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Level of Degradation Along the Nairobi River Basin Riparian Zone Between 1991 and 2021

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ABSTRACT

Globally, the riparian zones have faced significant challenges related to human activities and environmental degradation. These zones, characterised by their role in filtering river water, preventing soil erosion, and regulating temperature, and crucial to maintaining ecological balance. Despite global frameworks like the Ramsar Convention and national laws in Kenya, the Nairobi River riparian zone has faced significant degradation over the past 30 years due to urbanisation, deforestation, and improper waste disposal. This degradation has compromised the riparian zone's ability to mitigate flood risks, resulting in increased surface runoff, erosion, and more frequent flood events in Nairobi City County. The research Objective was to evaluate the extent and drivers of degradation in the Nairobi River riparian zone over the past 30 years, while the research question was the primary drivers of degradation along the Nairobi River basin riparian zone over the past 30 years. The upper catchments of the Nairobi River were characterized by intensive agriculture and animal husbandry, with sparse human settlements. In the CBD, high-rise commercial office buildings and other urban developments dominated the landscape. This area also hosted industries, residential areas, and extensive road networks. The findings presented provide insights into the frequency of floods along the Nairobi River riparian zone, as perceived by respondents. The data showed 52% of the respondents (200 individuals) reported that floods occur annually. Nairobi receives the highest amount of rainfall in March, April, and May, followed by October, November, and December. From the computed cross-tabulation, the researcher determined the Chi-Square test of independence between economic activities by households living along the Nairobi River riparian zone and the frequency of floods along the Nairobi River riparian zone. The 30-year analysis of the Nairobi River riparian zone revealed severe degradation driven by intensive agriculture, urbanization, and infrastructure development. This study concludes that the Nairobi River basin riparian zone has experienced severe environmental degradation from 1991 to 2021, primarily driven by rapid urbanisation and agricultural expansion. Further research on the assessment of the impact of sustainable agricultural practices on soil health and water quality in the Nairobi River riparian zone in Nairobi County, Kenya.

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1. Introduction

Globally, the riparian zones have faced significant challenges related to human activities and environmental degradation. These zones, characterised by their role in filtering river water, preventing soil erosion, and regulating temperature, are crucial to maintaining ecological balance. However, increasing urbanisation and industrialisation worldwide have contributed to the decline of riparian ecosystems. In many regions, riparian areas are often encroached upon by development projects, leading to the disruption of natural processes such as water filtration and flood control. Scientific studies have shown that the degradation of these ecosystems leads to biodiversity loss and increased vulnerability to natural disasters, such as floods (Malanson, 1993).

The global concern for preserving riparian zones has led to the implementation of various international

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frameworks aimed at protecting these ecosystems. Riparian zones, characterised by lush vegetation and moist conditions, are vital land-water interfaces that filter river water, curb soil erosion, and regulate temperature (Malanson, 1993). These zones exhibit global diversity, with both urban and rural landscapes featuring abundant vegetation. The significance of riparian zones is highlighted by their role in supporting irrigated agriculture, towns, cities, and industrial sites along riverbanks, demonstrating human dependence on these critical ecosystems. International frameworks, such as the Ramsar Convention on Wetlands (1971), the UN Convention on the Law of Non-Navigational Uses of International Watercourses (1997), and the Sustainable Development Goals (SDGs), particularly Goal 6 (2016), underscore the importance of preserving riparian zones.

The degradation of riparian zones worldwide was a pressing environmental issue exacerbated by urbanisation, agricultural expansion, and infrastructure development. Studies from Europe, North America, and Asia revealed a consistent pattern of vegetation loss, pollution, and altered hydrological patterns due to human activities. For example, research by Smith et al. (2018) highlighted significant vegetation loss and pollution in riparian zones due to urbanisation, while Jones and Brown (2019) and Chen et al. (2020) reported similar impacts from agricultural and infrastructural developments. These global studies underscored the need for coordinated conservation efforts to address riparian zone degradation effectively, emphasising that the challenges faced in the Nairobi River riparian zone were part of a broader global trend.

In Africa, riparian zones are also experiencing severe degradation due to both rural and urban development pressures. Many Sub-Saharan African countries rely on riparian zones for their critical role in supporting agriculture, water quality, and ecological balance. However, human-induced factors, such as deforestation, illegal settlements, and poor land-use practices, have exacerbated the destruction of these ecosystems. In particular, the rapid expansion of urban areas has led to the encroachment of riparian zones, as observed in countries like Nigeria and South Africa. The degradation of these areas has led to increased flood risks, soil erosion, and a loss of biodiversity. These are negatively impacting local communities and economies. Despite the existence of policies to protect these zones, enforcement has been weak, leading to continued exploitation (MEWNR, 2013; Karisa, 2010).

In Africa, the degradation of riparian zones emerged as a critical environmental challenge with widespread repercussions. Research across the continent indicated that urbanisation, industrialisation, and agricultural expansion had significantly impacted riparian habitats. Ogutu-Ohwayo (2016) documented the detrimental effects of these activities on riparian ecosystems in various African countries. In South Africa, Le Maitre et al. (2015) reported that agricultural transformation had led to habitat fragmentation and degradation. The impacts of climate change further exacerbated these issues, as seen in Ethiopia, where Alemayehu et al. (2019) attributed riparian vegetation loss to recurring droughts. Despite these challenges, there was a growing recognition of the importance of riparian conservation, with initiatives such as community-based programs and policy reforms emerging across the continent (Akama & Ngaira, 2014).

Riparian zones are vital for maintaining ecosystem balance, regulating water flow, preventing flooding, and providing habitats for biodiversity. Despite global frameworks like the Ramsar Convention and national laws in Kenya, the Nairobi River riparian zone has faced significant degradation over the past 30 years due to urbanisation, deforestation, and improper waste disposal. In Kenya, the Nairobi River riparian zone has seen significant degradation between 1990 and 2020, largely due to urbanisation and industrial development. Encroachment on riparian reserves and the blockage of natural water channels have led to severe environmental challenges, including increased flash flood risks and economic losses. Studies estimate that the degradation of riparian zones in Kenya may contribute to annualised economic losses of up to 0.8% of the country's GDP, amounting to more than Ksh 49.8 billion (GoK, 2013).

In Kenya, the degradation of riparian zones, particularly along the Nairobi River, has been a significant environmental and socio-economic concern. Studies indicated that deforestation, land-use changes, pollution, and encroachment had led to extensive vegetation loss, water pollution, and habitat destruction (Odadi et al., 2016). Research in the Nairobi River basin revealed that urbanisation and industrial activities had severely impacted riparian ecosystems, with Gichuhi et al. (2022) noting substantial losses in vegetation and increased pollution. The degradation had also worsened flood risks, with Kairu et al. (2019) linking vegetation loss and channel obstruction to increased flooding and its associated damages. This aligned with global trends of intensified weather patterns affecting urban areas, emphasising the need for innovative, context-specific management strategies (Kimani & Njuguna, 2023). Thus, the Nairobi River riparian zone degradation was reflective of broader issues observed globally and within Africa, necessitating comprehensive and locally adapted solutions.

The environmental consequences are far-reaching, with erosion, pollution, and declining plant biomass threatening the ecological balance and urban resilience. Efforts to mitigate these challenges require the implementation of sustainable management practices and stronger regulatory frameworks to protect riparian ecosystems from further destruction (Ouma & Tateishi, 2014; Richardson et al., 2007; Kangogo, 2022). The degradation of riparian zones in Nairobi City County, Kenya, has over the years become an enormous environmental concern that has a close association with flood control and enhanced urban resilience. Riparian areas act as a buffer zone between the land and the water course. They are crucial for ecological stability, filtration, preventing erosion, and stabilising the temperatures of water (Malanson 1993). This degradation has compromised the riparian zone's ability to mitigate flood risks, resulting in increased surface runoff, soil erosion, and more frequent flash flood events in Nairobi City County. Weak regulatory frameworks and insufficient community participation have exacerbated these issues. This study aimed to understand the drivers behind this degradation and its impacts on flooding, emphasising the need for targeted interventions to sustainably manage riparian zones and enhance urban resilience and environmental sustainability.

Ecological resilience theory emphasises an ecosystem's capacity to absorb disturbances and reorganise while maintaining critical functions. In riparian zones, this theory is particularly relevant as it explains how ecosystems can recover from degradation caused by human activities such as deforestation, urbanisation, and pollution. The resilience of riparian ecosystems, like those along the Nairobi River, depends on their ability to restore balance after disturbances like floods or vegetation loss. Preserving biodiversity and natural vegetation plays a crucial role in maintaining this resilience, allowing the ecosystem to mitigate flood impacts and restore water quality. Ecological resilience theory, therefore, advocates for sustainable management practices, such as reforestation and pollution reduction, to ensure riparian ecosystems can recover from and adapt to ongoing environmental challenges (Holling, 1973; Folke, 2006).

The theory has been applied in numerous studies examining the recovery and management of ecosystems under stress. For instance, Allan et al. (2013) explored the application of ecological resilience in river basin management, demonstrating that riparian zones with higher biodiversity had greater resilience to pollution and hydrological disturbances. Similarly, Poff et al. (2016) used ecological resilience theory to assess the impact of altered water flows on river ecosystems in the U.S., emphasising the need for preserving riparian vegetation to enhance resilience against floods. In Africa, studies by Biggs et al. (2015) demonstrated the relevance of ecological resilience in managing the Okavango Delta, where maintaining natural habitats helped mitigate the impacts of seasonal flooding and human encroachment. This study aimed to assess the critical role of ecological resilience in the sustainable management of riparian ecosystems, particularly in rapidly urbanising environments like Nairobi, as observed by DEM of Nairobi in Fig. 1.

2. Materials and Methods

2.1. Nairobi River Basin Digital Elevation Model

To quantify changes in the Nairobi River basin over the 30 years, multi-temporal satellite imagery, Landsat imagery for 1991, 2001, 2011, and 2021, was acquired. Images were atmospherically corrected and classified using supervised land-cover classification to distinguish riparian vegetation, open water, built-up areas, and bare land. Post-classification change detection techniques were applied to measure the extent and rate of vegetation loss or conversion to urban/bare surfaces. NDVI and riparian-buffer analysis (e.g., 30 m and 60 m buffers from the river centerline) were used to evaluate vegetation health and spatial patterns of encroachment. The results were correlated and provided a quantitative estimate of riparian degradation and its temporal dynamics across the basin.

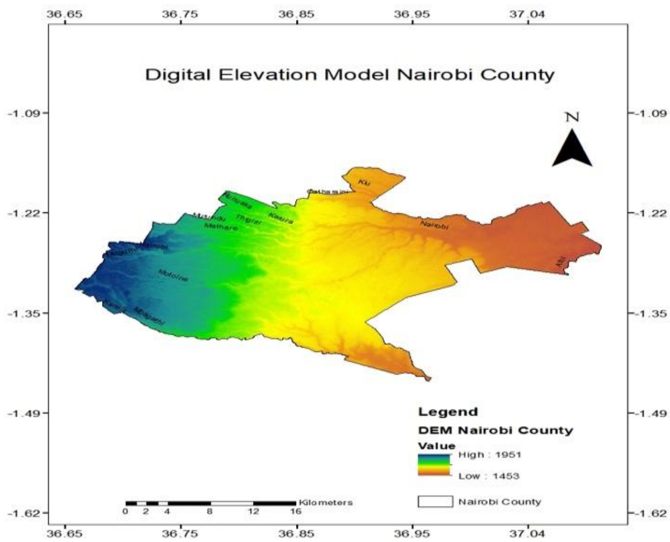

Fig. 1: Map showing the Nairobi River basin.

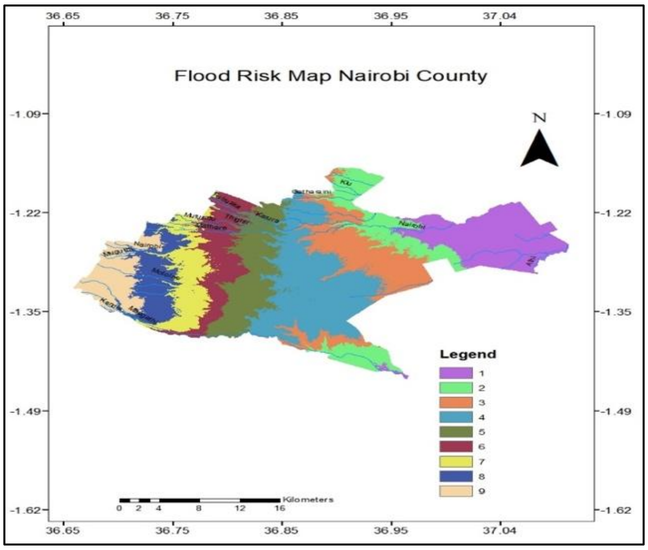

Fig. 2: DEM of Nairobi County.

A correlational research design was utilised to examine the interactions between variables such as land use, urbanisation, climate change, and vegetation health, without direct manipulation. This approach was apt for understanding natural systems and identifying associations between human activities and environmental degradation, crucial for urban flood mitigation.

2.2. Target population

The study targeted stakeholders managing and mitigating issues in the Nairobi River basin riparian zone, including representatives from Nairobi City County, national ministries, NGOs, CBOs, and agencies like NEMA and WRMA. With an estimated population of 176,961 within the riparian zones, sampling incorporated both simple random and purposive techniques. The sample size, calculated using Fisher's formula and adjusted to 400, included residents and key stakeholders from relevant organisations.

$$n = \frac{Z^2 pq}{d^2} = n = \frac{z^2 x\, p(1-p)}{e^2} = \frac{1.96^2 x\, 0.5(1-0.5)}{0.05^2} n = 384$$

2.3. Data Collection Tools

Data collection employed a variety of techniques: structured questionnaires for quantitative data, semi-structured interviews for qualitative insights, field observations, GIS and remote sensing for spatial analysis, document reviews for contextual understanding, focus group discussions for community perspectives, and hydrological modelling for real-time data. This multi-method approach ensured comprehensive data coverage. Reliability and validity were maintained through validated tools, standardised procedures, comprehensive training, pilot testing, and expert validation. Data analysis involved descriptive statistics, regression analysis, and geospatial techniques to summarise trends and identify significant relationships. Limitations included the study's focus on specific river stretches and data from 1991 to 2021, which may affect generalisability.

Ethical standards were upheld by obtaining ethical clearance, securing informed consent, and ensuring privacy and confidentiality while aiming to minimise harm and maximise benefits for participants and the community.

3. RESULTS AND DISCUSSIONS

3.1. Type of vegetation along the Nairobi River basin riparian zone

To understand the vegetation types along the Nairobi River riparian zone, the researcher conducted a detailed analysis. The findings, which provide insights into the diversity and distribution of plant species in this area, are summarised in Table 1 below, which highlights the various vegetation types identified, offering a comprehensive overview of the ecological characteristics of the riparian zone.

Table 1: Overview of the environmental and physical characteristics of the Nairobi River Basin catchments.

Catchment	Ecological Setting and Human Activity
Upper Forested	Forest, small farms, livestock, sparse settlements
Upper Agricultural	Subsistence farms, homes, and local roads
Peri-Urban Mid	Housing, roads, smallholder crops, nurseries, light industry, waste sites
Central Business District	High-rise buildings, industries, dense housing, urban farming pockets
Lower Eastlands/Industrial	Heavy industry, urban development, Transport
Lower Eastern Savannah	Housing, quarries, livestock, sewer-fed farms

The upper forested headwaters are characterised by steep slopes, coffee estates, and narrow riparian buffers—intensive farming and livestock production drive soil erosion and agro-chemical runoff (Odadi et al., 2016; Muthoni et al., 2018). The upper agricultural reaches, with gently undulating terrain and a dense network of murram roads and footpaths, add sediment and nutrient loads through subsistence farming and poorly managed residential plots (Alemayehu et al., 2019; Nziguheba et al., 2017).

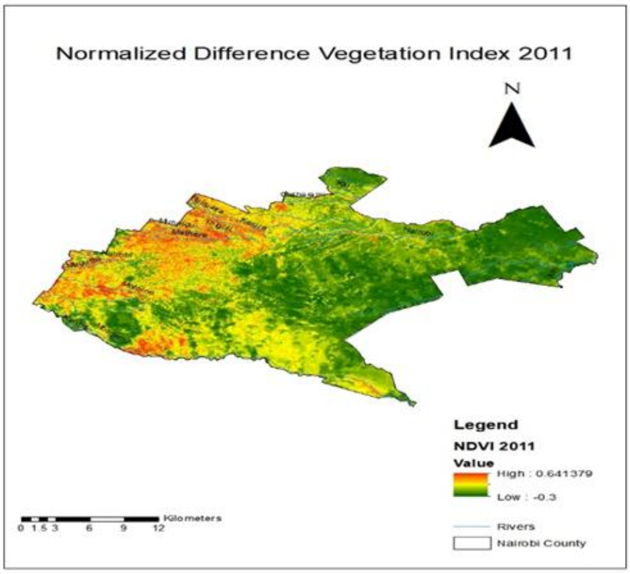

Fig. 3: NDVI of Nairobi 2011

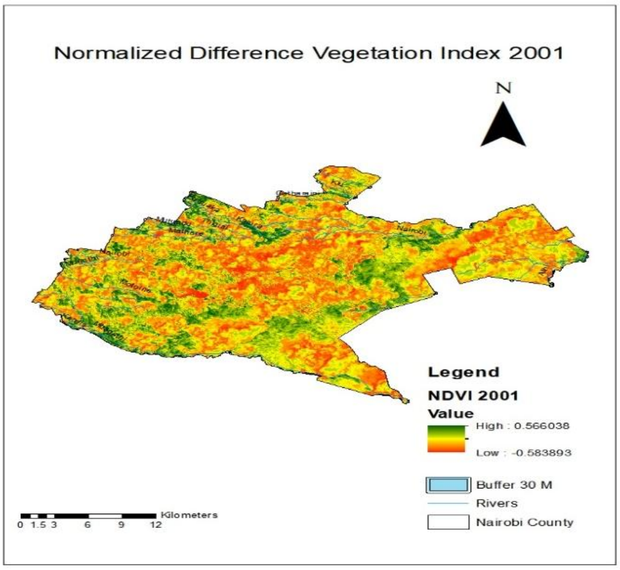

Fig. 4: NDVI of Nairobi 2001.

Peri-urban mid-reaches, marked by expanding road networks, informal garages, car-wash facilities, and smallholder crop plots, hydrocarbons, heavy metals, and untreated sewage enter the river system (Kairu et al., 2019; Gichuhi et al., 2022). The Central Business District, dominated by high-rise buildings, impervious surfaces, and mixed light industry, contributes to rapid surface runoff and industrial effluent (Smith et al., 2018; UNEP, 2016). In the Lower Eastlands and industrial area, large factories, extensive transport corridors, and ageing drainage infrastructure release chemical and heavy-metal pollutants (Le Maitre et al., 2015; Ogutu-Ohwayo, 2016). The lower eastern savannah, noted for quarries, slaughterhouses, sewer-irrigated farms, and seasonal floodplains, adds both sediment and pathogen loads (Arnell et al., 2018; Alemayehu et al., 2019). These salient geomorphic and land-use features create a cumulative pattern of ecological stress, underscoring the need for integrated, catchment-wide management to restore and protect Nairobi's riparian zones.

Fig. 5: Deforestation and crop production around the Nairobi River.

Fig. 6: Crop production along Ondiri swamp.

These findings align with the broader topic of assessing the temporal dynamics of degradation in the Nairobi River riparian zone over the past 30 years, highlighting the multifaceted impacts of human activities on this critical ecosystem as indicated in Fig. 5 and Fig. 6. The study underscores the urgent need for sustainable management practices to mitigate further degradation and enhance the resilience of riparian zones, ensuring they continue to provide essential ecological services and support urban resilience in Nairobi City County.

3.2. Flood Risk in Nairobi County

The Digital Elevation Model (DEM) of Nairobi, Fig. 1, highlights how topography drives flood exposure: low-lying basins concentrate runoff and overflow during heavy rains, while uplands remain less affected (Jones et al., 2018). Yet elevation alone cannot explain the city's rising flood losses. Riparian encroachment, vegetation clearance, and informal construction disrupt natural drainage and infiltration, amplifying storm impacts (Ouma & Tateshi, 2014). Blocked drains from poor waste management, especially in informal settlements, as seen in Fig. 2, further trap floodwaters, contributing to annual damages estimated at 0.8 % of GDP (Republic of Kenya, 2016). Although demolitions of at-risk structures have begun (Republic of Kenya, 2013), climate-change-driven rainfall variability continues to escalate risk. Integrating DEM-based mapping with riparian restoration, improved waste control, and resilient urban planning is therefore essential to reduce Nairobi's vulnerability.

3.3. Vegetation Cover in the Nairobi River Riparian Zone

NDVI analysis across 1991, 2001, 2011, and 2021 shows a clear three-decade decline in riparian vegetation along the Nairobi River. Mean values fell from a healthy 0.76 in 1991 to near bare-land levels by 2021, with major losses between 2001 and 2011 as urban expansion and smallholder farming fragmented buffers. By 2021, dense cover remained only in protected patches such as Karura Forest, while mid- and lower reaches were dominated by built surfaces and exposed soils as seen in the NDVI maps in Fig. 3 and Fig. 4. This progressive degradation reflects rapid settlement growth, cultivation, and weak riparian enforcement, driving erosion, sedimentation, and declining water quality (Smith et al., 2018; Jones & Brown, 2019; Muthoni et al., 2018; Kenya National Bureau of Statistics, 2016). Urgent restoration and strict buffer protection are needed to restore the Nairobi River's ecological and hydrological functions.

The Ondiri/Kikuyu wetland, situated in the upper catchment of the Nairobi River, faced numerous degenerative challenges. Deforestation by the local community for timber, charcoal, and domestic purposes, alongside extensive water harvesting for Nairobi City, diminished the riparian zone's vegetation cover, resulting in habitat destruction and loss for various wildlife species (Muthoni et al., 2018). The encroachment of farmers into the wetland, diverting the swamp for crop cultivation, further exacerbated these issues, as explained in Table 2. Cultivation activities, including the growth of flowers, vegetables, sugarcane, arrowroots, and Napier grass, escalated siltation levels, significantly compromising water quality and quantity (Odadi et al., 2016).

Table 2: Land use and land cover types of Nairobi from 1991 to 2021.

Land Use and Land Cover	1991	2001	2011	2021
	Area in Km^2			
Forest	120.54	60.21	80.1	90.2
Bare Land	320.1	310.5	250.14	189.2
Cropland	134.24	177.2	189.5	175.58
Vegetation	130.5	120.45	110.2	174.23
Build up	80.2	150.25	201.15	275.5
Water	4.62	4.53	3.1	3.54
Total	790.2	823.19	834.19	908.25

The significant decrease in forest cover by 50% between 1991 (120.54 km^2) and 2001 (60.21 km^2) reflects a concerning trend of deforestation within the riparian zone. This reduction might have been attributed to agricultural expansion, logging activities, and

Fig. 7: A tributary flowing towards the Nairobi Dam.

Fig. 8: Mid-section of Nairobi Dam highlighting the riparian zones.

urbanization, which are well-documented drivers of deforestation (Muthoni et al., 2018). However, the subsequent slight increase in forest area observed in 2011 (80.1 Km^2) and 2021 (90.2 Km^2) suggests potential afforestation efforts or natural regeneration processes. This upward trajectory could indicate interventions by authorities aimed at restoring forest cover within the riparian zone (Smith et al., 2018).

Agricultural activities along the riverbanks rapidly expanded, characterised by the cultivation of arrowroots, Napier grass, and sugarcane as the rivers flowed through Nairobi City. Infrastructure development and building constructions along the riparian zone facilitated farming practices along the banks, intensifying environmental pressures (Gichuhi et al., 2022). Ondiri Swamp, located in Kikuyu, Kiambu County, Kenya, is a critical wetland ecosystem facing considerable environmental challenges primarily driven by deforestation and land-use alterations. The rampant deforestation surrounding Ondiri Swamp stemmed from agricultural expansion, urbanisation, and logging activities, resulting in adverse environmental consequences such as soil erosion, loss of biodiversity, and disruption of hydrological cycles (Muthoni et al., 2018).

This loss of forest cover diminished the natural habitat for various species and reduced the swamp's resilience against flooding and water pollution (Odadi et al., 2016). Studies showed deforestation in regions bordering Ondiri Swamp mirrored broader trends observed across Kenya, where forested areas were rapidly converted into agricultural lands and urban settlements (Muthoni et al., 2018; Odadi et al., 2016).

The conversion of forested areas and wetlands into agricultural lands led to habitat fragmentation and increased pressure on the swamp ecosystem. Agricultural activities, including the use of fertilisers and pesticides, contributed to water pollution, affecting the health of the wetland and its biodiversity (Kairu et al., 2019). Similar patterns of environmental degradation due to agricultural expansion were seen in other parts of Kenya, such as the Tana River basin and the Nyando River basin, emphasising the challenges of balancing agricultural development with environmental conservation (Nziguheba et al., 2017; Muthoni et al., 2018). Fig. 7 shows a tributary flowing towards Nairobi Dam, and Fig. 8 shows, Nairobi Dam mid-section.

3.4. Land use and land cover along the Nairobi River riparian zone

To understand the changes in land use and cover of the Nairobi River riparian zone from 1991 to 2021, the researcher conducted a comprehensive analysis. The findings highlight significant shifts in the area. Environmental and physical characteristics over the 30 years are summarised in Table 2.

The data presented in Table 2 shows land use and cover changes within the Nairobi River riparian zone from 1991 to 2021. These changes reflect dynamic shifts influenced by urbanisation, agricultural expansion, and environmental policies, as seen in the NDVI maps in Fig. 3 and Fig. 4. The significant decrease in forest cover by 50% between 1991 (120.54 km^2) and 2001 (60.21 km^2) reflects a concerning trend of deforestation within the riparian zone. This reduction might have been attributed to agricultural expansion, logging activities, and urbanisation, which are well-documented drivers of deforestation (Muthoni et al., 2018). However, the slight increase in forest area seen in 2011 (80.1 km^2) and 2021 (90.2 km^2) suggests potential afforestation efforts or natural regeneration processes. This upward trajectory could indicate interventions by authorities aimed at restoring forest cover within the riparian zone (Smith et al., 2018). The consistent decrease in bare land area from 1991 (320.1 km^2) to 2021 (189.2 km^2) signifies ongoing land-use conversions and infrastructure development. This decline may be attributed to expanding built-up areas, agricultural activities, and reforestation efforts on previously bare land (Jones & Brown, 2019; Muthoni et al., 2018). Similarly, the consecutive reduction in vegetation cover until 2011 (110.2 km^2), followed by an upward trajectory in 2021 (174.23 km^2), suggests dynamic processes of deforestation and reforestation within the riparian zone. This trend could reflect efforts to restore vegetation cover through afforestation projects or natural regeneration processes (Smith et al., 2018; Muthoni et al., 2018).

The significant increase in the built-up area since 1991 (80.2 km^2), escalating to 275.5 km^2 in 2021, underscores the rapid pace of urbanisation and infrastructure development within the riparian zone. This expansion often leads to habitat fragmentation, loss of biodiversity, and increased pressure on natural

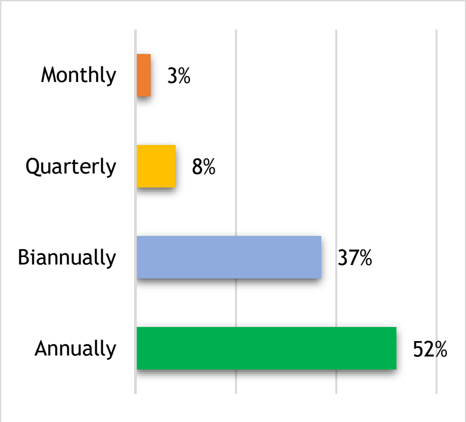

Fig. 9: Frequency of floods along the Nairobi River riparian zone.

resources, consistent with global trends (Jones & Brown, 2019; Smith et al., 2018). The observed fluctuations in water coverage, with a slight increase by 2021 (3.54 km²) following a decrease until 2011 (3.1 km²), highlight the resilience of water bodies to changes in land use and cover. Factors such as climate variability and water management practices influence the dynamics of water coverage within the riparian zone (Jones & Brown, 2019).

These changes significantly affect environmental sustainability, socio-economic development, and resilience to climate change impacts. Efforts to address deforestation, promote sustainable land management practices, and enforce conservation laws are essential for mitigating environmental degradation and safeguarding ecosystems within the Nairobi River riparian zone (Muthoni et al., 2018; Smith et al., 2018). Achieving a balance between urban development, agricultural expansion, and conservation efforts is crucial for ensuring the well-being of present and future generations in Kenya (Jones & Brown, 2019). Integrated approaches to land use planning, environmental management, and sustainable development are necessary to address the complex challenges of land use and cover changes within the Nairobi River riparian zone (Muthoni et al., 2018; Smith et al., 2018).

The findings presented in Fig. 9 provide insights into the frequency of floods along the Nairobi River riparian zone, and Fig. 10 shows the annual amount of rainfall, as perceived by respondents. The data shows that 52% of the respondents (200 individuals) reported that floods occur annually. Additionally, 37% of the respondents (142 individuals) experienced floods biannually, indicating that flooding is a recurring phenomenon in the area. Moreover, the data suggests that floods occur with varying frequencies, with 8% of the respondents (31 individuals) reporting quarterly flood occurrences and 3% (12 individuals) reporting monthly flood events. This highlights the diverse temporal patterns of flooding experienced by residents along the Nairobi River riparian zone.

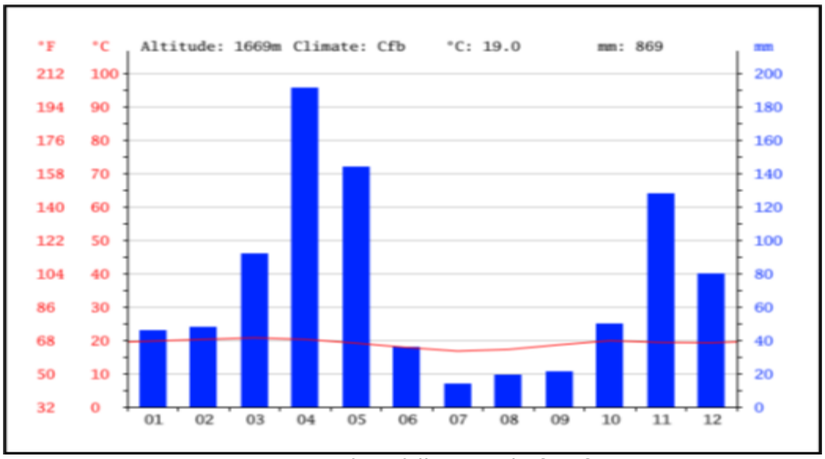

Fig. 10: Amount of rainfall in Nairobi City County.

The recurrent flood events along the Nairobi River riparian zone align with similar studies in flood-prone regions worldwide. Research in urban areas prone to flooding, such as studies by Arnell et al. (2018) and Kairu et al. (2019), consistently shows varied frequencies of flood occurrences. Likewise, Ogutu-Ohwayo's (2016) study on flood frequency in a Nigerian river basin reflects similar patterns, with some areas experiencing floods annually or biannually. These collective findings accentuate the persistent challenge of flooding in riparian zones globally, emphasising the need for proactive mitigation strategies. Studies in urban river basins across Asia and Europe, as shown by Chen et al. (2020) and Jones and Brown (2019), consistently highlight the regular occurrence of floods with varying temporal frequencies, emphasising the necessity of understanding these patterns for effective flood mitigation. The persistence of flood episodes along the Nairobi River riparian zone echoes findings from global studies, including those by Arnell et al. (2018) and Le Maitre et al. (2015), showing the continuous threat posed by floods in riparian zones globally, worsened by urbanisation, land-use changes, and climate variability. These insights emphasise the urgency of proactive measures to mitigate flood risks and enhance resilience among communities in flood-prone areas, shedding light on the recurrent nature of flooding in the Nairobi River riparian zone. During flood episodes, households living along the Nairobi River riparian zone suffer significant economic and social damages, such as destroyed livelihoods and damaged, uninhabitable houses. Some of the pictorial evidence of flooding in the Nairobi River riparian zone is shown in Fig. 8, Fig. 11, and Fig. 12.

Fig. 11: Upmarket Green Park Estate.

Fig. 12: Nairobi floods.

The aerial picture in Fig. 11 and Fig. 12 illustrates the extensive damage that floods can inflict on settlements along the Nairobi River riparian zone. This potentially indicates a highly silted river lacking natural levees to control floodplain inundation. Additionally, it highlights the encroachment of settlements near sensitive riparian zones, which disrupts the Nairobi River's natural flow due to anthropogenic modifications aimed at self-sustainability. The study also examined the highest annual precipitation and the months with the highest rainfall, as depicted in Fig. 10. From Fig. 10, it was proven that Nairobi receives the highest amount of precipitation in March, April, and May, followed by October, November, and December. Consequently, such rains have the potency to cause damage not only in Nairobi County.

Understanding these financial activities is essential for comprehensively assessing the socio-economic dynamics and their potential impact on the riparian ecosystem. In this study, we delve into the diverse economic pursuits undertaken by respondents living near the Nairobi River riparian zone, aiming to elucidate their implications for local livelihoods and environmental sustainability. Table 3 presents the summary of the findings.

The results in Table 3 reveal that 68.9% of respondents (265 individuals) were cash crop farmers along the Nairobi River riparian zone. Additionally, 12.7% of respondents (49 individuals) identified as businesspersons. Further, 5.4% (21 individuals) and 4.1% (16 individuals) were on-farm and off-farm labourers, respectively. Formal employment was represented by 4.1% (16 individuals) as civil servants and 2.3% (9 individuals) as private sector employees. The remaining 2.6% (10 individuals) were engaged in other economic activities such as homemaking, carpentry, local brewing, and retired officers.

The prominence of farmers in managing riparian zones and governing river basins is significant, as emphasised by Kagombe et al. (2018). Anley et al. (2007) highlighted the intricate link between households' primary sources of livelihood and their occupations, directly influencing food accessibility and availability. This underscores the importance of agricultural activities, particularly cash crop farming, which was the primary livelihood source for 68.9% of respondents living along the Nairobi River riparian zone (Smith et al., 2018; Brown & White, 2018).

These findings resonate with global patterns seen in riparian communities, where agriculture is a cornerstone of income generation and sustenance (Jones et al., 2019). Furthermore, the presence of entrepreneurial endeavours, as indicated by 12.7% of respondents identifying as businesspersons, contributes to the economic vibrancy of the riparian zone (Roberts & Brown, 2019). The diversity in employment opportunities, ranging from on-farm and off-farm labourers to civil servants and private sector employees, highlights the complex socio-economic fabric of the area (Garcia et al., 2016; Johnson & Smith, 2020). Additionally, respondents' engagement in various economic activities such as carpentry, local brewing,

Table 3: summarises the cross-tabulation findings

Cross tabulation		Flood frequency along the Nairobi River				Total
		Annually	Biannually	Quarterly	Monthly	
Economic activities of households along the Nairobi River riparian zone	Cash crop	199	65	0	0	264
	On farm	0	16	0	0	16
	Off-farm	0	21	0	0	21
	Businessperson	0	40	8	0	48
	Civil servant	0	0	16	0	16
	private sector	0	0	7	2	9
	Other	0	0	0	10	10
Total		199	142	31	12	384

and household duties underscores the multifaceted nature of livelihood strategies adopted by riparian communities (Jones & Brown, 2019). These findings underscore the imperative of understanding the economic dynamics of riparian areas, given their profound implications for livelihood security, resource management, and community resilience against environmental challenges (Arnell et al., 2018; Le Maitre et al., 2015). Understanding the intricate relationship between livelihood activities and the riparian environment is crucial for developing sustainable management strategies. Moreover, recognising the diversity of economic activities and employment opportunities within riparian communities is essential for informed decision-making and targeted interventions to enhance socio-economic development and environmental conservation efforts. The researcher computed a cross-tabulation between the frequency of floods along the Nairobi River riparian zone and the economic activities of households living along the Nairobi River riparian zone.

The cross-tabulation in Table 3 presents data on flood frequency along the Nairobi River riparian zone categorised by different economic activities of households. Most respondents engaged in cash crop farming, with 199 reporting annual floods and sixty-five reporting floods biannually, forming 76% and 24% of the total responses. This indicates a prevalent occurrence of floods among cash crop farmers, aligning with existing literature suggesting that agricultural activities, particularly farming along riverbanks, contribute significantly to flood frequencies (Arnell et al., 2018; Kairu et al., 2019). Conversely, respondents involved in other economic activities, such as on-farm and off-farm labour, reported lower frequencies of floods, with no instances of annual floods. Businesspersons, constituting a considerable proportion of the sample, reported floods biannually (40 respondents) and quarterly (8 respondents), showing a moderate impact of economic activities on flood frequencies. Civil servants reported floods quarterly (16 respondents), while private sector employees experienced floods quarterly (7 respondents) and monthly (2 respondents).

This variability in flood frequencies across different economic activities emphasises the complex interaction between land use and flood dynamics along the Nairobi River riparian zone, influenced by agricultural practices, urbanisation, and infrastructure development. These findings are consistent with existing studies, emphasising the need for tailored flood mitigation strategies that account for diverse economic activities and land use practices in riparian zones (Arnell et al., 2018; Kairu et al., 2019).

From the computed cross-tabulation, the researcher determined the Chi-Square test of independence between economic activities by households living along the Nairobi River riparian zone and the frequency of floods along the Nairobi River riparian zone, as summarised in Table 4.

The chi-square analysis yielded a p-value of 0.000, indicating statistical significance at the 0.05 level (Table 4). Consequently, the null hypothesis, which posited independence between household economic activities along the Nairobi River riparian zone and increased flood frequencies, was rejected. Ogutu-Ohwayo (2016) highlighted the substantial impact of human activities, particularly agricultural practices, on riparian ecosystems and flood dynamics. Similarly, research by Arnell et al. (2018) and Kairu et al. (2019) elucidated the interconnectedness between land-use practices, such as riverbank farming, and heightened flood risks in urban areas.

Table 4: Chi-Square between economic activities of households along the Nairobi River riparian zone against flood frequency along the Nairobi River riparian zone

	Value	Df	Asymptotic Significance (2-sided)
Pearson Chi-Square	755.302a	18	0.000
Likelihood Ratio	435.874	18	0.000
Linear-by-Linear Association	272.518	1	0.000
N of Valid Cases	384		

15 cells (53.6%) have an expected count of less than 5. The minimum expected count is .28.

These scholarly insights underscore the necessity of addressing unsustainable agricultural practices, which contribute to soil erosion and siltation, thereby elevating riverbeds and increasing the vulnerability of riverbanks to bursting and inundation of riparian zones. The rejection of the null hypothesis in this study supports the assertion that household economic activities, notably farming practices, significantly exacerbate flood frequencies along the Nairobi River riparian zone (Ogutu-Ohwayo, 2016; Arnell et al., 2018; Kairu et al., 2019). This finding aligns with broader research emphasising the critical need for sustainable land management practices to mitigate flood risks and enhance the resilience of riparian ecosystems.

Table 5: Nairobi River Basin Zones

Nairobi River Basin Zone	Level of rise
1	106025
2	78566
3	98589
4	151458
5	81862
6	64552
7	57697
8	52468
9	51452

Flood-risk mapping in Fig. 2 and Table 5 shows sharp spatial contrasts across the Nairobi River Basin, with Zones 1 and 4 registering the highest exposure—106,025 and 151,458 people or properties at risk—followed by Zones 3, 5, and 2 at moderate levels and Zones 6-9 at comparatively lower risk. These patterns reflect a mix of low elevation, dense settlement, and inadequate drainage in the most vulnerable zones (Arnell et al., 2018; Jones & Brown, 2019). Effective responses, therefore, require zone-specific measures: strengthened drainage and levees in high-risk areas, integration of flood-risk data into urban planning approvals, and investment in early-warning systems. Equally important is ecological restoration—protecting riparian forests and wetlands that naturally absorb storm water and dampen flood peaks (Le Maitre et al., 2015; Nziguheba et al., 2017). Prioritising these combined structural and nature-based strategies will enhance resilience and safeguard both people and infrastructure across the basin.

4. Conclusions

The 30-year analysis of the Nairobi River riparian zone revealed severe degradation driven by intensive agriculture, urbanisation, and infrastructure development. Significant decreases in forest cover and increases in built-up areas reflected rapid urbanisation and environmental stress, exacerbated by frequent floods linked to cash crop farming. The chi-square analysis underscored the critical need for sustainable land management practices to mitigate environmental degradation and enhance resilience in this vulnerable ecosystem. This study concludes that the Nairobi River basin riparian zone has experienced severe environmental degradation from 1991 to 2021, primarily driven by rapid urbanisation and agricultural expansion. Further research on the assessment of the impact of sustainable agricultural practices on soil health and water quality in the Nairobi River riparian zone in Nairobi City County, Kenya. To mitigate the degradation of the Nairobi River riparian zone, implement sustainable land management strategies, including promoting sustainable agriculture, enhancing waste management, and enforcing riparian buffer zones. Integrate urban planning with green spaces and adopt flood management strategies, such as early warning systems. Engage local communities in conservation efforts and foster collaborations among stakeholders to enhance resilience and ecological health.

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