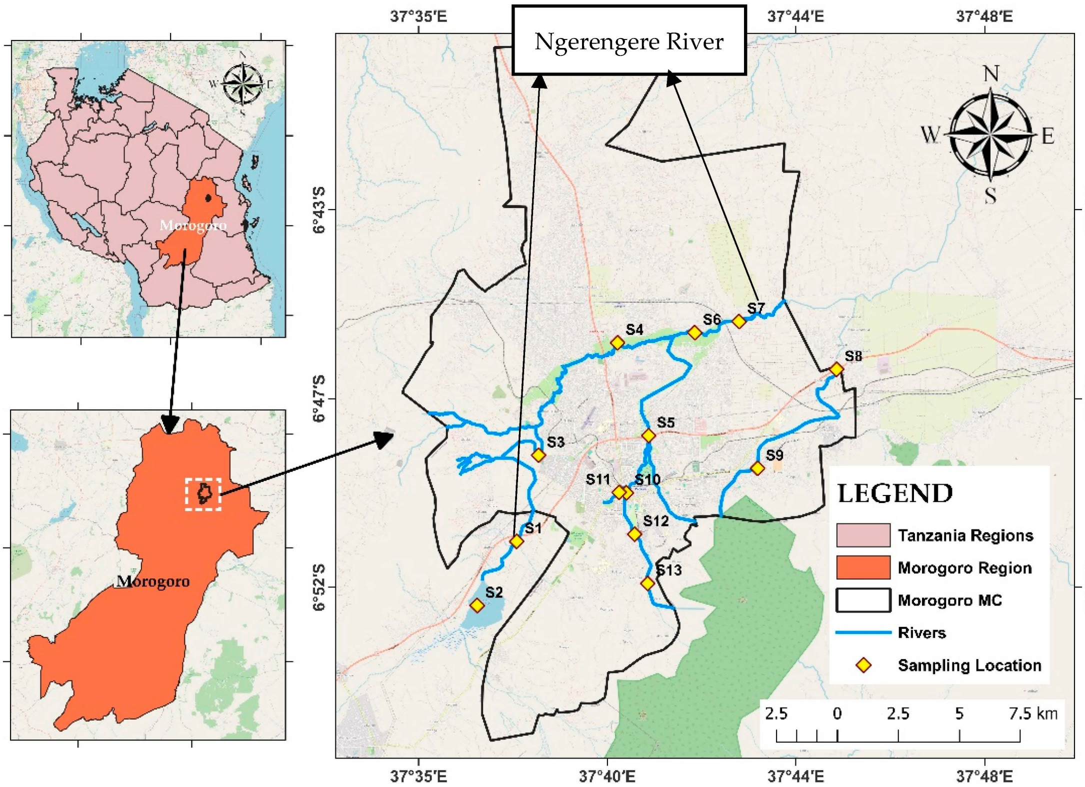


Figure 1. Map showing the catchment boundary Morogoro Municipality at the bottom left and sampling stations at the Ngerengere River and its tributaries.

The water quality parameters that were assessed encompassed physical parameters including salinity, conductivity, temperature, dissolved oxygen, total dissolved solids (TDSs), turbidity, color, heavy metal concentrations, nutrients, temperature, and pH values. During the sampling procedure, 1 L polyethylene containers were washed with clean water and thoroughly rinsed with water until all traces of detergent were removed. When in the field, these containers were first rinsed with water from the specific streams chosen for sampling before the actual sample collection. For each sampling site, triplicate samples were collected by submerging the open-ended polyethylene bottles into the water's surface streams, allowing the water to flow in and fill the containers. The collected samples were placed inside a chilled container and transported to the laboratory for additional analysis. To preserve the samples, a small quantity of nitric acid (HNO_3) was added, and they were stored in a refrigerator at approximately 4 degrees Celsius until the time of analysis [21,45]. The sampling events were conducted with three repetitions in both the dry and wet seasons of September and December 2023, respectively. Each campaign was comprised of three sampling events, allowing for a thorough examination of the environmental conditions across different climatic phases. The time interval between successive sampling events was approximately 10 weeks.

2.2.2. Laboratory Analysis

The heavy metal determination from the water and soil samples was performed by atomic absorption spectrophotometry using a Perking Elmer 850 Graphite Furnace and Perking Elmer AS 800 Auto-sampler with a computer interface for operational and reading display. The reagents used included distilled water, aqua regia 1:3 by volume (1 concentrated HCl/3 concentrated HNO_3 (65–68%)), and sulfuric acid [H_2SO_4] for digestion and extraction. The detection limit of the instrument was set to 0.01 mg/L. Quality assurance and quality control (QA/QC) procedures were used during all phases of this study to ensure the collection of contaminant-free samples that would provide accurate and reliable data on the heavy metals studied. Information regarding the methodologies has been previously outlined [46,47]. The sulphate content in the water samples was measured by adding Sulfa Ver 4 sulphate by taking 25 mL of the water sample, adding the Sulfa Ver 4 reagent to the water sample, shaking vigorously to mix, and allowing it to settle or 5 min for the reaction to take place; then, using a spectrophotometer programmed at 680 with a wavelength set to 450 mm, a blank 25 mL water sample (containing water only) was used for zeroing, followed by the sample mixed with the reagent. The same procedure was applied for the nitrate and phosphate determination. For the nitrate determination, Nitra Ver 5 Nitrate Reagent was used, with the spectrophotometer programmed at 490 mm and with a wavelength set to 890; for the phosphate determination, Phos Ver 3 Phosphate Reagent was added to the water sample, shaken vigorously to mix, and kept for 2 min for the reaction to take place, this time using a spectrophotometer programmed at 490 with the wavelength set to 890 mm; each was then followed by the reading as explained for the sulphate determination.

Physical parameters such as salinity, conductivity, temperature, dissolved oxygen, total dissolved solids (TDSs), turbidity, color, temperature, and pH values were recorded by using a multi-parameter water analyzer (Hach Co., Loveland, CO, USA) on-site. The water quality was compared with the Tanzania Water Quality Standards (TZS 789: 2008) and WHO drinking water quality standards (Table 2). This is because, in many regions across Africa, untreated river water is commonly utilized for a range of domestic activities, including drinking, often without undergoing any form of preliminary treatment [19].

Table 2. TBS and WHO drinking water quality standards.

Upper Limits for Heavy Metals and Nutrients of Water for Drinking										
	Cd	Cr	Cu	Ni	Pb	Zn	NO_3^-	NH_3	PO_4^{3-}	NO_2^-
TZS 789: 2008	0.05	0.05	3	-	0.1	15	75	1	-	-
WHO Standards	0.003	0.05	2	0.07	0.01	3	50	1.5	-	3

2.2.3. Sediment Sampling

To assess the influence of human activities on sediment pollution, thirteen (13) sampling sites were chosen for data collection in September and December of 2023 to capture the sediment dynamics during the transition from the dry to the wet season. The selection of these sites was influenced by prior research on the factors that influence water and sediment quality [47,48]. Each site's location was accurately determined using a handheld GPS device (Garmin Map 62). Relevant information, including the site name, GPS coordinates, and site characteristics, was recorded. For areas with low water velocity, sediment samples were obtained using stainless scoops at a 10 cm depth. These samples were then carefully placed in polyethylene bags, following the procedure described in another study [48]. In areas with high water velocity and greater depths, random sampling was conducted with the assistance of hand-operated manual augers. Before collecting the samples, these manual augers were meticulously cleaned and wrapped in clean aluminum foil until use. During the sampling process, the auger head was connected to the necessary rod extensions of a "T" handle. The auger was inserted into the sediment at an angle between 0° and 20° from the vertical to minimize any spillage of the sample. The augers were rotated clockwise to cut through the sediments, and then they were slowly withdrawn. The collected samples were placed in polyethylene bags and stored in an ice-cooled container maintained at a temperature of 4 °C. No additional chemical treatments were applied to the samples.

2.2.4. Water Level/Discharge of the Rivers

Water flow data, including discharge rates and flow patterns, at key monitoring points along the rivers were accessed from the Wami-Ruvu Basin; for the case where monitoring data from the basin were not available, the discharge was obtained using the velocity–area approach. In the case of a straight and consistently flowing channel, a buoyant object was permitted to move naturally alongside the water, spanning the length between two ends of the channel's straight portion. A stopwatch was used to gauge the time, denoted as tF, required for the object to traverse the distance, denoted as L, between these two reference points. The channel's flow characteristics, specifically the cross-sectional area (A), were ascertained by considering the depth of the water (h) and the channel's width (w). Furthermore, the discharge rate (Q) was determined through the use of Equation (4), as follows:

$$Q = (h \times w)L/(tF) = A \times (L/tF) = \propto (AU) \tag{4}$$

where U represents the maximum velocity [to control uncertainties] and ∝ is a correction factor for the velocity to account for the nonuniformity of velocity across the channel cross-section.

2.2.5. Sediment Texture Classification

A qualitative approach using a finger test method involving the placement of 25 g soil in a palm was used for on-site texture assessments, where distinct characteristics emerged through touch; this method has been recommended for most in situ assessments due to its practicality, immediacy, cost-effectiveness, and ability to allow for on-site analysis without the need for drying. Sand, with its larger particles, imparts a gritty feel; silt exhibits a smooth or floury texture and falls within a moderate particle size range; clay, with its smaller particles, yields a sticky and gummy sensation, with only around 20% clay particles contributing to this property. A detailed description of this method has been also reported in other studies [48,49]. The validation of the texture classes was performed by using a sieve analysis test using a standardized range for the sieve size. For this study, sediment samples weighing 500 g were utilized for the quantitative texture (sieving test) and subsequent extraction for the laboratory. Before the analysis and extraction process, the sediment samples were dried indoors, following which they underwent sieving using a (2 mm − 10 mesh) stainless steel screen to eliminate plant debris and larger detritus exceeding 2 mm in size.

2.3. Data Analysis

Statistical data were cluster analyzed by using Analysis of Variance (ANOVA) to determine the differences between the water quality parameters and quantity between sampling locations. Data obtained were presented in the form of tables, graphs, and figures. To analyze the seasonal variations in the river water quality, we categorized the 12 months of the year 2023 into the following two segments: the wet season and the dry season of sampling, as determined by monthly precipitation in the study area. As per the Tanzania Meteorological Authority (TMA), the study area undergoes distinct wet and dry seasons characterized by bimodal rainfall patterns, one from October to December and another from March to May. Dry spells typically prevail from January to February and from June to September. In our research, our objective was to analyze the sediment dynamics during the transition from the wet to the dry season. Consequently, we carefully selected the period for sediment and water sampling, as well as discharge measurements, to encompass both the wet and dry seasons. Our sampling campaigns were conducted in September and December of 2023 to facilitate the planned analysis.

Our investigation employed principal component analysis (PCA) with the varimax rotation method to pinpoint the potential sources of nutrients and heavy metals in the river water. Kaiser's rule guided the selection of principal components, retaining only the eigenvectors with eigenvalues surpassing one. Moreover, Pearson correlation analysis, a commonly utilized method for identifying pollutant sources, was used to evaluate the relationships between the nutrient and heavy metal concentrations. The software OriginPro 2024 was employed for the statistical analyses.

2.4. Quality Assurance and Quality Control

Stringent quality assurance and control protocols were upheld throughout the sampling and analysis process. Thirteen sampling locations, reflecting diverse pollution sources, were strategically chosen along the Ngerengere River and its tributaries. Water quality parameters were meticulously assessed, including heavy metal concentrations, nutrients, and physical parameters. Samples were collected using clean, pre-rinsed containers, preserved with nitric acid and stored at controlled temperatures until analysis. Laboratory analysis employed atomic absorption spectrophotometry for the heavy metal determination, with on-site measurements conducted using a multi-parameter water analyzer. Sediment sampling, conducted at thirteen sites, adhered to strict protocols to minimize contamination.

3. Results and Discussion

3.1. Water Discharge/Flow in Dry and Wet Seasons across the Sampling Stations

The average discharge at established sampling stations indicated a greater flow rate during the wet season compared to the dry season (Figure 2). In both wet and dry seasons, the upstream reaches consistently showed higher flow rates, specifically at sampling stations S12 and S13, where the measured flow rates were 3.73 m^3/s, 2.95 m^3/s, 1.52 m^3/s, and 0.99 m^3/s, respectively. The higher flow rate in the upstream reaches can be attributed to the presence of riparian vegetation, including the Uluguru forest levels, and lower water abstraction resulting from reduced human activities compared to the downstream and midstream areas. In these latter areas, various domestic and commercial activities such as car washing and agricultural practices were observed, which likely contributed to the altered flow dynamics.

Additionally, the study revealed that the elevated river flow rates at the sampling stations near the confluence point where the main Ngerengere River meets the Morogoro tributaries, as observed in station S6, recorded flow rates of 2.36 m^3/s and 0.39 m^3/s during the dry and wet seasons, respectively; these findings are consistent with the research conducted by Mbuligwe and Kasseva [50] in the Msimbazi River, drains within urban centers of Dar es Salaam. Their study demonstrated the impact of tributaries on the augmentation of Msimbazi River runoff. River discharge, especially the timing and intensity of high-flow events, plays a significant role in influencing the biodiversity and ecological processes within stream ecosystems [51]. Other research by Nilsson and Renöfält [52] has also established the implications of river discharge variability on water quality. The fluctuation in river discharge can also be ascribed to climatological conditions in the region. This observation might imply that sediment transportation from the upper reaches to the downstream reaches of the Ngerengere River, as suggested by a previous study that showed the clear and positive correlation between the flow of a river and its ability to transport sediment [53].

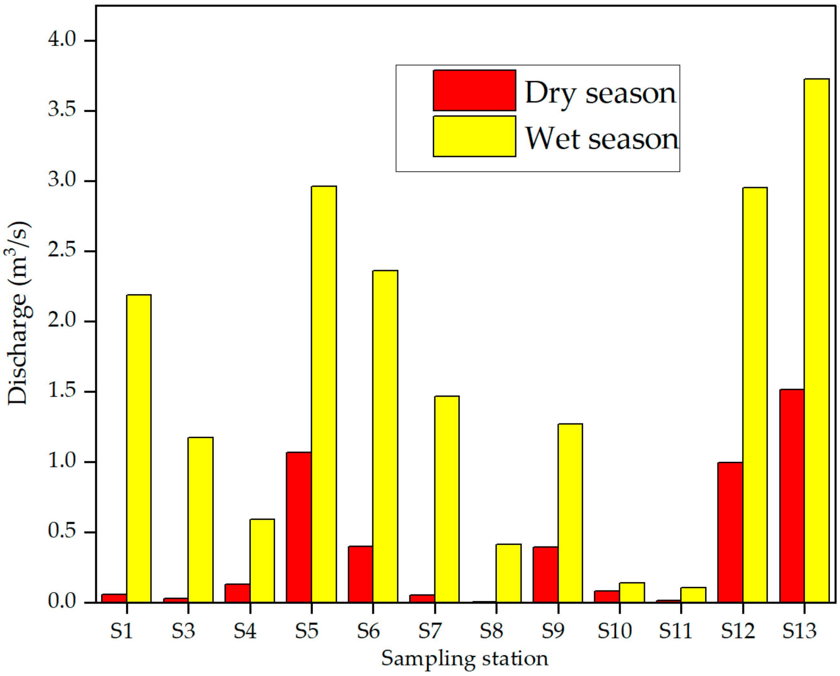


Figure 2. Variation in the discharge in the dry and wet seasons across the sampling stations accounting for the year 2023 (Data on the average storage capacity at S2 (Mindu Dam), measured in cubic meters, were obtained from the Wami-Ruvu Basin Water Board).

The increased flow rate during the wet season may be linked to rainfall events associated with El Niño precipitation. Additionally, factors such as geological characteristics, urban farming activities, and domestic water usage observed in the midstream and upstream reaches may be correlated with lower discharge levels at the sampling stations; this correlation has also been proposed by Kilonzo et al. [54]. Variations in the water quantity or flow rate directly influence the water quality and tend to affect pollutant concentrations, nutrient levels, and overall ecosystem health; low-flow conditions can lead to the concentration of pollutants, increased toxicity, and reduced dilution, while high flows may result in the washout of pollutants from adjacent areas, altering water quality dynamics [55]. The ANOVA results suggest a significant difference in the mean discharge between the dry and wet seasons. The p-value is 0.01, which is less than the typical significance level of 0.05; the F-statistic is 7.58 (Table 3), suggesting that there is a statistically significant difference in the mean discharge between the dry and wet seasons.

Table 3. ANOVA results for the mean discharge comparison between the dry and wet seasons in the sampling stations.

Groups	Count	Sum	Average	Variance		
0.0559	11	4.69	0.43	0.28		
2.1884	11	17.16	1.56	1.59		
Source of Variation	SS	df	MS	F	p-value	F crit
Between Groups	7.06	1	7.06	7.58	0.01	4.35
Within Groups	18.64	20	0.93			
Total	25.71	21				

In determining the discharge at the Mindu Dam (sampling station S2), information obtained from the Wami-Ruvu monthly monitoring database was utilized, considering the dam as the outlet of the Ngerengere River. During the dry season, the mean dam storage capacity was 9,740,000 m^3, while the highest and lowest values ranged from 9,040,000 m^3 to 10,600,000 m^3, respectively. Yawson et al. [56] stated that the storage capacity of the Mtera Dam is estimated to be 125,000,000 m^3 million, which is roughly estimated to be

25 times larger than the Kidatu Dam. Variability in the storage capacity of the dam might be attributed to different factors, including climatological conditions, water abstraction rates, land use and land cover, among others [57]. The dam's storage capacity and overall regulations might have adverse hydrological impacts on the downstream rivers and the intended functions of the dam [58]. The retention of sediment by the dams and reservoirs influences the distribution of flow velocities and leads to incisions in the river channels, and it has a significant and considerable influence on the recurrence and duration of floods in the river [59].

3.2. LU and LC in the Buffer Zone of Ngerengere River and Its Tributaries

3.2.1. LULC during the Study Year 2023

The Environmental Management Act, 2004, of the United Republic of Tanzania restricts human activities within 60 m of water sources; therefore, the study assessed the LULC based on the aforementioned legal requirements. The land-use/cover area distribution for 2023 in the rivers' buffer zone reveals that built-up areas dominate the landscape, constituting the largest proportion at 38%, indicating significant human settlement and infrastructure development in the area. Vegetation covers a considerable portion as well, comprising 24% of the total area. This suggests that, despite urbanization and development, there are still substantial natural habitats present within the buffer zone. Bare land, accounting for 28% (Figure 3), may indicate areas undergoing transition or disturbance due to agricultural activities or land degradation processes. The remaining 10% of the area indicates the presence of river coverage. These results highlight the dynamic interaction between human activities and natural ecosystems within the rivers' buffer zone. Vegetation and built-up areas demonstrate relatively high accuracy levels, with the PA and UA values above 80%, indicating the reliable classification of these land cover types.

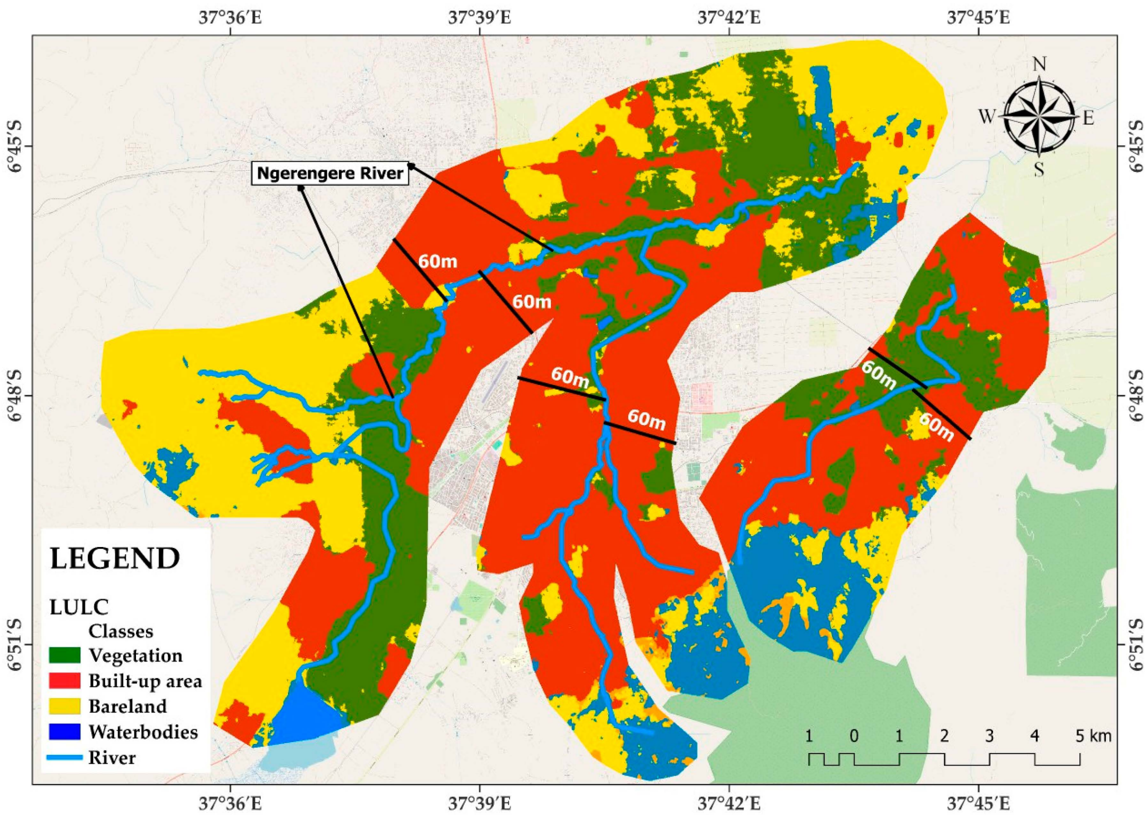


Figure 3. LULC in the buffer zone of the Ngerengere River and three tributaries for the study year 2023.

3.2.2. LULC in the River's Buffer from 2001 to 2021 (20 Years)

The land-use–land cover (LULC) assessment in the riparian zone (60 m from the Ngerengere River and its tributaries of Morogoro, Kikundi, and Bigwa) from 2001 to 2021 revealed significant changes (p-value = 8×10^{-7}). Analysis revealed that recent land-use types in the Ngerengere River and its tributaries within Morogoro Municipality were natural vegetation, urban/built-up areas, bare land, and water bodies, constituting 25%, 35%, 30%, and 10%, respectively (refer to Figure 4 and Table 4). This study is similar to the one conducted by Namugize et al., (2018), which examined the effects of land use and land cover changes on water quality in the uMngeni River catchment, South Africa [60]. The most notable trend is the substantial decrease in vegetation cover from 40% in 2001 to 25% in 2021. Furthermore, the increase in built-up areas from 20% in 2001 to 35% in 2021 indicated rapid urbanization in the river's buffer. The ground-truthing reaffirmed the aforementioned human activities in the Ngerengere River catchment, as reported in other previous studies [33].

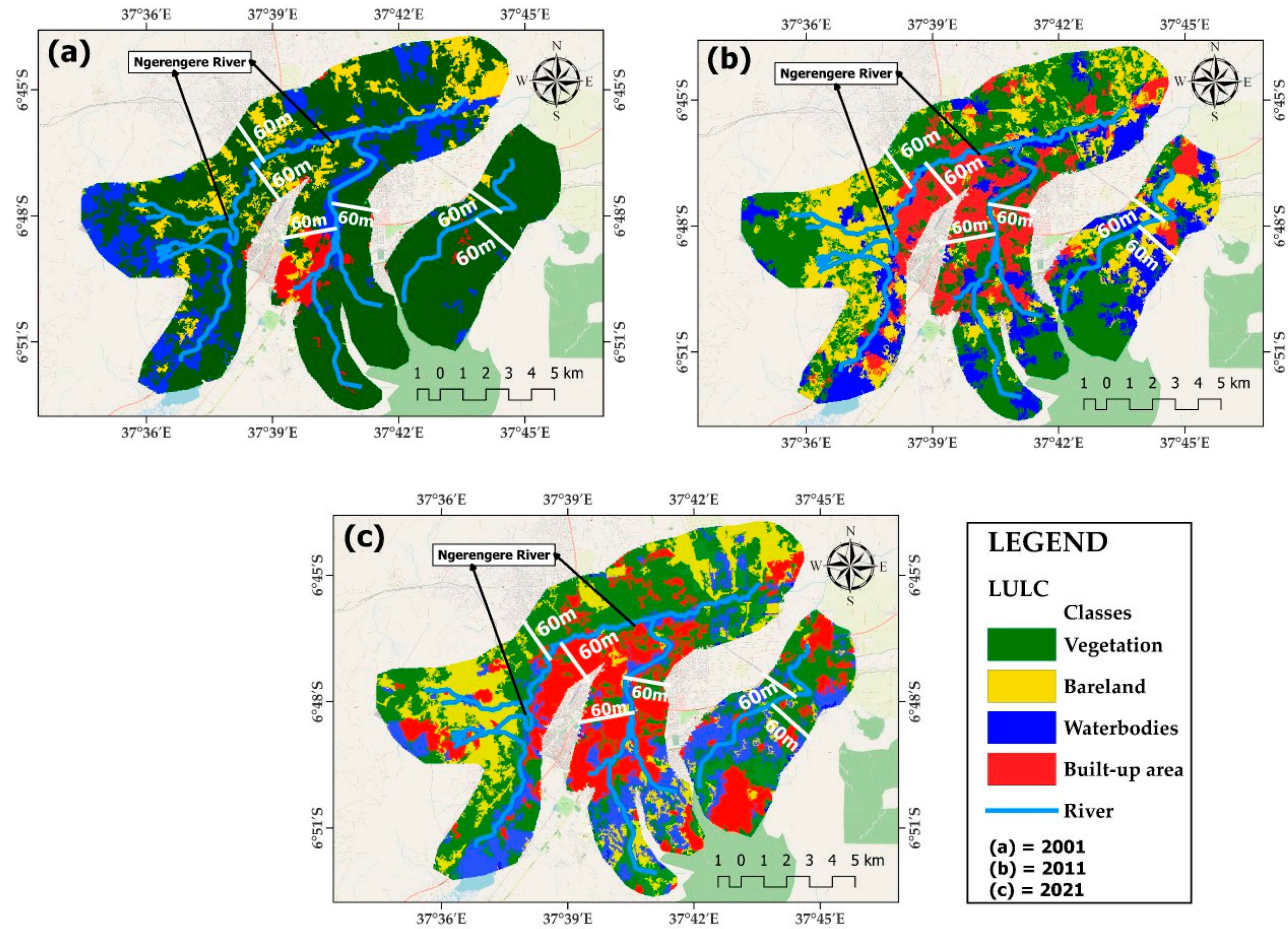


Figure 4. Land-use and land cover (LULC) patterns observed in the riparian zone, located 60 m from the Ngerengere River and its tributaries from 2001 to 2021. (**a**): LULC classification for the year 2001; (**b**): LULC classification for the year 2011; (**c**): LULC classification for the year 2021.

Table 4. LU/LC change in the buffer zone of the Ngerengere River and its tributaries within Morogoro Municipality from 2001 to 2021.

LULC Classes						
	2001 (ha)	**%**	**2011 (ha)**	**%**	**2021 (ha)**	**%**
Vegetation	13,809.60	40	11,048.3	32	8631	25
Built-up areas	10,356.6	20	11,048.3	32	12,081.4	35
Bare land	6904.8	30	8292.9	24	10,356	30
Water	3452.4	10	4146.3	12	3452.4	10
Total	34,524	100	34,524	100	34,524	100

The decrease in bare land from 30% in 2001 to 24% in 2021 suggests changes in land use that could influence sedimentation dynamics and erosion processes. On a positive note, the stability of water bodies at 10% throughout the study period suggests a degree of resilience in the riverine ecosystems. The alterations in the land-use and land cover (LULC) patterns observed in the riparian zone, located 60 m from the Ngerengere River and its tributaries, are expected to significantly influence hydrological processes and water quality, as mentioned in other studies [60].

The high Procedure Accuracy (PA) and User Accuracy (UA) values for all LULC classes across the years, coupled with an overall accuracy of 90.3% in 2021 (Table 5) and consistent Kappa statistics, support the assertion that the observed changes in land use and land cover are significant and not merely artefacts of the classification process [60].

Table 5. Procedure Accuracy (PA) and User Accuracy (UA) for land-use and land cover changes classification for the years 2001–2021.

LULC Classes	2001		2011		2021	
	PA	**UA**	**PA**	**UA**	**PA**	**UA**
Vegetation	92.3	92.2	94.3	92.3	92.2	90.3
Built-up areas	93.2	89.4	89.3	88.5	89.7	89.1
Bare land	90.5	88.7	85.2	88.3	88.2	87.2
Water bodies	88.2	87.1	88.6	84.2	88.1	87.1
Overall accuracy	92.2		90.1		90.3	
Kappa statistics	0.88		0.87		0.87	

3.2.3. Ground-Truthing and Verification of LULC

The control points established during the field surveys served as reference locations whose land cover was verified through ground-truthing. Ground-truthing in consultation with the Wami-Ruvu Basin and Morogoro Municipal Council involved physically visiting selected locations to confirm the land cover type, while high-resolution satellite imagery provided detailed visual information for comparison. During our ground-truthing activities at sampling stations S1 to S13 and surrounding areas, we observed various land cover types that contributed to the accuracy assessment of the LULC characterizations. Specifically, in the midstream and downstream regions, we noted the presence of agricultural activities, the establishment of car wash facilities, the development of commercial structures, and extensive areas of bare land within the river buffer zones. These observations were consistent with the land-use patterns indicative of human settlements and economic activities in these areas. In contrast, upstream reaches, particularly in the vicinity of Uluguru Mountain, exhibited a different land cover composition. Here, we observed dense forest cover, which is characteristic of natural ecosystems and less impacted by human activities compared to downstream areas.

3.3. Water and Sediment Quality Results

3.3.1. Physical Parameters in Water Samples

The river water samples in the dry season exhibited an acidic, neutral, and slightly alkaline pH range of 5.77 ± 0.01 to 7.77 ± 0.01 (Table 6). In the assessment, the results were compared against the established standards for water quality, particularly the ones outlined by the WHO and TBS for drinking water. This is crucial because, in many areas across Africa, untreated river water is directly utilized for various household needs, including drinking, sometimes without undergoing any preliminary treatment processes [61].

Table 6. Physical parameters in the river water in the dry season.

Sampling Station	pH	Temperature	TDS	Conductivity	Salinity	Turbidity	DO%	DO mg/L
S1	6.45 ± 0.01	27 ± 0	98 ± 3.61	192.67 ± 1.53	0.098 ± 0	12.33 ± 1.53	2.57 ± 0.06	0.21 ± 0.01
S2	6.12 ± 0.01	28.2 ± 0.1	77 ± 1	153.67 ± 1.15	0.08 ± 0	17.33 ± 1.53	2.53 ± 0.15	0.77 ± 0.98
S3	5.77 ± 0.01	27.2 ± 0.2	173.67 ± 2.1	345 ± 2.65	0.17 ± 0	46.33 ± 1.53	2.73 ± 0.06	0.22 ± 0.01
S4	6.84 ± 0.01	28.8 ± 0.2	921 ± 2.65	1844.33 ± 0.58	0.92 ± 0.003	15.67 ± 0.58	2.9 ± 0	0.22 ± 0
S5	6.63 ± 0.01	29.2 ± 0.1	96.33 ± 2.52	187.67 ± 0.58	0.096 ± 0.003	6.33 ± 0.58	3 ± 0.1	0.26 ± 0.01
S6	7.77 ± 0.01	32 ± 0	558.3 ± 3.79	1133.33 ± 1.53	0.558 ± 0.004	92 ± 2	2.17 ± 0.06	0.18 ± 0.01
S7	7.50 ± 0.02	30.8 ± 0.1	1104.7 ± 0.6	2207.33 ± 0.58	1.105 ± 0.001	32.22 ± 0.58	2.33 ± 0.06	0.79 ± 1.05
S8	6.75 ± 0.01	31.3 ± 0.1	1123.7 ± 1.2	2446.33 ± 0.58	1.124 ± 0.001	31 ± 1.73	2.067 ± 0.06	0.25 ± 0.01
S9	7.07 ± 0.03	26.8 ± 0.1	222.33 ± 1.2	408.67 ± 0.58	0.222 ± 0.001	2.33 ± 0.58	3.13 ± 0.06	0.27 ± 0.01
S10	6.99 ± 0.02	24.1 ± 0.2	86.67 ± 1.15	163.33 ± 0.58	0.09 ± 0.001	10.33 ± 1.15	3.27 ± 0.06	0.29 ± 0.01
S11	6.59 ± 0.02	25.2 ± 0.2	413.5 ± 1.80	831.33 ± 0.58	0.414 ± 0.002	412.67 ± 0.6	2.77 ± 0.06	0.36 ± 0.01
S12	7.13 ± 0.02	24.6 ± 0.1	48.67 ± 0.58	97.67 ± 0.58	0.049 ± 0.001	14.53 ± 0.58	4.23 ± 0.06	0.41 ± 0.01
S13	6.88 ± 0.04	22.7 ± 0.1	23 ± 0	46.33 ± 0.58	0.023 ± 0	10.67 ± 0.58	4.53 ± 0.06	0.46 ± 0.01
WHO	6.5–8.5	24–30	250–500	1200	n.m	<1	n.m	n.m
TBS	6.5–9.2	n.m	n.m	n.m	n.m	5.0–25	n.m	n.m

The pH range of the water samples was 7.58 ± 0.01 to 8.24 ± 0.05, which is related to the pH ranges measured in the Pangani River [19]. Upstream reaches exhibited lower pH levels of 6.12 ± 0.01 and 5.77 ± 0.01, respectively, during the dry season; these lower pH levels posed several implications to aquatic life [62]. Typically, pH levels below 4 tend to amplify the toxicity of the majority of metals [63], while the highest pH values (alkaline conditions) tend to reduce the mobility of toxic heavy metals [48]. In the wet season, the highest values were 8.24 ± 0.05 at the headwater of Morogoro River at the Uluguru Mountains; this elevated pH level might be attributed to natural factors like geological features or the riparian forest ecosystem that might influence the organic matter decomposition in the river.

The PCA was conducted to identify and explain the variations in the physical parameters in the surface water datasets. The PCA resulted in two principal components, PC1 and PC2. PC1 and PC2, including eigenvalues surpassing one, accounted for a cumulative variance of 67.75% (Table 5). The first principal component was loaded with TDS and conductivity, which accounted for 24.74% of the total variance and signified the influence of TDS in electrical conductivity due to an increase in the dissolved ions in the water, as reported by Kurkjian et al. [64]. The pH and DO % were responsible for 14.89% of the total variance loaded in PC2. The correlation test proved a high positive correlation between TDS and conductivity, turbidity, and salinity, with a correlation coefficient value of 0.99, 0.99, and 0.09, followed by temperature and DO % with a coefficient of 0.83 (Table 7).

The highest level of electrical conductivity, ranging between 1133.33 ± 1.53 µS/cm and 2446.33 ± 0.58 µS/cm, was observed from the midstream to the downstream during the dry season. A similar study performed by Kurkjian et al. [64] reported that a higher level of electrical conductivity indicated the presence of inorganic dissolved solids acquired from anthropogenic activities. Through this study, it was noted that the river banks and floor are highly dominated by silt clay soil that influences a higher level of electrical conductivity. Similar findings were reported in the Mekong River water that runs through areas with silt clay soils, which tends to have higher conductivity because of the presence of materials that ionize when washed into the water [65]. In the wet season, the highest recorded electrical conductivity was 445.33 ± 0.58 µS/cm and the lowest was 37.33 ± 2.08 µS/cm. The potential causes of the variability in the electrical conductivity in the wet and dry seasons might be associated with the effect of dilution, causing a lower level of EC in the wet season, while the higher EC in the dry season might be associated with the accumulation of dissolved ions in the river under the influence of excessive evaporation.

Table 7. Eigenvectors from the PCA and correlation matrix for the water samples in the dry season.

Parameters	Coefficients of PC1	Coefficients of PC2
pH	0.19	0.60
Temperature (°C)	0.41	−0.12
TDS (mg/L)	0.47	0.08
Conductivity (µS/cm)	0.47	0.07
Salinity (mg/L)	0.47	0.08
Turbidity (NTU)	0.44	−0.48
DO (%)	−0.36	0.45
DO (mg/L)	0.03	0.41
Cumulative Proportion of Variance (%)	52.76	14.89

Correlation Matrix	pH	Temperature (°C)	TDS (mg/L)	Conductivity (µS/cm)	Salinity (mg/L)	Turbidity (NTU)	DO (%)	DO (mg/L)
pH	1	0.25	**0.38 ***	**0.36 ***	**0.38 ***	−0.05	0.04	0.04
Temperature (°C)		1	**0.69 ****	**0.69 ****	**0.69 ****	−0.11	**−0.83 ****	−0.01
TDS (mg/L)			1	**0.99 ****	**0.99 ****	0.09	**−0.58 ****	0.08
Conductivity (µS/cm)				1	**0.99 ****	0.09	**−0.59 ****	0.07
Salinity (mg/L)					1	0.09	**−0.59 ****	0.08
Turbidity (NTU)						1	−0.18	−0.04
DO (%)							1	0.04
DO (mg/L)								1

* and **: correlation is significant at the 0.05 and 0.01 levels (2-tailed). Bold values are moderately/highly correlated.

Water temperatures varied between 22.67 ± 0.06 °C and 32.0 °C. This observation is in agreement with the temperature ranges reported for the Angaw River and Limpopo River basins, respectively [66,67]. During the wet season, the water temperatures across all sampling stations were in line with the WHO standards (Table 8), with the lowest temperature of 21.51 ± 0.03 °C and the highest temperature of 29.39 ± 0.07 as reported in Pangani River, Tanzania [20]. Generally, the water temperature tends to influence the DO levels, as higher temperatures tend to decrease the amount of oxygen that water can hold. However, this association is subject to modifications caused by various factors such as changing hydro-meteorological conditions [68].

Table 8. Physical parameters in water samples for the wet season.

Sampling Station	pH	Temperature	TDS	Conductivity	Salinity	Turbidity	DO%	DO mg/L
S1	7.96 ± 0.2	25.97 ± 0.01	47.67 ± 0.6	94.33 ± 0.58	0.04 ± 0	10.1 ± 0.2	3.2 ± 0	0.25 ± 0
S2	7.79 ± 0.1	26.92 ± 0.01	49.33 ± 0.6	98.67 ± 0.58	0.05 ± 0.01	8.8 ± 0.79	3.2 ± 0	0.24 ± 0
S3	7.67 ± 0.1	26.73 ± 0.01	103.33 ± 0.6	206.33 ± 0.58	0.1 ± 0	92.97 ± 2.32	3.3 ± 0	0.25 ± 0
S4	7.67 ± 0.1	26.73 ± 0.01	103.33 ± 0.6	206.33 ± 0.58	0.1 ± 0	92.97 ± 2.32	3.3 ± 0	0.25 ± 0
S5	7.85 ± 0	22.26 ± 0	65.33 ± 0.58	130.67 ± 1.15	0.06 ± 0	18.6 ± 1.37	3.6 ± 0	0.28 ± 0
S6	7.7 ± 0.06	26.91 ± 0	122.67 ± 0.6	245.33 ± 0.58	0.12 ± 0	37.43 ± 0.75	3.4 ± 0	0.26 ± 0
S7	7.73 ± 0.1	26.88 ± 0.02	125 ± 0	250 ± 1.0	0.12 ± 0	19.27 ± 0.12	3.5 ± 0	0.27 ± 0
S8	7.69 ± 0.6	25.04 ± 0	216.33 ± 0.6	432.33 ± 1.53	0.21 ± 0	40.6 ± 1.0	3.6 ± 0	0.29 ± 0.01
S9	8.08 ± 0	23.06 ± 0.01	36.33 ± 0.58	73 ± 0	0.03 ± 0	16 ± 1.04	3.9 ± 0	0.32 ± 0
S10	8.03 ± 0	23.36 ± 0.01	37.33 ± 0.58	75 ± 0	0.03 ± 0	24.17 ± 2.40	5.2 ± 0	0.42 ± 0
S11	7.58 ± 0	29.39 ± 0.07	222.67 ± 0.6	445.33 ± 0.58	0.21 ± 0	29.39 ± 0.07	6.3 ± 0	0.43 ± 0.03
S12	8.11 ± 0.3	22.26 ± 0	25 ± 0	50.67 ± 0.58	0.02 ± 0	13.67 ± 0.31	6 ± 0.1	0.48 ± 0.02
S13	8.24 ± 0.1	21.51 ± 0.03	18.67 ± 0.58	37.33 ± 2.08	0.019 ± 0	0.02 ± 0.01	6.47 ± 0	0.49 ± 0.01
WHO	6.5–8.5	24–30	250–500	1200	n.m	<1	n.m	n.m
TBS	6.5–9.2	n.m	n.m	n.m	n.m	5.0–25	n.m	n.m

A higher TDS concentration was observed during the dry season, particularly in the midstream and downstream reaches, and similar findings were recorded at the Ruvu River [69] and in the Odzi River [70]. A study conducted by Mato [71] demonstrated that total dissolved solid (TDS) concentrations ranging from 0 to 1500 mg/L signify good quality freshwater. Furthermore, TDS values below 500 mg/L indicate excellent freshwater quality with potentially lower levels of pollution. Conversely, when the TDS values exceed 1500 mg/L, the water may have a salty taste, indicating a higher concentration of dissolved solids. The TDS concentrations across all sampling stations in the wet season aligned with the WHO standards, with the TDS concentrations ranging from 18.67 $\pm$ 0.58 mg/L to 222.67 $\pm$ 0.58 mg/L. This observation can be associated with the increase in the river discharge during the wet season which tends to amplify the dilution process, as the lowest TDS of 18.67 $\pm$ 0.58 mg/L was recorded at a point with a higher discharge of 3.727 m^3/s.

The findings showed that there was significant variability in the salinity in the two seasons of the sampling campaigns, with a high level of salinity in the dry season. Salinity in the water samples during the dry season was in the range of 0.02 $\pm$ 0 mg/L to 1.12 $\pm$ 0 mg/L, indicating a substantial surge in dissolved solutes from upstream to downstream zones situated in proximity to residential areas, agricultural fields, and industries. Other potential sources of elevated salinity might be associated with increased dissolved salt originating from agricultural runoff, discharges from the on-site sanitation systems, and contaminated runoff from the urban area [72]. This finding aligns with the higher salinity observed in the river water, suggesting potential implications for human health due to the intake of saline river water [73]. In the wet season, the average salinity levels in the Ngerengere River and its tributaries within Morogoro Municipality were lower compared to the dry season, with salinity levels ranging from 0.02 $\pm$ 0 mg/L upstream to 0.21 $\pm$ 0 mg/L downstream. The study findings showed variability in the turbidity across the sampling stations in each sampling campaign. The ideal state for river water is colorless [74]; in the dry season, the study showed that the turbidity levels ranged from 2.33 $\pm$ 0.58 NTU in the upstream to 1034.67 $\pm$ 6.03 NTU in the downstream.

The turbidity levels of the surface water play a significant role in the aquatic ecosystem by influencing the amount of light penetrating the water, which can also affect the water temperature and overall habitat suitability for aquatic organisms. The average turbidity values in the wet season ranged from 0.02 $\pm$ 0.01 NTU to 92.97 $\pm$ 2.32 NTU, where the upstream stations were observed to have low turbidity levels. The lower turbidity observed in the upstream river water samples near the headwaters of Uluguru mountain can be attributed to the significant presence of forested areas in the region. Forest ecosystems act as natural buffers against sedimentation and pollutants, primarily through various mechanisms facilitated by dense vegetation.

During the dry season, the dissolved oxygen (DO) levels ranged from 2.067 $\pm$ 0.06% and 0.25 $\pm$ 0.01 mg/L to 4.53 $\pm$ 0.06% and 0.46 $\pm$ 0.01 mg/L, with temperature values of 31.33 $\pm$ 0.12 °C to 22.67 $\pm$ 0.06 °C, respectively. This trend is similar to the other previous studies [64,65]. This study revealed that the water flow rate data at the sampling stations have significant implications for the level of dissolved oxygen [75]. During the wet season, the highest DO level was recorded at the upstream reaches. The study performed in the Rungiri reservoir observed the average DO of the dam to be 4.91 $\pm$ 0.49 mg/L, which is quite dissimilar to the findings of this study; there is no specific recommended limit for dissolved oxygen in drinking water. Nevertheless, a desirable dissolved oxygen level for a healthy water source is considered to be 5 mg/L [76].

The water quality parameters in the Ngerengere River, as revealed by this study, showcase both similarities and distinctions when compared to other urban rivers globally. While the pH levels align with those observed in the other urban rivers of developing countries (Table 9), it was observed that the Karnaphuli urban river experiences higher temperatures. The salinity levels in the Ngerengere River are considerably lower than the Mutangwi River in Limpopo Province, South Africa, pointing to a distinct freshwater nature. The electrical conductivity (EC) in the Ngerengere River spans a wide range, surpassing most other rivers except for Mutangwi. Dissolved oxygen (DO) levels in the Ngerengere River are lower than in several comparable rivers, suggesting potential concerns for aquatic life. Turbidity in the Ngerengere River is notably higher compared to the Ngong River, Mutangwi River, and Lower Danube.

Table 9. A comparative examination of the water quality parameters from the current study and records from other urban rivers.

Parameter	Ngerengere River (This Study)	Pangani [19]	Ngong River, Nairobi City, Kenya [77]	Mutangwi River, Limpopo Province, South Africa [78]	Lower Danube [79]	Ugandan Stretch of the Kagera Trans-boundary River [80]	Karnaphuli Urban River of Bangladesh [81]
pH	5.77–8.24	6.77–8.94	6.83–7.72	7.03–7.15	7.14–8.24	5.8–6.01	5.78–7.6
Temperature (°C)	21.51–32	21.0–30.5	20.1–23.2	18.08–18.69	-	23.38–23.43	29.8–31.9
Salinity (mg/L)	0.019–1.12	-	-	83.89–110.67	-	-	0–3.20
EC (µS/cm)	37.33–2446	97–1350	314–1261	182.25–235.83	-	133.38–144.91	0.09–5.83
DO (%)	2.067–6.47	22.7–112	-	-	-	-	-
DO (mg/L)	0.18–0.49	2.0–8.3	-	-	6.01–10.21	3.85–5.26	-
TDS (mg/L)	18.67–1123	48–652	195–782	-	-	61.27–69.46	0.09–5.83
Turbidity (N.T.U)	8.8–1035	-	4.75–30.6	3.87–5.54	-	24.77–43.99	4.93–319.93

(-) signify that the value was not reported.

The PCA produced two principal components, PC1 and PC2, for the variance of physical parameters in river water during the wet season. PC1 and PC2, including eigenvalues surpassing one, accounted for a cumulative variance of 86.14% (Table 10). The first principal component was loaded with temperature, salinity, conductivity, turbidity, and TDS, which accounted for 61.745 of the total variances. DO, salinity, conductivity, TDS, and pH were responsible for 24.40% of the total variance loaded in PC2. The correlation test showed a high positive correlation between TDS and salinity, and conductivity and salinity, with correlation coefficient values of 0.999 and 0.999, respectively.

Table 10. Eigenvectors from the PCA for the water samples in the wet season.

Parameters	Coefficients of PC1	Coefficients of PC2
pH	−0.44	0.05
Temperature (°C)	0.38	−0.02
TDS (mg/L)	0.40	0.29
Conductivity (µS/cm)	0.40	0.29
Salinity (mg/L)	0.41	0.28
Turbidity (NTU)	0.27	−0.19
DO (%)	−0.19	0.62
DO (mg/L)	−0.25	0.58
Cumulative Proportion of Variance (%)	61.74	24.40

Correlation Matrix

	pH	Temperature	TDS	Conductivity	Salinity	Turbidity	DO%	DO mg/L
pH	1	**−0.85 ****	**−0.82 ****	**−0.82 ****	**−0.83 ****	**−0.61 ****	**0.46 ***	**0.59 ****
Temperature (°C)		1	**0.67 ****	**0.67 ****	**0.67 ****	**0.42 ***	**−0.33 ***	**−0.47 ***
TDS (mg/L)			1	1	**0.99 ****	**0.37 ***	−0.09	−0.20
Conductivity (µS/cm)			1	1	**0.99 ****	**0.37 ***	−0.09	−0.20
Salinity (mg/L)					1	**0.38 ***	−0.10	−0.22
Turbidity (NTU)						1	**−0.38 ***	**−0.42 ***
DO (%)							1	**0.98 ****
DO (mg/L)								1

* and **: correlation is significant at the 0.05 and 0.01 levels (2-tailed). Bold values are moderately/highly correlated.

3.3.2. Physical Parameters in Sediments

- Characterization of sediment texture

This study showed that the Ngerengere River and its tributaries' sediments are composed of loamy sand and silt clay as the dominant textural classes; this observation aligns with the study of Mkumbo et al. [45], which observed similar textural properties of the soil in Morogoro Municipality. The silt clay contents of the sediment were higher across the sampling stations. The particle size of sediment affects heavy metal accumulation and nutrients. Owen [82], reported that fine-grained sediment like silt clay is responsible for a significant proportion of the annual transport of metals. Various sources in the literature revealed that silt clay (fine-particle) has a high uptake of heavy metals due to the fact it has a large surface area [83,84]. A similar study performed by Vaithiyanathan et al. [85] reported that metal absorption rates are various at different grain sizes. The results indicated almost all the sampling stations were of a fine (silt clay) and sand type. These findings signify that sediment grains with fine sizes (silt clay) probably influence heavy metal accumulations in the sediments [83,84].

- Physical parameters

Across all the sampling sites in the dry season, the pH values ranged from 5.9 ± 0.1 to 7.1 ± 0.03. The electrical conductivity varied from 55 mS/cm to 1423.2 ± 10.2 mS/cm, the TDS ranged from 104 ± 2.6 mg/kg to 2846 ± 20.4 mg/kg, while the salinity ranged from 0.06 ± 0 mg/kg to 1.42 ± 0 mg/kg. The observed variability in the study findings can be attributed to the textural properties identified, the degree and extent of the pollution sources, and the recorded water discharge at the sampling stations. The study findings, particularly the pH ranges, are slightly related to the pH values provided by Onjefu et al. [86]. The average moisture content of the sediment samples ranged from 9.19 ± 0.3% to 41.46 ± 0.6%; the difference in the moisture content might be attributed to the textural properties of the sediment and other factors, such as the presence of total dissolved ions that reduce the saturation in the soil particles. In the wet season, the pH of the sediments ranged from slightly acidic to nearly neutral. The lowest and highest pH values were from 5.61 ± 0.14 to 7.93 ± 0.15, while the TDS, electrical conductivity, and salinity ranged from 42.89 ± 0.39 to 2562.3 ± 12.7 mg/kg, 21.44 ± 0.2 to 1281.2 ± 6.3 µS/cm, and 0.021 ± 0 to 1.28 ± 0.01 mg/kg (Table 11). The changes in the physical parameters of the sediments during the wet season were due to the increased runoff, higher flow rates, and potential inputs in the catchment, as revealed by the lowest TDS, EC, and salinity values upstream compared to midstream and downstream, which were dominated by the existence of point and non-point sources of pollution.

Table 11. Physical parameters of river sediments in the dry and wet seasons.

Sampling Stations	Physical Parameters in the Dry Season				Physical Parameters in the Wet Season			
	pH	TDS (mg/kg)	EC (µS/cm)	Salinity (mg/kg)	pH	TDS (mg/kg)	EC (µS/cm)	Salinity (mg/kg)
S1	5.9 ± 0.1	333.7 ± 6.7	166.8 ± 3.3	0.17 ± 0.1	6.73 ± 0.06	126 ± 1.9	62.88 ± 0.97	0.06 ± 0.01
S2	6.5 ± 0.1	419 ± 18.5	209.5 ± 9.3	0.21 ± 0.1	6.967 ± 0.21	375.3 ± 7.02	187.67 ± 3.5	0.19 ± 0
S3	5.9 ± 0.1	265 ± 4.6	132.5 ± 2.3	0.13 ± 0.1	6.27 ± 0.06	203.7 ± 7.02	101.8 ± 3.5	0.10 ± 0
S4	6.4 ± 0.2	2846 ± 20.4	1423.2 ± 10.2	1.42 ± 0	7.07 ± 0.15	1931 ± 17.7	965.5 ± 8.8	0.97 ± 0.01
S5	6.2 ± 0.1	2305.3 ± 7.6	1152.7 ± 3.8	1.15 ± 0	7.93 ± 0.15	1731.3 ± 3.8	865.67 ± 1.89	0.87 ± 0
S6	6.6 ± 0.1	1677.3 ± 29.2	838.7 ± 14.6	0.84 ± 0	5.61 ± 0.14	2562.3 ± 12.7	1281.2 ± 6.3	1.28 ± 0.01
S7	6.3 ± 0.1	911.7 ± 8.6	455.8 ± 4.3	0.46 ± 0	6.07 ± 0.16	1670 ± 4.6	835 ± 2.29	0.08 ± 0
S8	6.7 ± 0.1	1862 ± 10.1	931 ± 5.1	0.93 ± 0	7.03 ± 0.21	1357.7 ± 16.1	678.8 ± 8.04	0.68 ± 0.01
S9	6.7 ± 0.1	1402.7 ± 17.2	701.3 ± 8.6	0.70 ± 0	6.27 ± 0.16	919 ± 3.6	459.5 ± 1.8	0.46 ± 0
S10	7.1 ± 0	533.3 ± 4.7	266.7 ± 2.4	0.27 ± 0	7.36 ± 0.05	436.7 ± 4.5	218.33 ± 2.3	0.22 ± 0
S11	7.1 ± 0.1	1627 ± 6.1	813.5 ± 3.04	0.81 ± 0	6.07 ± 0.15	1238.7 ± 3.1	619.3 ± 1.5	0.62 ± 0
S12	6.8 ± 0	115.7 ± 1.5	57.8 ± 0.8	0.06 ± 0	6.96 ± 0.13	75 ± 1.00	37.5 ± 0.5	0.04 ± 0.01
S13	6.2 ± 0	104 ± 2.6	55.0 ± 0	0.06 ± 0	7.18 ± 0.07	42.89 ± 0.392	21.44 ± 0.2	0.02 ± 0

3.3.3. Variation in Heavy Metal Concentrations in Water and Sediments

The values of heavy metal concentrations in the river water samples during the dry and wet seasons across the sampling stations are represented in Figure 5.

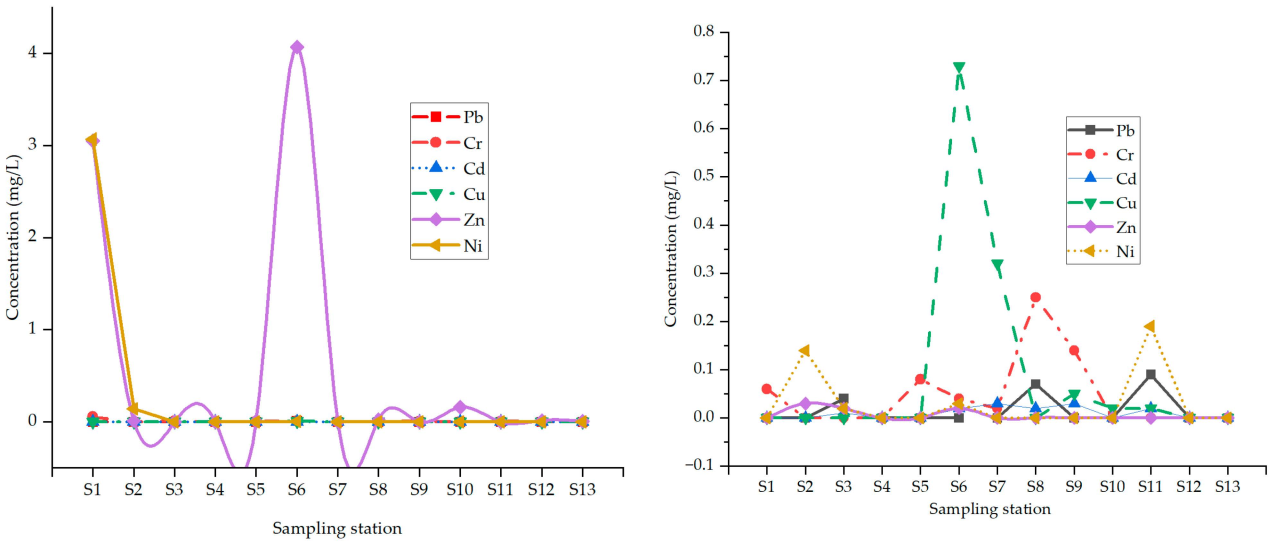


Figure 5. Heavy metal concentrations across the sampling stations in the wet (**left**) and dry seasons (**right**).

The study revealed that the order of magnitude of the heavy metal concentrations was Cu > Cr > Ni > Pb > Zn > Cd. During the dry season, the highest mean concentration of lead (Pb) was 0.08 ± 0, which was recorded at sampling station S11; the highest concentration of Pb might be associated with the nature of the activities, including garages, car washes, residential and commercial activities, and petrol station services. This research observed a positive relationship between Pb with Cr, similar to the study of Huang et al. [87], as well as Pb with Cd, Cd with Cu [30], Pb with Ni, Cr with Cd [88], Cd with Ni, Cu with Zn, and Zn with Ni. The Pearson correlation matrix showed that Pb and Ni were moderately correlated, with an R-value of 0.514. Pb with Cr, Pb with Cd, Cr with Cd, Cd with Cu, Cd with Ni, Cu with Zn, and Zn with Ni were weakly correlated, with R-values of 0.32, 0.33, 0.46, 0.46, 0.06, 0.30, and 0.39, respectively (Table 12). Furthermore, weak negative correlations were found between Pb with Cu, Pb with Zn, Cr with Cu, Cr with Zn, and Cr with Ni, as well as between Cd and Zn, and Cu with Ni.

Table 12. Correlation matrix for heavy metals in water samples in the dry season.

Parameters	Pb	Cr	Cd	Cu	Zn	Ni
Pb	1	**0.32** *	**0.33** *	−0.22	−0.09	**0.51** **
Cr		1	**0.46** *	−0.04	−0.25	−0.28
Cd			1	**0.46** *	−0.11	0.06
Cu				1	**0.30** *	−0.07
Zn					1	**0.39** *
Ni						1

* and **: correlation is significant at the 0.05 and 0.01 levels (2-tailed). Bold values are moderately/highly correlated.

During the dry season, the highest mean concentration of lead (Pb) was 0.08 ± 0, which was recorded at the Kikundi stream near its confluence with the Morogoro River; the highest concentration of Pb might be associated with the nature of the activities, including garages, car washes, residential and commercial activities, and petrol station services. The findings were not consistent with Liu et al. [89], which reported higher lead concentrations in water bodies surrounding the mining sites. The lowest Pb concentration was 0.04 ± 0.01 mg/L, which was quite similar to Singh et al. [24]. This study revealed that most of the upstream sampling stations were less polluted from lead concentrations. This observation is in line with the Tanzania standards for permissible lead limits in water, but is not consistent with the WHO guidelines. Chromium levels in the surface water were recorded to be within the WHO and TBS standards for most sampling stations, except for sampling stations S1 and S5, where the concentrations of chromium recorded were 0.06 ± 0 and 0.08 ± 0, respectively. The highest chromium concentration was recorded at the confluence of the Bigwa and Ngerengere Rivers. The potential attributes of high chromium concentrations might emanate from runoff and spillage from the Tanzam highway, which was observed during the sampling. Notably, most of the sampling stations were recorded to be less than below the detection limit. Chromium concentrations in most surface water ranged between 0 and 0.01 mg/L of chromium; however, these concentrations are usually influenced by the extent of the industrial activity [11,90].

The cadmium concentration in the dry season was recorded to be in the range below the detection limit. However, the highest mean concentration of cadmium was 0.03 ± 0.02 mg/L, which was located in the Mwele area, adjacent to car washing facilities and other commercial activities. The levels of cadmium in the Ngerengere River and its tributaries were in accordance with the standards set by both the World Health Organization (WHO) and Tanzania water quality standards. Other important sources of Cd pollution are the metal industry, plastics, and sewers. A major portion of Cd (30–50%) was contained in the most mobile fraction (either in exchangeable or carbonate bound), and therefore can easily enter the food chain [91]. Amongst the different metals, the Cd concentration was the lowest, but the toxicity was high. It was found that Cd was significantly higher in the dry season compared to the other seasons. At selected river tributaries of the Mara River in Tanzania, Nkinda et al. [88] reported that chromium concentrations ranged from 0.97 ± 0.49 mg/L to 2.58 ± 0.57 mg/L in the Somoche and Nyarusobindoro areas, citing the impacts of mining operations for the elevated level of chromium in the surface water [3]. Overall, most of the sampling stations along the Ngerengere River and its tributaries were recorded with the lowest concentrations of copper, notably below the detection limit. The highest copper concentrations were 0.73 ± 0.04 mg/L and 0.32 ± 0.02 mg/L, and the lowest concentrations were recorded to be <0.01 in the most upstream points of the river and its tributaries. Wang and Bjorn [90] highlighted the toxicity concerns of copper due to its exposure, citing gastrointestinal symptoms at lower exposure levels than those that cause chronic toxicity and other health implications, like neurological effects and memory impairment [18]. A significant amount of copper is in the immobile form and can be found in reducible (Fe-Mn oxide) and residual fractions [91]. Major sources of Cu pollution are the production of home tools, metals, manipulation, the timber industry, and ashes. The average concentration of zinc ranged from below the detection limit to 0.03 ± 0.02 mg/L. Zinc occurs in small amounts in almost all igneous rocks, and the major zinc ores are sulfides, including sphalerite and wurtzite. The natural zinc concentration in soils is estimated to be 1–300 mg/kg, while in the natural surface waters, the concentration of zinc is usually below 0.010 mg/L, and in groundwater is 0.01–0.04 mg/L [11].

Furthermore, the principal component analysis (PCA) results revealed two principal components, collectively explaining 58.34% of the variability in the dataset (Table 13). The initial principal component (PC1), responsible for 30.05% of the total variance, exhibited notably high positive loadings for Pb, Cd, and Cr, with a high loading of Cd followed by a moderate loading for Pb and Cr. It is well-established that chromium and cadmium are commonly linked in various rock types, suggesting their presence in soils derived from such geological formations [92]. Our study reaffirmed this association, showing a correlation coefficient (r) of 0.42 between these elements. It is worth noting that, apart from natural processes, anthropogenic sources like industrial effluents, mismanagement of solid waste disposal, and other agricultural runoffs aggravate the concentrations of Cr and Cd [93]. The second principal component, explaining 28.29% of the variance, exhibited a high positive loading for Ni, a moderate positive loading for Zn, and a low positive loading for Pb. According to Ahmed and Mokhtar [92], the primary sources of Pb and Ni in the aquatic environment emanate from the natural weathering of minerals and widespread anthropogenic activities, which is reaffirmed by our results, showing a correlation coefficient (r) of 0.54.

Table 13. Eigenvectors from the PCA for heavy metals in the water samples in the dry season.

Heavy Metals	PC1	PC2
Pb	0.56	0.18
Cr	0.49	−0.42
Cd	0.62	−0.002
Cu	0.15	0.2
Zn	−0.09	0.59
Ni	0.20	0.64
Cumulative Proportion of Variance (%)	30.05	28.29

The order of magnitude of heavy metal concentrations during the wet season across the sampling stations was as follows: Zn > Ni> Cr > Cu > Cd > Pb. The highest concentrations of Pb, Cr, Cd, Cu, Zn, and Ni were 0.01 ± 0 mg/L, 0.05 ± 0.04 mg/L, 0.02 ± 0 mg/L, 0.01 ± 0 mg/L, 4.07 ± 0.08 mg/L, and 3.07 ± 0.04 mg/L, respectively. This study indicated that the levels of Ni exceeded the WHO standards and TBS standards. Zn was higher than the maximum limits established by the WHO. The recoded values of Pb and Cu remain to be in line with the established WHO and Tanzania standards. The level of chromium was higher at S1, with a mean concentration of 0.05 ± 0.04. From the observed findings, it can be concluded that the midstream and downstream reaches of the urban catchment of the Ngerengere River have been highly impacted by heavy metal pollution. In the wet season, strong positive correlations were observed between Pb and Cd, Pb and Cu, Pb and Zn, Cd and Cu, Cd and Zn, and Cu and Zn, with R-values of 1.00, 0.99, 0.99, 0.99, 0.99, and 0.99 (Table 12). Moderately positive correlations were observed between Pb and Cr, Cr and Cd, Cr and Cu, as well as Cr and Zn. Furthermore, weak negative correlations were found between Pb with Ni, Cr with Ni, Cd with Ni, Cu with Ni, and Zn with Ni. The principal component analysis (PCA) results revealed two significant components, collectively explaining 99.24% of the variance (Table 14). The first principal component (PC1), responsible for 62.33% of the total variance, exhibited positive loadings for all heavy metals, with a high loading of Pb, Cd, Cu, and Zn, and followed by low loading for Cr and Ni. The second principal component, explaining 36.92% of the variance, exhibited a high positive loading for Cr and Ni, followed by moderate loading of Zn. Pb, Cd and Cu showed a negative loading.

Table 14. Principal component results for heavy metals in river water.

Heavy Metals	PC1	PC2
Pb	0.49	−0.19
Cr	0.17	0.63
Cd	0.49	−0.19
Cu	0.49	−0.21
Zn	0.48	0.24
Ni	0.11	0.65
Cumulative Proportion of Variance (%)	62.33%	36.92

Correlation Matrix

Variables	Pb	Cr	Cd	Cu	Zn	Ni
Pb	**1**	**0.51 ****	**1.00 ****	**0.99 ****	**0.99 ****	−0.07
Cr		**1**	**0.51 ****	**0.48 ***	**0.50 ****	−0.24
Cd			**1**	**0.99 ****	**0.99 ****	−0.07
Cu				**1**	**0.98 ****	−0.08
Zn					**1**	−0.07
Ni						**1**

* and **: correlation is significant at the 0.05 and 0.01 levels (2-tailed). Bold values are moderately/highly correlated.

3.3.4. Variation in Heavy Metal Concentrations in Sediments

The distribution of heavy metals in the sediments of the Ngerengere River and its tributaries in the dry and wet seasons is shown in Figure 6.

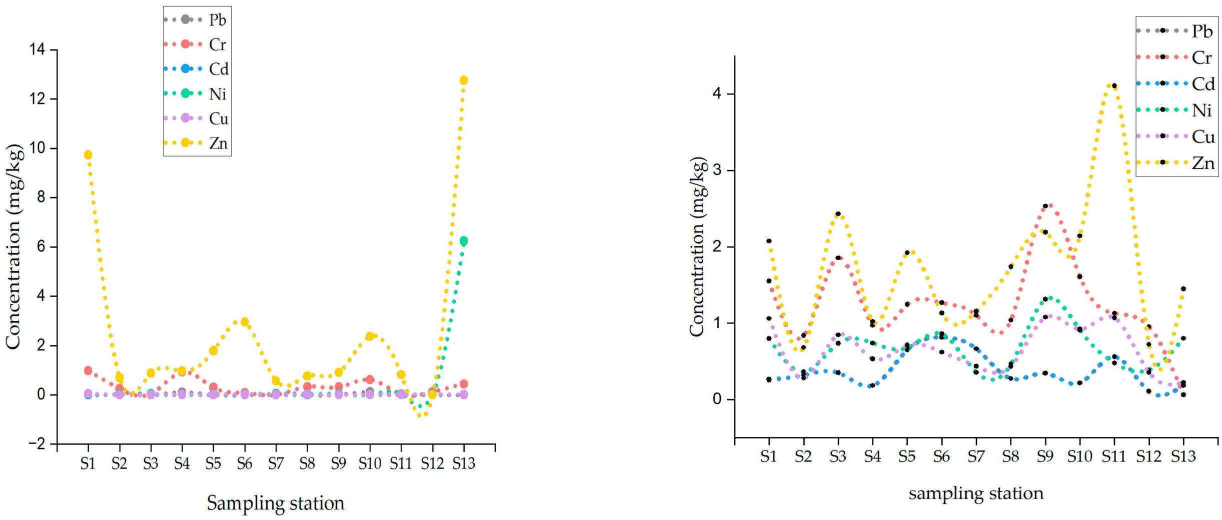


Figure 6. Heavy metal concentrations in the sediments of the Ngerengere River and its tributaries in the dry season (**left**) and wet season (**right**).

Although river sediments are known for their ability to absorb some heavy metals and ultimately reduce water pollution, they will also release heavy metals into the water, causing secondary pollution that is difficult to control. In the sediments, the results indicated that potential sources of heavy metals are anthropogenic activities [94] and the weathering of the high-grade metamorphic rocks like amphibolite, gneiss, and granulites rocks dominantly present in the urban reaches of the Ngerengere catchment. In the dry season, high concentration ranges of the major heavy metals in the Ngerengere River sediments were 1.08 ± 0.06 mg/kg, 1.27 ± 0.02 mg/kg, 2.53 ± 0.056 mg/kg, 4.11 ± 0.02 mg/kg, and 0.64 ± 0.01 mg/kg for Cu, Ni, Cr, Zn, and Pb, respectively.

These findings were compared to the US EPA Sediment Quality Guidelines, as there were no verified guidelines for sediment quality in Tanzania. The lowest concentrations of heavy metals in the sediments were 0.224 ± 0.012 mg/kg, 0.36 ± 0.01 mg/kg, 0.06 ± 0, 0.68 ± 0.01, and 0.15 ± 0.02 mg/kg for Cu, Ni, Cr, Zn, and Pb, respectively. Generally, these findings indicated that there is higher metal accumulation in the midstream and downstream reaches compared to the upstream due to the influence of point and non-point sources of heavy metal pollution in urban areas within Morogoro Municipality. Heavy metal concentrations in the surface sediments of the Ngerengere River exhibited variations in their concentrations owing to the non-uniformity in the grain size distribution of the river sediments, since differences in sediment components influence sorption and varying amounts of anthropogenic contributions. This study revealed that there is an increase in metal concentrations from coarse to fine fractions of the river sediments, which is similar to the observations made by Vaithiyanathan et al. [85].

Generally, the concentrations of heavy metals in the wet season were lower compared to the dry season due to the dilution effect. The highest concentrations of Cu, Ni, Cr, Zn, and Pb were 0.04 ± 0.01 mg/L, 6.24 ± 0.07 mg/L, 0.98 ± 0 mg/L, 12.76 ± 0.02 mg/L, and 0.12 ± 0 mg/L, respectively. Cadmium was not detected across all sampling stations in the wet season. The observed findings were compared with previous studies (Table 15), which showed higher heavy metal concentrations in the river sediment from other urban rivers.

Table 15. Variations in heavy metal concentrations in the sediments of other rivers.

References / Parameters	This Study	Mara River, Tanzania [3]	Upper Tigris River, Turkey [2]	Perak River, Malaysia [14]	Solwezi River and Kifubwa River, Zambia [16]	US EPA Guidelines [94]
Cu (mg/kg)	bdl-1.08	-	98.65–2860.25	6.60–183.52	0.13–10.35 ± 0.24	25–50
Ni (mg/kg)	0.03–6.24	-	122.14–534.58	-	-	20–50
Zn (mg/kg)	0.56–12.76	-	149.67–1061.54	21.31–160.48	0.03–0.15 ± 0.10	-
Mn (mg/kg)	0.25–51.06	-	786.234–1681.84	-	-	300–500
Fe (mg/kg)	31.19–1048.6	-	-	20.24–56.58 *	6.82–26.64 ± 0.50	25–75
Pb (mg/kg)	bdl-0.64	2.45 ± 0.05–17.45 ± 1.22	146.244–632.077	25.40–60.77	-	40–60
Cr (mg/kg)	bdl-2.53	0.97 ± 0.49–2.58 ± 0.57	72.12–158.35	-	-	25–75

(-) means the value(s) was not reported. *: correlation is significant at the 0.05 levels (2-tailed).

3.3.5. Nutrient Loading in Water and Sediments

This study revealed that there was significant temporal and spatial variability in ammonia-nitrogen, nitrate nitrogen, nitrate nitrogen, and phosphate concentrations in water and sediments. In the dry season, the concentrations of ammonia-nitrite were higher at the downstream reach of the Ngerengere River in Morogoro Municipality at sampling, with readings of 1.63 ± 0.01 mg/L and 1.55 ± 0.05 mg/L (Figure 7); this observation might be attributed by the presence of excreta in the river water, attributed by on-site sanitation systems and excreta from livestock [66,73]. The levels of ammonia were not in line with the Tanzania standards for drinking water supplies, per TZS 789: 2008. Nitrite nitrogen concentrations ranged from 0.08 ± 0.01 mg/L to 0.39 ± 0.53 mg/L, indicating nitrite nitrogen enrichment upstream compared to downstream.

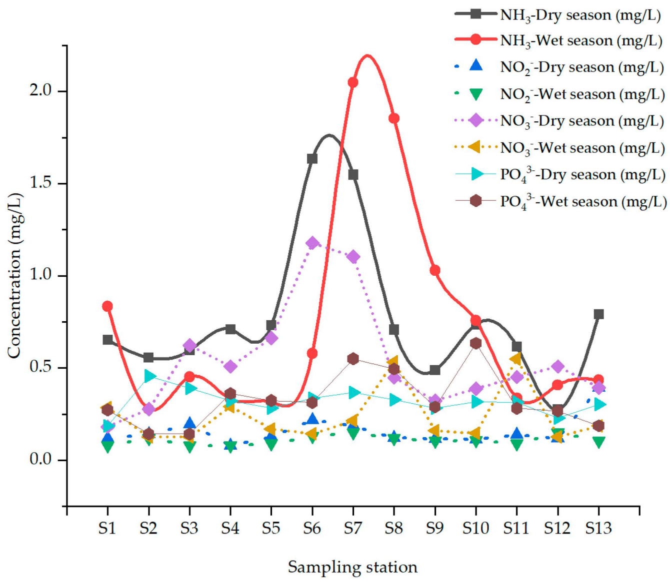


Figure 7. Concentrations of ammonia-nitrogen, nitrate nitrogen, nitrate nitrogen, and phosphate concentrations in river water for both the dry and wet seasons.

The nitrate levels ranged from 0.19 ± 0.04 mg/L to 0.39 ± 0.30 and 0.46 ± 0.47 mg/L. Higher nitrate concentrations might be attributed to upstream farming activities that transport nitrate-enriched runoff to Mindu Dam, while, at S3, the potential attribute of the nitrate concentration is due to ongoing farming practices and on-site sanitation practices; other potential sources of nutrients in the river might be the atmospheric nitrogen gases, because the aforementioned sampling stations are situated in the proximity of Tanzam highway. This has been also reported in the study of Akhtar et al. [94], which established the link of air–water interaction and the associated implications to the water quality. One potential public health consequence associated with elevated nitrate levels in the river is the increased risk of methemoglobinemia in infants, commonly known as “blue baby syndrome”. To prevent methemoglobinemia, the US Environmental Protection Agency

(EPA) has established maximum permissible levels of 10 mg/L for nitrite-nitrogen and 1 mg/L for nitrate-nitrogen. Additionally, the river may face challenges related to ammonia toxicity to aquatic organisms, particularly when concentrations exceed 0.2 mg/L, especially in instances of elevated pH and ammonia levels. Mitigating ammonia toxicity involves maintaining a pH level below 8 and ammonia concentrations below 1 mg/L. From an environmental management perspective, nutrient enrichment in the river raises concerns about eutrophication, leading to compromised ecological integrity in surface waters, the potential extinction of fish populations, the proliferation of toxic cyanobacteria blooms, and a reduction in oxygen levels [68]. The average phosphate concentration in river water ranged from 0.187 ± 0.038 mg/L at S1 to 0.456 ± 0.474.

The elevated phosphate concentration at S2 might be attributed to point sources and non-point/diffuse sources, possibly containing both organic and inorganic forms of this element; the water at the sampling station, being a dam with low water velocity, facilitates the gradual settling of suspended solids (SSs) along with particulate phosphorus (PP) [95], and this phenomenon is responsible for eutrophication in surface water. Diffuse sources involve inputs from the leaching of geological rocks and land use, whereas point sources consist of industrial discharge [96]. In surface waters, phosphate and polyphosphate inorganic compounds constitute the prevalent forms of phosphorus, while organic phosphorus arises from the life processes and decay of aquatic organisms, along with human activities that contribute to phosphorus release [97].

The study also signifies those tributaries (Morogoro and Bigwa) might influence the nutrient transportation to the Ngerengere River, as in their confluence and downstream, the nutrient levels appeared to be higher; this has been observed in sampling stations S6, S5, S7, and S11 for ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, and phosphorus (phosphate), respectively. At this juncture, the concentration of nutrients in the downstream reach of the Ngerengere River within Morogoro Municipality can be influenced by water from Morogoro River. Similar findings were observed in the downstream reaches of Kilombero Valley compared to the upstream reaches due to excessive agricultural activities [98]. In the wet season, the highest concentrations of ammonia, nitrite, nitrate, and phosphate in the river water were 2.05 ± 0.01 mg/L, 0.15 ± 0.01 mg/L, 0.53 ± 0.01 mg/L, and 0.63 ± 0.01 mg/L, respectively. The resulting increase in the nutrient loading in the wet season downstream was due to an increase in the surface runoff attributed to rainfall events within the catchment.

For a considerable period, sediments have been acknowledged as a repository for numerous pollutants released into surface water. The presence of contaminated sediments can lead to harmful ecological impacts on sediment-related organisms like macrophytes, benthos, and demersal fish, as well as on higher-level biota such as pelagic fish and aquatic birds [99]. In this study, particularly in the dry season, high nutrient concentrations in the sediments were 2.21 ± 0.12 mg/kg, 0.48 ± 0.14 mg/kg, 1.82 ± 0.26 mg/kg, and 34.29 ± 0.55 mg/kg for ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, and phosphorus (phosphate), respectively (Figure 8). Ammonium-N and nitrate-N are naturally present in water due to the decomposition of organic and inorganic matter, excretion by organisms, and the microbial reduction in atmospheric nitrogen [98]. Nonetheless, the elevated ammonium-N observed at S11 may be attributed to on-site sanitation systems located near the sampling station. The study also indicated that the sediment at the downstream reach of the river has a higher phosphate concentration than the upstream reach. This study also revealed that higher phosphate concentrations in the Morogoro tributary, particularly at sampling station S5, might cause an increase in the elevated phosphate concentrations downstream of the Ngerengere River; this might be attributed to sediment transported from tributaries, especially the Morogoro River. The percentage of total carbon in the soil was higher at midstream and lower at the upstream reaches.

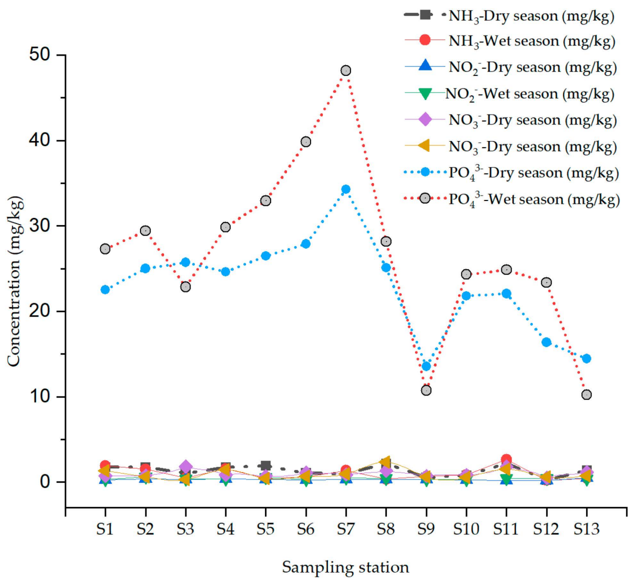
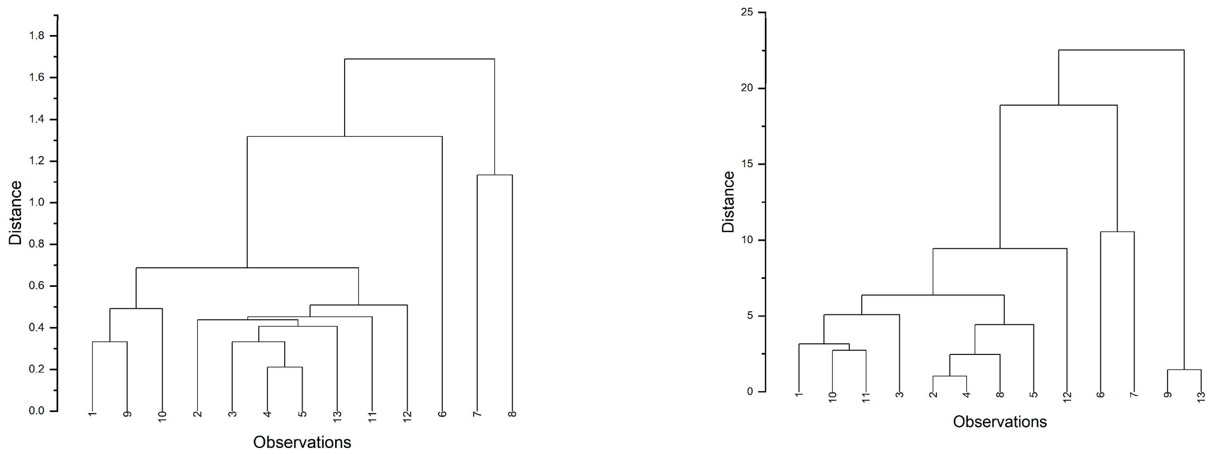


Figure 8. Concentrations of ammonia-nitrogen, nitrate nitrogen, nitrate nitrogen, and phosphate concentrations in river sediment during the dry and wet seasons.

This study also showed that the sulphate concertation in the urban catchment of the Ngerengere River was higher at the midstream, at 255.43 ± 0.01 mg/kg, and lower at the upstream, at 52.16 ± 0.71 mg/kg. Chloride concentrations were higher in the sediments collected upstream at S13, located within the Uluguru Mountains, at 269.92 ± 32.56, which is likely attributed to weathering processes and geological formations; the lowest chloride concentration was lower at the midstream reaches, with a reading of 66.14 ± 0.34. In the wet season, the highest concentrations of ammonia, nitrite, nitrate, and phosphate in the river sediment were 2.64 ± 0.03 mg/kg, 0.63 ± 0.01 mg/kg, 1.46 ± 0.01 mg/kg, and 48.16 ± 0.01 mg/kg, respectively.

The findings from the hierarchical cluster analysis (HCA) further showed that the urban catchment of the Ngerengere River in Morogoro Municipality was divided into two pollution clusters (C1 and C2) for both water and sediments. The dendrogram in Figure 9 summarizing the results of the HCA shows that the initial splitting of the tree forms two clusters for both water and sediments. The top cluster (Cluster 1) contains eleven stations (S1, S9, S10, S2, S3, S4, S5, S13, S11, and S12) and the bottom cluster (Cluster 2) contains two stations (S7 and S8) for water; for sediments, C1 contains S1, S10, S11, S3, S2, S4, S8, S5, S12, S6, and S7, and C2 contains S9 and S13. For the water samples, C1 and C2 entail the sampling stations of the middle–upstream and downstream, respectively. The nitrate concentrations of C2 were almost twice that of C1 (Table 16), indicating that there were significant impacts of human activities in the downstream and midstream reaches of the river and tributaries. For the sediment samples, C1 and C2 include the sampling stations at the middle–downstream and upstream reaches. The phosphate concentrations of C2 (upstream) were almost twice to that of C1 (downstream), signifying phosphate binding onto sediment in oxic conditions [100]. This was supported by this study, which recorded higher dissolved oxygen in the upstream reaches.

The Wilcoxon signed-rank non-parametric test compared the values of the nutrients in the water and sediments obtained between the two seasons and revealed that NH_3 in the dry season was equal to NH_3 in the wet season, NO_2^- in the dry season > NO_2^- in the wet season, NO_3^- in the dry season > NO_3^- in the wet season, and PO_4^{3-} in the dry season was equal to PO_4^{3-} in the wet season for the case of river water samples. Furthermore, in river sediments, NH_3 in the dry season was equal to NH_3 in the wet season, NO_2^- in the dry season < NO_2^- in the wet season, NO_3^- in the dry season was equal to NO_3^- in the wet season, and PO_4^{3-} in the dry season > PO_4^{3-} in the wet season.



(**a**) (**b**)

Figure 9. Dendrogram of the 13 sampling stations for NO_2^-, NO_3^-, NH_3, and PO_4^{3-} in water (**a**) and sediment (**b**).

Table 16. Mean values with standard deviation for nutrients in different clusters of the Ngerengere River and its tributaries, Morogoro Municipality.

	Pollution Cluster (Water)				**Pollution Cluster (Sediment)**			
	C1		**C2**		**C1**		**C2**	
Variables	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Ammonia-nitrogen	0.77	0.39	0.74	0.58	1.36	0.62	1	0.74
Nitrite-nitrogen	0.16	0.08	0.11	0.02	0.31	0.08	0.41	0.09
Nitrate-nitrogen	0.54	0.29	0.24	0.15	1.03	0.42	0.94	0.58
Phosphorus (phosphate)	0.32	0.07	0.33	0.15	23.07	5.70	27.07	10.21

Organic loading in the water showed that the (5-day Biochemical Oxygen Demand) BOD_5 concentrations in the dry season ranged from 24.76 ± 0.03 mg/L to 277.52 ± 0.16 mg/L, which signifies that the downstream reaches of the river have a higher organic loading compared to the upstream reaches, which can be attributed to the accumulation of waste. Notably, the midstream reaches recorded relatively higher BOD_5 concentrations, which was linked to the existence of point sources of organic pollution like industries, on-site sanitation systems, and poor solid waste management marked by presence of the Mafisa dumpsite. This study revealed that domestic waste, industrial activities, and runoff from agricultural activities resulted in higher COD concentrations, which was due to higher COD concentration values of 123.11 ± 0.02 mg/L, 115.83 ± 0.08 mg/L, 100.19 ± 0.05 mg/L, and 102.16 ± 0.16 mg/L. Tanzania's water quality standards specify the permissible limits for organic pollution introduced artificially and naturally in water bodies. In this study, we evaluated the total carbon in the water to accommodate the natural and artificial carbon in the water. This study revealed that the total carbon was higher downstream at 0.35 ± 0.03% and lower upstream at 0.13 ± 0.01%, which represented the pristine environment (headwater). Tanzania water quality standards have grouped sulphate and chloride ions together as salinity and hardness impact parameters. Sulphate concentrations ranged from 16.40 ± 0.91 mg/L to 116.79 ± 0.37, and these findings are quite related to the observations reported by Mbuligwe and Kasseva [50] at Msimbazi River; according to the Tanzania standards, the lower and upper limits for sulphate in water is 200 and 600 mg/L, respectively. Chloride was observed to be higher downstream, at 119.28 ± 0.22, than upstream, at 26.37 ± 0.22 mg/L, which signified the elevated salinity of the river water.

This study also showed that the total carbon in the bottom sediments of the river and its tributaries was higher (5.23 ± 0.16 mg/kg) in the midstream area, which was covered by mixed types of pollution sources responsible for organic loading in the river, while the lowest total carbon was higher at the upstream reaches, which can be associated to the textural properties of the sediment and the reduced disturbance from anthropogenic pollution sources responsible for organic pollution. Higher phosphorus and nitrogen concentrations in the sediments were recorded at 34.29 ± 0.55 mg/kg, 1.82 ± 0.03 m/kg, 0.48 ± 0.14, and 2.21 ± 0.12 mg/kg for phosphate, nitrate-nitrogen, nitrite-nitrogen, and ammonia-nitrogen, respectively; for sulphate and chloride, higher concentrations were recorded at 255.43 ± 0.01 mg/kg and 269.92 ± 32.56 mg/kg. The lowest phosphorus and nitrogen concentrations in the sediments were 13.56 ± 0.69 mg/kg, 0.51 ± 0.05 m/kg, 0.20 ± 0.04, and 0.28 ± 0.01 mg/kg for phosphate, nitrate-nitrogen, nitrite-nitrogen, and ammonia-nitrogen, respectively. The spatial variations in nutrients are influenced by land-use practices and the extent of urban development [73], where higher nitrogen and phosphorus concentrations usually occur in areas of urban and agricultural activities [50], while the temporal variability of the nutrients in the sediment is influenced by geological processes and weather seasons, as higher nutrient levels are normal during the wet season due to the effects of runoff from agriculture and urban centers. In the wet season, higher BOD_5, COD, and total carbon concentrations in the river water were recorded at 287.39 ± 0.55 mg/L, 110.51 ± 0.51 mg/L, and 0.30 ± 0.02%, respectively. Furthermore, the level of organic loads explained by the total carbon percentage was higher in the midstream reaches, with a TC reading of 3.3875 ± 0.03%.

3.3.6. Limitations of the Research

This study's limitations and potential sources of error span various aspects of its methodology and data analysis. Firstly, while the sampling design incorporated 13 strategically positioned sites along the Ngerengere River and its tributaries, variations in urbanization, human activities, and riparian vegetation may not have been fully captured. Moreover, the reliance on remote sensing data for land-use and land cover classification introduces uncertainties in characterizing the physical integrity, particularly in heterogeneous landscapes. In addressing this concern, this research conducted a thorough field visitation to verify the existing LULC in the established control points. Secondly, the laboratory analysis of the water and sediment samples using atomic absorption spectrophotometry and other techniques was subject to potential contamination during sample collection, storage, and analysis, despite employing quality assurance and quality control procedures. Additionally, the estimation of water discharge using the velocity–area method may introduce inaccuracies due to assumptions about channel morphology and flow uniformity, especially in sections with complex hydraulic conditions; in addressing this concern, a correction factor for velocity to account for the nonuniformity of the velocity across the river's cross-section was incorporated. Finally, while statistical analyses such as ANOVA and PCA were employed to explore the relationships between water quality parameters, nutrient sources, and heavy metal concentrations, the interpretation of the results should consider the inherent uncertainties and assumptions associated with these analytical techniques.

4. Conclusions

The purpose of this study was to assess the integrity of urban rivers, specifically the Ngerengere River and its tributaries within Morogoro Municipality, through the characterization of the LULC in the urban river buffer, discharge, and contamination status of nutrients and heavy metals in the river water and sediment. The reason for incorporating the tributaries emanated from previous studies that demonstrated the influence of tributaries in the transportation of contaminants to the main river and the augmentation of the main river runoff. It should be noted that the sampling seasons accounted for the year 2023. The land-use–land cover (LULC) assessment in the buffer zone of Ngerengere River and its tributaries during the sampling year revealed that built-up areas dominated the landscape, constituting the largest proportion at 38%, indicating significant human settlement and infrastructure development in the area. Furthermore, bare land accounted for 28%. In the study area, vegetation cover comprised 24% of the total area. The study revealed that the mean average discharge across the sampling stations showed higher discharge in the upstream reaches and near the confluences, where the measured flow rates were 3.73 m^3/s, 2.95 m^3/s, 1.52 m^3/s, and 0.99 m^3/s, respectively. The sampling stations located at the confluence recorded higher flow rates of 2.36 m^3/s and 0.39 m^3/s during the dry and wet seasons, respectively, demonstrating the impact of urban tributaries on the accumulated Ngerengere River runoff. The variations in the water flow were influenced by the differences in the riparian vegetation, the extent and level of water abstractions for domestic and economic activities, the slope, as well as climatological conditions. This research gauged the influence of the wet (rain) and dry (drought) seasons on the levels of nutrients and heavy metals in the sediments and surface water. This study revealed that the order of magnitude of the recorded concentrations of heavy metals in the water was Zn > Ni>Cr> Pb > Cu > Cd. The highest concentrations of heavy metals in the surface water in the dry and wet seasons were 0.09 ± 0.01, 0.25 ± 0.01, 0.03 ± 0.02, 0.73 ± 0.04, 4.07 ± 0.081, and 3.07 ± 0.04 mg/L, respectively, for Pb, Cr, Cd, Cu, Zn, and Ni, which exceeded the maximum permissible limits established by the Tanzania standards and WHO maximum limits. The order of magnitude for the heavy metal concentrations in the sediments in both sampling campaigns were Zn > Ni > Cr > Cu > Cd > Pb, with values of 12.76 ± 0.02 mg/kg, 6.24 ± 0.07 mg/kg, 2.53 ± 0.06 mg/kg, 1.08 ± 0.06 mg/kg, 0.81 ± 0.03 mg/kg, and 0.64 ± 0.01 mg/kg. The comparison of the nutrient levels between the dry and wet seasons in both river water samples and sediments revealed significant nutrient dynamics. In the river water samples, the ammonia (NH_3) levels remained consistent across seasons, while the nitrite (NO_2^-) and nitrate (NO_3^-) concentrations were higher during the dry season. Phosphate (PO_4^{3-}) levels showed no significant difference between seasons. Conversely, in the river sediments, the NH_3 levels remained constant between seasons, while the NO_2^- levels were lower during the dry season. The NO_3^- levels showed no significant variation between seasons, and the PO_4^{3-} levels were higher in the dry season compared to the wet season. Comparing the present study results with the dry and wet seasons, the physical parameters in the river and tributary waters ranged from 5.77 to 8.24, 21.51 to 32 (°C), 0.02 to 1.12 (mg/L), 37.33 to 2446 (µS/cm), 2.07 to 6.47 (%), 0.18 to 0.49 (mg/L), 18.67 to 1123 (mg/L), and 8.8 to 1035 N.T.U for the pH, temperature, salinity, electrical conductivity, percentage of dissolved oxygen, dissolved oxygen concentration, total dissolved solids, and turbidity. Changes in the physical quality of the water were evident in the dry and wet seasons due to the effect of the dilution and evaporation processes. This study recommends that continuous monitoring of the river water quality and quantity is essential for assessing the environmental health, identifying sources of pollution, and ensuring compliance with water quality standards. Simultaneously, effective land-use planning can help sustainably manage urban development, minimizing the impact of human activities on river ecosystems and water resources. In line with the objectives of the study, this paper focused on the urban catchment of the Ngerengere River and its tributaries (i.e., within the Morogoro Municipality boundary). Further studies should extend its borders to other rural areas drained by the river. Also, research should be performed to assess the levels of heavy metal concentrations in fresh leaf vegetables grown along the river and its tributaries in the case study area and their associated health risks, mainly due to ability of heavy metals to undergo bio-accumulation in plants and bio-magnification in livestock and humans given their positions in the food web.

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