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Original Article

Evaluation of the Role of Green Infrastructure in Mitigating Stormwater Runoff: A Case Study of Kinamba Catchment, Kigali City

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ABSTRACT

Floods are the most common natural disaster worldwide, and failing to evacuate flooded areas or entering flood waters can lead to injury or death. Kinamba catchment faces severe flood events that have led to loss of lives, crop destruction, and infrastructure damage. This study evaluated the impact of Green Infrastructure (GI) on stormwater runoff in the Kinamba Catchment, Kigali City, addressing the escalating challenges of urban flooding and water pollution exacerbated by rapid urbanization and climate change. The research aimed to assess the presence and coverage of GI, determine key factors contributing to stormwater runoff and analyze the effectiveness of GI in managing stormwater, ultimately reducing sewer overflows. Employing a mixed-methods approach, including cross-sectional, descriptive, and scenario-based modelling, the study integrated quantitative data from rainfall-runoff monitoring, GIS mapping, and hydrological modelling using the Rational methods, with qualitative insights from field observations and documentary reviews. The findings revealed a consistently low mean infiltration rate (0.38831) and high discharge variability, indicating a catchment prone to high runoff volumes and extreme events. The key findings from the Kinamba catchment showed the relationship between infiltration and discharge highlighted the complexity of hydrological interactions, while rainfall data from Gitega station underscored the importance of accurate spatial data for modelling. Land use analyses demonstrated a significant loss of green spaces, exacerbating runoff and compromising urban well-being. The study concluded that GI plays a critical role in mitigating stormwater runoff, enhancing infiltration, and reducing peak discharges, but its effectiveness is contingent upon soil properties, rainfall intensity, and maintenance. Therefore, the study recommends a comprehensive GI strategy tailored to high-risk zones, robust data collection and hydrological modelling using Gitega rainfall data, the integration of GI principles into urban planning and policy frameworks, community engagement, and sustainable funding mechanisms to enhance the resilience and sustainability of the Kinamba Catchment.

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INTRODUCTION

The world today faces numerous environmental challenges driven by rapid urbanization, concentrated economic activity, and the escalating impacts of climate change. Key concerns include flooding, water and air pollution, urban sprawl, and waste disposal, exacerbated by unplanned development and competition for space in densely populated areas (Uwera et al., 2020). These challenges are particularly acute where natural ecosystems are disrupted, leading to significant socio-environmental impacts.

Developed countries have long relied on "gray" infrastructure storm sewers, tunnels, and vaults, for stormwater management. While effective in diverting water, these systems are vulnerable to intense rainfall, resulting in overflows, flooding, and water quality degradation (Zimmerman et al., 2021). In response, green infrastructure (GI) has emerged as a sustainable alternative, supplementing traditional systems while providing ecological and social benefits. Examples include permeable pavements, rain gardens, and bioretention systems that mimic natural hydrological processes to reduce runoff and improve water quality at the source (Li et al., 2019). Globally, frameworks like Low Impact Development (LID) in the United States, Water Sensitive Urban Design (WSUD) in Australia, and the Sponge City initiative in China have integrated GI to mitigate flooding, enhance groundwater recharge, and reduce peak runoff rates (Hou et al., 2019).

However, Green Infrastructures potential remains largely unexplored in many developing nations, including Rwanda, where urbanization is rapidly outpacing infrastructure development. Across Africa, urbanization progresses faster than infrastructure expansion. Rwanda, one of Sub-Saharan Africa's fastest-growing economies, is experiencing rapid urbanization, land use changes, and increases in impervious surfaces (Czemiel Berndtsson, 2010). These changes impact urban hydrology by increasing surface runoff, reducing infiltration, and lowering groundwater recharge (Bell et al., 2016), while water quality declines (Chen et al., 2017). Climate change further heightens flood risks, compounded by heavy rainfall (Tao et al., 2014) and inadequate drainage systems (Wu et al., 2012).

Kigali, Rwanda's capital, is growing rapidly but faces vulnerabilities due to ineffective flood mitigation strategies and the degradation of natural ecosystems (Uwera et al., 2020). Expansion of built-up areas has altered hydrology, increasing runoff and flood frequency. Poor drainage systems have intensified these risks, especially in informal settlements like Kinamba Catchment (Mugisha & Nahayo, 2022). The loss of wetlands and floodplains has further reduced the city's capacity to manage stormwater effectively (Douglas et al., 2008). These vulnerabilities are expected to worsen with continued climate change (Benitez, 2020).

Heavy rainfall events, such as those on December 25, 2019, caused severe flooding, resulting in

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casualties, destruction of homes, and loss of crops (Alemayehu, 2020). Overwhelming stormwater runoff during such events exceeds sewer system capacities, polluting local water bodies (Tian, 2011), disturbing watershed hydrology, and degrading drinking water over time. Kigali's urban hydrology is heavily impacted by increased impervious surfaces, reduced infiltration (Czemiel Berndtsson, 2010), and insufficient drainage (Bell et al., 2016), contributing to greater surface runoff, lower groundwater recharge, and water quality deterioration (Chen et al., 2017).

Green infrastructure presents a promising solution for Kigali's stormwater challenges. By incorporating natural or semi-natural features, GI practices can reduce surface runoff (Liu et al., 2019), enhance stormwater quality (Ahiablame et al., 2012), and maintain pre-development hydrological conditions. However, limited research exists on GI application in Rwanda, particularly in vulnerable areas like Kinamba Catchment. Understanding its impact is crucial for sustainable urban planning and effective stormwater management.

The Kinamba area, with its rapid urbanization, has significantly altered natural hydrology, leading to increased runoff and frequent flooding. Expansion, especially in informal settlements, has transformed wetlands and floodplains into built-up areas, reducing stormwater management capacity. Existing drainage systems are inadequate, causing recurring flood hazards (Gasasira Higiro, 2020; Douglas et al., 2008). Although GI is globally recognized as a sustainable solution for stormwater management, its application in Rwanda remains underexplored.

Therefore, this study aims to evaluate the role of green infrastructure in mitigating stormwater runoff within Kinamba Catchment, Kigali City. The specific objectives are:

- To assess the presence and coverage of green infrastructure within the Kinamba catchment.
- To assess the key factors contributing to stormwater runoff in the Kinamba catchment.
- To analyze the relationship between green infrastructure and stormwater runoff in Kinamba.

MATERIAL AND METHOD

Study Area

The study area is the Kinamba catchment, located between three districts (Nyarugenge, Gasabo and Kicukiro District) in Kigali city and we emphasized as main flood hotspots such as Gisozi and Kinamba, which were chosen as a case study for its high susceptibility to flooding due to increase of stormwater runoff, Rapid urbanization, coupled with inadequate drainage systems, Impervious surfaces and land-use changes, contributes to the severity of flooding in this area.

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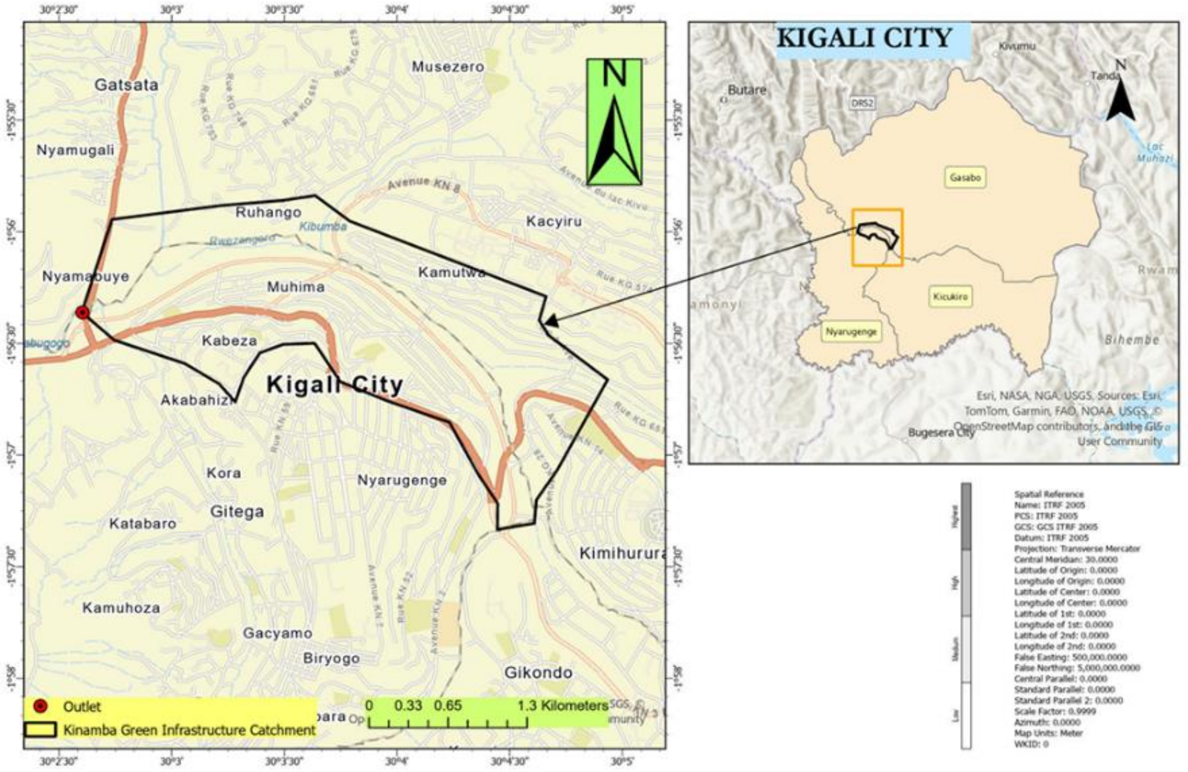
Figure 1: Study Area Map



Source*: Researcher, 2025.*

Research Design

The research design for this study employed a robust mixed-methods approach, combining cross-sectional, descriptive, and scenario-based modelling to comprehensively evaluate the impact of Green Infrastructure (GI) on stormwater runoff within the Kinamba Catchment. A cross-sectional design facilitated the analysis of spatial and hydrological data from diverse sources, including GIS mapping, rainfall-runoff monitoring, and historical records from the Rwanda Water Board (RWB) and the Rwanda Meteorology Agency (RMA), enabling the assessment of peak flow rates, runoff patterns, and GI effectiveness at a specific point in time. The descriptive component provided a baseline understanding of existing GI implementation through a detailed assessment of its presence and coverage, while scenario modelling, utilizing collected data and hydrological models, explored the potential impact of different GI strategies on runoff volume, peak discharge, and infiltration rates. This multifaceted approach ensured a holistic examination of sustainable flood management strategies, directly addressing the study's objectives of assessing GI presence, identifying runoff contributors, and analyzing GI effectiveness.

Complementing the mixed-methods approach, a quantitative research paradigm was adopted, emphasizing numerical data collection and analysis. Methods such as the Hydrological Model approach were employed to estimate peak flow rates and Runoff volume, while GIS mapping provided detailed insights into catchment characteristics. Rainfall and runoff monitoring offered empirical validation, and a thorough literature review contextualized the findings. The descriptive design further enhanced the study's rigour by systematically documenting and analyzing the existing conditions of stormwater runoff and flooding in the Kinamba catchment. This design facilitated the collection of comprehensive data on hydrological characteristics, land use patterns, and community perceptions through field observations, creating a detailed profile of the catchment area. This profile served as a foundation for subsequent analyses

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and recommendations, ensuring a structured evaluation of GI's role in stormwater management and a holistic understanding of the challenges and opportunities within the Kinamba catchment.

Data Sources

Both secondary and primary data were utilized in the study. Secondary data were obtained through a literature review of books, articles, and reports relevant to stormwater runoff and green infrastructure. Sources included government documents, manuals, journals, and internet resources. Primary data were collected through direct field observations of real-time conditions in the Kinamba Catchment.

Historical flood event data and rainfall records, Discharge and Infiltration data, were obtained from the Rwanda Water Board (RWB) and the Rwanda Meteorology Agency (RMA). Additional secondary data, including Land Use and Land Cover (LULC) information from ESRI Rwanda, Google Earth, and USGS maps, as well as Digital Elevation Models (DEM) and soil type data, were used to derive critical spatial analyses.

Data Collection Techniques

Field Observation

Field observations were crucial for collecting primary data on stormwater runoff, flooding, and drainage system performance. This involved visiting flood-prone areas identified through GIS mapping, inspecting drainage infrastructure, analyzing flood marks, and assessing land-use impacts on stormwater dynamics. GIS-based visual mapping supported spatial analysis and GI planning, helping identify priority areas for flood mitigation.

Documentary Review

Secondary data sources provided essential historical stormwater event data, rainfall intensity and frequency information, and land use/land cover analysis. Rainfall data from RMA for various return periods enabled the modelling of runoff patterns and peak discharge levels. Flood impact records from RWB offered insights into past storm events, while topographic and soil datasets aided in delineating drainage patterns, evaluating infiltration rates, and assessing GI feasibility.

Data Analysis

The impact of GI on stormwater runoff was evaluated using both hydrological modelling and GIS analysis. The Rational Method was applied to estimate peak runoff, using the formula $Q = KCIA$, where Q is peak runoff, K is a unit conversion constant, C is the runoff coefficient, I is rainfall intensity, and A is the catchment area. Rainfall intensity data were sourced from RMA, while land cover and soil data determined appropriate runoff coefficients.

GIS-based analysis included the delineation of watershed boundaries using DEMs, slope analysis, drainage network identification, and land use/land cover mapping. Hydrological soil group classification was conducted to assess infiltration capacity. The analysis revealed a progressive loss of green spaces from 2000 to 2024, resulting in higher runoff volumes and reduced infiltration rates.

Research Reliability and Validity

Reliability and validity were ensured by utilizing verified data sources, such as rainfall data from RMA and hydrological data from RWB. The Rational Method and GIS tools were applied rigorously to guarantee precision in runoff estimation and spatial analysis. Comparative validation against existing literature strengthened the credibility of the findings and recommendations.

Ethical Considerations

Ethical Use of Data

Ethical considerations guided every stage of the study. Secondary data were properly cited, and sensitive information was handled responsibly. The research adhered to environmental and hydrological standards, aiming to contribute positively to sustainable urban development. Scientific rigour, transparency, and minimization of biases were prioritized, with findings clearly documented and shared with policymakers to support practical application. The study emphasized the broader environmental and community implications of green infrastructure interventions in addressing urban stormwater challenges.

RESULTS AND DISCUSSION

This section presents the results of the study and discusses the key findings. It focuses on the analysis of factors contributing to stormwater runoff in the Kinamba Catchment and examines the relationship between green infrastructure and stormwater management. The results are interpreted in light of existing literature and contextualized within Kinamba's urban and hydrological landscape.

To Assess the Presence and Coverage of Green Infrastructure within the Kinamba

Types of Green Infrastructure Identified

According to the field observations and **Figure 2** below (showing different existing green infrastructure present in the Kinamba area), there is clear evidence of insufficient and poorly functioning green infrastructure. This includes degraded drainage channels, a lack of adequate rain gardens, and widespread impermeable pavements. These conditions reduce the catchment's ability to absorb and slow stormwater runoff, intensifying flood risks and water quality challenges.

Figure 2: Existing Green Infrastructure in Kinamba Area

Source, *Author 2025*

Figure 2. illustrates the current distribution of green infrastructure within the catchment. The dominant GI elements include grassland patches interspersed with tree-covered areas, concentrated primarily in less densely built-up regions. While these green spaces are present, their spatial coverage is limited and fragmented, suggesting potential challenges in providing continuous ecological services for effective stormwater management.

Furthermore, beyond hydrological benefits, green infrastructure in Kinamba Catchment contributes to ecosystem services, urban cooling, and aesthetic enhancement. Trees and green spaces not only absorb excess rainwater but also reduce the urban heat island effect and provide recreational benefits for the community. The study suggests that investing in green infrastructure is cost-effective in the long term, as it minimizes the need for expensive drainage systems and flood control measures. However, successful implementation requires policy support, stakeholder engagement, and proper maintenance to ensure sustained benefits, and **Figure 3** below showcases different Green Infrastructure which can be introduced in Kinamba area.

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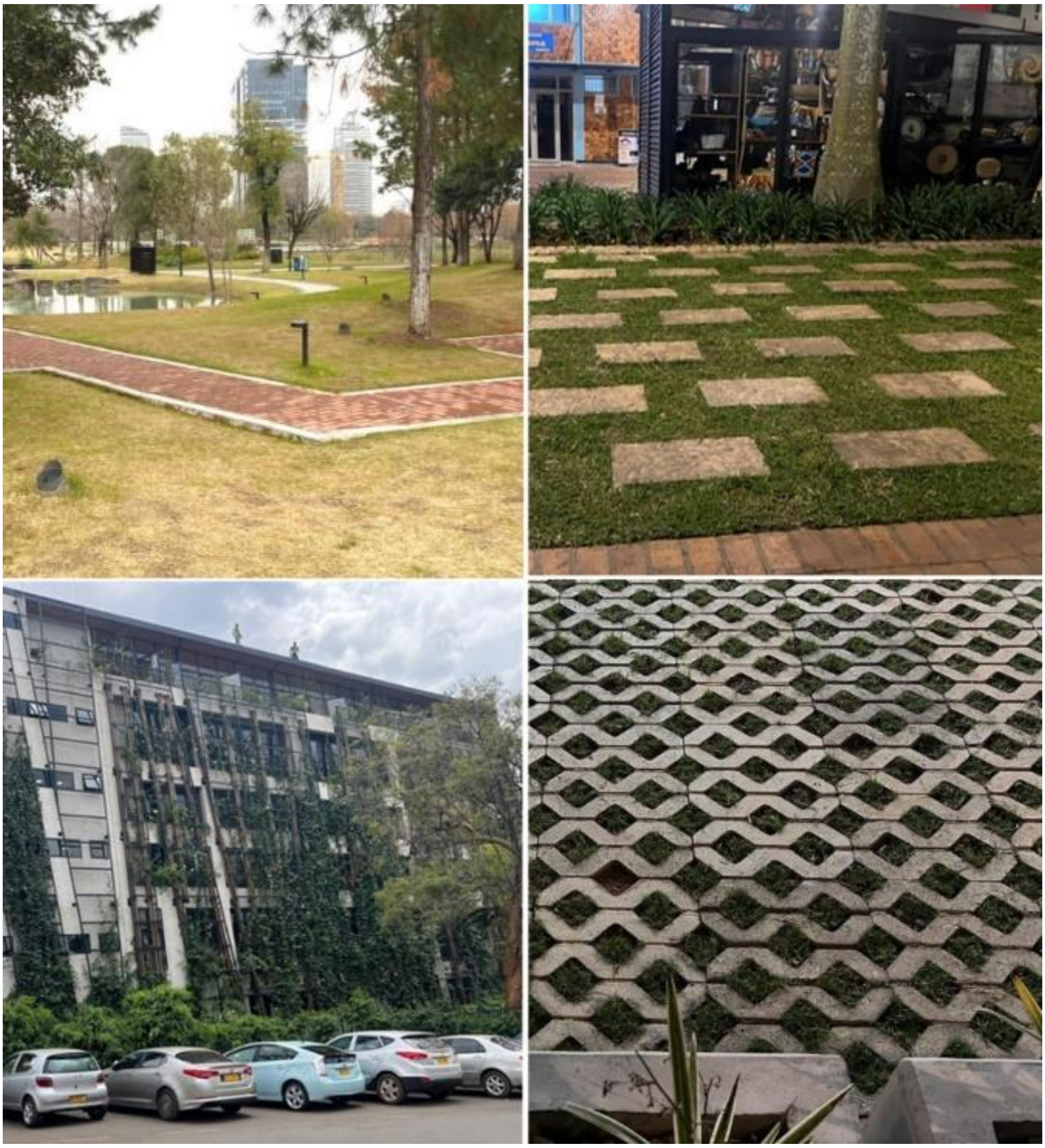
Figure 3: Different Types of Green Infrastructure Which Can Be Introduced in Kinamba Area



Source, *Author 2025*

Urbanization and Land Cover Changes (2017–2023)

Land use and land cover changes between 2017 and 2023 provide insight into urbanization patterns and their implications for green infrastructure. As shown in **Figure 4.a)** and **Figure 4.b),** the built-up area in Kinamba decreased from 78% in 2017 to 64% in 2023. Concurrently, tree cover increased from 3% to 12%, while grassland areas decreased slightly from 15% to 10%. Cropland declined from 8% to 5%, and water coverage diminished from 0.5% to 0.1%.

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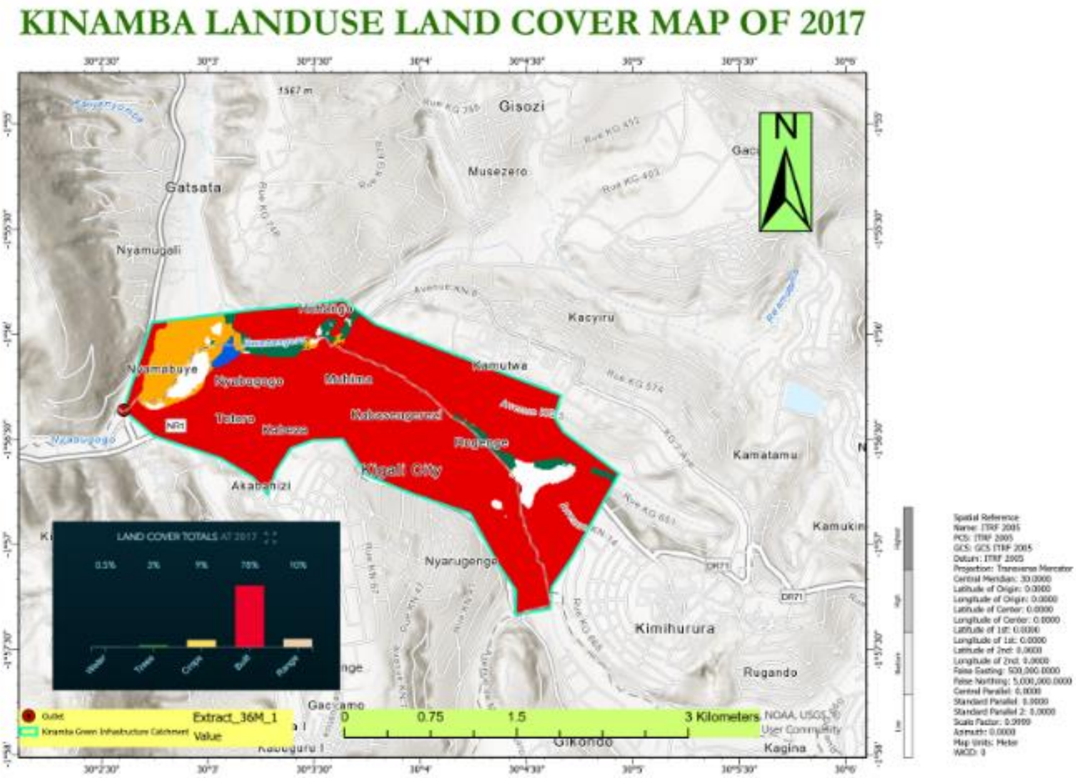
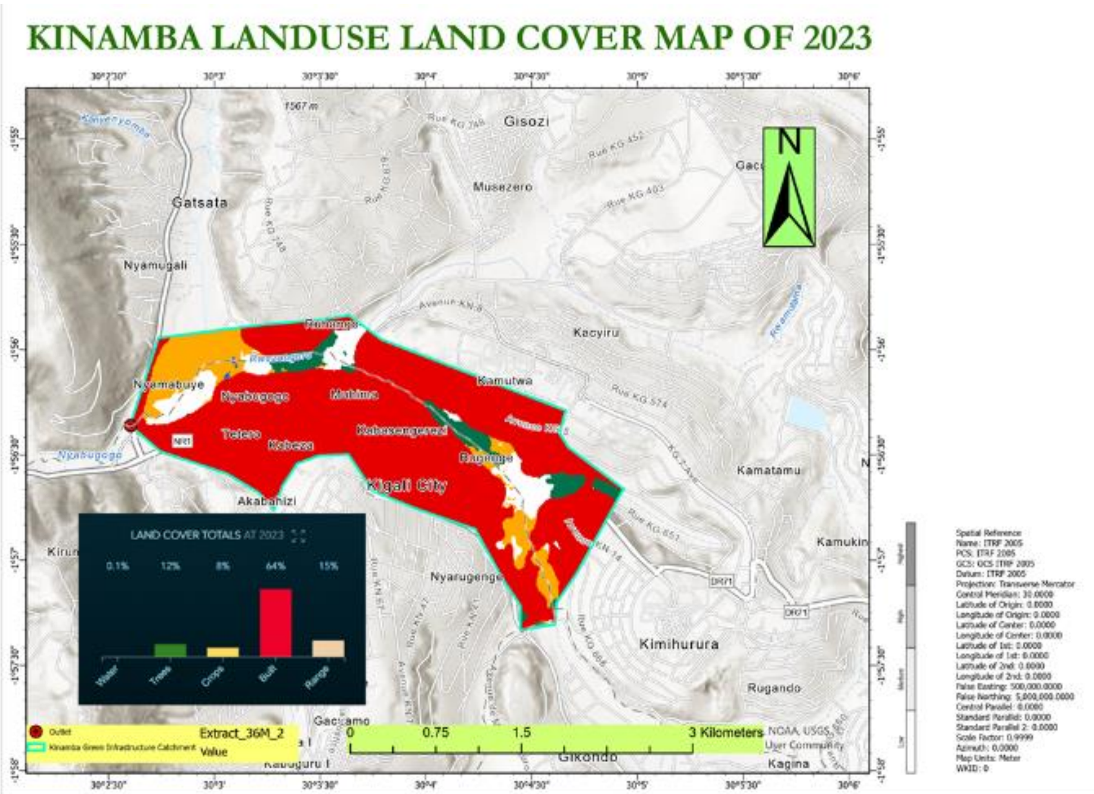
Figure 4: a) Kinamba Land Use Land Cover Map of 2017



Source, *Author 2025*

Figure 4: b) Kinamba Land Use Land Cover Map of 2023



Source: *Author's analysis (2025)*

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These trends indicate a gradual shift from impervious surfaces towards increased vegetative cover, particularly through afforestation and reforestation initiatives. Although this expansion of tree cover is a positive development for enhancing infiltration and reducing runoff, the decline in grassland and cropland may partially offset these benefits. The reduction in built-up areas suggests a reversal of some urban expansion, potentially opening opportunities for further green infrastructure interventions.

Table 1, below presents data comparing land cover percentages for two different periods or locations in Kinamba. From the analysis of the land covers and their changes, we can observe several key patterns and trends.

Table 1: Changes in Land Use and Land Cover in Kinamba Catchment (2017–2023)

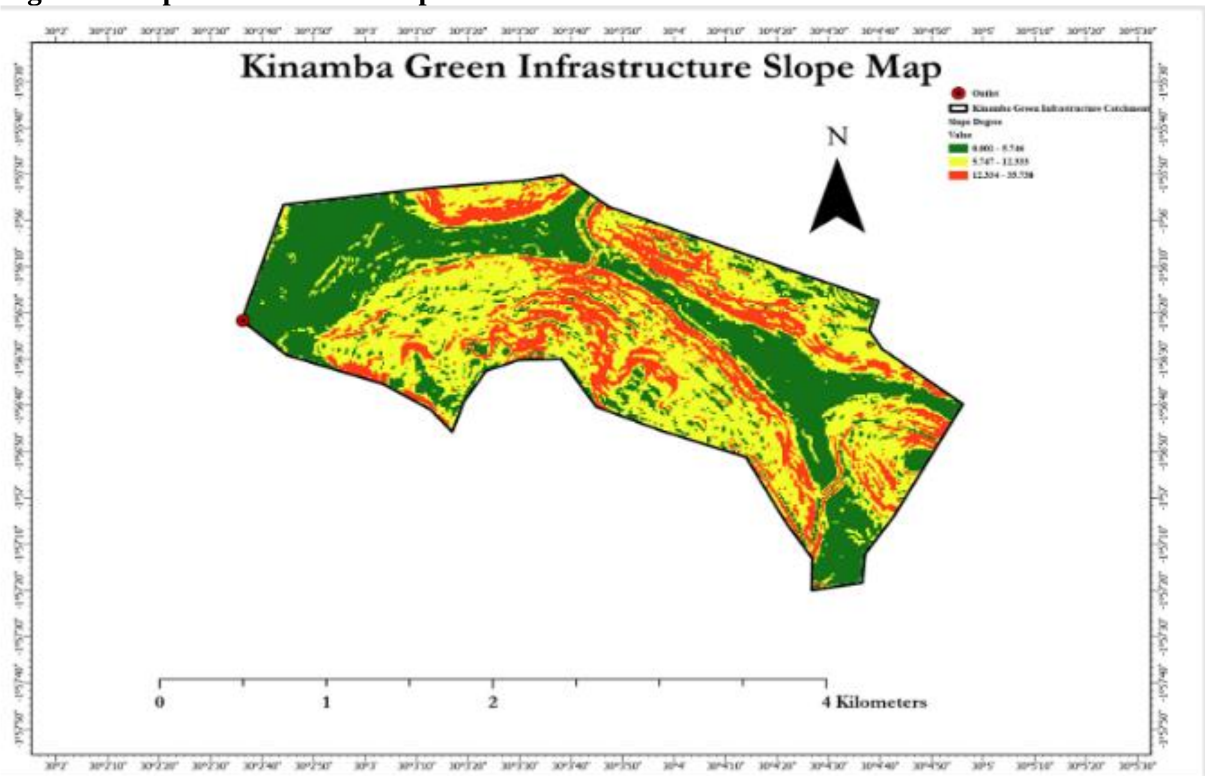
Land Use Category	2017 (%)	2023 (%)
Built-up area	78	64
Tree cover	3	12
Grassland	15	10
Cropland	8	5
Water bodies	0.5	0.1

Source: *Author's analysis (2025)*

Catchment Characteristics Influencing Green Infrastructure Functionality

Slope analysis Figure 5. shows that the Kinamba catchment is characterized by steep slopes, particularly in upstream areas. Steeper terrain increases the velocity of surface runoff, reducing opportunities for water infiltration even in vegetated zones. According to the slope classification, approximately 42.5% of the catchment falls within a slope range of 5–10%, while 12.8% exceeds a slope of 10%.

Figure 5: Slope Classification Map of Kinamba Catchment



Source: *Author's analysis (2025)*

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The vegetation cover in Kinamba catchment has undergone significant changes between 2017 and 2023, as presented in Table 2 below and it is another important characteristic influencing stormwater runoff in Kinamba. The presence of vegetation such as grass, shrubs, and trees can help to slow down the flow of water, allowing more of it to infiltrate into the soil. In areas with dense vegetation cover, the canopy and root systems play a crucial role in reducing the impact of stormwater runoff by trapping water and reducing surface water flow. However, areas with sparse or disturbed vegetation cover are more susceptible to increased runoff and soil erosion. Deforestation or improper land use can exacerbate this problem, leading to reduced water retention capacity and increased runoff. The table below reflects how green infrastructure improvements (increased vegetation and grassland) positively affect stormwater management, while the loss of water bodies may increase runoff and flooding risks.

Table 2: Vegetation Cover Changes in Kinamba (2017–2023)

Vegetation Type	2017 (%)	2023 (%)
Tree Cover	3%	12%
Grassland	10%	15%
Cropland	5%	8%
Water Bodies	0.5%	0.1%

Source*: Author's analysis (2025)*

Land use and urban development also contribute to the catchment characteristics that affect stormwater runoff in Kinamba. As urbanization increases, impervious surfaces such as roads, buildings, and pavements are introduced, significantly reducing the natural infiltration of water into the soil. This causes an increase in surface runoff, as water is unable to penetrate the ground and is instead channelled into drainage systems.

Consequently, the urbanized areas of Kinamba experience higher volumes of runoff during storms, which can lead to flooding, damage to infrastructure, and water quality issues due to the transport of pollutants from urban surfaces. Proper planning and the incorporation of green infrastructure can help mitigate the negative effects of these changes.

Key Factors Contributing to Stormwater Runoff in the Kinamba Catchment

Runoff Volume

The analysis of runoff volume in Kinamba Catchment, Kigali, indicates significant variations in surface runoff due to urbanization and land use changes. The increased impervious surfaces, such as roads and buildings, have reduced the land's ability to absorb water, leading to higher runoff during rainfall events. The water that doesn't infiltrate into the ground travels across the landscape, eventually flowing into rivers, streams, or other bodies of water.

The research revealed significant variability in discharge, with values ranging from a minimum of 0 m^3/s to a maximum of 555.401 m^3/s, and a mean discharge of 9.961 m^3/s, indicating notable fluctuations in runoff due to varying rainfall intensity and seasonal changes. The average infiltration rate was 0.39, suggesting limited water absorption and contributing to higher surface runoff.

Over the period from 2017 to 2023, land use changes in the catchment saw built-up areas increase to 64% of the total land area, correlating with the rise in runoff, while green spaces grew from 3% to 12%, but the overall capacity for infiltration remained low due to urbanization. These findings highlight the need for improved stormwater management to mitigate the increased runoff in the catchment.

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Table 3: Analysis of Runoff Volume in the Kinamba Catchment

Parameters	Value
Minimum Discharge	0 m³/s
Maximum Discharge	555.401 m³/s
Mean Discharge	9.961 m³/s
Average infiltration rate	0.39
Built-up Area (2017–2023)	64%
Green Space (2017–2023)	3% to 12%

Source*: Rwanda Meteorological Agency (2025)*

Peak Discharge

As presented in **Table 3,** water discharge, or stream flow, is a critical hydrological parameter that represents the volume of water moving through a river or stream over a given period. It is measured in cubic meters per second (m³/s) or litres per second (L/s), depending on the scale of observation. Discharge is affected by precipitation, infiltration, and runoff.

Higher discharge generally means that there was more runoff during the given period. The table presents the discharge statistics with a mean of 9.961 m³/s and a range of 555.401, which indicates substantial variation in discharge. A high discharge value suggests significant runoff in some cases, particularly when infiltration is unable to absorb all the precipitation.

Table 4: Discharge results of Kinamba Catchment

N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Discharge	20352	0	555.401	9.961	19.34784	374.3391

Source*: Rwanda Meteorological Agency*

The variance in discharge is quite high (**374.3391**), indicating considerable fluctuations in the volume of water flowing at different times, which could be due to seasonal changes, soil properties, vegetation cover, or other environmental factors that influence infiltration and runoff.

Interpretation of Discharge Variability

The high range observed in the discharge values could be attributed to differences in precipitation events, surface runoff characteristics, and the effectiveness of green infrastructure (GI) interventions in the catchment area.

Since stormwater runoff is heavily influenced by rainfall intensity, urbanization, and soil permeability, the fluctuating discharge values indicate that external factors such as land cover and drainage system efficiency play a crucial role in the stormwater dynamics of Kinamba Catchment.

The standard deviation of **19.34784** suggests that, while there is variation in discharge, most of the values are relatively close to the mean. However, the high variance **(374.3391)** indicates the presence of extreme discharge values, likely due to heavy storm events or inefficient absorption by green infrastructure. These variations may suggest that green infrastructure has not yet fully mitigated stormwater runoff or that additional measures are necessary to enhance its efficiency.

Implications of Discharge Trends for Green Infrastructure Effectiveness

The observed discharge data underscores the importance of evaluating the performance of green infrastructure interventions. If green infrastructure effectively reduces peak runoff, we would expect a more consistent and lower discharge rate over time. However, the considerable variability suggests that the existing green infrastructure measures may be inadequate or that additional factors are influencing runoff behaviour.

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Infiltration and Retention Rate

Infiltration refers to the process by which water enters the soil from the surface and moves through the subsurface layers. Understanding infiltration rates is crucial for hydrological studies, water resource management, and environmental sustainability. The dataset analyzed consists of **51,616** observations, providing valuable insights into infiltration characteristics.

Overview of Infiltration Data

As presented in Table 3.4, the infiltration data exhibits a relatively narrow range **(5.507)** and a low standard deviation **(0.001104),** indicating consistent infiltration rates across the catchment, which is important for understanding the soil's ability to absorb water. The mean infiltration rate **(0.38831)** suggests a moderate baseline infiltration.

Table 5: Infiltration results of Kinamba Catchment

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Infiltration	51616	5.507	1.548	3.959	0.38831	0.001104	0.063

Source: *Rwanda Meteorological Agency*

These baseline statistics are crucial for evaluating the effectiveness of green infrastructure interventions (Objective iii) in altering these parameters, with the aim of increasing infiltration and reducing discharge to mitigate stormwater runoff. Further analysis will involve correlating these statistics with GI coverage (Objective i) and other catchment factors to assess their impact on stormwater management.

Infiltration Analysis

The descriptive statistics for infiltration data, characterized by a substantial sample size of 51,616 observations, suggest a robust dataset capable of yielding reliable statistical inferences. The range of 5.507, derived from a maximum of 3.959 and a minimum of 1.548, indicates a moderate spread of infiltration values, implying variability in the catchment's capacity to absorb water.

However, the mean infiltration rate of 0.38831 points to a generally low overall infiltration capacity within the Kinamba catchment. The exceptionally low standard deviation of 0.001104 reflects minimal variability in infiltration rates across the dataset. This suggests a consistent, albeit low, infiltration pattern, potentially indicative of dominant land cover types or soil characteristics that consistently limit water absorption. The relatively low variance of 0.250932 further corroborates this observation.

Interpretation and Implications

The low mean infiltration, coupled with minimal variability, suggests that the Kinamba catchment is inherently prone to high runoff volumes, exacerbating the risk of sewer overflow and flooding. This underscores the critical need for green infrastructure interventions that can effectively enhance infiltration rates.

The consistency of low infiltration rates across a large dataset implies that localized GI solutions might not be sufficient; rather, a comprehensive, catchment-wide approach is necessary. The low variability also hints at potential constraints imposed by urbanization and land cover changes, such as extensive impervious surfaces, which may override localized infiltration improvements.

Several Potential Explanations for this Variability Include:

- **Insufficient green infrastructure coverage**: The extent of green infrastructure in Kinamba Catchment may not be large enough to absorb or delay runoff effectively.
- **Soil saturation and permeability**: If the soil in the area has low permeability or is frequently saturated, its capacity to absorb additional runoff diminishes, leading to higher discharge.
- **Storm intensity and frequency**: Intense rainfall events may overwhelm existing green

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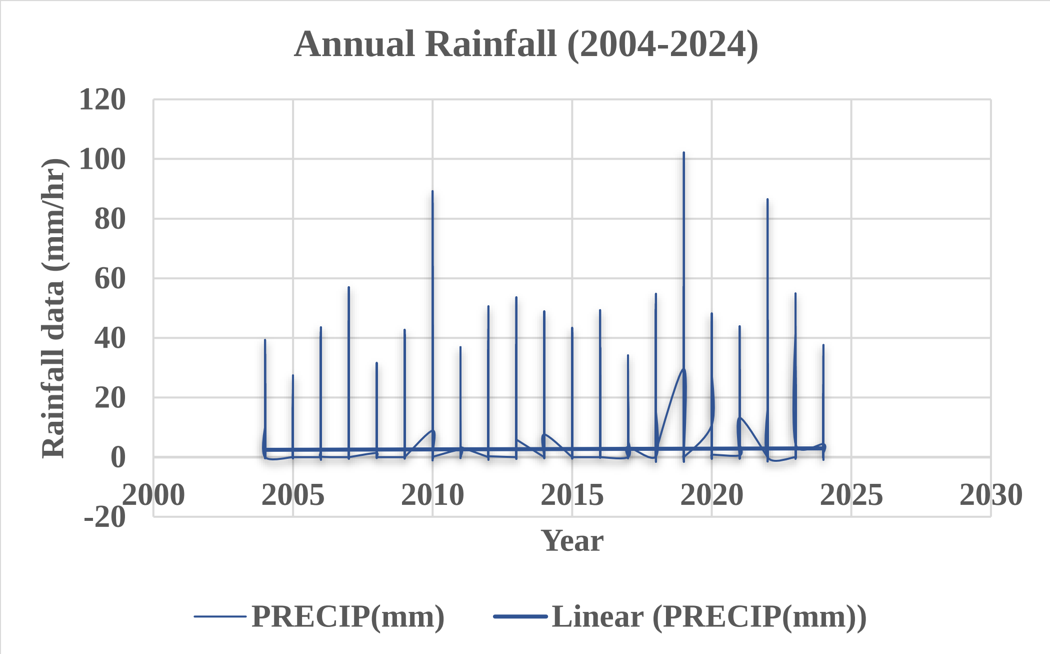
infrastructure, causing excess stormwater to flow directly into drainage systems.

- **Urbanization and impervious surfaces**: The presence of impervious surfaces (e.g., roads, buildings, and paved areas) limits the effectiveness of green infrastructure by preventing water infiltration.

Rainfall Intensity

Rainfall intensity refers to the rate at which rain falls, typically expressed in millimetres per hour (mm/h). It is an important factor in hydrology because it determines how much water will be available for infiltration into the ground and how much will contribute to surface runoff, potentially causing discharge in streams, rivers, or other water bodies.

Figure 6. Annual Rainfall (2004-2024), source: Author, 2025



Source: *Rwanda Meteorological Agency (2025)*

The results of the rainfall data analysis from Kigali Aero, as shown in Figure 6, indicate the increase in rainfall over different years. The peak daily rainfall recorded on December 25, 2019, was 102.2 mm/hr. This peak corresponds to the specific date mentioned in the literature review and the background of the study, highlighting the significance of this event in relation to stormwater management challenges in the Kinamba Catchment.

Such intense rainfall events can lead to increased runoff, exacerbating flooding risks and underscoring the need for effective green infrastructure interventions to mitigate these impacts.

Hydrological Characteristics of Kinamba

Kinamba's hydrology is influenced by various factors, including rainfall patterns, drainage systems, and local geological formations. The area experiences seasonal variations in precipitation, which significantly impact surface water flow and groundwater recharge. During the rainy season, runoff increases due to limited infiltration in some areas, potentially leading to localized flooding. Conversely, in dry periods, water availability decreases, affecting both surface and underground water sources.

The drainage system in Kinamba is a mix of natural streams and human-made infrastructure. Some areas may have poor drainage due to urbanization, leading to water stagnation and soil erosion. Additionally, the underlying geology

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plays a role in water retention and movement. Permeable soil and rock formations enhance groundwater recharge, while impermeable surfaces, such as roads and buildings, contribute to rapid runoff.

Recent land cover changes in Kinamba from 2017 to 2023 have had notable effects on runoff and infiltration rates. The built-up area decreased from 78% in 2017 to 64% in 2023, primarily due to informal settlements where increased stormwater runoff was negatively affecting the community. This shift reflects efforts to address these issues, potentially by moving away from unsustainable urban development and improving drainage infrastructure.

Meanwhile, green space increased from 3% to 12%, which could reduce runoff and improve water absorption. The average infiltration rate in the area is approximately 0.39 mm/h, which is relatively low but could improve with further greening and conservation efforts.

In terms of water quality, pollution from domestic and industrial waste is a concern, affecting water safety. The drainage and runoff systems need improved management to ensure clean water availability. Proper stormwater and wastewater management are crucial to maintaining the hydrological balance in the region.

The hydrology of Kinamba is shaped by a dynamic interplay of natural and human-induced factors. The reduction in built-up areas, particularly in informal settlement zones affected by stormwater runoff, and the increase in green spaces suggest that sustainable urban planning and conservation practices could mitigate runoff and flooding risks. Moreover, managing water quality and drainage systems is vital to ensuring the availability and safety of water resources in the catchment.

To Analyze the Relationship between Green Infrastructure and Stormwater Runoff in Kinamba

One of the major benefits of green infrastructure in Kinamba is its ability to reduce flooding, which is a common problem in urban areas with inadequate drainage. Traditional stormwater management methods, such as concrete drains, often become overwhelmed during heavy rainfall, leading to localized flooding. In contrast, green infrastructure facilitates natural water absorption into the ground, replenishing groundwater supplies while decreasing the burden on conventional drainage systems. However, the efficiency of these measures may vary depending on the scale of implementation and the commitment of local authorities to maintaining the infrastructure.

According to **Figure 4.a** and **Figure 4.b** the Land Use and Land Cover (LULC) results indicate inadequate green infrastructure (GI) within the Kinamba catchment. Data from 2017 to 2023 highlights several significant changes:

- Water coverage has decreased from 0.5% to 0.1%
- Tree coverage has noticeably increased from 3% to 12%
- Cropland has decreased from 8% to 5%
- The built-up area has reduced substantially from 78% to 64%
- Grassland has slightly decreased from 15% to 10%

These changes reflect a shift in the landscape that may impact stormwater management and the effectiveness of green infrastructure, suggesting a need for strategic planning in urban development.

Furthermore, the infiltration rate and discharge results illustrate the challenges faced in the Kinamba catchment. The discharge statistics show a mean of **9.961 m^3/s** with a range of **555.401 m^3/s,** compared to a mean infiltration rate of **0.38831 mm/hr** with a narrow range of **5.507 mm/hr.** This disparity indicates that while discharge levels are high, the capacity for infiltration remains limited. Such findings underscore the urgent need for enhanced green infrastructure solutions to effectively manage stormwater, thereby mitigating flooding risks and improving overall water management in the Kinamba catchment.

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Table 6: Comparison of parameters with and without GI intervention

Parameter	Without GI	With GI
Runoff Volume (m^3)	High	Reduced
Peak Flow Rate (m^3/s)	High	Lower
Infiltration Rate (mm/hr)	Low	Higher
Groundwater Recharge (%)	Minimal	Increased
Possibility of Flooding	High	Reduced
Water Quality (Pollutant Load: sediments, nutrients, contaminants)	Poor	Improved (natural filtration)

Source: Author's analysis (2025)

As shown in **Table 6,** green infrastructure plays a vital role in improving water quality by filtering out pollutants before they enter rivers and water bodies. In Kinamba, where pollution from urban activities is a growing concern, vegetative buffers and bioretention systems help remove contaminants such as oil, heavy metals, and sediments from stormwater. This enhances the overall health of aquatic ecosystems and reduces the risk of waterborne diseases in communities relying on local water sources. Nevertheless, the long-term success of these systems requires regular monitoring, community awareness, and integration with broader urban planning strategies.

In **Table 7,** a list of green infrastructure practices is presented, describing five GI practices that demonstrate their significant impact on the reduction of stormwater runoff due to their implementation. These interventions not only help mitigate flooding and erosion but also enhance water quality, promote biodiversity, and provide aesthetic and recreational benefits, making them highly beneficial for the Kinamba Catchment.

Table 7: Green Infrastructure Practices and Their Applicability

Green Infrastructure Type	Function	Applicability to Kinamba
Green Roofs	Absorbs rainfall, reduces heat, and mitigates runoff.	Reduces the amount of runoff that rushes into a watershed all at once.
Permeable Pavements	Increases infiltration and reduces surface runoff.	Suitable for pathways and parking areas.
Rain Gardens & Planter Boxes	Captures runoff, filters pollutants	Ideal for residential and community spaces.
Bioswales	Slows runoff, filters sediments and contaminants.	Suitable for roadside drainage areas.
Urban Tree Canopy	Increases water retention and promotes infiltration.	Applicable in open public spaces.

Source: Author's analysis (2025)

Despite its benefits, the adoption of green infrastructure in Kinamba faces challenges, including limited funding, lack of technical expertise, and resistance to change from conventional stormwater management approaches. Ensuring its effectiveness requires coordinated efforts among government agencies, environmental organizations, and residents to promote sustainable practices. Policymakers must prioritize investment in green infrastructure while encouraging public participation in its implementation and maintenance. With proper planning and continued investment, green infrastructure can serve as a cost-effective, environmentally friendly solution to stormwater management challenges in the Kinamba catchment.

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Overall, the findings of the study reveal the significant impact of green infrastructure (GI) on stormwater runoff in the Kinamba Catchment, Kigali City, revealing critical insights into the catchment's hydrological dynamics, highlighting the significant influence of urbanization and climate change, which have led to increased runoff, flooding, and water pollution.

These outcomes align with findings by Munyaneza (2011) and The World Bank (2019), which emphasized the contribution of rapid urban growth and inadequate infrastructure to stormwater management challenges in Kigali. Analysis of infiltration and discharge data revealed a consistently low mean infiltration rate, indicating a limited capacity for water absorption across the catchment. This, coupled with high discharge variability, suggests the occurrence of extreme runoff events and the potential inadequacy of existing drainage systems, similar to what Kamayirese and Ntwali (2024) found in Nyarugenge District, where GI integration proved essential in reducing flood risk.

Rainfall data from neighbouring stations, particularly Gitega, underscored the importance of spatial rainfall variability and accurate data for hydrological modelling. The importance of localized data and climate sensitivity in GI performance has also been highlighted in studies by Mugume et al. (2024), who identified climate-adapted blue-green infrastructure (BGI) strategies as vital for effective urban resilience. Land use analyses, comparing catchment conditions in 2000 and 2024, vividly illustrated the progressive loss of green spaces, contributing to increased runoff and compromised urban well-being. Similar land cover change impacts on runoff dynamics were observed by Uwera et al. (2020), who noted the ineffectiveness of existing GI due to poor spatial distribution and planning.

The study identified that residential, agricultural, commercial, industrial, and transportation zones within the Kinamba Catchment suffer from a significant lack of green infrastructure, exacerbating stormwater management challenges. These findings mirror broader patterns in Sub-Saharan Africa, where Zimmerman et al. (2021) and Nkurunziza et al. (2023) emphasized how weak institutional frameworks and funding constraints hinder the implementation of sustainable drainage systems (SUDS) and GI solutions. The effectiveness of GI in reducing runoff is contingent upon factors such as soil properties, land cover, rainfall intensity, and maintenance practices. The study found that urban compaction and clayey soils may limit infiltration rates, while heavy rainfall events can overwhelm GI systems, challenges also reported by Venkataramanan et al. (2019) in global urban GI applications.

The integration of GI requires robust policy support, community engagement, and strategic urban planning. The findings highlight the critical role of GI in enhancing infiltration, reducing peak discharge, and improving water quality, ultimately contributing to the long-term sustainability and resilience of the Kinamba Catchment. The study supports calls by Arthur and Hack (2022) for multifunctional GI that contributes not only to flood mitigation but also to ecological and social co-benefits. This research contributes uniquely by focusing on the practical application of green infrastructure within the specific hydrological and urban dynamics of the Kinamba Catchment, offering localized strategies to enhance Kigali's stormwater resilience. It advocates for a holistic approach to stormwater management that integrates green infrastructure solutions with conventional drainage systems, while emphasizing the need for further research to optimize these interventions and effectively mitigate the adverse impacts of urbanization and climate change.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study's comprehensive evaluation of green infrastructure (GI) impacts on stormwater runoff in the Kinamba Catchment, Kigali City, reveals a complex hydrological landscape shaped by rapid urbanization and climate variability.

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The consistent, yet low, mean infiltration rate (**0.38831**) across a large dataset (**N = 51,616**) underscores the catchment's inherent susceptibility to high runoff volumes—a condition exacerbated by extensive impervious surfaces and soil compaction. Simultaneously, the significant variability in discharge data, marked by a wide range (**555.401**) and extreme values, reflects the dynamic nature of stormwater events, influenced by high rainfall intensities, insufficient GI coverage, and potentially the limitations of existing conventional drainage systems. The statistical significance of these findings further emphasizes the complex interplay of hydrological parameters, necessitating a shift towards multivariate modelling to accurately represent runoff dynamics.

The spatial variability of rainfall, exemplified by the Gitega station's data (proximal to the Kinamba Catchment), highlights the critical role of accurate rainfall measurements in hydrological assessments. Land use analyses comparing catchment conditions in 2000 and 2024 vividly demonstrate the progressive loss of green spaces and the consequent increase in runoff, water pollution, and compromised urban well-being across residential, agricultural, commercial, industrial, and transportation zones.

These findings collectively underscore the indispensable role of GI in enhancing infiltration, reducing peak discharge, and improving water quality—aligning with the study's objectives. The comparative analysis with conventional drainage methods reinforces the potential of GI to mitigate urban flooding and support ecological sustainability. However, the study also reveals that GI effectiveness is contingent upon factors such as maintenance, strategic urban planning policies, and the extent of green space implementation.

Therefore, a holistic stormwater management strategy, integrating GI solutions with conventional drainage systems, is imperative for the long-term sustainability and resilience of the Kinamba Catchment. This study provides a foundational understanding for policymakers and urban planners in Kigali City, emphasizing the necessity of prioritizing GI interventions to address the escalating challenges of urban stormwater management in rapidly developing urban environments.

Recommendations

The Kinamba Catchment, facing the challenges of rapid urbanization and climate variability, requires a strategic and integrated approach to stormwater management. This study, evaluating the impact of green infrastructure (GI) on runoff and sewer overflow, has highlighted the catchment's vulnerabilities and the potential of GI to mitigate these issues. The following recommendations tailored to the study's objectives of assessing GI presence, identifying key runoff factors, and analyzing GI effectiveness are presented to guide policymakers and practitioners in enhancing urban resilience.

Strategic GI Implementation for Runoff Reduction and Sewer Overflow Mitigation

- Prioritize GI implementation in areas identified with high impervious surface coverage and documented high runoff volumes.
- Utilize land use maps and spatial analysis to pinpoint critical zones requiring immediate intervention.
- Implement a range of GI systems tailored to the Kinamba Catchment's specific soil types and land use characteristics, focusing on systems that maximize infiltration (e.g., rain gardens, bioretention cells, permeable pavements).
- Design GI features to effectively manage peak discharge events, incorporating retention basins and swales to mitigate sewer overflows during intense rainfall.
- Where possible, retrofit existing grey infrastructure with green infrastructure components to improve the overall catchment capacity to handle stormwater.

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Data-Driven Evaluation and Modeling for GI Effectiveness Analysis

- Establish a comprehensive monitoring program to collect baseline data on infiltration, discharge, and rainfall patterns.
- Utilize Gitega rainfall station data as a primary input for hydrological modelling, given its proximity and representativeness of the Kinamba Catchment.
- Employ advanced hydrological models (e.g., SWMM, HEC-HMS) to simulate runoff dynamics and assess the impact of GI interventions.
- Conduct spatial analysis to map and understand the distribution of GI features, runoff generation areas, and other relevant factors.
- Implement a regular monitoring and evaluation program to assess the long-term performance of GI features and inform adaptive management strategies.

Policy, Planning, and Community Engagement for Sustainable GI Integration

- Incorporate GI principles into Kigali City's urban development plans and building codes, mandating the use of sustainable drainage systems in new developments.
- Develop and enforce regulations that promote the use of permeable pavements, green roofs, and other GI features.
- Launch community education and awareness campaigns to promote GI adoption and participation in maintenance activities.
- Establish incentive programs to encourage private landowners and developers to implement GI features.
- Enhance collaboration among governmental and non-governmental organizations involved in stormwater management.
- Provide capacity-building programs for engineers, urban planners, and environmentalists to enhance their knowledge of GI design, implementation, and maintenance.

Addressing Land Use Impacts and Ensuring Long-Term Sustainability

- Develop strategies to manage and regulate informal settlements, minimizing their impact on runoff generation and ensuring access to sustainable drainage solutions.
- Implement urban reforestation programs to increase vegetation cover and enhance evapotranspiration.
- Promote the use of cover crops, hedgerows, and riparian buffers in agricultural areas to reduce runoff and enhance soil health.
- Allocate dedicated funding for GI projects through government budgets, international aid, and public-private partnerships.
- Develop and implement sustainable maintenance protocols and allocate sufficient funding for GI maintenance and monitoring.

By adopting these recommendations, Kigali City can effectively leverage green infrastructure to mitigate stormwater runoff, reduce sewer overflows, and enhance the overall resilience and sustainability of the Kinamba Catchment.

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