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SCHOOL OF ARCHITECTURE AND BUILT ENVIRONMENT

## ***DEPARTMENT OF SPATIAL PLANNING***

*MSc. Of Geo-Information Science for Environment and Sustainable Development  
(GI-ESD)*

### ***Evaluation of storm water in Kigali City.***

*Case study of Nyarurama Cell catchment, Gatenga Sector, Kicukiro District.*

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in partial fulfillment of the requirements for the award of the Degree of Master of  
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## Declaration

This thesis is my original work and has not been presented for a degree in any other university. It was defended in August 2024, corrected and re-submitted in September 2024.

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## **Dedication**

This work is dedicated to the memory of my father and my beloved grandparents, who raised me and supported my education.

To my mother and stepdad, who continued to guide and support me,

To my sisters, brothers, uncles, and cousins,

And to all my friends and other relatives.

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## Contents

<b>1</b>	<b>Chapter I. Introduction.....</b>	<b>1</b>
<b>1.1</b>	<b>Background.....</b>	<b>1</b>
<b>1.2</b>	<b>Problem statement.....</b>	<b>3</b>
<b>1.3</b>	<b>Objectives.....</b>	<b>4</b>
1.3.1	Main Research objective.....	4
1.3.2	Specific research objectives and Research Questions.....	5
<b>1.4</b>	<b>Research Compatibility matrix.....</b>	<b>5</b>
<b>1.5</b>	<b>Justification of study.....</b>	<b>7</b>
1.5.1	Significance of the Study.....	7
1.5.2	Novelty the Study.....	8
1.5.3	Alignment with United Nations Sustainable Development Goals (SDGs).....	9
<b>1.6</b>	<b>Scope of the study.....</b>	<b>9</b>
<b>2</b>	<b>Chapter II. Literature review.....</b>	<b>10</b>
<b>2.1</b>	<b>Drainage Planning and Management.....</b>	<b>10</b>
<b>2.2</b>	<b>Challenges of Urbanization in Kigali.....</b>	<b>11</b>
<b>2.3</b>	<b>Sustainable Drainage Practices and Storm Water Management Strategies.....</b>	<b>11</b>
<b>2.4</b>	<b>Applications of GIS in Storm Water Management.....</b>	<b>13</b>
<b>2.5</b>	<b>Physical aspect of the study area.....</b>	<b>15</b>
2.5.1	Soil characteristics of Nyarurama Cell.....	17
2.5.2	Soil Type and Soil Texture.....	17
2.5.3	Aquifer Types of Nyarurama.....	19
2.5.4	Topographic and Elevation.....	21
2.5.5	Land Cover Change from 2017 to 2023.....	24
2.5.6	Overview of the planned land use for the Nyarurama cell by 2050.....	24
<b>2.6</b>	<b>Seasonal rainfall and Rainfall Intensity of Gatenga sector.....</b>	<b>28</b>
2.6.1	Monthly precipitation and Future Trends.....	29
<b>3</b>	<b>Chapter III. Materials and methods.....</b>	<b>31</b>
<b>3.1</b>	<b>Presentation of the study area.....</b>	<b>31</b>
3.1.1	Roads topography.....	32
<b>3.2</b>	<b>Methodology.....</b>	<b>34</b>
3.2.1	Research Design.....	34
3.2.2	Data Collection and processing.....	35
3.2.3	Data categories and formats.....	37
3.2.4	Sampling Method.....	37
3.2.5	Targeted Roads and Sample Size.....	38
3.2.6	Sample Size Determination.....	39
3.2.7	Stratified sampling method.....	40
3.2.8	Data analysis.....	43

3.2.9	Runoff estimation .....	44
3.2.10	Rainfall intensity estimation .....	46
<b>3.3</b>	<b>Research Materials .....</b>	<b>46</b>
3.3.1	Tools for Data Collection and Data Analysis .....	47
<b>4</b>	<b><i>Chapter IV. Results presentation and discussion .....</i></b>	<b>49</b>
<b>3.4</b>	<b>Results presentation.....</b>	<b>49</b>
3.4.1	Drainage System in Nyarurama Cell.....	49
3.4.2	Soil characteristics.....	59
3.4.3	Hydrological Changes Due to Road Construction .....	60
3.4.4	Slope, Land Use change and Runoff Coefficients .....	63
<b>3.5</b>	<b>Runoff Calculation .....</b>	<b>69</b>
3.5.2	Evaluation of Drainage System Capacities.....	79
3.5.3	Required Storage Volumes Rain water form roof areas.....	79
	Key Parameters for Design .....	79
<b>3.6</b>	<b>Runoff in 2050.....</b>	<b>81</b>
3.6.1	Assessing the Capacity of the Existing Drainage System in Nyarurama .....	81
3.6.2	Required Storage Volumes in 2050.....	82
<b>3.7</b>	<b>Results discussion .....</b>	<b>83</b>
<b>4</b>	<b><i>Chapter V. Conclusion and recommendation.....</i></b>	<b>85</b>
<b>4.1</b>	<b>Conclusion.....</b>	<b>85</b>
<b>4.2</b>	<b>Recommendations.....</b>	<b>87</b>
<b>4.3</b>	<b>Implications of the Research.....</b>	<b>89</b>
<b>5</b>	<b><i>References .....</i></b>	<b>90</b>
<b>6</b>	<b><i>Appendices.....</i></b>	<b>98</b>

## List of tables

Table 1: Specific research objectives, Research Questions. ....	5
Table 2: Research Compatibility matrix .....	6
Table 3: Soil characteristics of Nyarurama Cell .....	17
Table 4: study area land use .....	26
Table 5: Data Category Details .....	37
Table 6: Tools for Data Collection and Data Analysis .....	48
Table 7: The variability in drainage shapes observed in Nyarurama.....	51
Table 8: Runoff coefficient (C) for land cover in study area.....	68
Table 9: parameters for rainfall intensity calculation .....	70
Table 10: Maximum rainfall intensity.....	70
Table 11: the percentage change in peak discharge from 2024 to 2050 .....	74
Table 12: Required Storage Volumes Rain water form roof area (2023) .....	80
Table 13: Adjusted Rainfall Intensities for 2050 (mm/hr).....	81
Table 14: Required Storage Volumes for Different Return Periods and Durations in 2050 .....	82

## List of figures

Figure 1 : Lithology map of study area.....	16
Figure 2: Nyarurama Ground Water Aquifer Lithology .....	20
Figure 3: Topographic and Elevation of Nyarurana Cell.....	22
Figure 4: Elevation of Nyarurana Cell .....	23
Figure 5: Land cover change from 2017-2023.....	24
Figure 6: Land Use Masterplan.....	25
Figure 7: Mean Daily rainfall and Seasonal Rainfall Intensity from 1981 to 2021.....	28
Figure 8: Gatenga Sector annual rainfall and temperature data. ....	29
Figure 9: Maps of Study area.....	32
Figure 10: Slope and roads location (slope range) Map .....	33
Figure 11: Research Design Chart flow .....	34
Figure 12: Map Showing Types and Location of Collected data. ....	36
Figure 13.a: All Roads and natural drainage (water channels) distribution Study area.....	41
Figure 13.b: Sampled roads map.....	42
Figure 14.a: Hydrological modelling and watershed delineation chat.....	43
Figure 15: current Road Drainage Characteristics .....	50
Figure 16: The variability in drainage shapes observed in Nyarurama. ....	51
Figure 17: Drainages shape types map.....	52
Figure 18.a: Hydrological model analysis for Nyarurama watersheds delineation. ....	54
Figure 18.b: Nyarurama watersheds delineation and Risk zones. ....	55
Figure 19.a: Bisambu-Bigo ravine and human activities.....	56
Figure 19.b: Bisambu-Bigo ravine and Risk zones in Nyarurama cell catchment .....	57
Figure 19.c: Culverts are inadequate to handle storm water in Bisambu-Bigo ravine .....	58
Figure 20.a: Surface runoff and road directions.....	61
Figure 20.b: Road runoff accumulation and its direction. ....	62
Figure 20.c: The changes in storm water flow direction have led to erosion and road damage... ..	62
Figure 20.c: The changes in storm water flow direction have led to erosion and road damage... ..	63
Figure 21.a: Slope reclassification classification for runoff coefficient C.....	64
Figure 21.b: 2024, Land Use and Runoff Coefficients in Nyarurama catchment.....	65
Figure 21.c: 2050 Land Use and Runoff Coefficients in Nyarurama catchment.....	66
Figure 21.d: Runoff coefficient and land use change in 2024 and 2050.....	67
Figure 22.a: Peak Discharge Comparison for 2024 and 2025 in different and return periods. ....	71
Figure 22.b: Peak discharge for different land use, durations and return periods. ....	73
Figure 22.c: Peak discharge ( $m^3/s$ ) for different durations and return periods in 3D. ....	73
Figure 23.a: Peak Discharge comparison between 2024 and 2050 for various Return Periods. ..	76
Figure 23.b: Change in Percentage for Peak Discharge (Q) from 2024 to 2050 .....	76
Figure 24: Critical Road areas vulnerable to high Runoff, erosion, and flooding. ....	78

## List of appendices

Appendix 1: Peak Discharge values for both 2024 and 2050 .....	98
Appendix 2: The potential runoff coefficients(C) for different land use, soil type and slope. ....	102

## List of acronyms and abbreviations

ASCE	American Society of Civil Engineers
CoK	City of Kigali
CST	College of Science and Technology
DEM	Digital Elevation Model
DTM	Digital Terrain Model
FAO	Food and Agriculture Organization
GIS	Geographic Information System
ICRAF	International Centre for Research in Agroforestry
IDE	Integrated Development Environment
IUCN	International Union for Conservation of Nature
GoR	Government of Rwanda
LiDAR	Light Detection and Ranging
MININFRA	Ministry of Infrastructure
MLMS	Mobile Lidar Mapping Systems
NISR	National Institute of Statistics Rwanda
QGIS	Quantum Geographic Information System
NLA	National Land Authority
RNLUMP	Rwanda National Land Use Development Master Plan
RSA	Rwanda Space Agency
RSB	Rwanda Standards Board
RTDA	Rwanda Transport Development Agency
RUDP- II	Second Rwanda Urban Development Project
RWB	Rwanda Water Board
SUDS	Sustainable Urban Drainage Systems
SWS	Storm Water Solution
SAGA	System for Automated Geoscientific Analyses
UN	United Nations
UR	University of Rwanda

## Abstract

Globally, the rapid expansion of impermeable surfaces in urban areas has exacerbated stormwater management challenges, necessitating more effective drainage systems, and this is the case in Rwanda. This study aims to evaluate the current drainage infrastructure in Kigali City, Gatenga Sector, Nyarurama sub-catchment areas and assess the impact of land use changes on runoff patterns. Using GIS tools (QField, SAGA Next Gen, QGIS), the study applied the Rational Method and Manning's Equation to estimate runoff and evaluate drainage effectiveness. Results reveal that 91.3% of roads are unpaved, leading to substantial stormwater overflow. Rectangular (U-shaped) drainages cover 89.6% of paved areas but only 4.9% of unpaved zones, leaving 83.1% of the region lacking adequate drainage. Land use changes forecasted from 2024 to 2050 show a significant increase in built-up areas (from 19.9% to 74.4%) and a decline in grassland and cropland (from 61.8% to 7.0%). The projected changes in runoff from 2024 to 2050 for various return periods and rainfall durations were analyzed. For the short durations (0.5 hr to 6 hr), the peak discharge in 2050 shows both increases and decreases compared to 2024, with changes ranging from a +60.55% increase in peak discharge during a 2-year return period for 24-hour rainfall events to a -35.44% decrease during a 50-year return period for a 6-hour rainfall event. Notably, higher return periods (50 and 100 years) demonstrate more significant reductions in peak discharge by 2050, reaching up to -33.69% for a 6-hour event and -23.59% for a 24-hour event under a 100-year return period. The results suggest that climate change will have varying impacts on flood risks depending on the rainfall duration and return period. The study highlights that without immediate infrastructure improvements, the increasing urbanization and changing rainfall patterns will exacerbate erosion and flood risks. Enhanced drainage systems and adaptive planning are essential to manage future stormwater runoff effectively. The substantial upgrades in drainage systems were recommended including the addition of water reservoirs, to mitigate the impacts of urbanization and climate change on stormwater management in Nyarurama cell.

**Keywords:** urbanization, GIS modeling, drainage infrastructure, stormwater management, Rational Method, peak discharge, runoff.

## **1 Chapter I. Introduction**

This chapter introduces the context and significance of the research focused on stormwater management and drainage planning in Nyarurama Cell sub-catchment, Gatenga Sector, Kicukiro District, Kigali. It begins with an overview of the background that outlines the existing issues and sets the stage for the study. Following this, the problem statement is detailed to highlight the specific challenges the research aims to address. The chapter then delineates the main research objective and the specific objectives along with the research questions guiding the study. The research compatibility matrix is presented to show the alignment of the study with existing literature and research practices. Additionally, the justification for the study is discussed, emphasizing its significance and novelty. The chapter concludes with an outline of the study's scope, summarizing the sections covered in the subsequent chapters. In this chapter, we have Section 1.1 presenting the background of the study, Section 1.2 detailing the problem statement, and Sections 1.3 to 1.6 covering the objectives, research compatibility matrix, justification, and scope of the study, respectively.

### **1.1 Background**

Rainwater, a valuable natural resource, is an integral part of the Earth's hydrological cycle (Acker et al., 2014). Originating from the evaporation of surface water, it ascends into the atmosphere, condenses into clouds, and returns to the Earth as precipitation, primarily in the form of rain (ASCE, 1992). The distribution of rainfall worldwide is subject to significant variations dictated by climate, geography, and seasonal changes. Rainfall patterns are influenced by diverse climatic conditions, ranging from arid regions with minimal precipitation to areas with heavy and regular rainfall (Trenberth et al., 2013).

Globally, stormwater management has become a pressing issue, especially in urban environments where rapid urbanization and industrialization have increased impervious surfaces, resulting in higher runoff rates (Cheshmehzangi et al., 2024; Grison et al., 2023). Cities across the world, particularly in densely populated regions, face challenges of flooding, erosion, and water contamination due to inadequate infrastructure (Tanyanyiwa et al., 2023). Developed nations have implemented advanced stormwater management strategies, including green infrastructure, sustainable drainage systems (SUDS), and integrated water resource management (IWRM) to mitigate these risks (Fletcher et al., 2015; Rentachintala et al., 2022; Sørup et al., 2019).

However, developing countries often lack the necessary resources, leaving urban areas vulnerable to the adverse effects of unmanaged stormwater (Gaye & Tindimugaya, 2019).

In Africa, stormwater management poses unique challenges due to a combination of climate variability, rapid urban expansion, and limited infrastructure (Nyika & Dinka, 2023). Many African cities experience frequent flooding, soil erosion, and water quality degradation, exacerbated by seasonal rainfall patterns and the impacts of climate change (Tanyanyiwa et al., 2023). The African Union and international organizations like UN-Habitat have emphasized the importance of integrating sustainable urban planning with effective stormwater management to enhance the resilience of cities across the continent. Nonetheless, the capacity to implement such systems is often hindered by financial and institutional limitations (Cheshmehzangi et al., 2024; Grison et al., 2023; Tanyanyiwa et al., 2023).

In Rwanda, a landlocked East African nation, diverse climates across regions shape hydrological challenges, particularly in urban areas. Issues such as inadequate storm water drainage, uncontrolled runoff, erosion, and flooding can lead to water contamination (Alemayehu & Benitez, 2020; Buso et al., 2014). Steep terrain exacerbates these challenges, with rapid rainwater runoff posing risks to the environment and human settlements, causing erosion and increasing the likelihood of floods (MININFRA, 2017; Matto & Joiner, 2019; RWB & IUCN, 2022).

Rainfall variations further impact storm water dynamics. Annual precipitation ranges from approximately 800mm in the eastern lowlands to 2,000mm in the highland areas (Matto & Jainer, 2019; Wagesho & Claire, 2016). High mountains, reaching up to 4.5 km above sea level, dominate the west and northwest, influencing the flow of storm water (RWB & IUCN, 2022).

The storm water channel planning deals with runoff of excess water which cannot find a way to the subsurface. The storm water management requires efficient institutional capacities and somewhat costly infrastructure (MININFRA, 2017). Sustainable solutions for storm water is the Master plan with an urban drainage infrastructure reserve space and green areas (MININFRA, 2023; Morriello et al., 2020). The World Bank has highlighted the importance of integrated planning in cities like Kigali to manage stormwater and prevent flooding (Alemayehu & Benitez, 2020). While projects aimed at improving infrastructure —such as roads, sidewalks, and drainage

systems— have been launched (World Bank, 2020a), these efforts are often insufficient to address the scale of the problem (CoK, 2023; World Bank Group, 2021).

Land use changes, particularly in residential areas, can significantly impact drainage requirements (Bibi et al., 2023). The transformation of natural landscapes into urban and residential zones alters the flow of rainwater, resulting in increased runoff (ASCE, 1992). This intensification of runoff, coupled with impermeable surfaces like roads and buildings, places greater demands on drainage infrastructure to manage the excess water effectively (Bibi et al., 2023).

## **1.2 Problem statement**

Globally, urbanization has intensified stormwater management challenges, particularly in rapidly growing cities. With the increase in impervious surfaces, such as roads and buildings, cities around the world face issues related to excess runoff, inadequate drainage systems, and frequent flooding (Cheshmehzangi et al., 2024). Many cities in both developed and developing countries struggle to keep up with the infrastructure demands needed to manage stormwater effectively (Karamoutsou et al., 2024). In places like New York, Tokyo, and London, extensive and expensive infrastructure projects have been undertaken to address these challenges (Rentachintala et al., 2022). However, in developing regions, especially across Africa, limited resources and rapid urban growth complicate efforts to manage stormwater efficiently (Mahfooz et al., 2022).

In Africa, urbanization is happening at an unprecedented pace, leading to significant pressures on existing infrastructure (Gaye & Tindimugaya, 2019; Nyika & Dinka, 2023; Tanyanyiwa et al., 2023). Many cities, such as Lagos, Nairobi, and Accra, face acute challenges in stormwater management (Karamoutsou et al., 2024). The combination of poorly planned urban expansion, limited stormwater drainage systems, and extreme weather events results in frequent flooding, road damage, and soil erosion. Climate change is further exacerbating these issues by increasing the frequency and intensity of storms across the continent (Chang et al., 2013).

In Rwanda, the capital city of Kigali is no exception. Kigali, one of Africa's fastest-growing cities, has seen significant urban development in recent years. However, the city's hilly terrain, combined with rapid urban expansion, presents unique stormwater management challenges (World Bank

Group, 2021). The situation is further aggravated by new construction developments, which increase the amount of impervious surfaces, placing additional strain on the already overstretched drainage systems (Alemayehu & Benitez, 2020; Bibi et al., 2023).

In particular, Nyarurama Cell in Gatenga Sector, Kigali City, is experiencing rapid urban development, with urbanization by 20250 (Morriello et al., 2020; NISR, 2022) This growth presents significant challenges for stormwater runoff and drainage infrastructure (MININFRA, 2023; Mustafa et al., 2023). Despite various stormwater management projects (World Bank, 2020b), new residential areas like Nyarurama are often overlooked, leading to inadequate drainage systems that are unable to cope with increasing runoff. Roads are frequently constructed without sufficient drainage planning, causing stormwater to erode pathways and damage both roads and downstream properties (Rentachintala et al., 2022; RTDA, 2022).

This study focuses on stormwater challenges in the Nyarurama Cell catchment, , and assesses how new developments impact drainage capacity. By analyzing factors like topography, slope, soil type, land use (the implementation of the Kigali city's master plan), the research evaluates drainage systems, identifies flood-prone areas, and assesses erosion risks. It also examines how the master plan's land use changes and infrastructure projects will affect stormwater flow and drainage patterns. The study provides a comprehensive understanding of stormwater dynamics, offering actionable recommendations to improve stormwater management and drainage infrastructure in Kigali's rapidly growing urban areas.

## **1.3 Objectives**

### **1.3.1 Main Research objective**

This research aims to evaluate the impacts of land use changes on storm water runoff and drainage requirements in new residential areas considering Kigali Master Plan and catchment area, with a specific focus on Nyarurama Cell Gatenga Sector, Kicukiro District, Kigali.

### 1.3.2 Specific research objectives and Research Questions

Table 1: Specific research objectives, Research Questions.

Objectives	Research Questions	Hypotheses
<p><b>Objective 1:</b> To characterize and evaluate the capacity of the existing drainage system in residential areas of Nyarurama Cell.</p>	<p>-What is the current status of the drainage system in newly developed residential areas of Nyarurama Cell?</p> <p>- How effective is the existing drainage system in Nyarurama Cell at managing storm water runoff during heavy rainfall events?</p>	<p><b>H0:</b> The drainage system in newly developed residential areas of Nyarurama Cell is effectively managing storm water runoff without significant issues, even during heavy rainfall events.</p> <p><b>H1:</b> The drainage system in newly developed residential areas of Nyarurama Cell is facing challenges in managing storm water runoff, especially during heavy rainfall events, potentially resulting in drainage issues like overflows or flooding.</p>
<p><b>Objective 2:</b> To assess the impact of land use change and identify areas within Nyarurama Cell that are vulnerable to drainage issues.</p>	<p>-What impact does land use change have on the effectiveness of the existing drainage system in Nyarurama Cell?</p> <p>- Which areas within Nyarurama Cell are particularly vulnerable to drainage issues such as overflows and flooding?</p>	<p><b>H0:</b> Land use changes do not significantly impact the effectiveness of the existing drainage system in Nyarurama Cell, and no specific areas are particularly vulnerable to drainage issues.</p> <p><b>H1:</b> Land use changes significantly impact the effectiveness of the existing drainage system in Nyarurama Cell, leading to overflows and flooding in certain areas.</p>
<p><b>Objective 3:</b> To suggest recommendations for improving storm water management and drainage planning in Nyarurama Cell.</p>	<p>What strategies and interventions can be implemented to improve storm water management and drainage planning in Nyarurama Cell?</p>	<p>This objective is more about providing solutions and recommendations, so a hypothesis may not be applicable here</p>

### 1.4 Research Compatibility matrix

This matrix provides a structured framework for conducting a research study aimed at assessing and enhancing the drainage system in Nyarurama Cell, Gatenga Sector, Kicukiro, focusing on data

collection, analysis, and proposing recommendations for improvement The table 2 outlines the objectives, research questions, data needed, data collection methods, data analysis methods, expected outcomes, and data sources.

Table 2: Research Compatibility matrix

Objectives	Research Questions	Data Needed	Data Collection Method	Data Analysis Method	Expected Outcome
Objective 1: To characterize and evaluate the capacity of the existing drainage system in residential areas of Nyarurama Cell.	-What is the current status of the drainage system in newly developed residential areas of Nyarurama Cell?  -How effective is the existing drainage system in Nyarurama Cell at managing storm water runoff during heavy rainfall events?	Data on drainage infrastructure, storm water flow rates, rainfall data, and flooding incidents.	Field surveys, Ground measurement of drainages and ravines, and analysis rainfall data.	Statistical analysis of flow rates and rainfall data; GIS mapping of drainage infrastructure and flood-prone areas.	Comprehensive understanding of the current drainage system's capacity and effectiveness, highlighting any existing issues.
Objective 2: To assess the impact of land use change and identify areas within Nyarurama Cell that are vulnerable to drainage issues.	-What impact does land use change have on the effectiveness of the existing drainage system in Nyarurama Cell?  -Which areas within Nyarurama Cell are particularly vulnerable to drainage issues such as overflows and flooding?	Historical and current land use data, drainage performance data, and records of drainage issues.	Analysis of land use maps, historical records, and field observations.	Comparative analysis of land use changes and drainage performance over time; GIS-based vulnerability mapping.	Identification of the impact of land use changes on drainage effectiveness and vulnerable areas within Nyarurama Cell.

Objective 3: To suggest recommendations for improving storm water management and drainage planning in Nyarurama Cell.	What strategies and interventions can be implemented to improve storm water management and drainage planning in Nyarurama Cell?	Best practices in storm water management, stakeholder inputs, and expert opinions.	Literature review, stakeholder interview s, and expert consultations.	Qualitative analysis of best practices and stakeholder inputs; development of actionable recommendations.	A set of practical and effective strategies for improving storm water management and drainage planning in Nyarurama Cell.
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**Note:** The data sources listed include government records, meteorological data, field observations, and academic literature.

### 1.5 Justification of study.

GIS Applications hold significant importance as it enables effective urban planning, facilitates the mitigation of flooding risks, optimizes resource allocation, promotes environmental sustainability, enhances data-driven decision-making processes, builds resilience to climate change impacts, and fosters interdisciplinary collaboration. By exploring GIS applications in this context, researchers can contribute to more efficient and sustainable storm water and drainage management practices, ultimately leading to improved urban infrastructure, reduced flood vulnerability, and enhanced environmental stewardship in urban areas.

Lastly, this research enriches the advancement of sustainable urban development, highlighting the importance of efficient storm water and drainage management. The insights gained from this study can provide valuable guidance for the adoption of sustainable practices not only in Gatenga but also in other areas.

#### 1.5.1 Significance of the Study

This research provides a comprehensive understanding of the current state of storm water and drainage planning and management in Gatenga. The findings from this study will show the areas of concern that require immediate attention and also inform policy-making and decision-making processes at both the city and sector levels.

In addition, this research enhances the current understanding of GIS applications in storm water and drainage planning and management, providing valuable insights for other researchers and practitioners in the field. Moreover, this study contributes to the promotion of sustainable urban development, with a critical focus on effective storm water and drainage management. The findings from this study can guide the implementation of more sustainable practices in Gatenga and beyond.

### 1.5.2 Novelty the Study

**Holistic Urban Planning Approach:** Unlike many existing drainage studies, this research takes a holistic approach by considering the impact of new buildings on drainage capacity. It recognizes that effective storm water management requires integrated planning that accounts for both existing and future developments.

**Focus on Neglected Residential Areas:** By evaluating new residential sites, the study addresses a critical gap. These areas often receive less attention in drainage planning, leading to inadequate systems. The research sheds light on the specific challenges faced by these neglected zones.

**Open-Source GIS Tools:** The use of open-source tools like SAGA Next Gen and QGIS is noteworthy. Unlike proprietary software, these tools offer cost-effective solutions and promote accessibility. This approach democratizes storm water management knowledge and empowers planners beyond Rwanda.

**Broader Impact:** Beyond Rwanda, the research has implications for other African countries. By emphasizing accessible technology, it contributes to sustainable urban development across the continent. This potential impact sets it apart from localized studies. Furthermore, this research adds to the existing body of knowledge on GIS applications in storm water and drainage planning and management, benefiting other researchers and practitioners in the field.

### 1.5.3 Alignment with United Nations Sustainable Development Goals (SDGs)

This study on “Evaluation of storm water in Kigali City, Case study of Nyarurama Cell catchment, Gatenga Sector, Kicukiro District” aligns with several United Nations Sustainable Development Goals (SDGs)(UNEP, 2017). Here are the most relevant ones:

**SDG 6: Clean Water and Sanitation** (UN Environment, 2017): This goal aims to ensure the availability and sustainable management of water and sanitation for all. This research on storm water and drainage planning directly contributes to this goal by working towards sustainable water management in Nyarurama Cell.

**SDG 11: Sustainable Cities and Communities:** This goal aims to make cities inclusive, safe, resilient, and sustainable. By focusing on storm water and drainage planning, this research will contribute to building resilience and sustainability in urban areas, particularly in Nyarurama Cell.

**SDG 13: Climate Action:** This goal aims to take urgent action to combat climate change and its impacts. Effective storm water and drainage management is crucial for mitigating the effects of extreme weather events, which are expected to increase due to climate change.

**SDG 15: Life on Land:** This goal aims to protect, restore and promote sustainable use of terrestrial ecosystems. By ensuring proper storm water and drainage management, this research will help protect local ecosystems from pollution and degradation.

### 1.6 Scope of the study

The scope of this study on “GIS Applications in Support of Storm water and Drainage Planning and Management in Kigali City” with a focus on Gatenga Sector, Nyarurama Cell can be defined along the following dimensions:

1. **Geographical Scope:** The study is geographically confined to the Nyarurama Cell boundary, Gatenga Sector in Kigali City. The findings may be most applicable to this area.

2. **Temporal Scope:** The study is conducted at a specific point in time. The data used range from 2007 to 2024 and does not account for changes that may occur in the future. However, the methodologies and findings could be applicable for similar studies in the future.

## **2 Chapter II. Literature review**

The literature review chapter provides a comprehensive overview of existing knowledge and research relevant to stormwater management and urbanization challenges. It begins by discussing drainage planning and management practices, setting the foundation for understanding the current state of stormwater management. The chapter then addresses the specific challenges of urbanization in Kigali and explores sustainable drainage practices and stormwater management strategies. It also examines the applications of GIS in stormwater management, which is crucial for modern analytical approaches. The chapter further investigates the physical aspects of the study area, including soil characteristics, aquifer types, topographic features, land cover changes, and future land use planning. Finally, seasonal rainfall and intensity trends in the Gatenga Sector are reviewed. In this chapter, Section 2.1 covers drainage planning and management, Section 2.2 discusses urbanization challenges, and Sections 2.3 to 2.6 delve into sustainable practices, GIS applications, physical aspects of the study area, and rainfall trends.

### **2.1 Drainage Planning and Management**

Drainage planning and management involve designing, implementing, and maintaining systems to collect and convey storm water runoff safely and efficiently. This is crucial for preventing flooding, water pollution, and erosion, which are common issues in rapidly urbanizing areas (Morriello et al., 2020). Proper drainage management ensures that storm water is effectively directed away from populated areas and infrastructure, reducing the risk of damage and promoting environmental sustainability (GoR, 2019).

A watershed is a catchment basin bound by topographic features, draining storm water to destinations such as rivers, ponds, streams, lakes, or estuaries (Morriello et al., 2020). Watersheds receive water from the atmosphere, leading to infiltration and percolation to the subsurface. Kigali encompasses 25 watershed areas, each with extensive networks of natural drains that collect and discharge water to wetlands and streams, eventually connecting to Lake Muhazi and the Nyabarongo River (Morriello et al., 2020; RWB & IUCN, 2022).

In Kigali, 27.4% of rainwater storage involves underground ditches, a common method of water management. However, a 2014 baseline survey revealed that rainwater harvesting remains

underutilized, with only 28.6% reliance on it in districts like Kicukiro. This highlights the need for more comprehensive catchment-based or communal systems to manage runoff effectively and address water scarcity challenges (Bizimana, 2017; Matto & Jainer, 2019).

## **2.2 Challenges of Urbanization in Kigali**

Rwanda, particularly its capital Kigali, is experiencing rapid population growth and urbanization, placing significant demands on the city's infrastructure, including its storm water management systems. Kigali, with a population of over 1.7 million people, accounting for 13.2% of Rwanda's population, faces severe challenges due to inadequate storm water infrastructure (NISR, 2022). The existing drainage systems are struggling to cope with the increasing volume of storm water runoff, leading to frequent flooding, water pollution, and erosion (MININFRA, 2017; Rentachintala et al., 2022). By 2017, the "Water and Sanitation Sector Strategic Plan 2018 - 2024" further emphasized the impact of rapid urbanization on storm water management. Increased impervious surfaces in urban areas have led to higher volumes of storm water runoff, overwhelming existing drainage systems and necessitating upgrades to handle the growing demand and prevent flooding (GoR, 2019; MININFRA, 2017).

The " National Water and Sanitation Policy " (2023) identified significant challenges in storm water management, including land erosion, infrastructure damage, and environmental pollution. These issues require coordinated efforts across various sectors, such as urban planning, erosion control, and environmental health, to develop effective solutions (MININFRA, 2023).

The Kigali City Master Plan 2020 recognizes the critical need for improved drainage planning and management. The plan outlines objectives to enhance the city's drainage system, including reducing flood risks, protecting public health and safety, improving water quality, mitigating erosion, and supporting sustainable urban development (Morriello et al., 2020). These objectives aim to create a resilient urban environment capable of withstanding the challenges posed by rapid urbanization and climate change (MININFRA, 2017).

## **2.3 Sustainable Drainage Practices and Storm Water Management Strategies**

In response to these challenges, the City of Kigali has initiated various projects to improve its drainage infrastructure. In 2021, a significant drainage project was launched to enhance

infrastructure in several neighborhoods, through RUDP-II, funded by the World Bank and expected to be completed by 2025. This project represents a crucial step in addressing the deficiencies in the current system and aims to provide long-term solutions to the city's storm water management issues (World Bank, 2020b).

Specific activities undertaken as part of this drainage planning and management effort include mapping drainage areas, identifying potential flooding hazards, designing and implementing new drainage networks, and maintaining and upgrading existing infrastructure (MININFRA, 2017; Morriello et al., 2020; RWB & IUCN, 2022). These activities are essential for developing a comprehensive and effective storm water management system that can adapt to the city's growing needs (MININFRA, 2017; RSB, 2015).

Promoting sustainable drainage practices is another critical component of Kigali's strategy. Techniques such as rainwater harvesting and the use of green roofs help reduce runoff and enhance water conservation. These practices not only mitigate flooding risks but also contribute to the sustainable management of water resources, which is vital for the city's long-term resilience (MININFRA, 2017; RSB, 2015; RTDA, 2022).

Raising public awareness and educating residents about the importance of proper drainage and sustainable practices are also key elements of the city's approach. Public engagement and education are crucial for fostering community support and participation in storm water management initiatives, ensuring that the benefits of these efforts are widely understood and embraced (MININFRA, 2017).

Effective storm water management strategies involve integrating various approaches to address the multifaceted challenges of urban runoff. Implementing permeable pavers and swales on streets can increase rainwater absorption into the soil, reducing surface runoff and flood risks. Additionally, combining infiltration measures with rainwater collection systems enhances water conservation and reduces the burden on storm water infrastructure (GoR, 2019).

Maintaining drainage systems is crucial for their effective functioning. Regular maintenance helps prevent blockages caused by litter and debris, which can lead to system failures and increased

flood risks. Effective risk assessment and management strategies are essential for reducing the impact of natural events and system failures on urban areas (GoR, 2019; MININFRA, 2023).

The condominium approach, highlighted in the "Water and Sanitation Sector Strategic Plan 2018 - 2024," emphasizes community-based management of water and sanitation services. This approach involves shared infrastructure for small groups of households, promoting cost-effective and sustainable solutions for storm water management. By leveraging community participation, the condominium approach ensures better maintenance and operation of drainage systems, addressing the challenges posed by rapid urbanization and limited resources (MININFRA, 2017).

In conclusion, effective drainage and storm water management in Kigali involve a combination of structural and non-structural measures. These include the use of permeable pavers, swales, rainwater harvesting systems, and regular maintenance of drainage infrastructure. By integrating these strategies into urban planning and promoting public awareness, significant improvements can be achieved in mitigating flood risks, preventing erosion, and ensuring sustainable urban development (GoR, 2019; MININFRA, 2017, 2023). Addressing these challenges requires a coordinated effort and the implementation of innovative and sustainable practices to create a resilient urban environment (MININFRA, 2023).

## **2.4 Applications of GIS in Storm Water Management**

Geographic Information Systems (GIS) have become integral to storm water management due to their ability to analyze spatial data and support decision-making processes. GIS applications in this field encompass a range of activities, from mapping storm water infrastructure to modeling runoff patterns and evaluating the impact of land use changes on water quality and flooding (Abdelgiom, 2024; Habonimana et al., 2015; Kogure & Takasaki, 2019; Schilling & Tränckner, 2022).

Several studies have highlighted the efficacy of GIS in storm water management. For instance, Badamasi (2022) emphasized that GIS tools facilitate the integration of hydrological models with spatial data, enabling detailed assessments of storm water flows and watershed characteristics (Awadallah et al., 2017; Badamasi, 2022). This integration allows for the development of more

accurate and comprehensive management plans that address both current and future storm water challenges (Badamasi, 2022).

In a more recent study, Mustafa (2023) demonstrated how GIS-based modeling could be used to predict flood-prone areas by analyzing historical rainfall data, topography, and land use patterns. Their findings underscored the importance of using GIS for proactive storm water management and disaster mitigation in urban settings (Mustafa et al., 2023).

Additionally, research by Jusić et al. (2020) showed how GIS could be applied to simulate the impacts of different storm water management practices, such as green infrastructure, on runoff volumes and pollutant loads. Their work illustrated the potential of GIS to support sustainable storm water management practices that mitigate the adverse effects of urbanization on water systems (Jusić et al., 2020).

Mortaheb and Jankowski (2023) explored the use of GIS in urban planning and management and integrating city planning with Big Data, Geographic Information Science, and Data Science to form Geospatial Artificial Intelligence (GeoAI) for smart cities. GeoAI aims to enhance urban service efficiency, improve quality of life, address societal challenges, and generate human-urban dynamics data (Mortaheb & Jankowski, 2023).

A study by Habonimana, (2015) assessed the potential of GIS and remote sensing for urban flood risk management. Their findings suggested that integrating GIS with remote sensing data could provide comprehensive insights into urban flooding patterns, helping city planners develop more effective flood mitigation strategies. They focused on Kigali's storm water management issues and highlighted the role of GIS in mapping and analyzing storm water drainage floods. They found that GIS-based analyses could identify areas with insufficient drainage capacity and inform the design of new infrastructure to reduce flood risks. Their work demonstrated the practical applications of GIS in managing storm water in a rapidly growing urban environment like Kigali (Habonimana et al., 2015).

Further research by Lin et al. (2021) assessed the importance of maintaining roadside ditches to prevent flooding and pavement damage. It employs high-resolution point clouds from mobile LiDAR mapping systems (MLMS) to map ditches and conduct hydrological analyses. Various MLMS units, including unmanned aerial and ground vehicles, are evaluated for mapping accuracy.

The portable backpack system emerges as the most cost-effective method, followed by the medium-grade wheel-based system. A framework for ditch line characterization is proposed and tested, with hydrological analyses used to extract drainage networks. The study demonstrates automatic extraction of ditch profiles from LiDAR data, aligning closely with highway design standards (Lin et al., 2021).

Overall, these studies underscore the critical role of GIS in enhancing storm water management practices, particularly in urban areas facing rapid growth and complex environmental challenges. The insights gained from these applications highlight the potential for GIS to support more sustainable and resilient urban water management strategies in Kigali and similar contexts.

## **2.5 Physical aspect of the study area**

This section focuses on the lithological characteristics of Nyarurama cell, with a particular emphasis on its predominant rock type. Lithology, which examines the physical characteristics of rocks or sediments including texture, composition, and grain size, reveals that shale dominates the area, covering approximately 89% of the terrain with 555 hectares (ICRAF, 2015). Shale is a fine-grained sedimentary rock composed mainly of clay minerals and small fragments of quartz and calcite, formed from the compaction of silt and clay-sized particles (Bjørlykke et al., 2007).

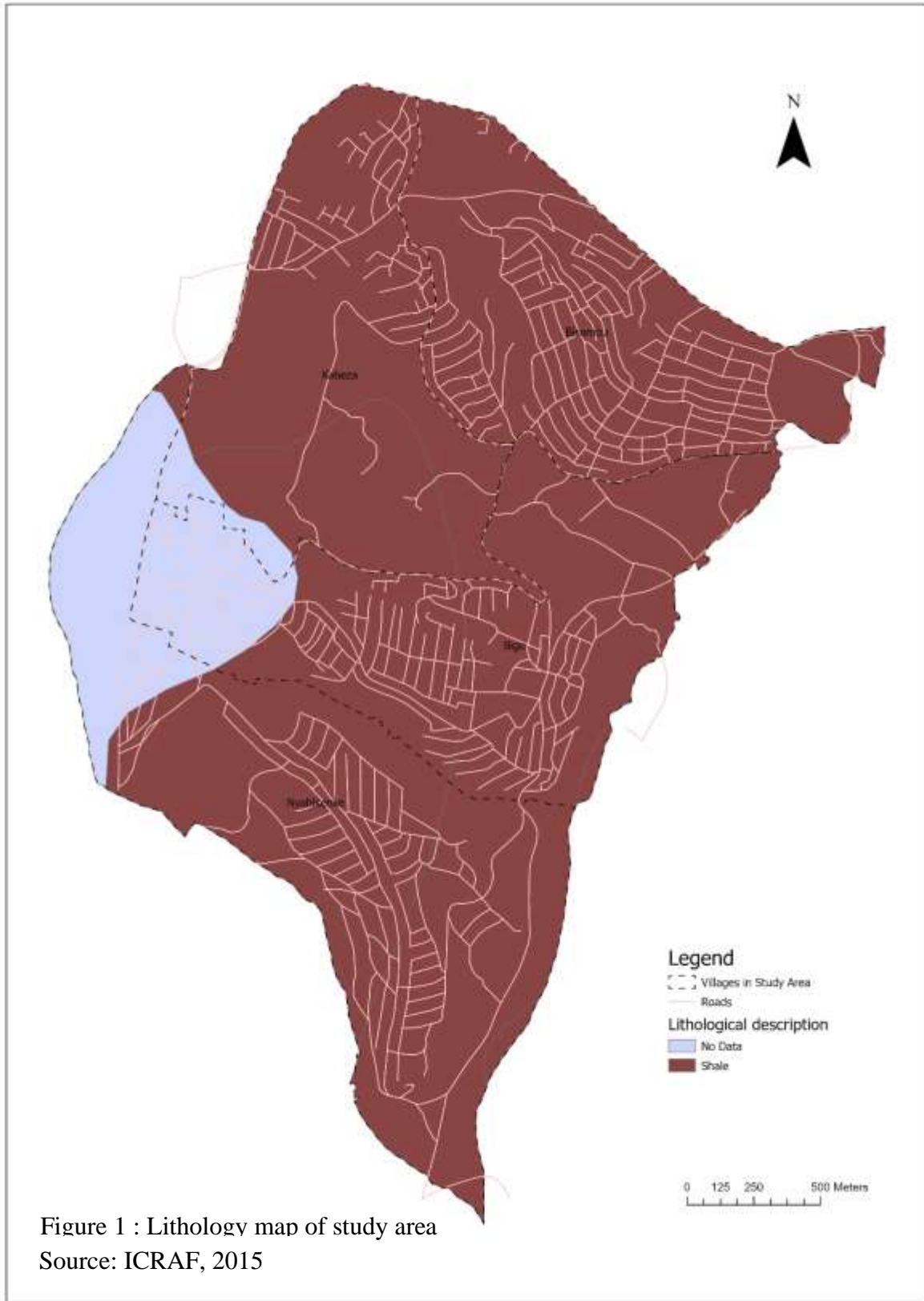


Figure 1 : Lithology map of study area  
Source: ICRAF, 2015

The Figure 1 of the study area highlights the extensive presence of shale, with 11% of the area lacking data. This detailed lithological analysis of Nyarurama cell provides critical insights into the area's geological composition and potential implications for land use and environmental management. Shale's key characteristics include very fine grain size, smooth texture, and low permeability. These attributes influence its formation in calm environments where fine sediments accumulate. Additionally, shale weathers to form clay-rich soils, impacting land use. Shale is visually identifiable by its typically smooth appearance, ability to split into thin layers (fissility), and variable but often dark color due to organic content. These distinguishing features set it apart from other fine-grained sedimentary rocks like siltstone and mudstone (M. Dane Picard, 1971).

### 2.5.1 Soil characteristics of Nyarurama Cell

The soil in Nyarurama Cell, Gatenga, is characterized by high clay content, slightly acidic pH, low organic carbon, and moderate bulk density. These characteristics influence the soil's drainage capacity, water retention, and overall fertility. Effective storm water management strategies will need to address the high clay content and low organic matter to improve infiltration and reduce runoff (Bjørlykke et al., 2007; FAO, 2007; M. Dane Picard, 1971).

Table 3: Soil characteristics of Nyarurama Cell

Location	Orthic Ferralsols	Sand % topsoil	Sand % subsoil	Silt % topsoil	Silt % subsoil	Clay % topsoil	Clay % subsoil	pH <sub>2</sub> O topsoil	pH <sub>2</sub> O subsoil	OC % topsoil	OC % subsoil	BD topsoil	BD subsoil
Nyarurama Cell	FO	28.7	25.8	18.4	17.3	52.9	56.9	5.1	5.3	1.92	0.67	1	1

Source: FAO, 2007

### 2.5.2 Soil Type and Soil Texture

As shown in Table 3, the soil in Nyarurama Cell, Gatenga, is classified as Orthic Ferralsols. These soils are typically found in tropical regions and are known for their high weathering, iron and aluminum oxide content, and low natural fertility (FAO, 2007).

The sand content of the soil is 28.7% in the topsoil and 25.8% in the subsoil, indicating a moderate level of drainage and aeration. Sandy soils generally have good infiltration rates, which can be beneficial for reducing surface runoff and aiding storm water management. The silt content is 18.4% in the topsoil and 17.3% in the subsoil, contributing to the soil's overall texture and its

ability to retain moisture without becoming overly compacted. The clay content is high, with 52.9% in the topsoil and 56.9% in the subsoil. This suggests that the soil has a significant potential for water retention, but it can also lead to poor drainage and higher surface runoff, which is critical for understanding potential flood risks and planning effective drainage systems (FAO, 2007).

The pH levels are slightly acidic, with a topsoil pH of 5.1 and a subsoil pH of 5.3. Acidic soils can influence nutrient availability and the soil's overall health. Managing pH levels is important for maintaining soil structure and preventing erosion (FAO, 2007). The organic carbon (OC) content is relatively low, with 1.92% in the topsoil and 0.67% in the subsoil. Organic matter is crucial for soil fertility, structure, and water retention. Enhancing organic carbon content could improve the soil's ability to support vegetation and manage storm water. The bulk density (BD) values suggest that the soil is moderately compacted, with 1 g/cm<sup>3</sup> in both the topsoil and subsoil. Lower bulk density is generally favorable for root growth and water infiltration. Managing compaction through proper land use practices can improve storm water absorption and reduce runoff (FAO, 2007).

The cation exchange capacity (CEC) values are 11 meq/100g in the topsoil and 6.5 meq/100g in the subsoil, indicating the soil's ability to hold and exchange nutrients. Higher CEC is beneficial for soil fertility and plant growth. The base saturation (BS) is 28% in the topsoil and 31% in the subsoil, indicating a limited availability of essential nutrients like calcium, magnesium, and potassium, which can affect plant growth and soil health. The nitrogen content is low, with 0.22% in the topsoil and 0.1% in the subsoil, which can limit plant growth as this affects surface runoff of storm water. Improving nitrogen levels through organic or inorganic amendments could benefit soil fertility. The presence of calcium carbonate (CaCO<sub>3</sub>) is minimal, with 0.1% in both the topsoil and subsoil, reflecting the acidic nature of the soil (FAO, 2007).

The understanding soil composition is crucial for effective storm water management. The percentage of sand in both topsoil and subsoil indicates the soil's ability to absorb water, reducing surface runoff. Similarly, the silt content influences soil texture, affecting drainage and water retention. High clay content can impede drainage and increase runoff, highlighting its importance in storm water management. Soil pH plays a role in soil stability and erosion potential, impacting drainage planning. Organic carbon enhances soil structure, improving water retention and

infiltration. Lower bulk density signifies better soil porosity, which is advantageous for infiltration and minimizing surface runoff. By analyzing these parameters, one can assess soil characteristics to optimize storm water absorption and drainage systems effectively (GoR, 2019; Jusić et al., 2020; RSB, 2015; RWB & IUCN, 2022).

### **2.5.3 Aquifer Types of Nyarurama**

This section provides a comprehensive description of the aquifer types in Nyarurama, highlighting their varied hydrogeological characteristics and implications for groundwater management. The region is characterized by three main aquifer types: alluvial aquifers, low permeable fractured aquifers, and semi-permeable fractured aquifers.

Alluvial aquifers, covering 132.3 hectares, consist of unconsolidated sediments such as sand, gravel, silt, and clay deposited by rivers. These aquifers exhibit high porosity and permeability, allowing for substantial water storage and movement, making them prime sources for groundwater extraction (Asghari Moghaddam et al., 2014; Ayenew et al., 2008).

Low permeable fractured aquifers, predominantly found in schist and mica-schist, cover 477.3 hectares. These aquifers have low porosity and rely on fractures for water storage and flow, resulting in limited and variable water yields (Desbarats et al., 1999).

Semi-permeable fractured aquifers, found in mixed metamorphic rocks such as schist, mica, and quartzite, cover a smaller area of 16 hectares. These aquifers exhibit moderate porosity and permeability, with water movement facilitated by both fractures and some degree of matrix porosity, often resulting in better water yields compared to purely low permeable fractured (Martínez-Nájera et al., 2011).

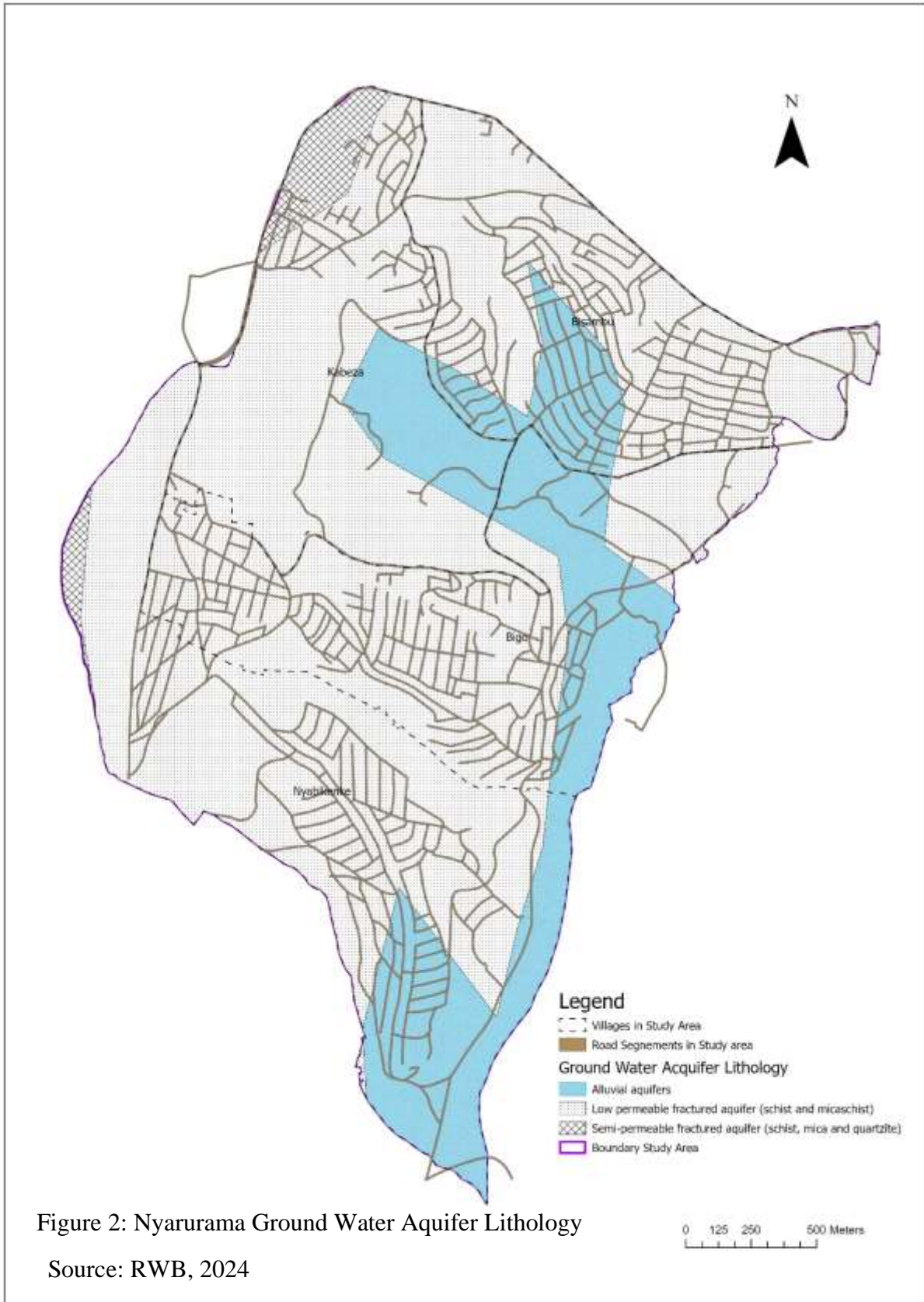


Figure 2: Nyarurama Ground Water Aquifer Lithology

Source: RWB, 2024

The detailed understanding of these aquifer types, as illustrated in Figure 2. The total area of groundwater aquifers in Nyarurama is 625.6 hectares, with the predominance of low permeable fractured aquifers. The predominance of low permeable fractured aquifers (76.3%) has significant implications for storm water and drainage management. These aquifers, with their limited water storage and slow recharge rates, can affect the infiltration and storage capacity of storm water , potentially leading to increased surface runoff and flooding risks. Managing storm water in areas with such aquifers requires careful planning to prevent waterlogging, erosion, and water quality degradation. Additionally, the complex hydrogeological dynamics of low permeable fractured aquifers can influence drainage patterns and the effectiveness of drainage systems, necessitating tailored approaches to mitigate potential drainage challenges and ensure sustainable storm water management practices (Ayenew et al., 2008; Bastia et al., 2021; RTDA, 2022).

#### **2.5.4 Topographic and Elevation**

The topographic maps in Figure 3 of Nyarurama Cell shows varied terrain with elevations reflecting the hilly landscape of the region. The figure 4 represents the elevation that ranges of 1400 to 1810m in the study area plays a crucial role in shaping both runoff and storm water, and erosion patterns. This elevation range can intensify storm water management issues and erosion patterns by influencing high flow velocities during runoff events, highlighting the importance of considering topographical factors when addressing these environmental concerns.

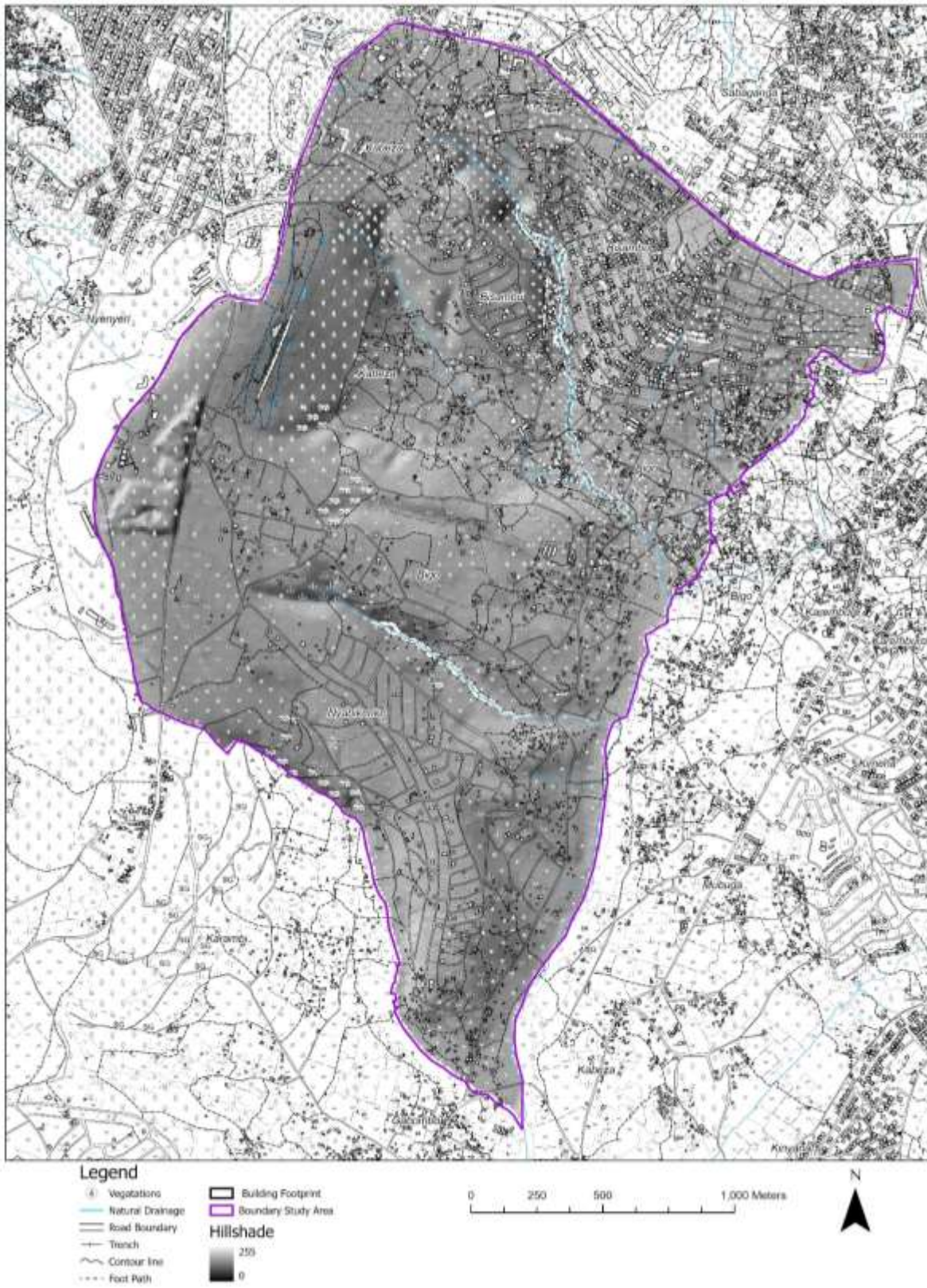


Figure 3: Topographic and Elevation of Nyarurana Cell

Source: NLA, 2024

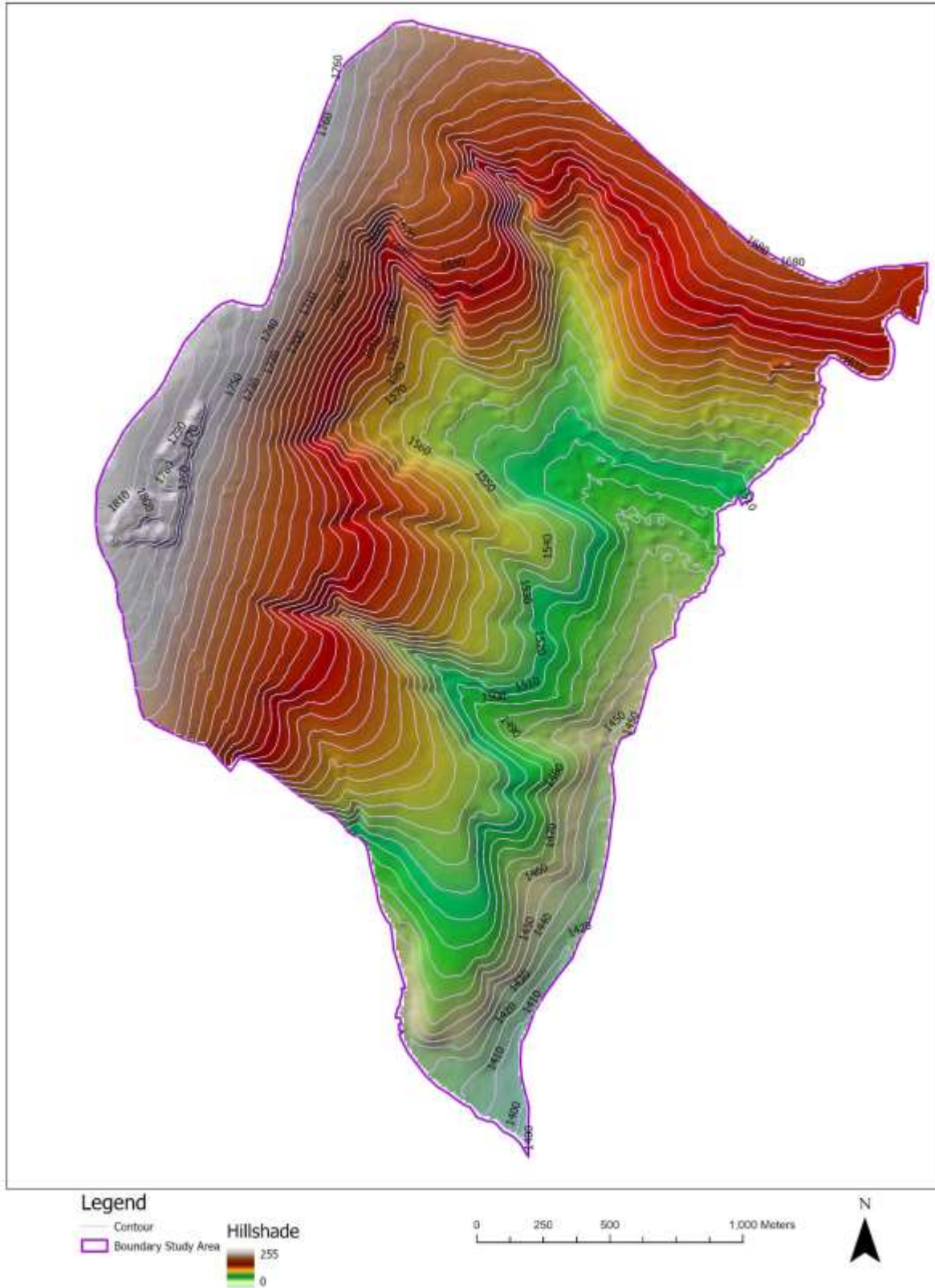


Figure 4: Elevation of Nvarurana Cell  
 Source: NLA, 2024

### 2.5.5 Land Cover Change from 2017 to 2023

The proportion of built-up areas in Nyarurama Cell, Gatenga, has seen a significant increase, rising from 50% in 2007 to 69% in 2023 (Esri, 2023). This upward trend is expected to persist, with projections indicating that built-up areas will continue to expand. By 2050, it is estimated that the built-up area will encompass 4,923,972.3 square meters (Morriello et al., 2020).

Figure 5 illustrates the annual increase in built-up areas, highlighting the steady growth in urban development. In contrast, cropland has remained relatively constant at 11% over the last three consecutive years, while forested areas have experienced a slight decline. This trend underscores the ongoing urbanization and its impact on land use patterns in the region.



Figure 5: Land cover change from 2017-2023

Source: *Sentinel-2 Land Cover Explorer*, 2023

### 2.5.6 Overview of the planned land use for the Nyarurama cell by 2050

According to Kigali city masterplan (2020), Nyarurama cell is composed with different land use however this study was focused on zones planned for as residential (Morriello et al., 2020). Map in figure 6 and table 4 provide a detailed projection of land use in Nyarurama cell, illustrating a the planned residential, commercial, natural, and infrastructural need by 2050.

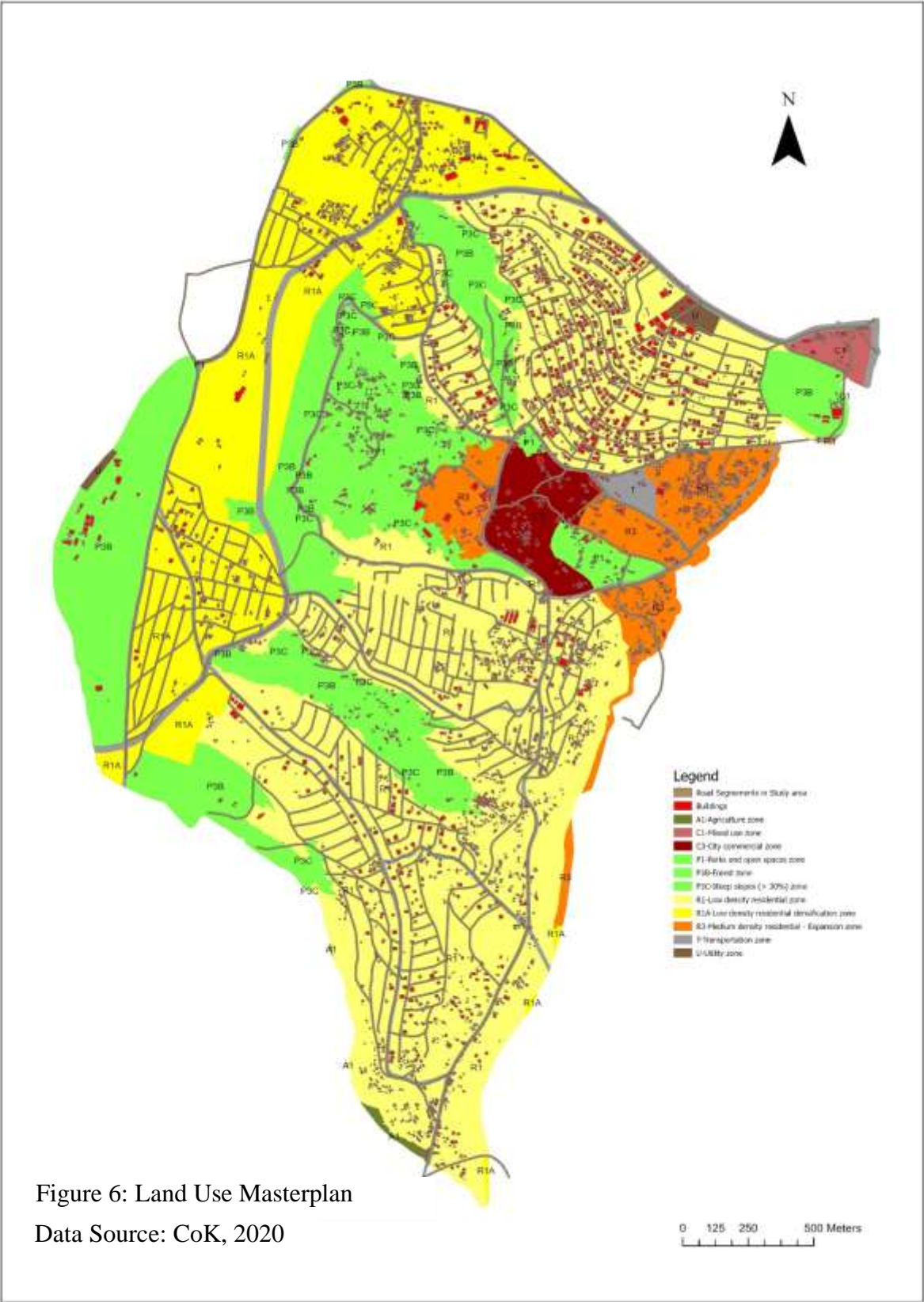


Figure 6: Land Use Masterplan

Data Source: CoK, 2020

This strategic allocation aims to create a sustainable and vibrant community, addressing the diverse needs of its residents while ensuring long-term ecological and economic health.

Table 4: study area land use

S/N	Land Use	Area (m <sup>2</sup> )	%
1	City Level Commercial (C1)	136,353	2.11
2	Crop Farming / agriculture (A1)	8,571.2	0.13
3	General Commercial (C1)	36,300	0.56
4	Low Density Residential (R1)	3,493,579.5	54.13
5	Medium Density Residential (R3)	338,969.3	5.25
6	Natural Forest (P3B)	901,198	13.96
7	Parks and Open Spaces (P1)	258,206.2	4.00
8	Road Reserve and Transport (T)	22,054.9	0.34
9	Roads (T)	918,770.5	14.24
10	Steep Slopes (P3C)	319,436.8	4.95
11	Water (U)	20,092.58	0.31
	Total	6,453,531.98	100

Source: CoK,2020.

Table 4 provides an in-depth overview of the planned land use for the Nyarurama cell by 2050, highlighting the area's development priorities and strategic allocation of space. The data reveals a clear emphasis on residential development, with Low Density Residential (R1) areas occupying the largest portion, amounting to 3,493,579.5 square meters. This significant allocation indicates a prioritization of housing to accommodate a growing population, suggesting a vision of urban expansion and a desire to provide ample living space for residents.

In addition to residential areas, the table 4 shows a considerable allocation for commercial use, with City Level Commercial (C1) and General Commercial (C1) areas covering 136,353 and 36,300 square meters, respectively. These figures reflect the importance of creating vibrant commercial hubs within Nyarurama, catering to the economic activities and business needs of the community. This balanced approach ensures that while residential needs are met, there are also ample opportunities for economic growth and development.

The table 4 also highlights a relatively small area dedicated to Crop Farming / Agriculture (A1), totaling 8,571.2 square meters. This limited allocation underscores the urban character of the area, with a reduced focus on agricultural activities. However, the presence of agricultural land suggests a commitment to maintaining some level of local food production, which is essential for sustainability and resilience.

Natural and recreational spaces are well-represented in the land use plan, with Natural Forest (P3B) areas covering 901,198 square meters and Parks and Open Spaces (P1) occupying 258,206.2 square meters. These allocations emphasize the importance of green spaces for environmental health, recreational opportunities, and overall quality of life for residents. Such spaces are crucial for providing ecological benefits, such as air purification and climate regulation, while also serving as areas for leisure and community activities.

Transport infrastructure is another key component of the land use plan, with Roads (T) covering 918,770.5 square meters and Road Reserve and Transport (T) areas occupying 22,054.9 square meters. This extensive allocation for transportation highlights the need for a well-developed road network to ensure accessibility and connectivity within Nyarurama. A robust transport infrastructure is vital for the efficient movement of people and goods, which supports both residential and commercial activities.

The inclusion of Steep Slopes (P3C) areas, totaling 319,436.8 square meters, acknowledges the topographical challenges present in Nyarurama. Careful planning is required to manage these areas, mitigating risks such as erosion and landslides. Additionally, the relatively small area designated for Water (U), at 20,092.58 square meters, indicates limited water bodies within the cell. This aspect will need to be considered in future planning to address potential impacts on local ecology and urban drainage systems, especially during heavy rainfall events.

## 2.6 Seasonal rainfall and Rainfall Intensity of Gatenga sector

The Historical daily precipitation patterns and statistics spanning from 1981 to 2021 offer detailed insights into the intensity of rainfall in this specific location. Simultaneously, the Daily Precipitation Analysis in the Maproom utilizes historical data to calculate simple seasonal statistics, offering a broader perspective on daily precipitation trends over the years (MetheoRwanda, 2022). This combined approach enables a comprehensive understanding of both localized rainfall intensity and overall historical precipitation patterns in the region.

Figure 7 below shows the mean precipitation analysis in the Maproom(MetheoRwanda, 2022). Mean Daily rainfall on left and Seasonal Rainfall Intensity on right side.

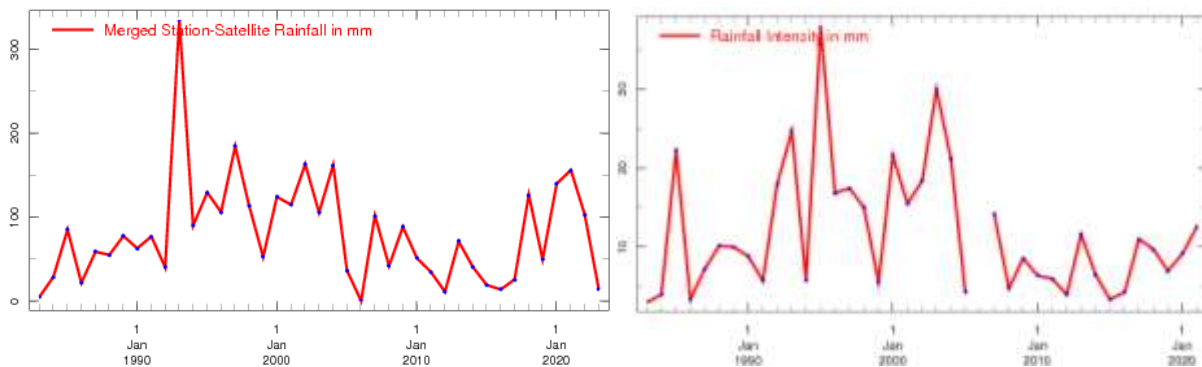


Figure 7: Mean Daily rainfall and Seasonal Rainfall Intensity from 1981 to 2021.

Source: Meteo Rwanda, 2022

The wettest season is March April and May while the driest is June July August (JJA) season. In Gatenga Sector the average annual rainfall is approximately 950 millimeters (37.4 inches). July is the driest month with about 11 mm (0.4 inches) of rain, while April is the wettest, experiencing around 154 mm (6.1 inches) of rainfall. During wetter months, the average daily rainfall duration is about 1 hour. The temperature varies between 14 and 30°C (MetheoRwanda & REMA, 2022).

The figure 8 shows the monthly minimum and maximum temperature monthly rainfall of Gatenga sector.

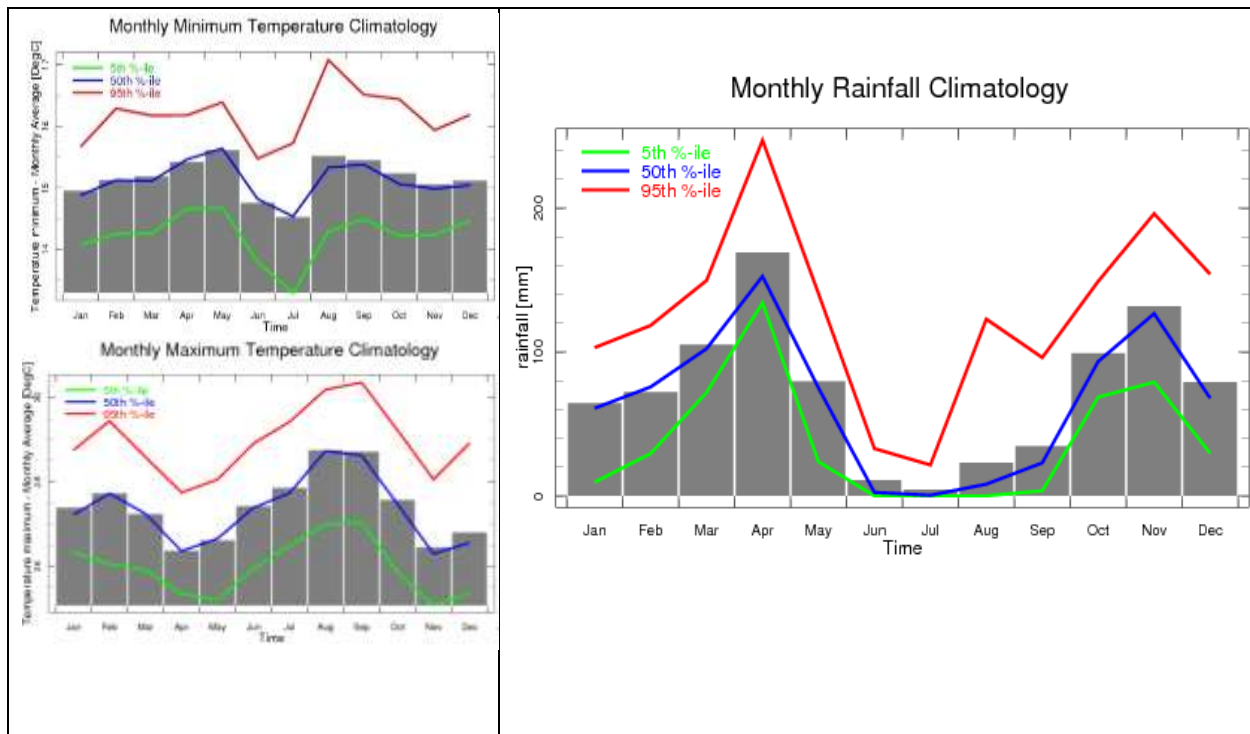


Figure 8: Gatenga Sector annual rainfall and temperature data.

Source: Rwanda Meteorology Agency, 2024

### 2.6.1 Monthly precipitation and Future Trends

In the projected climate changes expected by the 2050s, several significant trends are anticipated in Rwanda. These include an increase in the average annual temperature by 1.4–2.3°C, leading to warmer conditions globally. Moreover, there is a prediction for an extended duration of heat waves, potentially lasting 7–22 days longer than current patterns. Changes in precipitation are also expected, with a likely rise in average rainfall levels within a range of -3 to +9 percent. Additionally, there could be an increase in the frequency (7–40 percent) and intensity (2–11 percent) of heavy rainfall events. Furthermore, the duration of dry spells is anticipated to likely increase, spanning from 0 to +7 days, indicating potential shifts in precipitation patterns and water availability in the future climate scenario (World Bank Group, 2021).

REMA predicts that the rainy seasons will become short-term and more intense, with rainfall expected to become increasingly irregular. The current maximum annual rainfall is 106 mm in Kigali city, and the extreme maximum rainfall is expected to be 147.605 mm in a return period of 50 years (MetheoRwanda & REMA, 2022). During the June-July-August (JJA) season,

precipitation is expected to decrease from northwest to southeast, with reductions ranging between less than 50 mm and 150 mm from 2021-2050, 2041-2070, and 2071-2100. While Kigali city and southeastern provinces are projected to experience negative changes in precipitation, an increase in rainfall is anticipated by 2100 across all scenarios (MetheoRwanda & REMA, 2022).

The rise in the proportion of annual precipitation occurring during heavy rainfall events can have various consequences on the environment. This increase often results in rapid runoff and flooding, as the volume of water exceeds the soil's ability to absorb it efficiently. Consequently, this phenomenon diminishes groundwater recharge rates. Moreover, heavy rainfall contributes to the siltation of rivers, lakes, and reservoirs, leading to sediment build-up that can impact aquatic ecosystems and water quality. Additionally, the runoff from heavy rainfall events can contaminate industrial, agricultural, and domestic water sources, posing risks to both human health and the environment (World Bank Group, 2021)

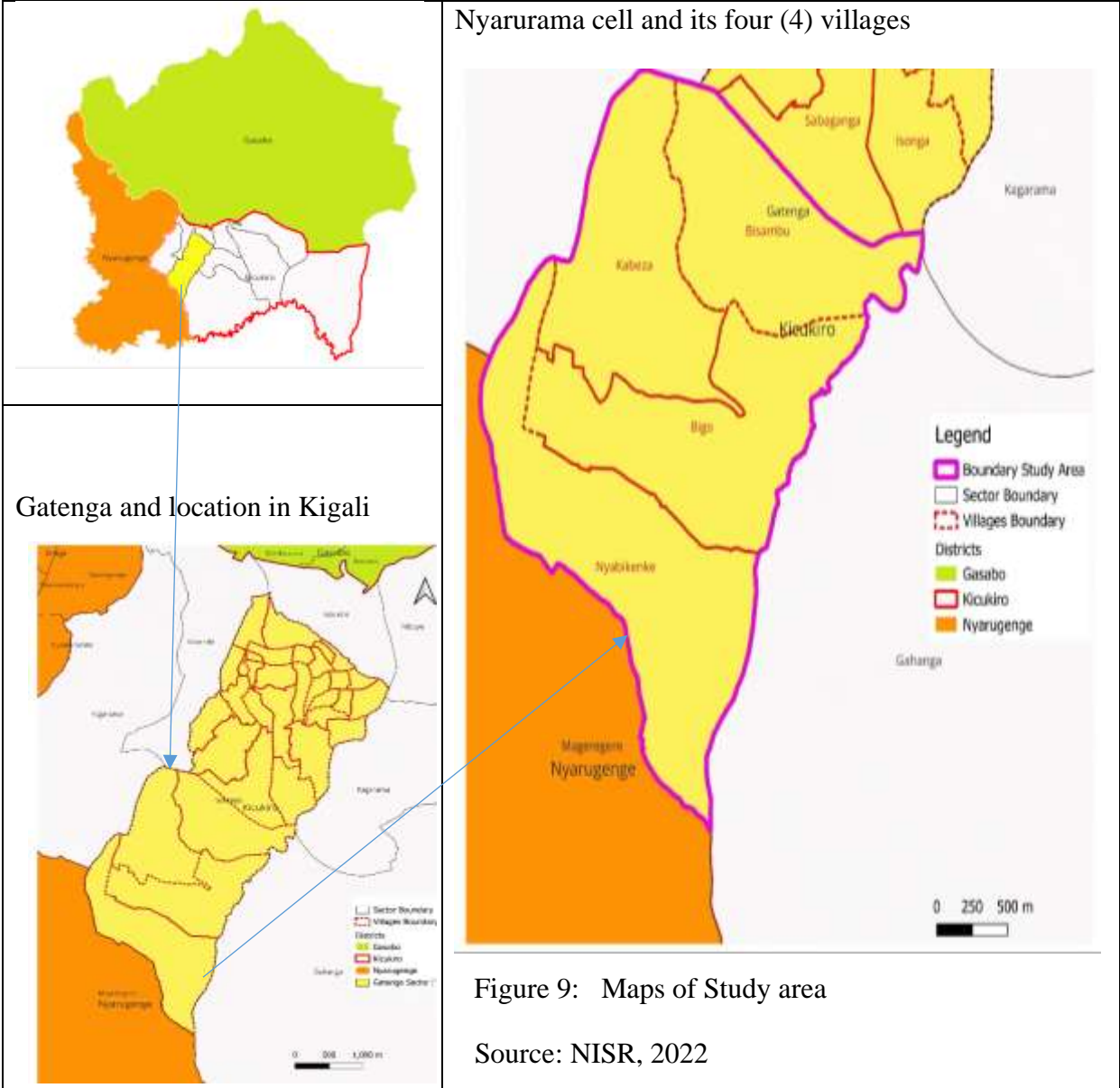
### **3 Chapter III. Materials and methods**

This chapter outlines the methodological framework employed in the study to evaluate storm water management and drainage systems. It begins with a presentation of the study area, providing context for the research. The chapter then details the methodology used, including research design, data collection, and processing methods. Specific emphasis is placed on the types and locations of data collected, as well as the data categories and formats. Sampling methods and sample size determination are explained, followed by a description of data analysis techniques used to estimate runoff, and peak discharge. The chapter concludes with an overview of the research materials and tools used for data collection and analysis. In this chapter, Section 3.1 presents the study area, Section 3.2 covers methodology, including research design and data collection, and Section 3.3 details the research materials and tools.

#### **3.1 Presentation of the study area**

Nyaruram cell, Gatenga Sector is one of the nine sectors of Kicukiro District in Rwanda. It is located in the eastern part of the district, bordering Gasabo District to the north, Nyarugenge District to the east, and Nyamata District to the south. Gatenga Sector has a population of over 67,084 people and 12.44km<sup>2</sup> and population density of 5393 is one of the most densely populated sectors in Rwanda (NISR, 2022).

Nyarurama cell is composed by four villages which are Bigo, Bisambu, Kabeza, and Nyabikenke and all are located in Nyarurama Cell as shown in in figure 9.



**3.1.1 Roads topography**

The map in Figure 10 illustrates the roads classified by slope range. Most roads are located on land with slopes ranging from 0% to 25%, while those situated on slopes greater than 50% are significantly fewer.

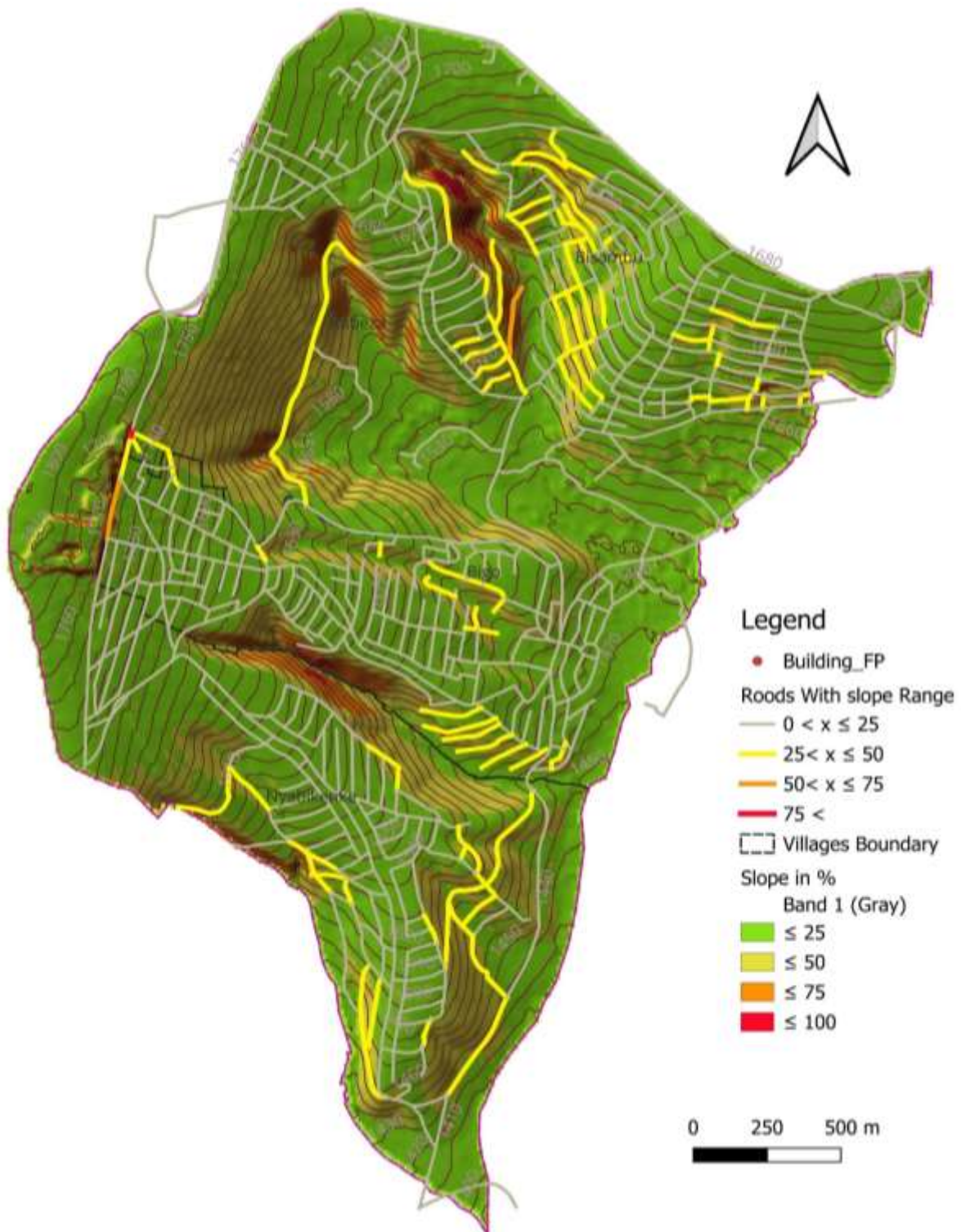


Figure 10: Slope and roads location (slope range) Map

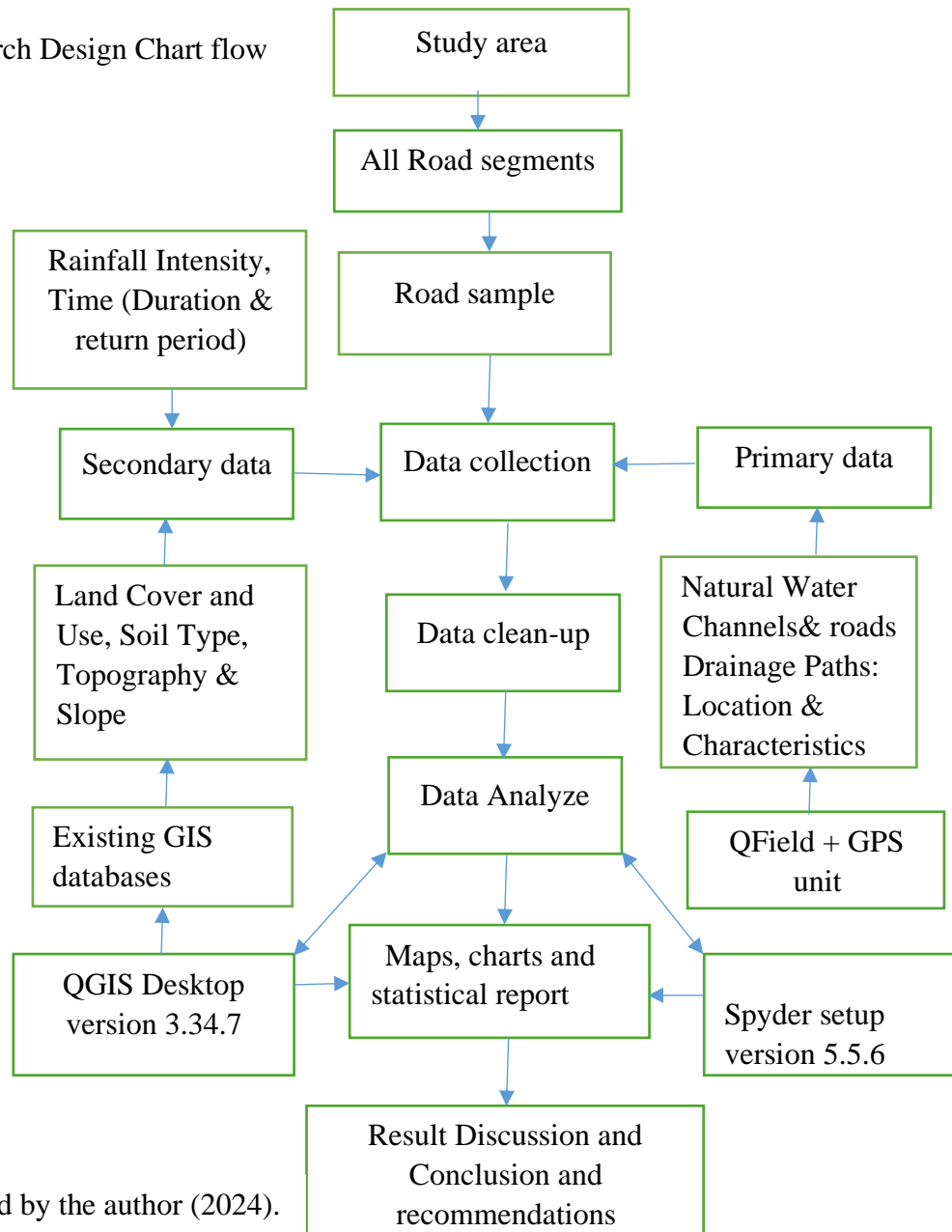
Source: NLA, 2024

## 3.2 Methodology

### 3.2.1 Research Design

The research design provides the strategy of investigation for the research. It defines the parameters and criteria to compile the data to evaluate results and conclude. The research design for this thesis is structured to answer the research questions using empirical data. As illustrated in fig.11. The research design combines different components of research, involving the use of different data collection and data analysis techniques logically to answer the research questions.

Figure 11: Research Design Chart flow



Source: Designed by the author (2024).

### 3.2.2 Data Collection and processing

Data for this study was collected through a variety of methods, including library research, field observations, field surveys, and ground measurement of drainages and ravines. The research leveraged both secondary and primary data sources to gain a comprehensive understanding of the drainage system in the Gatenga Sector.

Secondary data sources played a critical role in this study. These included satellite imagery, topographic maps, and existing GIS databases, which provided essential information about the geographical features, land use patterns, population distribution, and other relevant factors within the Nyarurama Cell. Data was sourced from reputable organizations such as the Rwanda Space Agency (RSA), Rwanda Water Board (RWB), National Institute of Statistics of Rwanda (NISR), National Land Authority (NLA), and the City of Kigali (CoK) and Food and Agriculture Organization of the United Nations (FAO). This secondary data facilitated a broad analysis of the study area's characteristics and supported the interpretation of primary data findings.

Primary data collection was conducted through field surveys using a Global Positioning System (GPS) unit and the Qfield application. Ravines and natural drainage paths were recorded, the condition of the existing drainage system, the survey involved recording detailed measurements of drainage systems, including length, height (depth), top width (B), and bottom width (b), which are vital for evaluating capacity and effectiveness. Additionally, locations of roads segments and ravine in flood-prone areas were identified and marked, and existing culverts and Retention ponds were documented along with potential sites for additional culverts. The survey further assessed road conditions, noting whether roads were paved or unpaved, destroyed or flooded and documented various drainage shapes such as Rectangular (U shape), Trapezoidal (V shape), and irregular. By integrating secondary data with primary field observations, the study offers a thorough understanding of the storm water and drainage conditions in Nyarurama Cell, providing a basis for informed recommendations to enhance urban planning and storm water management strategies.

Data preparation involved preprocessing steps to ensure compatibility with GIS software. This included formatting the data, identifying and correcting errors, and cleaning the data to ensure accuracy. The study gathered various categories of data, including rainfall data, land use

information, elevation details, existing drainage systems, historical flood events, and other relevant parameters. This data was obtained from reputable sources, including government agencies and open-source repositories.



Figure 12: Map Showing Types and Location of Collected data.

Data Source: Field survey and Google Image, June, 2024.

The figure 12 shows the types and locations of collected data related to the evaluation of road and drainage systems, identification of flood-prone areas, and detailed information, including drainage system shapes and ravine structures, in Nyarurama Cell, Gatenga Sector.

### 3.2.3 Data categories and formats

Table 6 outlines the categories and formats of data used in this study, along with the variables measured, data types, collection methods, and notes on their relevance.

Table 5: Data Category Details

Category	Data	Variable/ Aspect	Data Type	Data Collection Method	Notes/Comments
<b>Land Use/Land Cover</b>	Imagery, Zoning	Land types, Rules	Vector, Text, Raster	Remote sensing, Review	E.g., Residential, Commercial, Regulations.
<b>Soil Type</b>	Soil Maps, Surveys	Soil Composition, Permeability	Vector, Text, Raster	Field Surveys, Laboratory Analysis	Important for understanding infiltration rates.
<b>Elevation</b>	DTM, DEM Map	Heights, Contours	Raster, Vector	Survey, Digitization	Elevation data for modeling.
<b>Rainfall</b>	Weather Stations, Historical Records	Rainfall data	Time series, Tables	Records, Literature	Historical and IDF data.
<b>Infrastructure</b>	GIS database, Surveys	System design	CAD/GIS shape file	Field data, Building footprints	Details of drainage infrastructure.
<b>Scenarios</b>	Simulations, Analysis	Runoff, Capacity	Numeric	Modeling, Statistics	Model outcomes and comparisons.
<b>Results</b>	Outputs, Maps	Runoff rates, Maps	Numeric, Images	QGIS analysis results	Calculated peak runoff and visuals.

Source: Designed by the author (2024).

These categories collectively provide a comprehensive foundation for analysing and improving drainage systems in the Gatenga Sector.

### 3.2.4 Sampling Method

The focus of this study is on the roads within the Nyarurama cell, Gatenga Sector of Kigali City. Unlike typical studies that focus on human populations, this research targets road segments as the units of analysis. The sample size was determined based on the total number of road segments and

the specific research questions. A stratified sampling method was employed to ensure adequate representation of different areas within the study area.

### **3.2.5 Targeted Roads and Sample Size**

This study employs a comprehensive survey approach to evaluate the storm water and drainage infrastructure in the Nyarurama Cell of Gatenga Sector, Kigali City. The survey integrates secondary data with primary field data to provide a detailed assessment of the road network and its associated drainage systems. Initially, a road shapefile, which includes the spatial distribution of road segments within Nyarurama Cell, was loaded into QField, a mobile GIS application. While this shapefile provided essential information on road locations and attributes, it notably lacked detailed data on drainage systems.

To address this gap, field surveys were conducted to collect primary data on the size, shape, and condition of drainage systems along each road segment. On-site observations, on-ground measurements were carried out on drainage and ravines; and recorded using QField. The field data was crucial for supplementing the existing shapefile and identifying areas where drainage infrastructure was inadequate or missing. Additionally, the study integrated information on the drainage systems connected to ravines, which are crucial for managing runoff but do not pass directly under roads.

This study focuses on sampled roads and infrastructure instead of people for several reasons. By targeting road segments and associated drainage systems, the study aims to objectively analyze the condition and effectiveness of storm water infrastructure, providing detailed technical insights and recommendations for improvements. Road segments and drainage systems directly influence storm water management, allowing for the identification of areas needing enhancements to mitigate flooding risks. Precise data collection through field surveys and measurements facilitates understanding of current drainage system states. While the study's primary focus is on infrastructure, the ultimate goal is to indirectly benefit residents by improving quality of life through better storm water management, reducing flooding, protecting property, and enhancing public safety. The study's scope is limited to infrastructure evaluation due to its technical nature, with a broader study design required for comprehensive human impact assessment. By

concentrating on the technical aspects, the study aims to offer actionable insights and solutions for a better-managed storm water system, ultimately improving living conditions in the study area.

### 3.2.6 Sample Size Determination

To determine the sample size for descriptive studies involving road segments, Cochran's formula (Cochran, 1977) was used. This formula is particularly useful for estimating the required sample size when dealing with population proportions (Cochran, 1977). The formula is as follows:

$$n = \frac{Z^2 \cdot p \cdot (1-p)}{E^2} \quad (1)$$

Where:

$n$  represents the required sample size.

$Z$  is the Z-score corresponding to the desired confidence level (e.g., 1.96 for a 95% confidence level).

$p$  is the estimated proportion of the population with a specific characteristic (e.g., the proportion of people who prefer a certain product).

$E$  is the desired margin of error (expressed as a proportion).

The targeted population for this study comprises the road segments of the Gatenga Sector in Kigali City, specifically within the Nyarurama Cell. The sample size was determined based on the total number of road segments and the nature of the research questions. A stratified sampling method was used to ensure that different areas within the study site are adequately represented in the sample. For estimating the proportion of road segments with adequate storm water drainage, the Cochran formula was used to calculate the required sample size for a 95% confidence level and a 5% margin of error:

$$n = 1.96^2 * 0.5 (1 - 0.5) / 0.05^2$$

This would give a sample size of 384 Road segments.

### 3.2.7 Stratified sampling method

A stratified sampling method was used. Stratification based on factors such as population density, land use type, or geographical features (Carayannis, 2018; Hassan, 2023). The formula for stratified

sampling is: 
$$n_h = \frac{N_h}{N} * n \quad (2)$$

where: ( $n_h$ ) is the sample size for stratum ( $h$ ), ( $N_h$ ) is the population size for stratum ( $h$ ),

( $N$ ) is the total population size, and ( $n$ ) is the total sample size

With a calculated total sample size of 384 road segments, 201 road segments were initially allocated to the residential zone within Nyarurama Cell, Gatenga Sector, which comprises 805 road segments. However, following field observations, the sample size was increased to 497 road segments (61.9% of the total) due to the less presence of roads with drainage as it is illustrated in figure 13.b. In legend of figure 13.b, 'No' = roads not in sample (38.1%), 'Yes' = roads in sample (61.9%). In addition, all natural drainages and ravines that were considered 100% while and during field data correction as shown in figure 13.a.

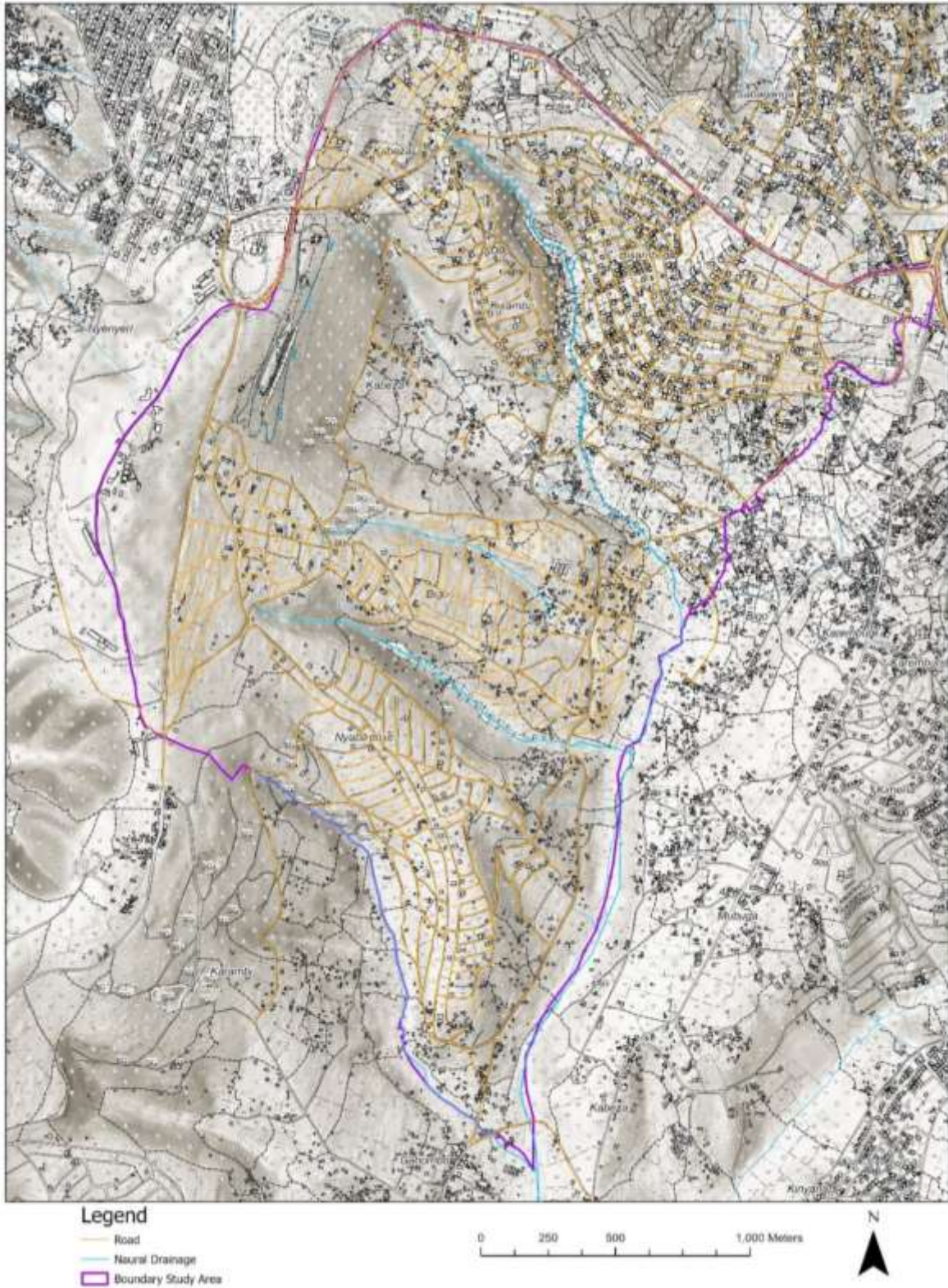
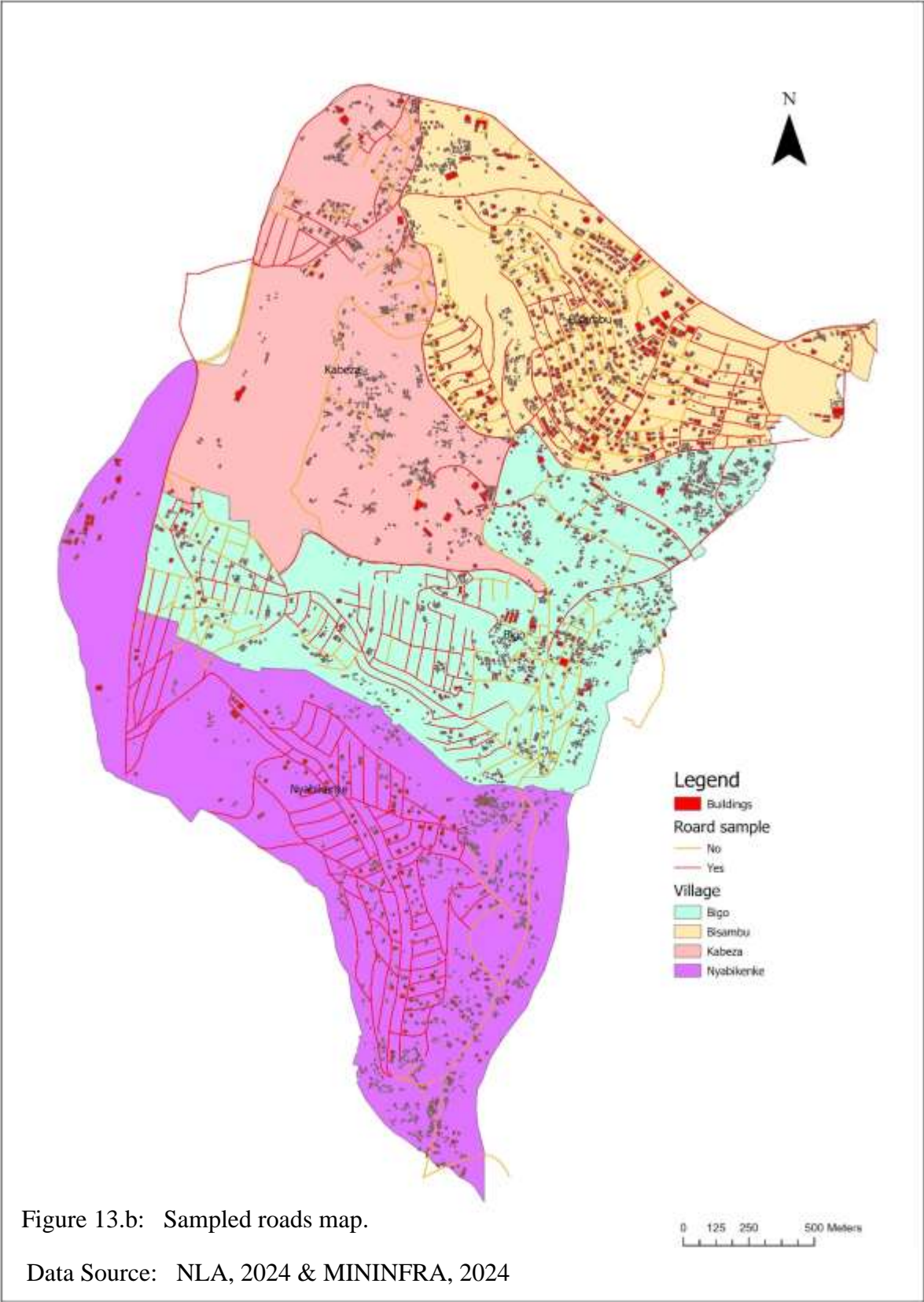


Figure 13.a: All Roads and natural drainage (water channels) distribution Study area.

Data Source: NLA, 2024 & MININFRA, 2024



### 3.2.8 Data analysis

The analysis process began with GIS Mapping, involving the initial mapping of the study area using QGIS. This step included visualizing road segments and existing drainage infrastructure to establish a foundational understanding of the area's layout.

Following GIS Mapping, the Field Survey Integration phase commenced. Primary data on drainage systems was collected using QField and through QGIS cloud plugin primary data integrated with the existing road shape file to ensure comprehensive attribute documentation. As shown in figure 6 data integration helped in creating a detailed dataset for further analysis. Subsequently, the analysis moved to Hydrological Modeling as shown in figure 1.4.a. Storm water runoff patterns were set up and simulated using the SAGA Next Gen tool within the QGIS environment. This simulation enabled the evaluation of drainage performance under different rainfall scenarios, providing insights into how the existing infrastructure responds to varying levels of precipitation.

#### Hydrological modelling

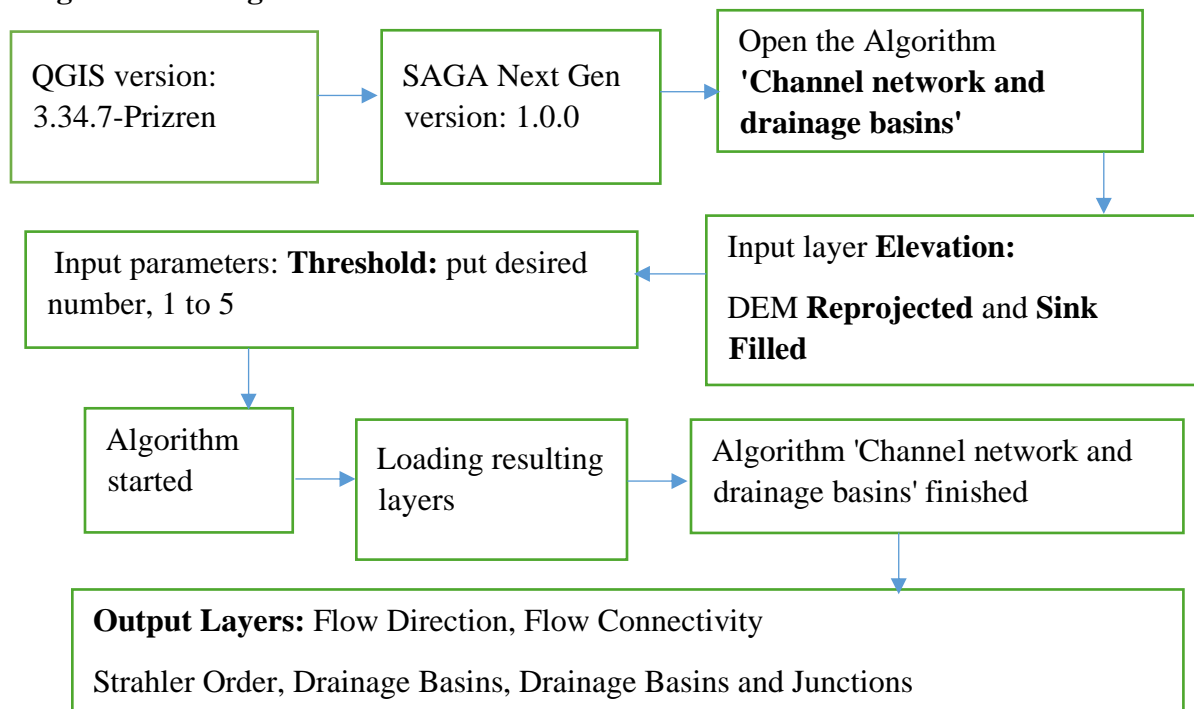


Figure 14.a: Hydrological modelling and watershed delineation chart.

Source: Designed by the author (2024).

The figure 14.a outlines the data processing and integration steps used for storm water runoff simulation. Data collection methods included obtaining real-time weather data, land use, and soil type information, which were essential for accurate and dynamic modeling. GIS data were integrated to enhance the precision of the simulations, allowing for detailed analysis of various factors affecting storm water runoff. Advanced algorithms were employed to predict runoff more effectively, incorporating comprehensive datasets to reflect the actual conditions in Gatenga. This systematic approach ensured that the storm water runoff simulations were both accurate and reliable, providing valuable insights for managing storm water in urban areas.

### 3.2.9 Runoff estimation

To ensure accuracy in flow calculations, the specific values for Manning's roughness coefficient ( $n$ ), hydraulic radius ( $R$ ), and channel slope ( $S$ ) were determined for different channel shapes and materials in the study area.

#### 3.2.9.1 Runoff estimation (Peak discharge)

$$Q = CIA \quad \text{Equation (3)}$$

Where:

***Q*** is the peak discharge [total Runoff]

(cubic feet per second or cubic meters per second).

***C*** is the runoff coefficient. ***C*** is an important indicator of soil type of the watershed. It ranges between 0 and 1, the value of ***C*** approaches to 0 for sandy soil type and toward 1 for clayish soil type.

***I*** is the rainfall intensity (millimeters per hour).

***A*** is the drainage area [the area of catchment] (square meters).

The Rational Method to estimate storm water runoff was used to estimate rainfall intensity (ASCE & Rossmiller, 1992; Wagesho & Claire, 2016)

The flowchart in figure 14.b. illustrates a clear process for integrating and analysing data in your study, ensuring each step is methodically addressed to achieve accurate and comprehensive results.

Chart below show data processing and integration steps

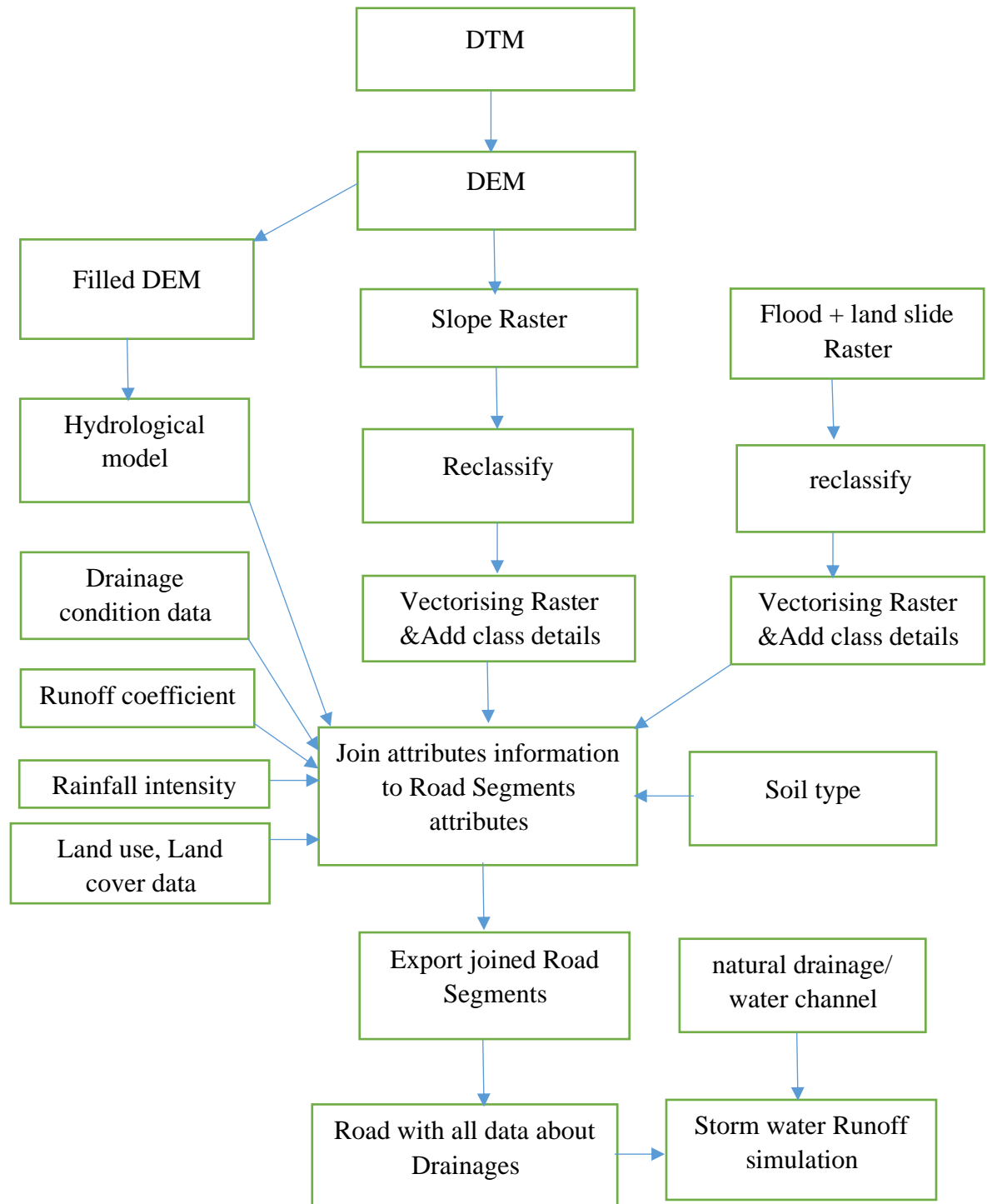


Figure 14.b: Data integration and analysing chart

Source: Designed by the author (2024).

### 3.2.10 Rainfall intensity estimation

$$I = \frac{\alpha}{(t+\gamma)^c} \quad \text{Equation (4)}$$

where  $I$  = maximum intensity (mm/hr);  $t$  = rainfall duration (min.);  $\alpha$  = regression coefficient (mm/hr);  $\gamma$  = time

constant (min) and  $c$  = exponent with values less than unity. In Equation (1) the constants  $\gamma$  and  $c$  do not depend on return period, however, the constants vary significantly with location and estimated for specific region.

By using these formulas, the study was able to estimate the peak discharge in the drainage channels of the study area, providing crucial insights into the current storm water management challenges and identifying areas needing improvement.

### 3.3 Research Materials

The study utilized a range of materials and tools to achieve its objectives of characterizing, evaluating, and improving the drainage system in the residential areas of Nyarurama, Gatenga Sector. This section provides a comprehensive list of materials used, descriptions of each material, and justifications for their selection.

The Qfield application was employed for conducting field surveys and gathering primary data on the current state of storm water and drainage systems. This mobile data collection tool was chosen for its efficiency in collecting real-time data in the field, essential for accurately assessing the drainage system's current condition. Geographic Information System (GIS) software, specifically QGIS, was used for manipulating, analyzing, and visualizing spatial data. GIS software is critical for spatial analysis and visualization, allowing for detailed examination of drainage infrastructure and identification of vulnerable areas.

Satellite imagery provided Google Satellites were used to observe and analyze land use, topography, and changes over time. The comprehensive and up-to-date views offered by satellite imagery facilitated the analysis of land use changes and their impact on drainage. Additionally,

topographic maps, which are detailed maps showing the physical features of the area, were used to understand terrain and drainage patterns.

Historical rainfall data was used to analyze precipitation patterns and intensity. This data is essential for analyzing rainfall patterns, which directly influence storm water runoff and the performance of drainage systems. Thanks to QGIS plugins called runoff modeling tools were also utilized to simulate water flow and assess the capacity of drainage systems. These tools enable detailed simulation of water flow, helping to evaluate the capacity and effectiveness of existing drainage systems.

To gather qualitative data, interviews were conducted with local residents. The data about local drainage issues, community perspectives and recommendations were collected. Literature sources, including academic journals and best practice guides, provided background information and benchmarks for storm water management. These sources offer established knowledge and best practices, serving as benchmarks for evaluating current systems and recommending improvements.

### **3.3.1 Tools for Data Collection and Data Analysis**

The study employed several key tools for data collection and analysis. QField was used for field surveys to gather primary data on storm water and drainage systems. GIS software, including QGIS and Microsoft Excel, facilitated data processing, the manipulation and spatial analysis of the data. **Spyder** allowed to use Matplotlib, a popular plotting library in Python, to create various types of graphs such as line plots, scatter plots, bar charts, histograms, and more. **Spyder** is a versatile IDE designed for scientific computing. It offers a user-friendly interface for tasks like data analysis and visualization. Key features include a code editor, variable explorer, plotting tools, a Python console, debugger, file explorer, and plugin support. Table 6, outlines the specific tools and methods used for data collection and analysis to achieve the study's objectives.

Table 6: Tools for Data Collection and Data Analysis

Research Questions	Data Collection	Data Analysis
What is the current status of the drainage system in newly developed residential areas of Nyarurama Cell?	- Conduct field surveys using QField application to collect primary data about the current state of storm water and drainage systems. - Use GIS software to manipulate and analyze the collected data.	- During data processing and analysis, Microsoft Excel and QGIS were used.
- How effective is the existing drainage system in Nyarurama Cell, Gatenga Sector at managing storm water runoff during heavy rainfall events?  - Which areas within Nyarurama Cell, Gatenga Sector are particularly vulnerable to drainage issues such as overflows and flooding?	- Use secondary data sources such as satellite imagery, topographic maps, and existing GIS databases. - Collect rainfall data and storm water runoff data.	- Conduct spatial analysis to identify patterns, relationships, and trends in the data.  Use Spyder to create various types of graphs
What strategies and interventions can be implemented to improve storm water management and drainage planning in Nyarurama Cell?	- Review literature on best practices in storm water management and interviews	-Conduct stakeholder analysis to understand the needs and perspectives of different community groups

Source: Designed by the author (2024).

## **Chapter IV. Results presentation and discussion**

The results presentation and discussion chapter reveal the findings of the research and interprets their significance. It begins with the presentation of data on drainage shape characteristics, soil properties, and rainfall intensities. The chapter further explores hydrological changes due to road construction and provides detailed runoff calculations and peak discharge analysis. It also evaluates the capacities of existing drainage systems and discusses the natural drainage system and ravines. The chapter includes calculations for adequate drainage dimensions and assessments of future runoff and drainage system capacity through 2050. The discussion integrates these results to provide a comprehensive analysis of the current state and future needs of the drainage system. In this chapter, Section 4.1 presents results on drainage characteristics and soil properties, Section 4.2 covers runoff calculations, Section 4.3 details peak discharge analysis, Section 4.4 discusses natural drainage systems and ravines, and Sections 4.5 to 4.7 provide calculations for adequate drainage dimensions and discussions on future runoff.

### **3.4 Results presentation**

The results presentation presents and discusses the findings obtained from the data collected in Nyarurama Cell, focusing drainage systems including both road infrastructure natural ravines. Finding from detailed on-the-ground observation, measurement, and GIS data analyses provide a comprehensive understanding of the existing conditions and identify areas for potential improvement. The field surveys and interviews conducted in Nyarurama Cell provide a comprehensive understanding of the drainage systems and storm water management. This approach enabled a detailed assessment of the existing conditions and informed planning for necessary improvements in the area.

#### **3.4.1 Drainage System in Nyarurama Cell**

##### *3.4.1.1 Road Status*

The analysis of road status in Nyarurama Cell reveals a significant disparity between paved and unpaved road lengths. The data highlights a predominant presence of unpaved roads in the area where 8.7% are paved, while 91.3% are unpaved.

Figure 15 illustrates the destruction of paved (asphalt) roads due to stormwater overflow, attributed to inadequate drainage systems (15a&b).

The narrow drainage facilities have been identified as a contributing factor to this damage. Although there were attempts to expand the drainage systems (figure15c), these expansions were not adequately planned or dimensioned, leading to severe downstream damage

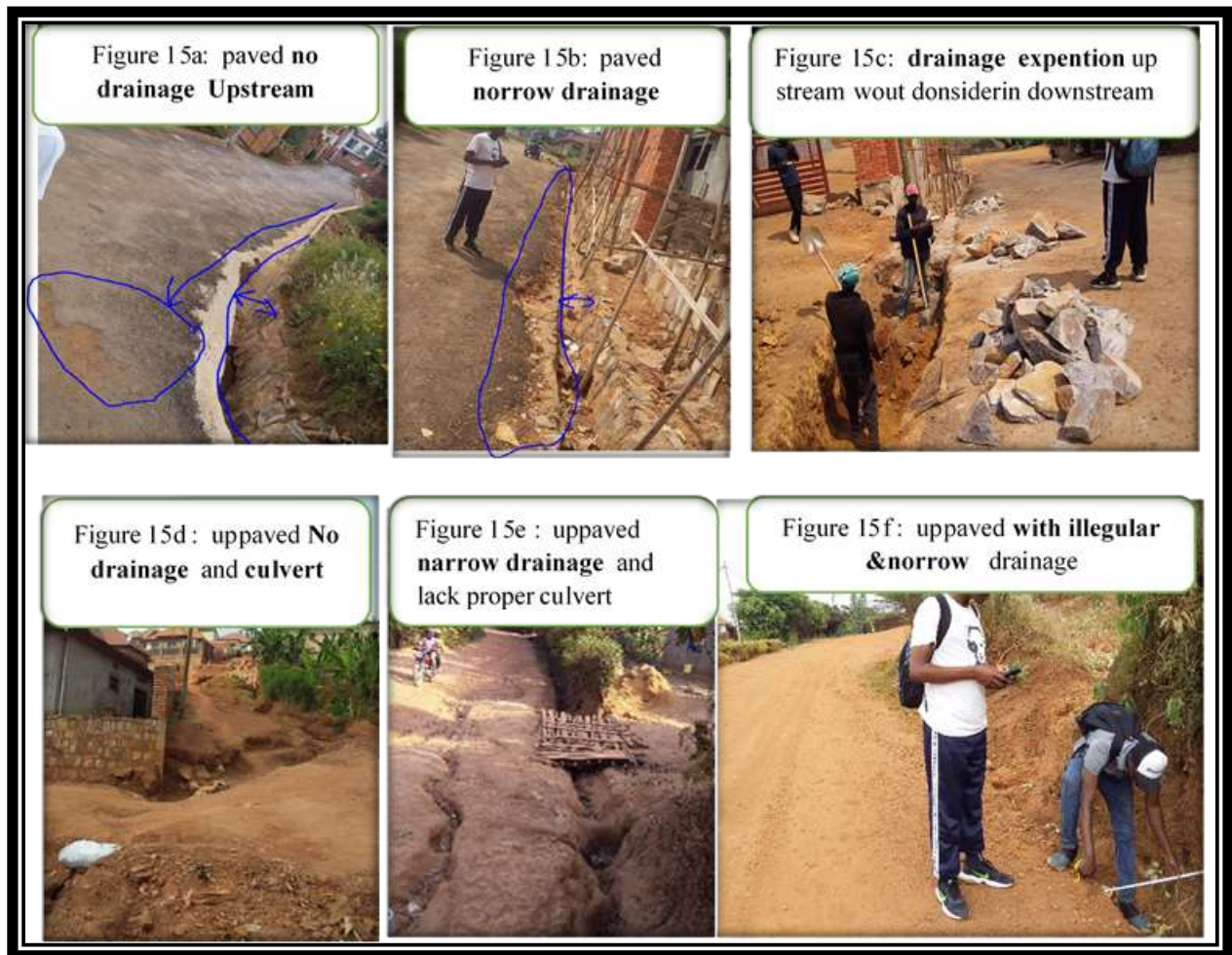


Figure 15: current Road Drainage Characteristics

Source: Photos taken by Author, Field Survey, 2024

Figure 15 further underscores the critical issues with the drainage infrastructure, indicating that drainage systems were insufficiently considered during site development.

### 3.4.1.2 Road drainage systems

The evaluation of drainage shape characteristics in Nyarurama Cell provides further insight into the distribution and condition of drainage systems. The data outlines the lengths of various drainage types, both unpaved and paved, as well as their respective proportions.

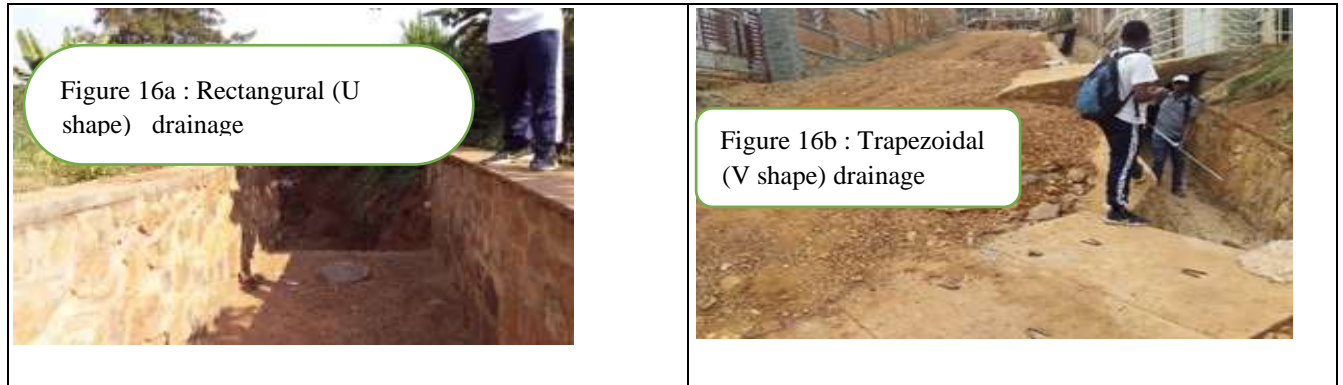


Figure 16: The variability in drainage shapes observed in Nyarurama.

Source: Field survey, June,2024

Drainage Shape Type	Unpaved Drainage (m)	Paved Drainage (m)	Total Drainage (m)	% Of Unpaved Drainage	% Of Paved Drainage	% Of Total Drainage
Rectangular (U shape)	2,538.2	6,336.8	8,875.0	4.9	89.6	15.3
Trapezoid (V shape)	41.8	92.5	134.3	0.1	1.3	0.2
Irregular Drainage	1,390.0	0.0	1,390.0	2.7	0.0	2.2
No Drainage	47,645.4	639.4	48,284.8	92.3	9.0	83.1
<b>Grand Total</b>	<b>51,615.4</b>	<b>7,068.7</b>	<b>58,684.1</b>	<b>100.0</b>	<b>100.0</b>	<b>100.0</b>

Table 7: The variability in drainage shapes observed in Nyarurama.

Data source: Road drainage field survey, June,2024

The figure 16 and table 7 contains images with a table that illustrate the variability in drainage shapes observed in Nyarurama Cell. The analysis from field survey shows that irregular drainage accounts for 2.7% of unpaved drainage, while there is no irregular drainage in paved areas. The most significant category is the lack of drainage, which affects 92.3% of unpaved roads and 9.0% of paved roads. Rectangular (U shape) drainage systems are more common in paved areas (89.6%) compared to unpaved areas (4.9%). Trapezoidal (V shape) drainage is the least common, representing only 0.1% of unpaved and 1.3% of paved drainage systems.

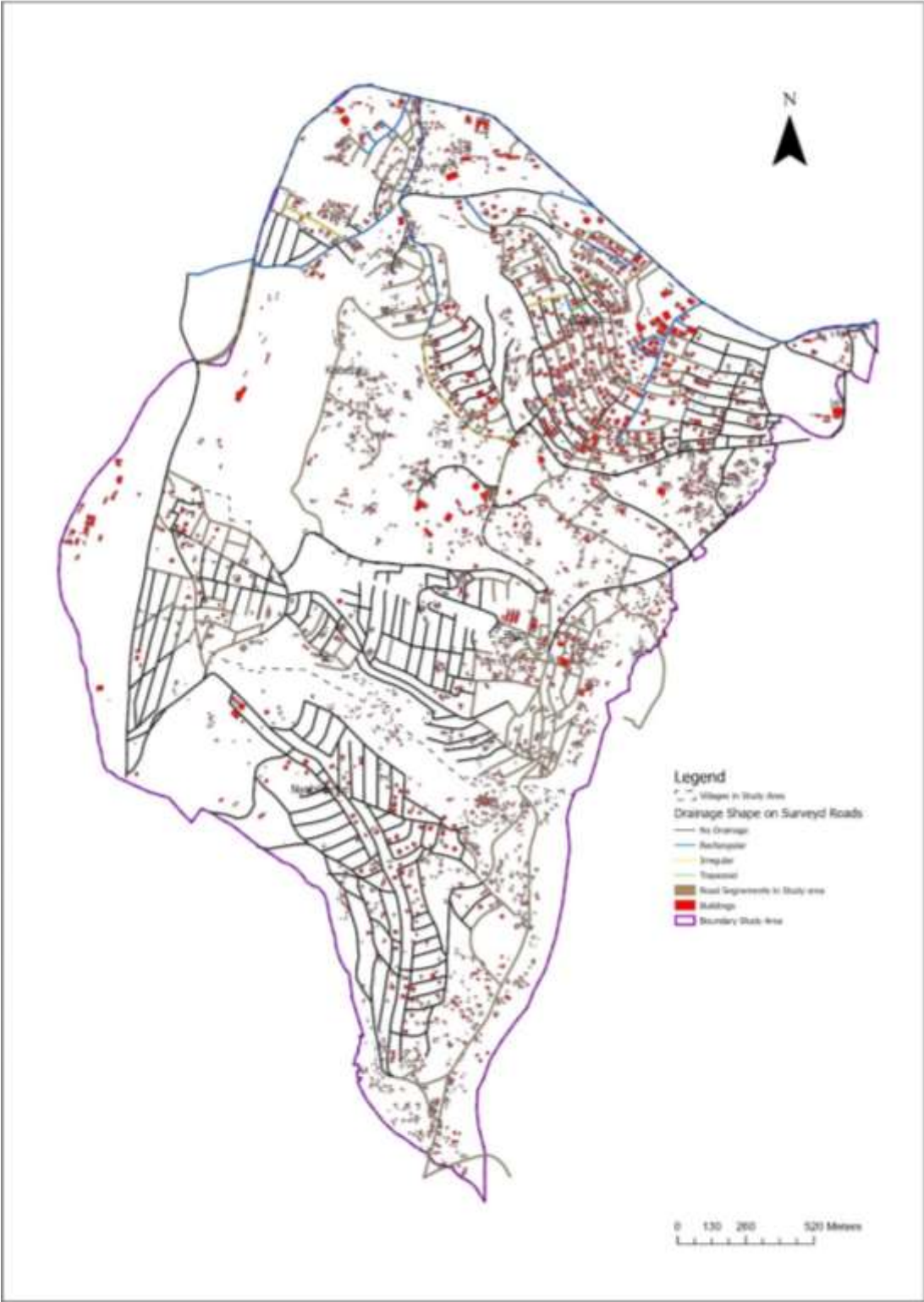


Figure 17: Drainages shape types map

Source: MININFRA, 2024

Drainages distribution in figure 17 highlights substantial deficiencies in drainage infrastructure, particularly on unpaved roads, where the absence of proper drainage is predominant.

Overall, lack drainage infrastructure is the predominant condition, representing 83.1% of the total drainage system in Nyarurama Cell. This highlights substantial deficiencies in drainage infrastructure, particularly in unpaved areas. Rectangular (U shape) drainage systems, though more common in paved areas, still represent only 15.3% of the total, indicating the need for improvement and expansion.

#### *3.4.1.3 Natural drainage system and ravines*

The Nyarurama natural drainage system encompasses five (5) main ravines with a total length of 12,882 meters, with the Bisambu-Bigo ravine being the longest at 5,462.7 meters.

The hydrological model analysis results are depicted in Figure 17.a, which demonstrates the delineation of watersheds and sub-catchments -also known as basins- using QGIS. This figure also shows the stream order, representing the hierarchy of channels within the watershed, illustrating how water and runoff should flow naturally through the landscape. The stream order highlights the primary channels that guide the movement of stormwater from smaller tributaries to larger streams, ensuring efficient drainage within the catchment area.

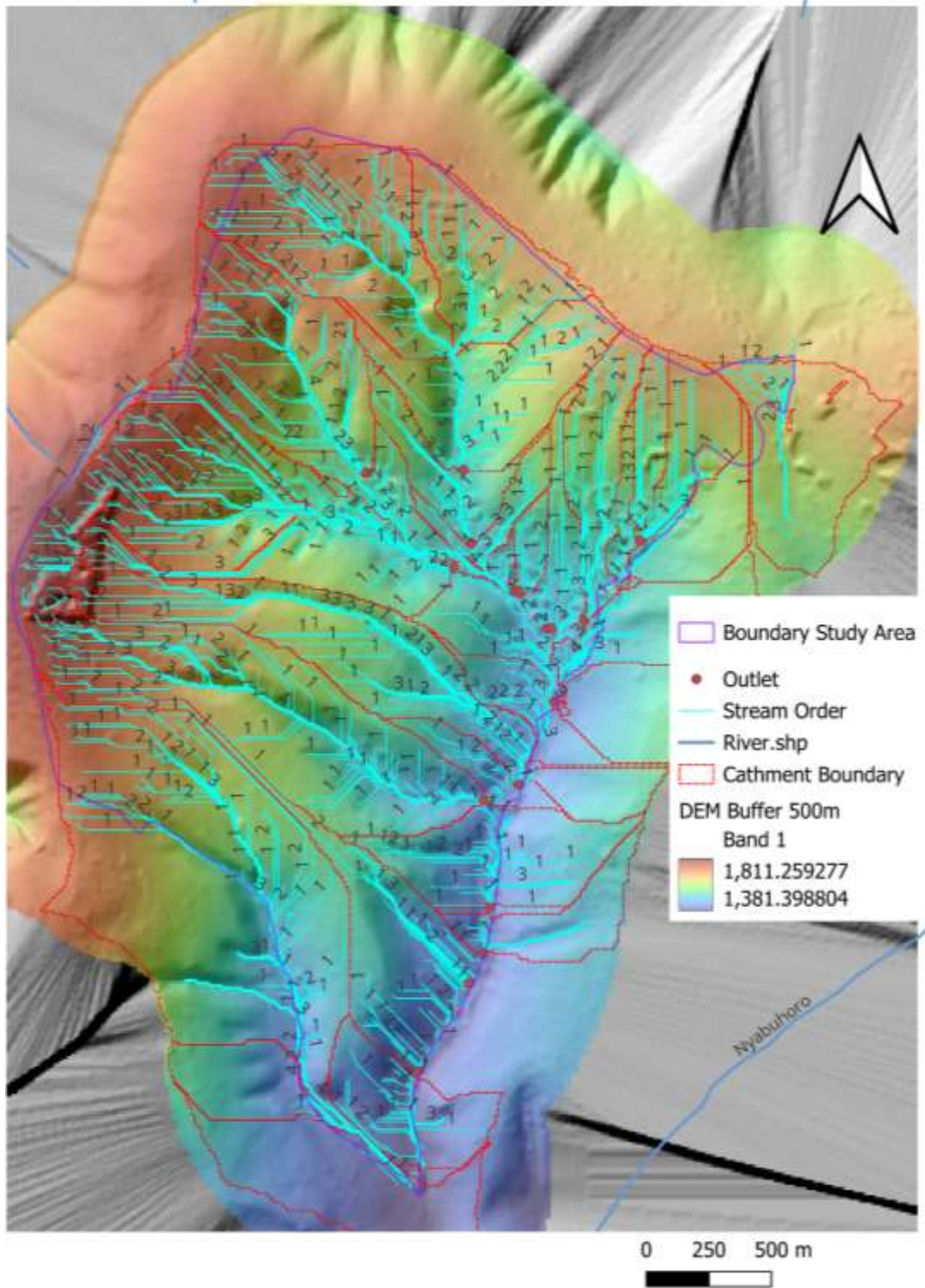


Figure 18.a: Hydrological model analysis for Nyarurama watersheds delineation.  
 Source: DEM analysis generated from DTM;( NLA ,2024

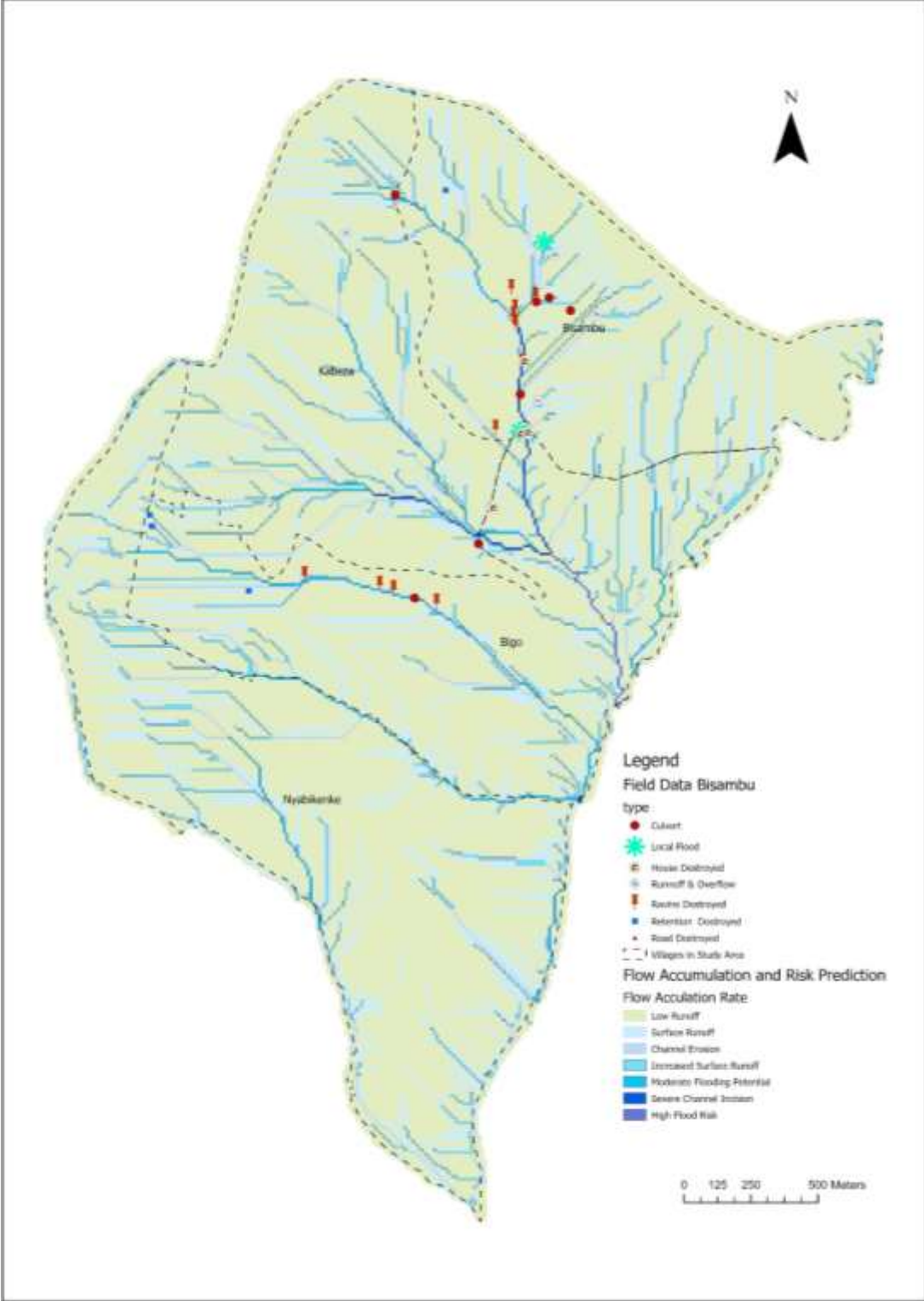


Figure 18.b: Nyarurama watersheds delineation and Risk zones.

Source: Generated from DTM; NLA ,2024 & Field verification done in June, 2024.

Source: Hydrological modelling generated from DTM points (figure 18a.), and field verification (figure 18.b).

These ravines are characterized by their unpaved nature, illegal shapes, severe destructions and deep trenches.

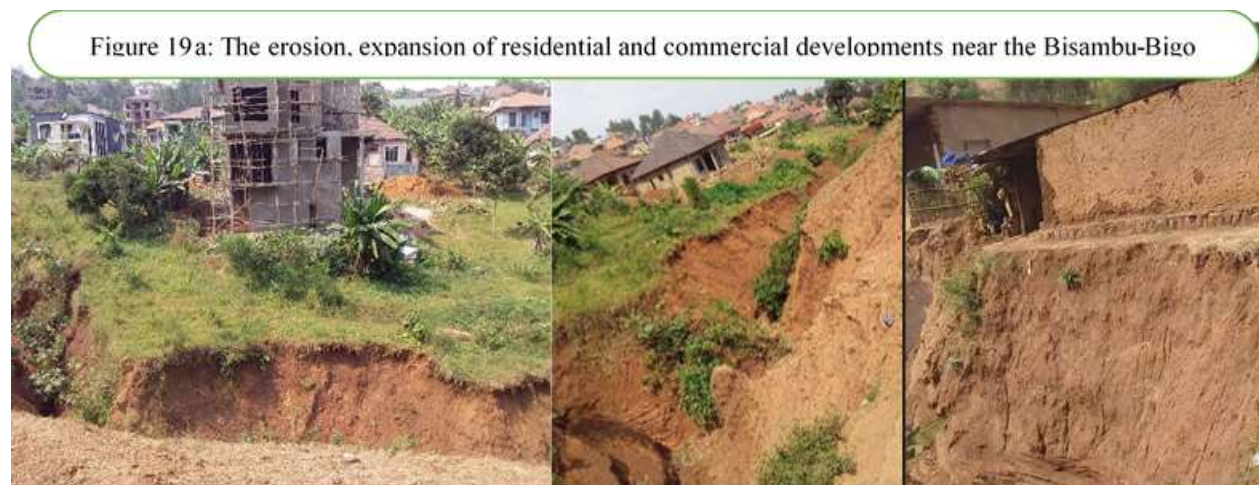


Figure 19.a: Bisambu-Bigo ravine and human activities

Source: Photos taken by Author, Field Survey, April, 2024

The drainage system in Nyarurama cell has witnessed a significant transformation, where natural drainages have evolved into large ravines due to encroaching built-up areas and human activities. The expansion of residential and commercial developments has disrupted the natural flow of water, leading to increased erosion and the formation of extensive ravines and gullies. Figure19.a depicture how these alterations have not only impacted the local ecosystem but have also intensified the effects of storms and rainfall events on the landscape.

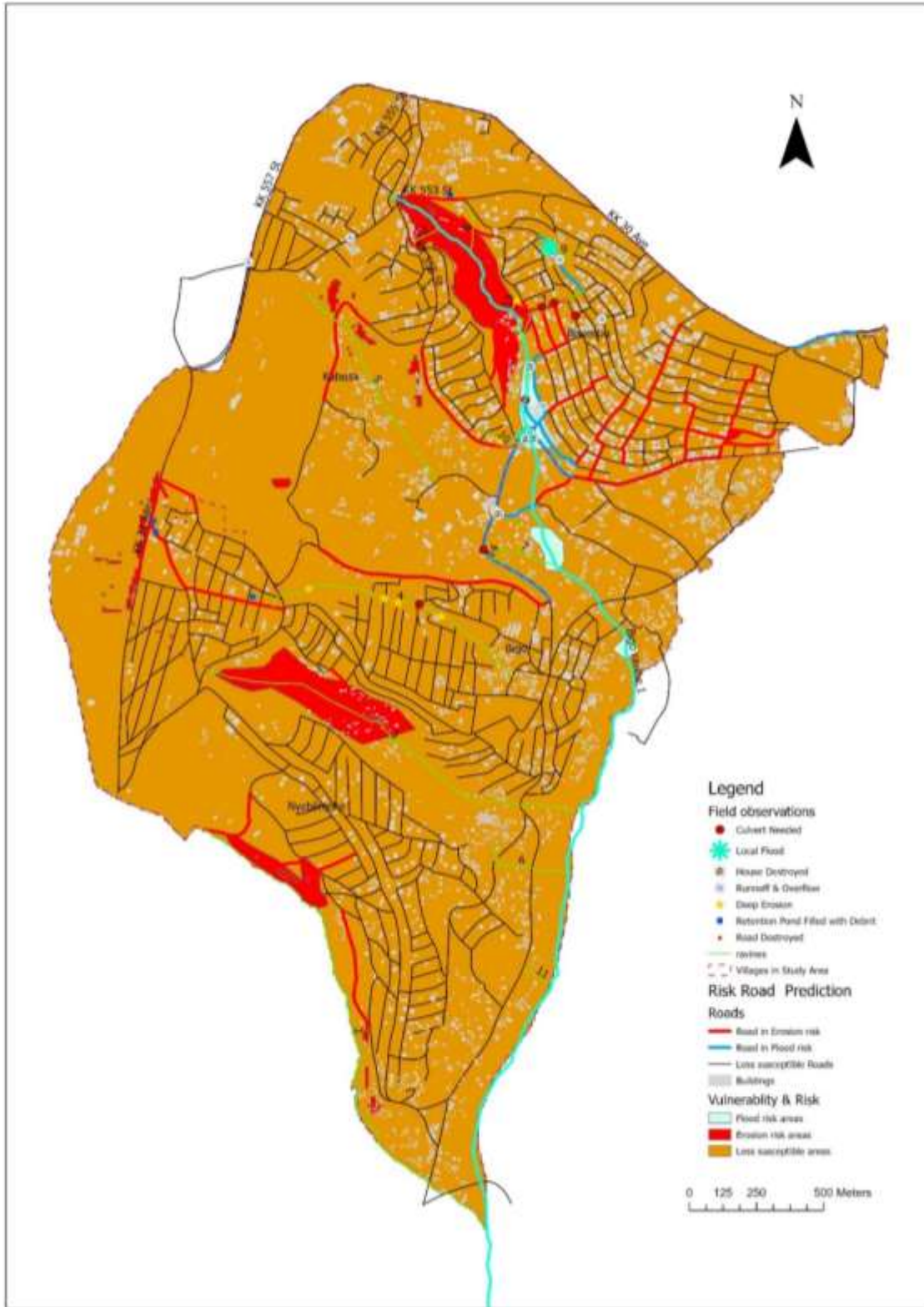


Figure 19.b: Bisambu-Bigo ravine and Risk zones in Nyarurama cell catchment

Data Source: MININFRA, 2024 & Field verification done in June, 2024.

Storm water management presents substantial challenges, particularly regarding erosion, flooding, and the displacement of residents living near the Bisambu-Bigo ravine. Erosion along the Bisambu-Bigo ravine poses a direct threat to the community, resulting in the destruction of eight houses and culverts during heavy rainfall in April to May 2024. The map in figure 19.b shows the location of destroyed properties and risk zones. It highlights areas where inadequate drainage or steep slopes make roads vulnerable to runoff damage, identifying key regions for stormwater management interventions like improved drainage, erosion control, and road design adjustments to prevent further deterioration and flooding. The escalating frequency of storms exacerbates these issues, emphasizing the critical need for erosion control measures and sustainable solutions to safeguard residents and their livelihoods.

The economic repercussions of ravines and gullies in Nyarurama cell are profound and varied. The devastation caused by erosion and flooding led to property and infrastructure damage, resulting in significant financial burdens for individuals, businesses, and local authorities. The costs associated with repairs, reconstruction, and mitigation measures further strain limited resources, affecting the economic stability of the community.



Figure 19.c: Culverts are INADEQUATE to handle storm water in Bisambu-Bigo ravine

Source: Photos taken by Author, During Field Survey, 2024.

The Existing culverts are not capable to handle storm water in Bisambu-Bigo ravine as shown in figure 19.c. Furthermore, the disruption of infrastructure, such as damaged culverts and transportation routes, isolates communities and impedes access to essential services like education and healthcare facilities.

#### *3.4.1.4 Critique of Existing Average Drainage Dimensions findings*

The critique of existing drainage dimensions for Trapezoidal (V shape) and Rectangular (U shape) shapes provides insights into their effectiveness. For Trapezoidal (V shape) drains, with a depth of 0.6475 meters, a top width of 0.75 meters, and a bottom width of 0.4125 meters, several issues are noted. The bottom width is considerably narrower than the top width, which may restrict flow capacity during peak discharge events. Additionally, the depth seems adequate for moderate flows, but the efficiency of the Trapezoidal (V shape) shape is dependent on an appropriate top-to-bottom width ratio to avoid turbulence. A narrow bottom width might also lead to sediment deposition, necessitating frequent maintenance. For Rectangular (U shape) drains, with a depth of 0.6379 meters, a top width of 0.6486 meters, and a bottom width of 0.6486 meters, similar issues arise. The Rectangular (U shape) shape's capacity for handling storm water is limited by its dimensions, which may become inadequate during extreme weather conditions.

### **3.4.2 Soil characteristics**

The soil characteristics Nyarurama Cell play a crucial role in determining how rainwater interacts with the land. Analyzing the soil composition provides valuable insights into water infiltration, runoff potential, nutrient availability, and overall water management strategies in the region. The soil data for Gatenga, Nyarurama Cell reveals significant implications for rainwater management: The soil profile shows a high clay content in both the topsoil (52.9%) and subsoil (56.9%). This high clay content implies slow water infiltration, increased surface runoff, and good water holding capacity once water infiltrates the soil. The slightly acidic pH levels of the topsoil (pH 5.1) and subsoil (pH 5.3) may affect nutrient availability and increase the potential for nutrient leaching when rainwater percolates through the soil. Low Organic Matter: With a relatively low organic matter content in the topsoil (1.92%), the soil may exhibit reduced water infiltration, lower nutrient retention, and increased susceptibility to erosion and runoff.

**Shale Dominance and Impact on Drainage:** it was observed that red shale, a fine-grained sedimentary rock prevalent in Nyarurama cell, exhibits impermeable characteristics, hindering water infiltration and leading to heightened surface runoff during precipitation. The data revealed that approximately 11% of the area lacked lithological information, likely due to insufficient geological surveys. Notably, red shale constituted 89% of the area, emphasizing its significant presence. The research emphasized the critical importance of addressing the challenges posed by shale dominance in storm water management. Strategies identified to enhance drainage and storm water systems included upgrading infrastructure to handle increased runoff, implementing infiltration techniques such as permeable pavements and rain gardens to reduce surface water volume, ensuring regular maintenance of drainage systems, and engaging the community in activities that promote effective drainage practices.

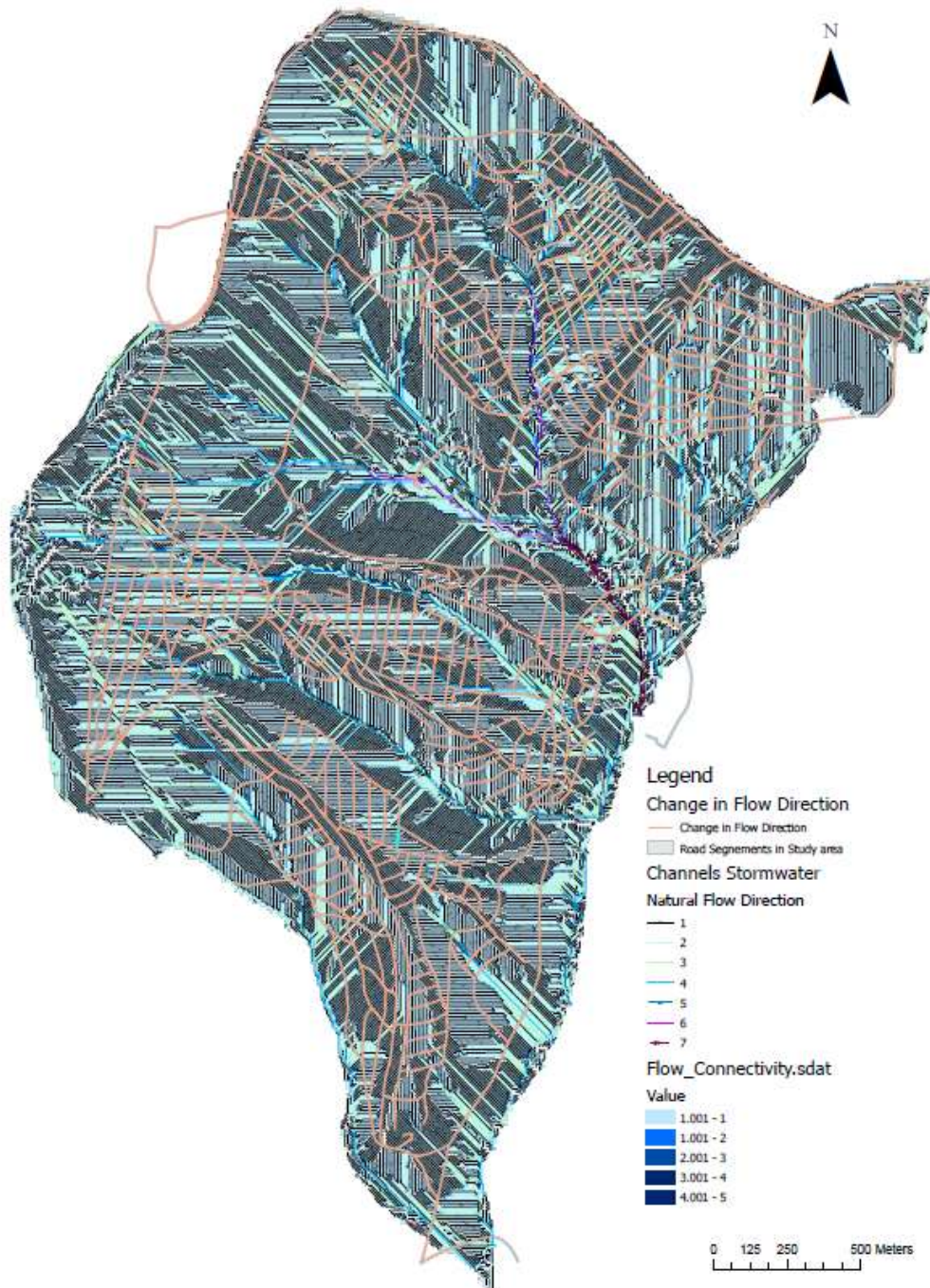
### **3.4.3 Hydrological Changes Due to Road Construction**

Before road construction in the Nyarurama cell, the natural flow of stormwater was largely undisturbed, following existing contours and either gradually infiltrating the soil or draining towards natural channels. This process helped to minimize surface runoff and mitigate risks of erosion and flooding. Post-construction analysis reveals that roads, without proper drainage systems, disrupt these natural flow paths, leading to increased water accumulation and altered flow patterns.

In Figure 20.a, runoff accumulation on roads and drainage systems in Nyarurama is evident, while Figure 21.b (highlighted in blue) indicates runoff accumulation from roads and its direction associated with erosion and flooding. Roads with horizontal alignments have exacerbated flooding issues, with excessive runoff cutting through roads due to the lack of drainage infrastructure. This results in surface water buildup, localized flooding, and damage to roads and downstream properties, underscoring the need for effective drainage systems in road construction.

Figure 20.c illustrates how roads, acting as barriers, can block stormwater from moving naturally, causing it to pool or follow unintended paths. This disruption can intensify erosion, promote the formation of ravines and gullies, and heighten the risk of flooding in nearby areas.

Figure 20.a: Surface runoff and road directions.



Data Source: DTM from NLA, 2024 and Roads from MININFRA, 2024

Figure 20.b: Road runoff accumulation and its direction.



Data Source: 2050 Kigali City Masterplan, CoK, 2020 & Field Observation, 2024



Figure 20.c: The changes in storm water flow direction have led to erosion and road damage

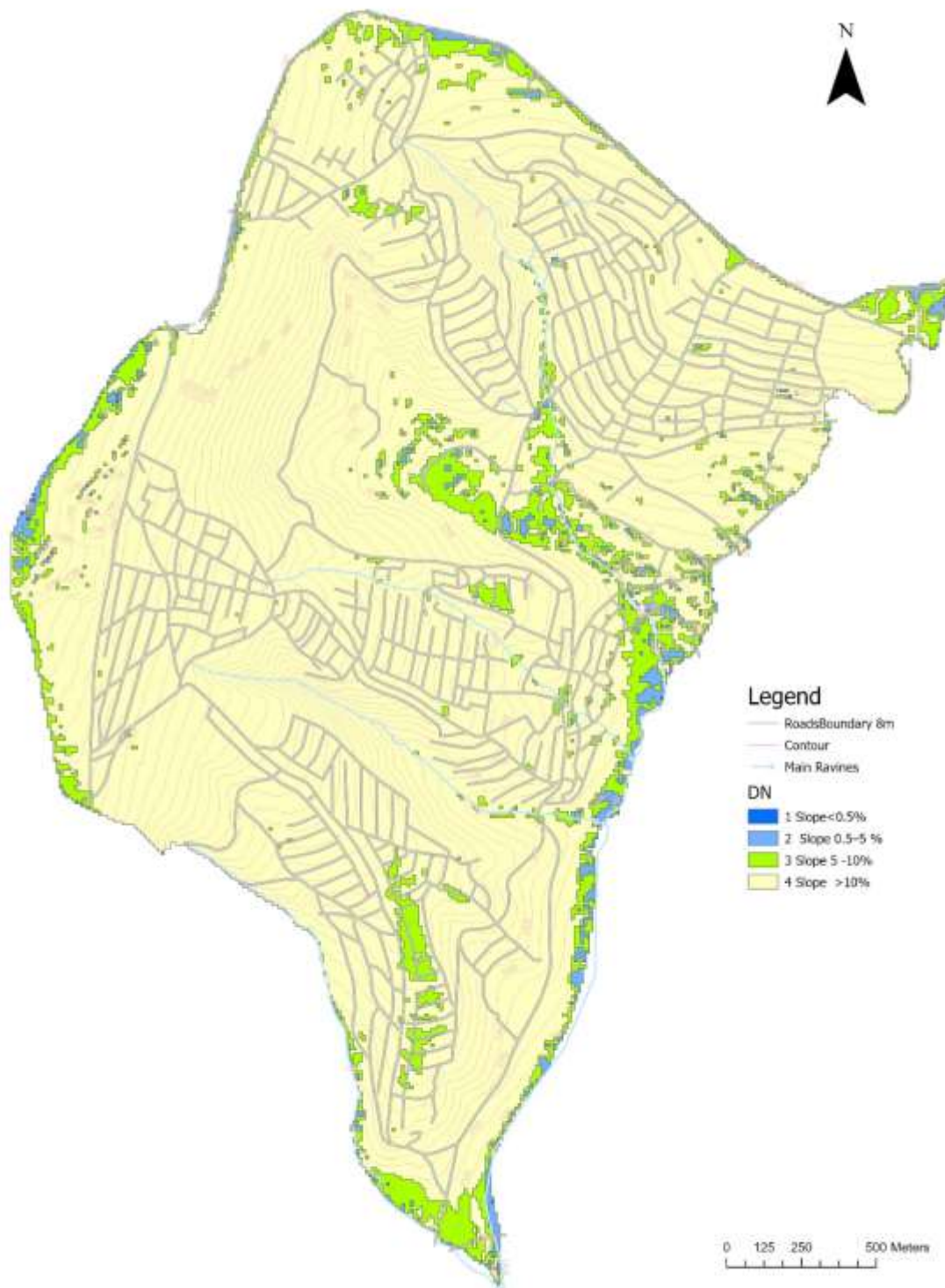
Source: Pictures taken from field observation, June 2024

#### 3.4.4 Slope, Land Use change and Runoff Coefficients

As depicted in Figure 21.a, the reclassification of slope highlights areas where water is likely to accumulate versus areas where water will flow more rapidly. Flat areas, defined as having slopes of less than 0.5%, are more likely to experience water accumulation. Slopes ranging from 0.5% to 5% are also considered areas of moderate runoff. In contrast, areas with steep slopes (5-10%) and those exceeding 10% are associated with faster water runoff and higher runoff coefficients.

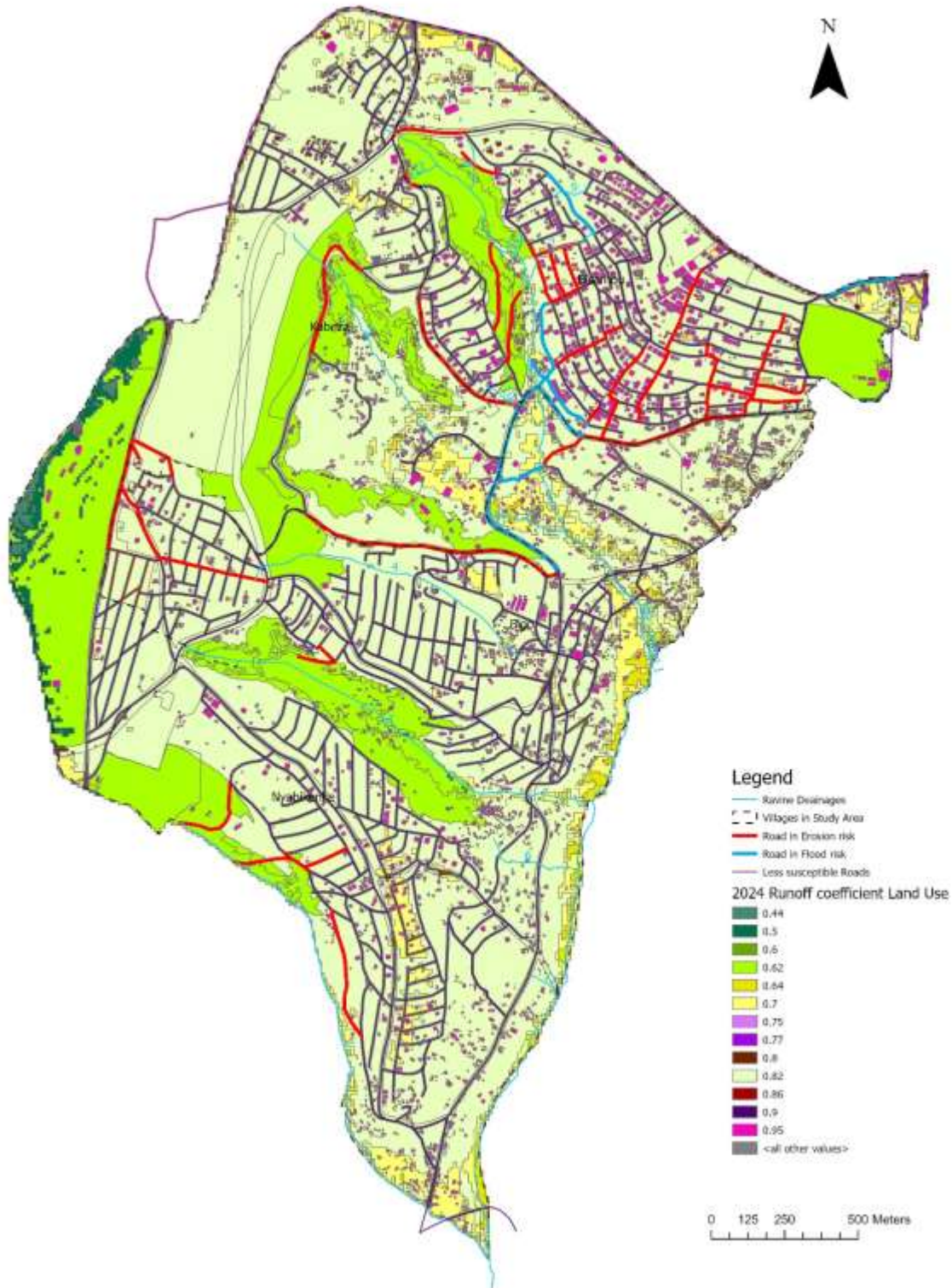
This relationship between slope and runoff is essential for understanding flood risks and drainage patterns, as steeper slopes contribute to faster water flow and reduced absorption compared to flat areas. The figure 21.b; 21.c. and 21.d. illustrate runoff coefficient and land use change from 2024 to 2050. The land use analysis for 2024 and 2050 reveals notable shifts in the distribution of land across various categories. Forest land remains stable, accounting for 18.3% of the total area in both 2024 and 2050.

Figure 21.a: Slope reclassification classification for runoff coefficient C.



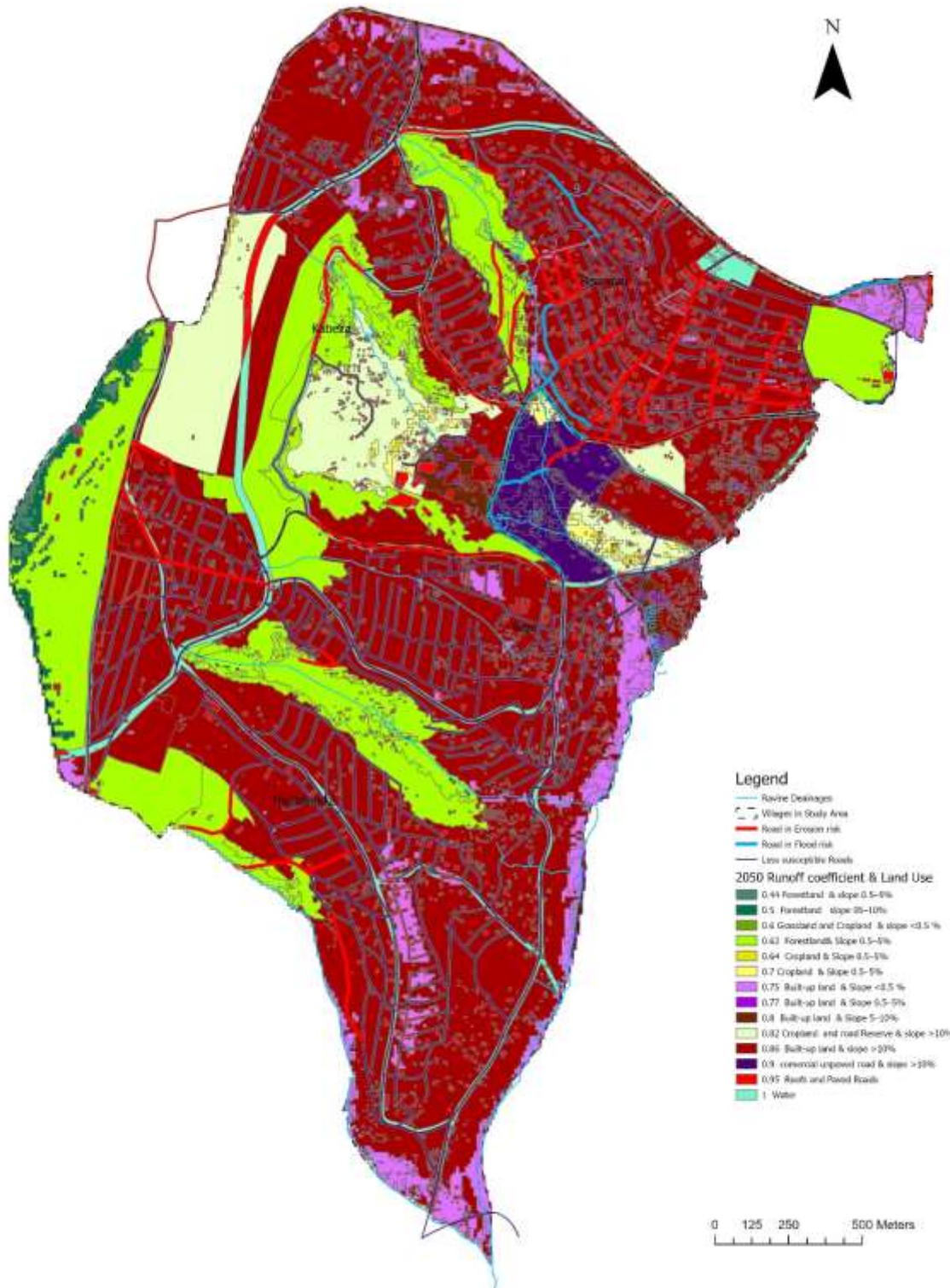
Data Source: NLA, 2024

Figure 21.b: 2024, Land Use and Runoff Coefficients in Nyarurama catchment.



Source: CoK, 2020 & Google Image, 2024

Figure 21.c: 2050 Land Use and Runoff Coefficients in Nyarurama catchment.



Source: 2050 Kigali City Master Plan, CoK, 2020

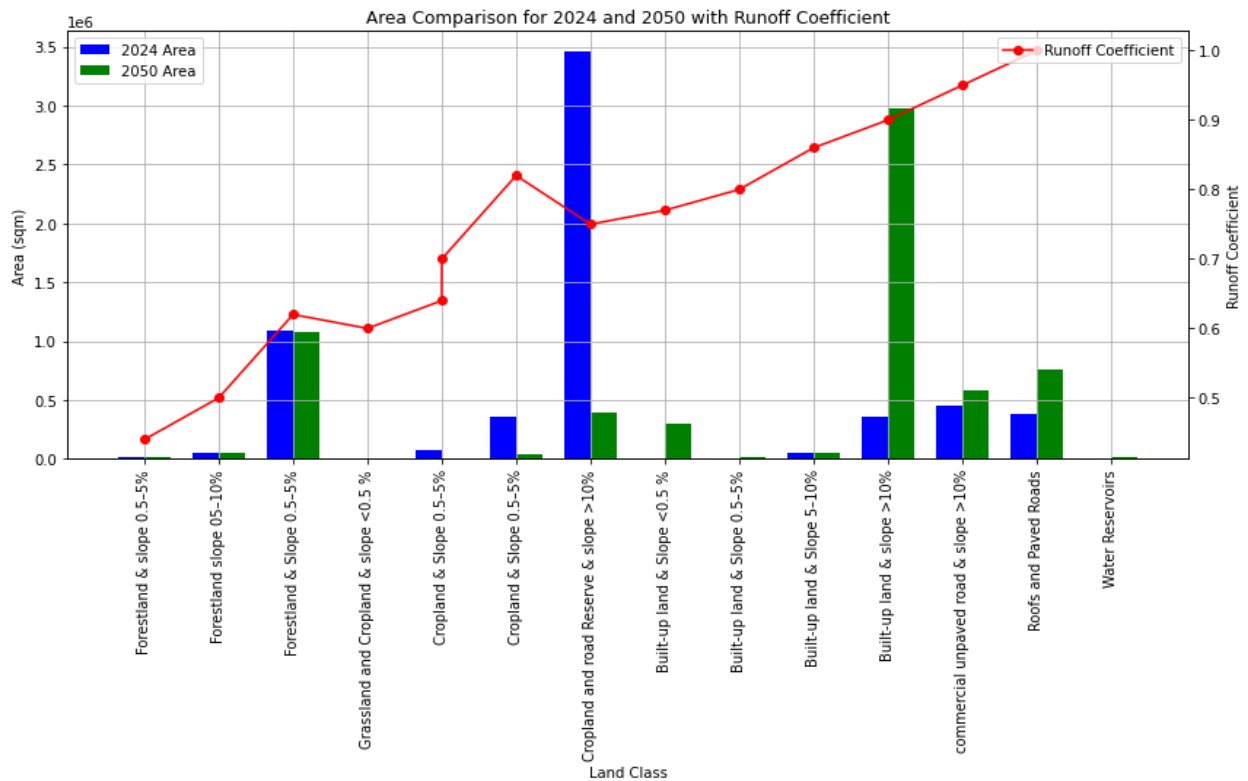
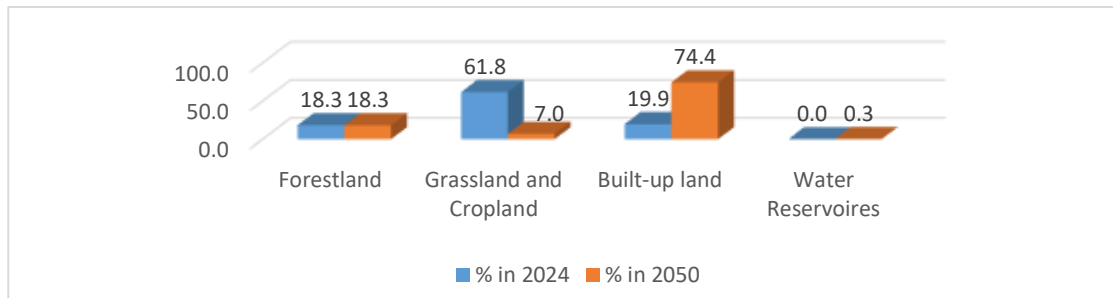


Figure 21.d: Runoff coefficient and land use change in 2024 and 2050

Source: Existing Land use from Google Image, June 2024 and planned Land use in 2050 from COK; 2020 & analyzed using Spyder, 2024, Runoff coefficients refers to Karamage et al.,2017

However, a significant transformation is observed in the grassland and cropland category, which undergoes a steep decline. In 2024, grassland and cropland cover 61.8% of the total area, but this reduces dramatically to just 7.0% by 2050, reflecting a shift in land use practices, likely due to urban expansion, infrastructure development, or other land-use policies.

In contrast, built-up land sees a remarkable increase, growing from 19.9% in 2024 to 74.4% in 2050. Water reservoirs, while minimal in 2024, show a slight increase to 0.3% by 2050 after masterplan implementation. These changes indicate a clear trend towards urbanization and development, with a reduction in agricultural and natural land cover over the years.

Table 8: Runoff coefficient (C) for land cover in study area.

Land class	Runoff coeff (C)	2024 Area in sqm ( A )	2050 Area in sqm	C*A in 2024 in ha	C*A in 2050 (ha)
Forestland & slope 0.5–5%	0.44	16032.86416	16028.58926	0.705446023	0.705257927
Forestland slope 05–10%	0.5	56018.78383	55678.10611	2.800939191	2.783905305
Forestland& Slope 0.5–5%	0.62	1084182.95	1080061.798	67.21934289	66.96383146
Grassland and Cropland & slope <0.5 %	0.6	983.198211	698.48917	0.058991893	0.04190935
Cropland & Slope 0.5–5%	0.64	78937.52745	7711.131286	5.052001757	0.493512402
Cropland & Slope 0.5–5%	0.7	360169.3049	36353.37232	25.21185134	2.544736062
Cropland and road Reserve & slope >10%	0.82	3458757.324	399468.123	283.6181005	32.75638608
Built-up land & Slope <0.5 %	0.75	114.416354	302438.9983	0.008581227	22.68292487
Built-up land & Slope 0.5–5%	0.77	9701.144056	14037.22793	0.746988092	1.080866551
Built-up land & Slope 5–10%	0.8	54818.55601	54898.53473	4.385484481	4.391882779
Built-up land & slope >10%	0.86	355954.2415	2974986.169	30.61206477	255.8488105
commercial unpaved road & slope >10%	0.9	451941.761	588296.5306	40.67475849	52.94668775
Roofs and Paved Roads	0.95	379548.5595	759551.0722	36.05711316	72.15735186
Water Reservoirs	1	0	16952.48942	0	1.695248942

*Note: Runoff coefficients refers to Karamage et al.,2017 but with roof and paved road*

The table 8 provides data on different land classes, slope ranges, runoff coefficients, and areas for the years 2024 and 2050 in Nyarurama Cell. Various land classes such as Forestland, Grassland, Cropland, Built-up land, Commercial Unpaved Road, Roofs and Paved Roads, and Water Reservoirs are analysed. Runoff coefficients vary based on land class and slope range, influencing the potential for stormwater runoff. Forestland areas show moderate runoff coefficients ranging from 0.44 to 0.62, with total areas ranging from 16032.86416 to 1084182.95 sqm. Cropland areas with different slope ranges exhibit runoff coefficients ranging from 0.64 to 0.7, with areas varying between 7711.131286 and 360169.3049 sqm. Built-up land areas have runoff coefficients ranging from 0.75 to 0.86, with areas ranging from 114.416354 to 2974986.169 sqm. Water Reservoirs show a runoff coefficient of 1 with an area of 16952.48942

sqm, indicating no stormwater runoff from these areas. Understanding these coefficients is essential for effective stormwater management and planning, as they help mitigate the impact of runoff.

### 3.5 Runoff Calculation

To calculate the runoff referred as peak discharge for each return period and rainfall duration using the Rational Method formula, the steps involve converting the area from square meters to hectares by dividing the area (in table 9) in square meters by 10,000. Then, the peak discharge is determined using the formula  $Q = C \times I \times A$ , where  $Q$  represents the peak discharge in cubic meters per second,  $C$  is the runoff coefficient from appendix 2,  $I$  is the rainfall intensity in millimeters per hour from Table 8: maximum rainfall intensity, and  $A$  is the area converted to hectares (Table 9: Runoff coefficient ( $C$ ) for land cover in study area). By following these steps and utilizing the provided data, the peak discharge for each land use, slope range, and rainfall intensity duration calculated effectively. The apexes 1 provided all peak discharge in tabular form:

#### 3.5.1.1 *Rainfall intensities for different return periods and durations.*

To get the table 8 of maximum rainfall intensities for different return periods and durations we used the Equation (4):

This study examines rainfall intensity in Nyarurama cell, located in Region 4, which includes five meteorological stations: Gakoma, Gitega, Kabaya, Kigali, and Nyamiyaga. Using the Moment Ratio Diagram (MRD) and L-Moment Ratio Diagram (LMRD) methods, homogeneous regions for observed 24-hour maximum annual rainfall were identified (Wagesho & Claire, 2016).

To calculate maximum rainfall intensities for different return periods and durations, Equation (4) was applied:  $I = \frac{\alpha}{(t+\gamma)^c}$  .

## Given Parameters for region

Table 9: parameters for rainfall intensity calculation

Return Period	$\alpha$ (mm/hr)	$\gamma$ (hr)	C
2 yrs	724.64	0.0525	0.79
5 yrs	847.46	0.0393	0.78
10 yrs	994.08	0.0525	0.78
25 yrs	1076.6	0.0365	0.77
50 yrs	1133.46	0.0103	0.76
100 yrs	1983.76	0.1538	0.83

The maximum intensity  $I$  for each combination of return period and duration was calculated: Given parameters in table 9 were used for calculations. The parameters for return periods of 2, 5, 10, 25, 50, and 100 years were converted to minutes, and the formula was applied to each combination of return period and duration. The table 10 summarizes the maximum rainfall intensities in mm/hr for different return periods and rainfall durations:

Table 10: Maximum rainfall intensity

Duration	2 yrs	5 yrs	10 yrs	25 yrs	50 yrs	100 yrs
0.5 hr = 30 minutes	45.60	56.27	64.78	74.32	84.15	94.36
1 hr = 60 minutes	27.40	33.74	39.19	44.76	50.07	58.89
3 hr = 180 minutes	11.82	14.61	17.08	19.56	21.84	25.56
6 hr = 360 minutes	6.88	8.55	10.01	11.53	12.91	14.68
12 hr = 720 minutes	3.99	4.99	5.85	6.77	7.63	8.34
24 hr = 1440 minutes	2.31	2.91	3.41	3.98	4.51	4.72

The findings on maximum rainfall intensity are crucial for understanding and managing storm water runoff in Nyarurama. The data provides essential insights for designing effective drainage systems and mitigating flood risks in the region. The maximum rainfall intensity in table 10 provides a clear picture of maximum rainfall intensities for various return periods and durations. As the return period increases (from 2 years to 100 years), the maximum rainfall intensity also increases.

This indicates that less frequent, more severe storms will have higher intensities. Additionally, as the duration increases (from 0.5 hours to 24 hours), the intensity decreases. This is expected since longer storms tend to spread the rainfall over a longer period, reducing the intensity.

The analysis of maximum rainfall intensities for different return periods and durations reveals a trend where less frequent, more severe storms exhibit higher intensities. For instance, the intensity for a 2-year return period over 0.5 hours is 45.60 mm/hr, whereas for a 100-year return period it increases to 94.36 mm/hr. Similarly, for longer durations, the intensity decreases due to the spreading of rainfall over time, which is evident from the intensities ranging from 2.31 mm/hr to 4.72 mm/hr for a 24-hour duration across different return periods.

### 3.5.1.2 Peak Discharge Analysis Change from 2024 to 2050

The peak discharge analysis (Appendix 1) for various return periods (2, 5, 10, 25, 50, and 100 years) reveals key challenges in stormwater management due to changing land use and slope variations in Nyarurama. Projected land use changes from 2024 to 2050, particularly increased built-up areas, will raise runoff coefficients and stormwater volumes. This highlights the urgent need to upgrade drainage infrastructure to manage higher runoff and reduce flooding risks.

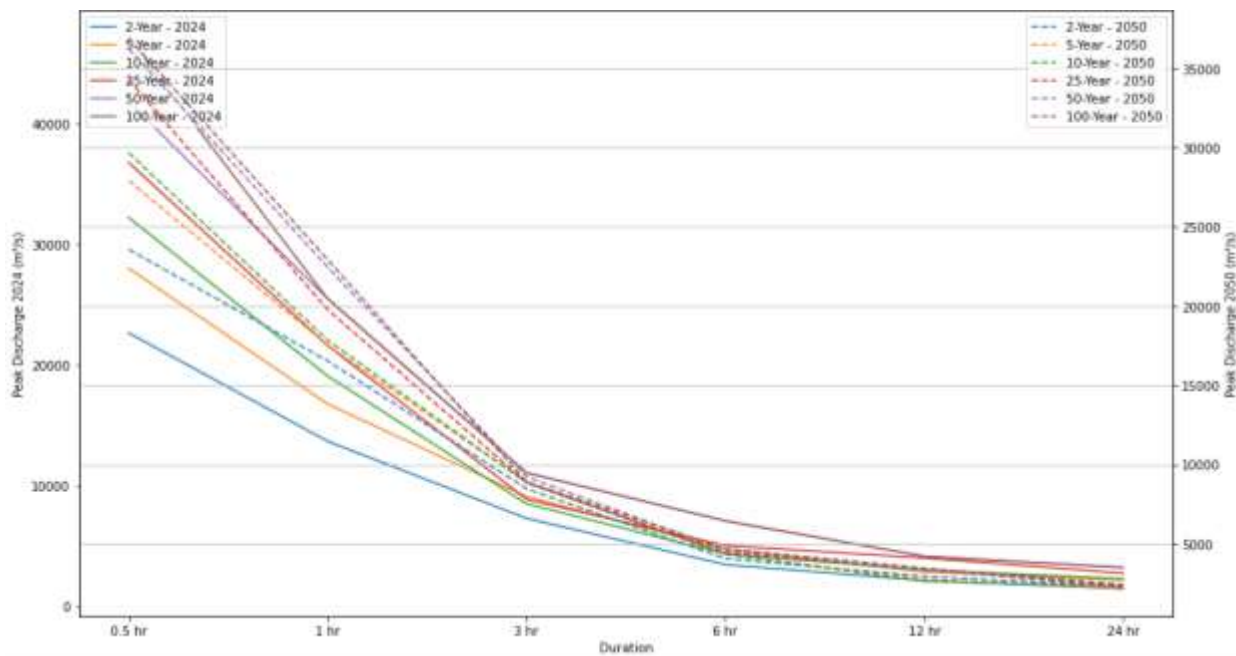


Figure 22.a: Peak Discharge Comparison for 2024 and 2050 in different return periods.

Source: Wagesho & Claire, 2016., Google Image, June 2024 and Kigali City Master Plan 2020-2050

Figure **22.a** compares peak discharge values for the years 2024 and 2050, highlighting the changes across various return periods (2, 5, 10, 25, 50, and 100 years). It visually demonstrates the increasing trend in peak discharge over time, indicating that as land use intensifies and built-up areas expand, the volume of runoff during storm events will rise. The comparison underscores the growing pressure on the drainage infrastructure, requiring upgrades to prevent flooding and manage increased stormwater.

Figure **22.b** showcases the peak discharge for different land use types, storm durations, and return periods. It helps in understanding how varying land uses (e.g., residential, commercial, or undeveloped areas) affect stormwater runoff. For instance, areas with more impervious surfaces, such as urbanized zones, are associated with higher peak discharges. This figure serves as a critical tool for designing tailored stormwater management solutions, based on the specific land use characteristics in the Nyarurama sub-catchment.

Figure **22.c** is a 3D representation provides a visual analysis of peak discharge values, mapping stormwater flows across different durations (e.g., 30 minutes, 1 hour, etc.) and return periods. The three-dimensional view helps to better grasp the interactions between storm duration and the frequency of storm events, showing how longer storms with high return periods generate significantly higher peak discharges. This visualization highlights areas where infrastructure upgrades will be crucial to managing larger stormwater flows in the future.

Together, these figures provide a detailed assessment of how peak discharge patterns evolve under different scenarios, land use types, and storm conditions, emphasizing the need for robust drainage systems to cope with future hydrological changes in Nyarurama.

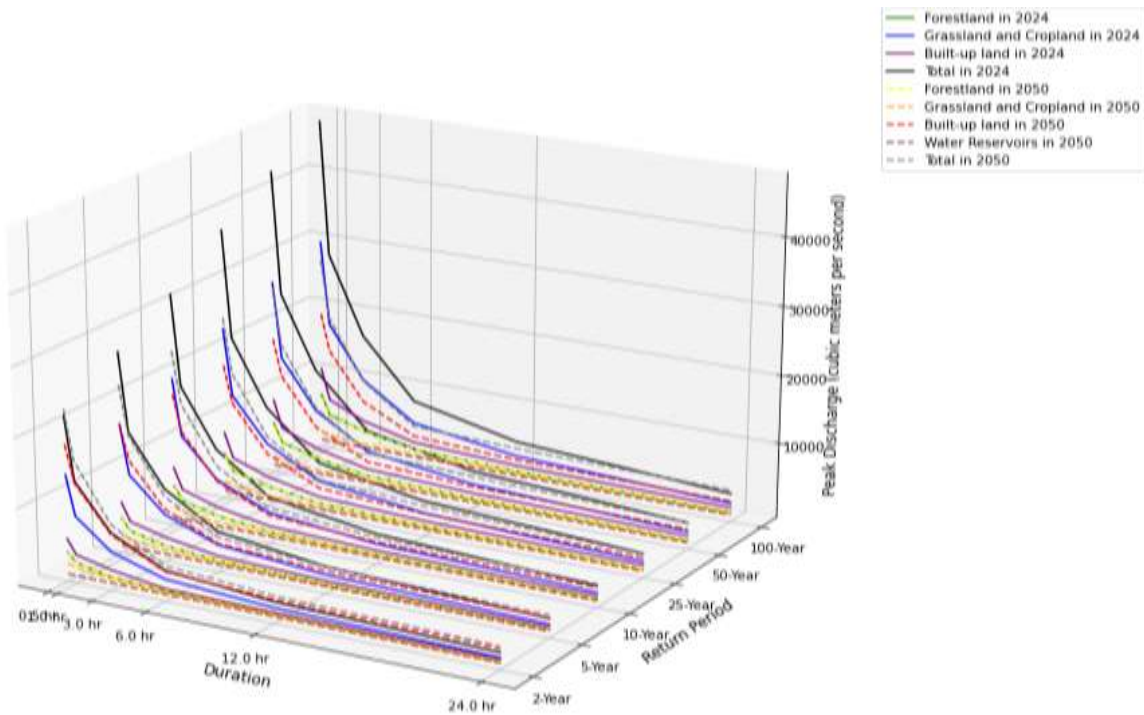


Figure 22.b: Peak discharge for different land use, durations and return periods.  
 Source: Wagesho & Claire, 2016., Google Image, June 2024 and Kigali City Master Plan 2020-2050

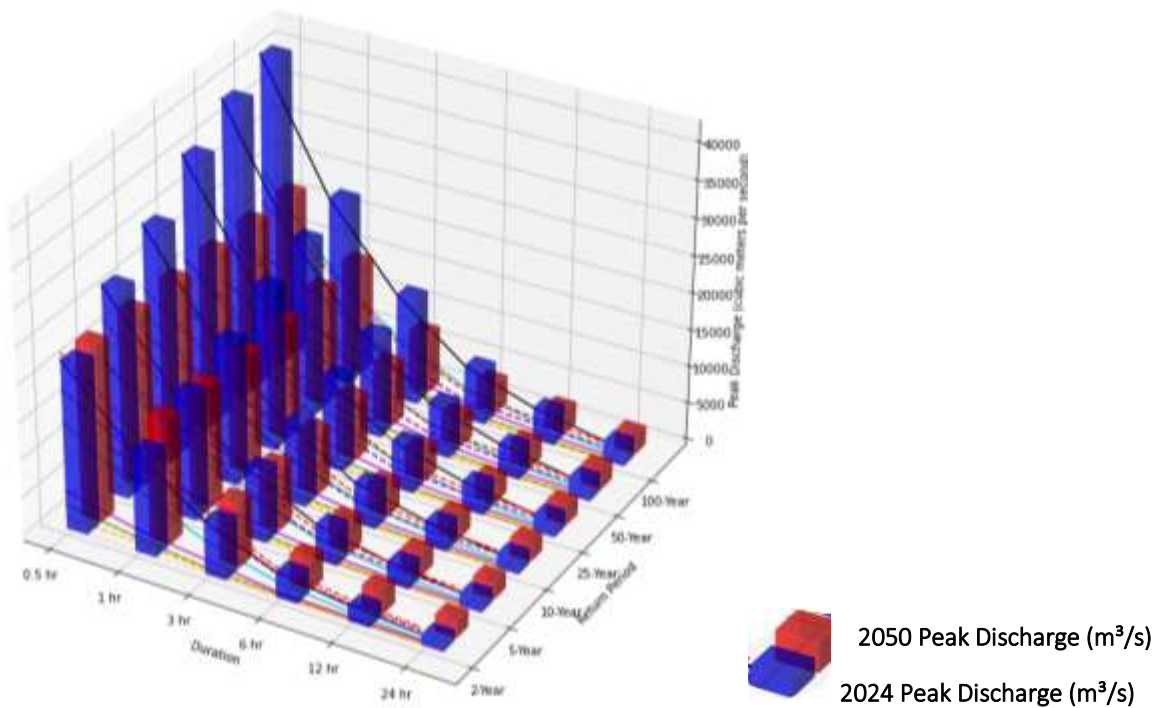


Figure 22.c: Peak discharge (m<sup>3</sup>/s) for different durations and return periods in 3D.  
 Source: Wagesho & Claire, 2016., Google Image, June 2024 and Kigali City Master Plan 2020-2050

The table 11 summarizes the percentage change in peak discharge from 2024 to 2050 for different return periods and durations form appendix 1 in Nyarurama cell catchment.

Table 11: the percentage change in peak discharge from 2024 to 2050

<b>Return Period</b>	<b>Duration</b>	<b>Peak Discharge 2024 (m<sup>3</sup>/s)</b>	<b>Peak Discharge 2050 (m<sup>3</sup>/s)</b>	<b>% Change</b>
2-Year	0.5 hr	22,642.71	23,566.84	+4.09%
	1 hr	13,656.30	16,536.91	+21.07%
	3 hr	7,255.14	8,466.76	+16.68%
	6 hr	3,422.00	4,056.36	+18.53%
	12 hr	2,104.76	2,944.05	+39.88%
	24 hr	1,419.79	2,280.30	+60.55%
5-Year	0.5 hr	27,996.71	27,909.36	-0.31%
	1 hr	16,745.93	17,525.68	+4.65%
	3 hr	9,067.06	8,863.88	-2.24%
	6 hr	4,704.06	4,321.23	-8.14%
	12 hr	2,812.50	2,749.04	-2.26%
	24 hr	2,145.13	2,157.09	+0.56%
10-Year	0.5 hr	32,211.78	29,673.60	-7.88%
	1 hr	19,071.26	17,842.36	-6.45%
	3 hr	8,469.51	8,856.41	+4.57%
	6 hr	4,303.16	4,341.17	+0.88%
	12 hr	2,976.85	2,617.19	-12.07%
	24 hr	2,244.95	2,316.11	+3.17%

25-Year	0.5 hr	36,778.07	34,283.45	-6.80%
	1 hr	21,603.95	19,776.38	-8.45%
	3 hr	8,843.31	8,853.62	+0.12%
	6 hr	4,997.36	4,406.88	-11.81%
	12 hr	3,970.76	3,391.57	-14.61%
	24 hr	2,707.64	2,252.77	-16.79%
50-Year	0.5 hr	41,813.79	36,238.49	-13.33%
	1 hr	25,478.40	22,452.70	-11.88%
	3 hr	11,035.68	9,241.90	-16.27%
	6 hr	7,044.93	4,546.38	-35.44%
	12 hr	4,104.14	3,371.07	-17.89%
	24 hr	3,177.69	2,377.27	-25.15%
100-Year	0.5 hr	47,099.18	36,904.78	-21.67%
	1 hr	25,478.40	22,921.10	-10.04%
	3 hr	11,035.68	8,910.03	-19.27%
	6 hr	7,044.93	4,670.73	-33.69%
	12 hr	4,104.14	3,447.22	-16.01%
	24 hr	3,177.69	2,427.68	-23.59%

Source: Regional IDF parameters adopted from Wagesho & Claire, 2016.

Figure 23.a. visually compares peak discharge values for different return periods (2, 5, 10, 25, and 50 years) in 2024 and 2050. It highlights how projected changes in land use and development impact stormwater runoff over time. In general, for shorter return periods (e.g., 2 years), a modest increase in peak discharge is observed, while higher return periods (e.g., 50 years) may show either increases or decreases depending on specific factors such as land use type, slope, and storm intensity. This comparison helps identify the return periods most affected by future changes, guiding drainage infrastructure upgrades.

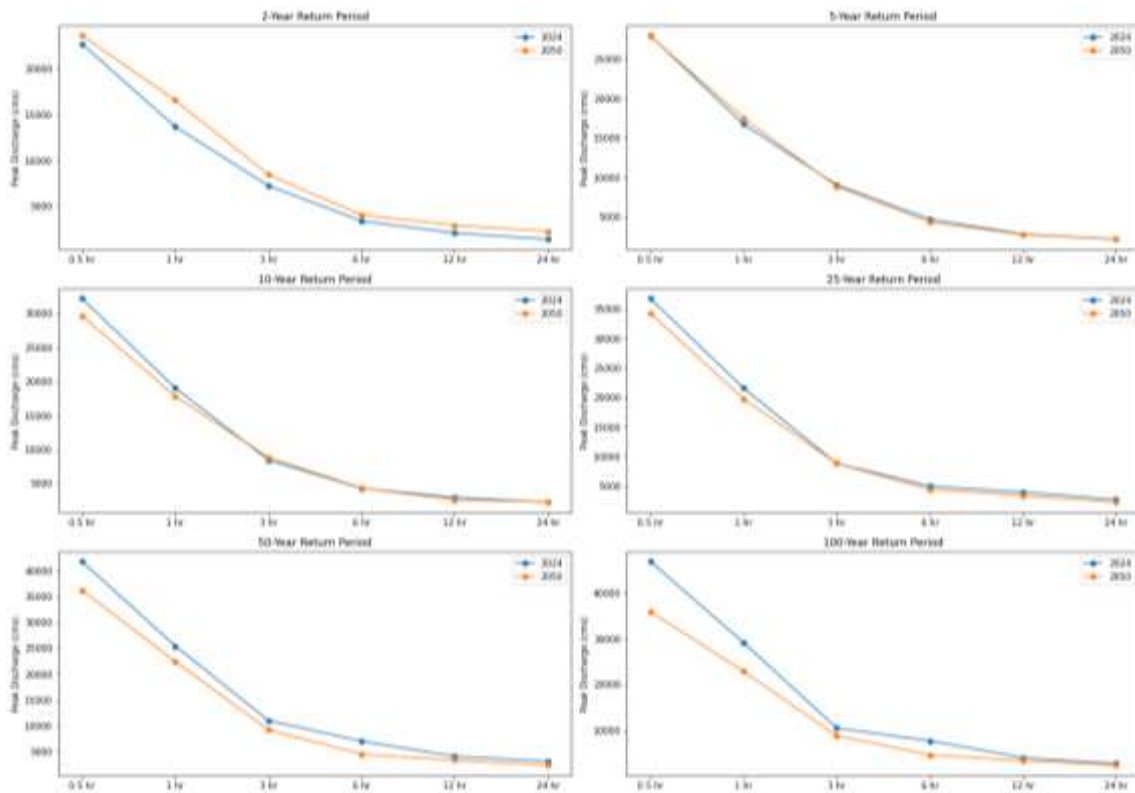


Figure 23.a: Peak Discharge comparison between 2024 and 2050 for various Return Periods.

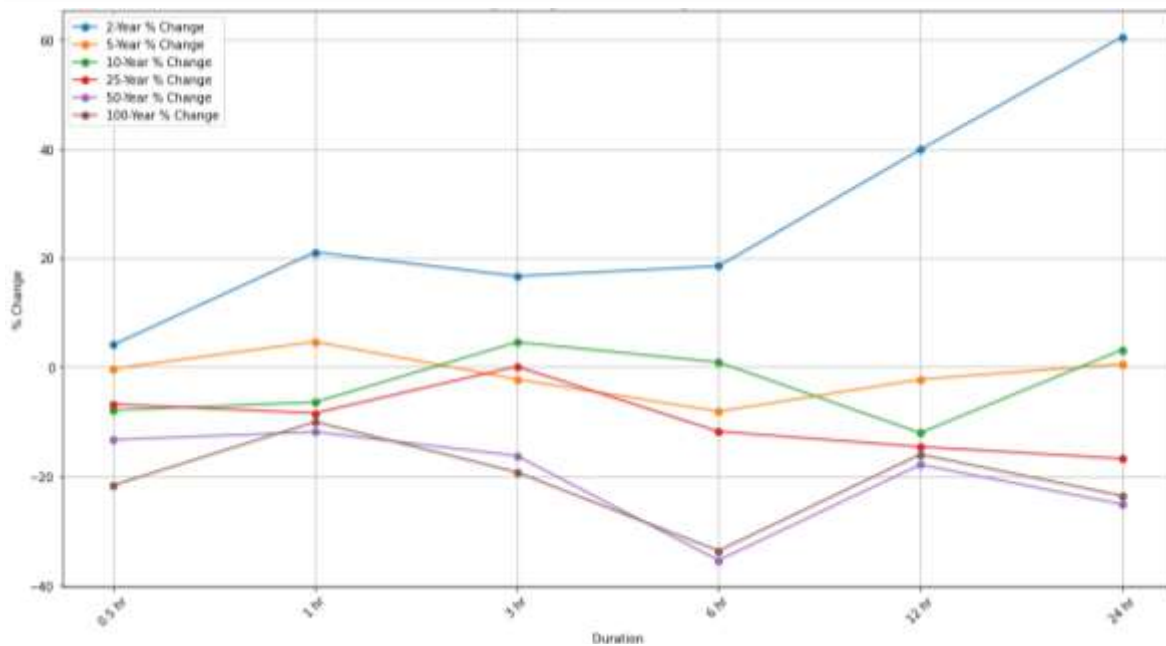


Figure 23.b: Change in Percentage for Peak Discharge (Q) from 2024 to 2050

Source: Source: Regional IDF parameters adopted from Wagesho & Claire, 2016 and Planned Land Use from COK; 2020 & analysed using Spyder, 2024

Figure 23.b. shows the percentage change in peak discharge between 2024 and 2050 for various return periods, including the 100-year event. It helps to quantify how much peak discharge will increase or decrease due to projected land use changes, especially the expansion of impervious surfaces. For shorter return periods, slight increases in peak discharge are common, whereas longer return periods (e.g., 50 and 100 years) tend to show larger fluctuations, with some significant reductions in peak discharge. This figure emphasizes the importance of adjusting stormwater management plans to handle the variability in runoff across different time frames.

### *3.5.1.3 Key Insights: Impact of Land Use Change from 2024 to 2050*

The impact of land use change from 2024 to 2050 on peak discharge presents various insights that are critical for urban planning and storm water management in the Gatenga Sector. For shorter durations, particularly for the 2-year return period, there is a noticeable increase in peak discharge in 2050 compared to 2024. This increase is especially pronounced for the 24-hour duration, where peak discharge rises by 60.55%. However, the 5-year return period shows mixed results, with slight decreases or minimal changes in peak discharges.

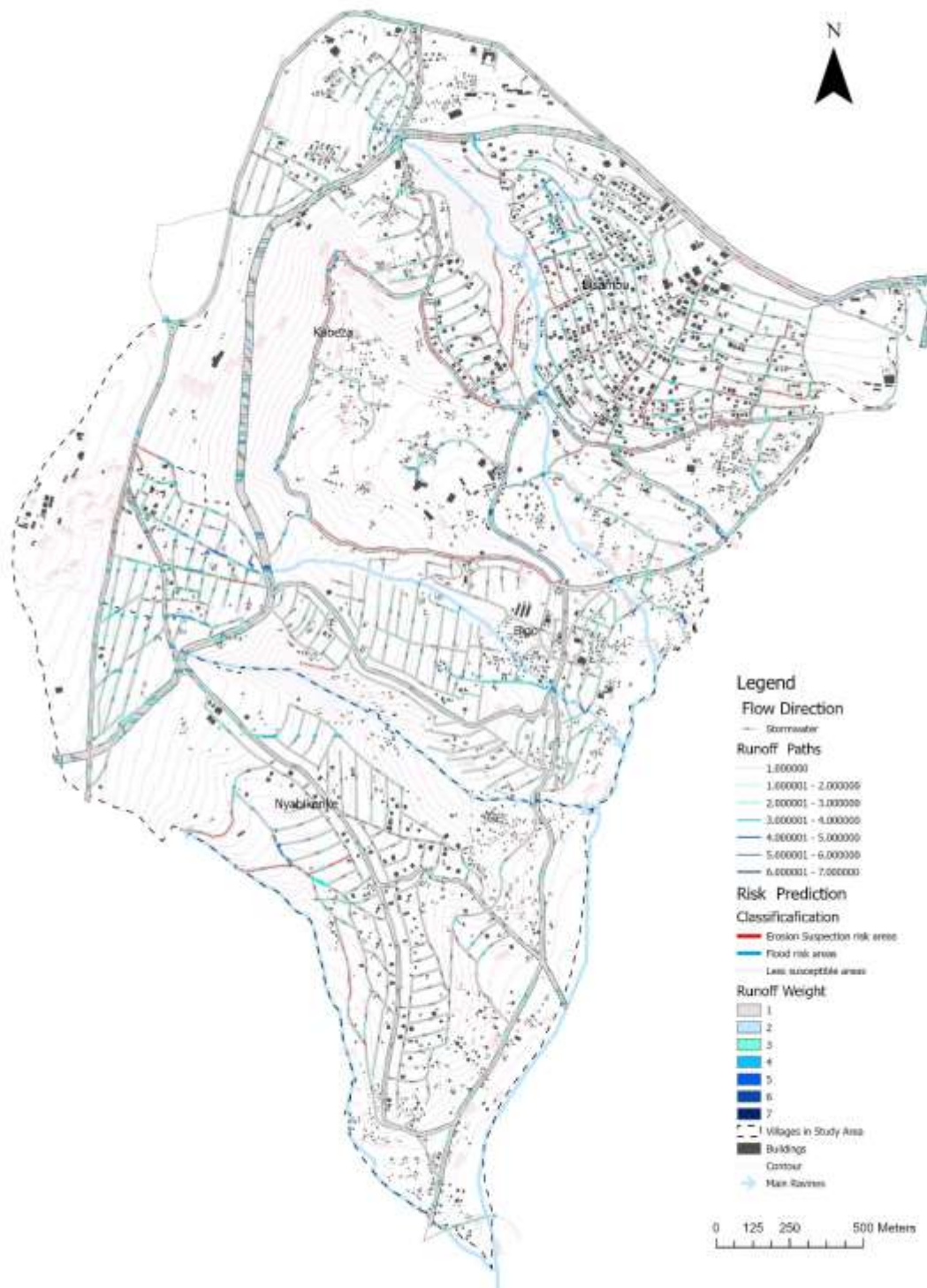
In contrast, for longer durations and higher return periods (10, 25, 50, and 100 years), the peak discharges generally decrease in 2050 compared to 2024. These reductions are more significant for longer durations, potentially due to the introduction of water reservoirs in 2050, which help mitigate peak discharges by storing excess runoff. This trend highlights the effectiveness of strategic infrastructure improvements in managing stormwater.

The increased peak discharge for shorter durations necessitates substantial enhancements to the existing stormwater management infrastructure. The current system is inadequate for handling the anticipated peak discharges, particularly during extreme weather events. This calls for adaptive measures such as increasing green spaces, promoting sustainable urban drainage systems (SUDS), and constructing additional water reservoirs to mitigate the impacts of increased runoff.

The transition in land use poses significant challenges, such as managing flood risks and protecting properties and infrastructure from increased runoff due to urbanization. However, it also presents opportunities to innovate and implement more efficient and sustainable stormwater management practices. By addressing these challenges and leveraging the opportunities, Nyarurama Cell can effectively manage the impacts of land use change on its drainage system, ensuring sustainable and resilient urban growth.

Runoff with weight from 4 to 7 poses a threat to roads due to high runoff, potentially causing destruction, especially to unpaved roads. The map in the figure 24 identifies specific road sections within the Nyarurama sub-catchment that are particularly vulnerable to high runoff, erosion, and flooding.

Figure 24: Critical Road areas vulnerable to high Runoff, erosion, and flooding.



Data Source: Kigali City Masterplan 2025, COK; 2020.

### 3.5.2 Evaluation of Drainage System Capacities

The calculations for the Rectangular (U shape) drains, with dimensions of depth  $d=0.6379$  meters, top width  $b=0.6486$  meters, and bottom width  $b=0.6486$  meters, yield a flow capacity of  $0.0235 \text{ m}^3/\text{s}$ . For Trapezoidal (V shape) drains, with dimensions of depth  $d=0.6475$  meters, top width  $T=0.75$  meters, and bottom width  $B=0.4125B$  meters, the flow capacity is slightly lower at  $0.0196 \text{ m}^3/\text{s}$ . These calculations assume a Manning's roughness coefficient of  $n=0.015n$  and a gentle slope of  $S=0.01$ .

When comparing these capacities to the peak discharge values, which are significantly higher—ranging from approximately  $22,642.71 \text{ m}^3/\text{s}$  to  $41,813.79 \text{ m}^3/\text{s}$  for 2024 and from  $23,566.84 \text{ m}^3/\text{s}$  to  $36,904.78 \text{ m}^3/\text{s}$  for 2050—the inadequacy of the existing drainage systems becomes apparent. The flow capacities of both drain types fall far short of the peak discharge values for any return period in both projected years.

Given this stark disparity, it is clear that the current drainage infrastructure is insufficient to manage the anticipated stormwater volumes. Immediate action is needed to address this shortfall. This may involve redesigning and upgrading the drainage systems to include larger capacity drains, as well as incorporating additional stormwater management strategies such as retention basins, permeable pavements, and green infrastructure. Upgrading these systems will be crucial to ensure effective stormwater management and to mitigate potential flooding risks in the future.

### 3.5.3 Required Storage Volumes Rain water form roof areas

To design tanks or retention ponds for storm water management, we need to consider the volume of runoff that needs to be managed for various storm events. The design will be based on the calculated peak discharge values and the total roof area. The main goal is to determine the size of tanks or ponds needed to store runoff and prevent flooding.

#### Key Parameters for Design

1. **Total Roof Area:**  $321,340.6 \text{ sqm}$
2. **Largest Roof Area:**  $1254.58 \text{ sqm}$
3. **Runoff Coefficient for Paved Roads and Roofs:**  $0.95$

4. **Rainfall Intensity:** Using the regional maximum rainfall intensity data provided for different return periods and durations.
5. **Return Periods:** 2 years, 5 years, 10 years, 25 years, 50 years, 100 years

### Calculating current Runoff Volume

The volume of runoff  $V$  for a given area can be calculated using the formula:  $V=C \times I \times A \times t$

where:  $C$  = Runoff coefficient (dimensionless),  $I$  = Rainfall intensity (mm/hr),  $A$  = Catchment area (sqm) and  $t$  = Duration of the rainfall event (hours)

For example, for a 2-year return period and a 1-hour duration:  $V=0.95 \times 27.40 \times 321,340.6 \times 1 \times 10^{-3}$

$V=837,050.95$  cubic meters ( $m^3$ )

Table 12 shows the required storage volume for the given return periods

Table 12: Required Storage Volumes Rain water form roof area (2023)

<b>Return Period</b>	<b>0.5 hr Volume (<math>m^3</math>)</b>	<b>1 hr Volume (<math>m^3</math>)</b>	<b>3 hr Volume (<math>m^3</math>)</b>	<b>6 hr Volume (<math>m^3</math>)</b>	<b>12 hr Volume (<math>m^3</math>)</b>	<b>24 hr Volume (<math>m^3</math>)</b>
<b>2 years</b>	437,235.39	837,050.95	1,807,649.99	2,737,292.83	3,895,668.90	7,048,896.69
<b>5 years</b>	539,026.52	1,031,276.29	2,236,796.12	3,398,344.63	4,878,620.57	8,887,793.65
<b>10 years</b>	620,809.06	1,198,406.00	2,613,749.70	3,974,383.94	5,715,984.71	10,409,728.97
<b>25 years</b>	711,469.23	1,370,756.16	2,994,558.12	4,578,530.77	6,605,007.68	12,142,996.95
<b>50 years</b>	805,688.77	1,534,562.95	3,345,058.95	5,125,238.64	7,442,708.89	13,763,289.58
<b>100 years</b>	903,466.81	1,807,002.40	3,914,270.99	5,824,531.90	8,128,224.61	14,408,213.15

Source: Regional IDF parameters adopted from Wagesho & Claire, 2016

### 3.6 Runoff in 2050

To calculate the required storage volumes for rainwater from the increased built-up area (4,923,972.3 square meters) for different return periods and durations, we'll use the adjusted rainfall intensities for 2050 and the same runoff coefficient of 0.95. In addition, we need to consider potential changes in rainfall intensity due to climate change. While precise future rainfall intensities require detailed climate modeling, we used a reasonable increase factor based on climate change projections.

Assuming a general increase of 10% in rainfall intensity by 2050 - a commonly used estimate in many climate impact studies-(World Bank Group, 2021)-. As shown in table 13, we adjusted the provided regional maximum rainfall intensity values accordingly and then calculate the required storage volumes as

#### Converting the adjusted intensities:

Table 13: Adjusted Rainfall Intensities for 2050 (mm/hr)

Return Period	0.5 hr (mm/hr)	1 hr (mm/hr)	3 hr (mm/hr)	6 hr (mm/hr)	12 hr (mm/hr)	24 hr (mm/hr)
2 years	50.16	30.14	13.00	7.57	4.39	2.54
5 years	61.90	37.11	16.07	9.41	5.49	3.20
10 years	71.26	43.11	18.79	11.01	6.44	3.75
25 years	81.75	49.24	21.52	12.68	7.45	4.38
50 years	92.57	55.08	24.02	14.20	8.39	4.96
100 years	103.80	64.78	28.12	16.15	9.17	5.19

Source: Regional IDF parameters adopted from Wagesho & Claire, 2016

#### 3.6.1 Assessing the Capacity of the Existing Drainage System in Nyarurama

The current drainage system appears insufficient to manage the expected rise in runoff volumes. Detailed assessment is necessary to determine the system's ability to handle increased storm water resulting from climate change and evolving land use practices. As the built-up area expands, runoff volumes are expected to exceed the current capacities of the drainage system significantly. The

projected peak discharge and storage requirements suggest potential strains during heavy rainfall, potentially leading to overflows and localized flooding.

### 3.6.2 Required Storage Volumes in 2050

The comparison between the present roof area and the projected built-up area in 2050 reveals a significant increase in required storage volumes across all return periods and durations. For instance, the required storage volume for a 0.5-hour rainfall event for a 2-year return period increases from approximately 4,921.3 m<sup>3</sup> to 2,105,425.77 m<sup>3</sup>. This increase is primarily due to the substantial expansion in the built-up area, which increases impervious surfaces, leading to higher runoff volumes.

Table 14: Required Storage Volumes for Different Return Periods and Durations in 2050

Return Period	0.5 hr Volume (m <sup>3</sup> )	1 hr Volume (m <sup>3</sup> )	3 hr Volume (m <sup>3</sup> )	6 hr Volume (m <sup>3</sup> )	12 hr Volume (m <sup>3</sup> )	24 hr Volume (m <sup>3</sup> )
2 years	2,105,425.77	2,479,809.60	2,965,161.74	3,301,177.90	3,705,179.83	4,137,172.00
5 years	2,598,787.98	3,054,406.51	3,665,184.28	4,101,283.39	4,635,108.55	5,222,936.66
10 years	2,989,049.46	3,546,118.44	4,287,013.48	4,800,507.29	5,428,328.41	6,127,359.84
25 years	3,430,176.18	4,046,496.48	4,915,179.15	5,520,598.50	6,277,308.25	7,167,848.25
50 years	3,883,114.83	4,525,533.88	5,484,524.47	6,187,432.15	7,065,570.84	8,121,078.22
100 years	4,354,278.85	5,321,299.88	6,426,905.82	7,035,452.00	7,707,118.47	8,510,406.84

Source: Wagesho & Claire, 2016

The volumes in the table 14 above represent the required storage capacity to capture the rainfall from the total built-up area (4,923,972.3 sqm) for various return periods and durations in 2050. The calculations are based on an assumed 10% increase in rainfall intensity due to climate change. The runoff coefficient of 0.95 is used, which is typical for built-up areas, indicating that 95% of the rainfall will contribute to runoff that needs to be stored.

### 3.7 Results discussion

The comprehensive analysis of the drainage systems in Nyarurama Cell reveals significant deficiencies, with approximately 83.1% of the roads lacking any form of drainage infrastructure, amounting to 44,650.85 meters of road length without drainage. The survey documented various drainage shapes, including Rectangular (U shape), Trapezoidal (V shape), and irregular designs, which have proven inadequate in managing stormwater, particularly during extreme weather events. This finding echoes challenges noted in Uwineza and Mitsuteru's (2022) study on rainwater harvesting systems in Nyabugogo Valley, Kigali.

The Nyarurama natural drainage system, which includes five main ravines totaling 12,882 meters, with the Bisambu-Bigo ravine being the longest at 5,462.7 meters, has significantly deteriorated due to urban expansion and human activities. Originally natural channels, these ravines have transformed into deep, eroded trenches exacerbated by increased impervious surfaces and disrupted water flow. This transformation aligns with findings from studies such as Fu et al. (2022) on urban stormwater management in China and Wagesho and Claire (2016) on rainfall intensity in Rwanda, which predict increased runoff and flooding due to urban encroachment. Global research by Jusić et al. (2020) and Bastia et al. (2021) also highlights the broader impact of urban development on natural drainage systems, underscoring the need for effective stormwater management.

Wagesho and Claire (2016) analyzed the rainfall intensity-duration-frequency relationships in Rwanda and predicted increases in rainfall intensity. Their findings are consistent with our analysis, which shows that for a 2-year return period, peak discharge is projected to increase from 22,642.71 cubic meters per second in 2024 to 23,566.84 cubic meters per second in 2050. For a 100-year return period, the peak discharge is projected to rise from 41,813.79 cubic meters per second in 2024 to 46,904.78 cubic meters per second in 2050. This prediction underscores the urgency of upgrading the existing drainage infrastructure in Nyarurama Cell. Additionally, the MetheoRwanda & REMA (2022) report also predicts increased rainfall intensity, stressing the importance of adjusting flood risk assessments to accommodate these changes, which aligns with our findings and highlights the need for improved drainage systems.

The predominance of clay soil and low permeability aquifers in Nyarurama Cell exacerbates surface runoff, consistent with Ayenew et al.'s (2008) research on soil composition and its impact on runoff in Ethiopian aquifers. This issue is compounded by rapid urbanization in the region, where built-up areas have increased substantially. Our land use analysis indicates that built-up land will rise from 19.9% in 2024 to 74.4% by 2050, while grassland and cropland will decrease dramatically from 61.8% to 7.0%. Water reservoirs, though minimal in 2024, are projected to increase slightly to 0.3% by 2050.

These changes reflect a significant reduction in agricultural and natural land cover and underscore the growing challenges of managing increased runoff due to urban expansion. This finding aligns with the Sentinel-2 Land Cover Explorer (Esri, 2023), which reports that built-up areas increased from 50% in 2007 to 69% in 2023, emphasizing the rapid urbanization in the region. These trends highlight the urgent need for effective stormwater management strategies to address the impacts of increased impervious surfaces and reduced natural land cover.

Comparing required storage volumes for different return periods and durations, considering the projected built-up area in 2050, underscores the substantial impact of land use changes on stormwater management. This is supported by Jusić et al. (2020) and Bastia et al. (2021), who emphasize the need for upgrades and green infrastructure solutions to handle increased runoff effectively. Sørup et al. (2019) highlights the benefits of integrated stormwater management approaches, though their findings are based on urban environments in Denmark and may not fully capture the unique challenges in Nyarurama Cell.

In summary, while similar studies provide valuable insights into stormwater management, the specific urbanization patterns and soil characteristics of Nyarurama Cell necessitate tailored solutions that consider these unique factors.

## **4 Chapter V. Conclusion and recommendation**

In Chapter 5, the study concludes with a comprehensive overview of the findings and insights gathered throughout the research process. The chapter delves into key recommendations based on the identified challenges and presents strategic suggestions for addressing these issues effectively.

### **4.1 Conclusion**

In alignment with the first objective, which aimed to characterize and evaluate the capacity of the existing drainage infrastructure in residential areas of Nyarurama Cell, the study findings reveal significant variability in its condition. While some areas have relatively well-maintained drainage systems, many newly developed regions are inadequately served, resulting in frequent waterlogging and suboptimal stormwater management. Approximately 83.1% of the roads lack adequate drainage facilities, translating to 44,650.85 meters of road length without drainage. The assessment of existing drainage systems—comprising Rectangular (U shape), Trapezoidal (V shape), and irregular designs—indicates that these systems are significantly deficient, particularly during severe weather conditions. The transformation of natural drainage pathways into extensive ravines and gullies, largely due to human encroachment and urban expansion, exacerbates these deficiencies. Notably, the four principal ravines, including the Bisambu-Bigo ravine, which extends 5,462.7 meters, are unpaved, irregularly shaped, and heavily eroded. These findings support the alternative hypothesis (H1), suggesting that the drainage system in newly developed residential areas of Nyarurama Cell faces challenges in managing stormwater runoff, especially during heavy rainfall events.

Regarding the second objective, which focused on assessing the impact of land use changes and identifying vulnerable areas within Nyarurama Cell, the study uncovered that urbanization and new road developments have significantly altered hydrological patterns. The expansion of built-up areas and the formation of large ravines have exacerbated flood risks, particularly in regions with low slopes. The transformation of natural drainage systems into major ravines, such as the Bisambu-Bigo, has worsened flooding issues, demonstrating that current drainage solutions are inadequate for handling increased stormwater runoff. The analysis revealed that peak discharge for a 2-year return period is projected to increase from 22,642.71 cubic meters per second in 2024 to 23,566.84 cubic meters per second in 2050, while for a 100-year return period, it is projected to rise from 41,813.79 cubic meters per second in 2024 to 46,904.78 cubic meters per second in 2050.

This observation supports the alternative hypothesis (H1), which posits that land use changes significantly impact the effectiveness of the existing drainage system in Nyarurama Cell, leading to overflows and flooding in certain areas.

In relation to the third objective, which aimed to propose strategies for improving stormwater management and drainage planning, the study underscores the necessity for substantial upgrades to existing infrastructure. Given the anticipated growth in built-up areas and changing rainfall patterns, it is crucial to implement effective and well-constructed drainage systems. Recommendations include developing robust drainage solutions capable of managing increased stormwater volumes and addressing challenges posed by soil properties, such as high clay content, low organic matter, and slightly acidic pH. Proactive measures are needed to enhance urban resilience against flooding and support sustainable development practices. As this objective focused on providing solutions, a specific hypothesis was not applicable.

Overall, the study highlights the critical need for targeted improvements in stormwater management and strategic planning to adapt to evolving land use and precipitation patterns. The conclusions reject the null hypotheses for both objectives. For the first objective, the evidence shows that the drainage system in newly developed residential areas of Nyarurama Cell faces significant challenges in managing stormwater runoff during heavy rainfall, leading to overflows and flooding. For the second objective, the findings indicate that land use changes significantly impact the effectiveness of the drainage system, causing overflows and flooding in specific areas, particularly in newly developed residential and commercial zones. Addressing these deficiencies is essential for mitigating flood risks and ensuring effective drainage in Nyarurama Cell.

## 4.2 Recommendations

Based on the findings of this research concerning stormwater management and drainage planning in Nyarurama Cell, several urgent recommendations are proposed to address the identified challenges effectively.

**Infrastructure Upgrades:** Immediate enhancements to the drainage systems are essential, especially for the 83.1% of roads currently lacking adequate drainage, which totals 44,650.85 meters. Upgrading the dimensions and configurations of existing drainage systems will help prevent downstream damage and ensure effective water flow management.

**Infiltration Techniques Implementation:** Adoption of infiltration techniques such as permeable pavements, rain gardens, and retention ponds is crucial. Retention ponds, designed to capture and temporarily store runoff, can reduce peak flow rates and mitigate flood risks. These ponds should handle the volume of stormwater typical for the area and include provisions for sediment removal and regular maintenance.

**Culverts and Ravine Management:** Properly designed culverts are essential for managing stormwater flow across roads and other infrastructure. Installing adequate culverts will prevent blockages and efficiently channel stormwater away from vulnerable areas. Additionally, targeted management of ravines is necessary to address extensive erosion caused by inadequate drainage and urban encroachment. Rehabilitation should include reforestation, soil stabilization with vegetation, and bioengineering techniques. Measures such as planting deep-rooted grasses, implementing check dams made of natural materials, and reshaping ravine banks will help restore ravines and reduce erosion.

**Condominium Systems:** In high-density urban areas, condominium systems can manage stormwater effectively. On-site stormwater management systems, such as green roofs, rain barrels, and underground detention systems, should be integrated into new condominium designs or retrofitted into existing buildings to reduce the impact of stormwater on the broader drainage network.

**Handling Dead-End Road Drainages:** For dead-end roads, installing end-of-pipe treatments like small detention basins or infiltration trenches is crucial. These solutions capture and temporarily

store runoff before it exits the road, reducing localized flooding. Proper grading and the use of permeable materials will also aid in managing stormwater more efficiently.

**Rainwater Harvesting Improvements:** Individual rainwater harvesting tanks often fail during heavy rainfall events. Installing community-scale rainwater harvesting systems with larger storage tanks or cisterns can improve capacity. These systems should be connected to multiple downspouts and include overflow systems to channel excess rainwater to retention ponds or other stormwater management facilities.

**Resident Education and Community Engagement:** Educating residents about maintaining clean drainage systems and the benefits of condominium and infiltration systems is essential. Engaging the community in maintenance and promoting sustainable practices will increase investment and awareness of stormwater management issues. Encouraging community contributions to a savings fund and fostering a sense of ownership will enhance the effectiveness and sustainability of drainage infrastructure.

**Regular Maintenance:** Consistent maintenance of existing drainage systems, including culverts and retention ponds, is necessary to prevent blockages, sediment buildup, and structural failures. Regular inspections and maintenance will ensure the long-term functionality of these systems.

**Urban Planning Integration:** Future urban planning must prioritize drainage considerations, particularly in relation to land use changes, slope analysis, and road construction. Integrating these factors into planning processes will help prevent adverse hydrological impacts and enhance system resilience.

**Site-Specific Adjustments:** Designing and implementing drainage infrastructure should involve tailoring solutions to specific field conditions, making site-specific adjustments for retention ponds and condominium systems based on local hydrological conditions.

**Strategic Infrastructure Placement:** Proper placement of storm drains, catch basins, culverts, and retention ponds, combined with green infrastructure elements and erosion control measures on steep slopes, is vital for improving stormwater management.

Overall, enhancing urban planning is crucial; future physical plans should integrate comprehensive stormwater management considerations, including green infrastructure and sustainable urban

drainage systems (SUDS). Upgrading and maintaining drainage systems to handle heavy rainfall events and constructing new drainage channels where necessary can mitigate flooding risks. Protecting and managing natural drainage paths and ravines through vegetation re-establishment and bioengineering techniques will improve their capacity for stormwater management. Engaging the local community in maintaining and improving drainage infrastructure, and educating them about sustainable practices, will enhance overall resilience.

### **4.3 Implications of the Research**

The evaluation of road infrastructure, drainage systems, and flood management in Nyarurama Cell carries significant implications for policymakers, decision-makers, and the academic community. For policymakers, the study underscores the urgent need for comprehensive infrastructure improvements to address the significant deficiencies observed in existing drainage systems. Clear guidelines and standards for drainage design and maintenance are essential, particularly in light of the observed variability in road types and drainage configurations.

As urbanization continues to increase, integrating green infrastructure—such as permeable pavements and rain gardens—into urban planning becomes crucial for mitigating flood risks and managing stormwater effectively. This approach aligns with global best practices and provides a proactive strategy for adapting to the challenges posed by rapid urban growth.

From a scientific perspective, the research enriches our understanding of the interplay between land use, drainage infrastructure, and flood risk. By examining the impact of impervious surfaces and varying runoff volumes, the study highlights the need for innovative stormwater management strategies. The methodology employed, which combines on-ground assessments with secondary data, sets a precedent for future research. This integrated approach offers a more accurate basis for developing models and simulations that predict the impacts of urbanization on water management systems.

Collaboration with stakeholders to disseminate these findings can foster the development of tailored, integrated drainage solutions that address local geological and hydrological conditions. Such collaborative efforts will support sustainable development and effective stormwater management in rapidly urbanizing areas like Nyarurama Cell, ultimately enhancing resilience and promoting long-term environmental sustainability.

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## 6 Appendices

### Appendix 1: Peak Discharge values for both 2024 and 2050 .

#### For 2-Year Return Period

Land Use	A* C	0.5 hr	1 hr	3 hr	6 hr	12 hr	24 hr
Forestland in 2024	70.7257281	3,215.16	1,940.97	834.31	486.88	282.55	163.26
Grassland and Cropland in 2024	313.9409455	14,300.68	8,629.63	4,509.29	2,160.42	1,245.21	726.89
Built-up land in 2024	112.4849902	5,126.87	3,085.70	1,911.54	774.70	577.00	529.64
Total in 2024	497.1516639	22,642.71	13,656.30	7,255.14	3,422.00	2,104.76	1,419.79
Forestland in 2050	70.45299469	3,211.87	1,927.45	834.28	484.31	282.35	162.76
Grassland and Cropland in 2050	35.8365439	1,631.14	1,206.37	609.69	295.61	210.87	168.12
Built-up land in 2050	409.1085243	18,646.58	13,349.76	6,993.97	3,258.85	2,438.91	1,941.42
Water Reservoirs in 2050	1.695248942	77.25	53.33	28.82	18.58	12.92	8.00
Total in 2050	517.0933118	23,566.84	16,536.91	8,466.76	4,056.36	2,944.05	2,280.30

#### For 5-Year Return Period

Land Use	A* C	0.5 hr	1 hr	3 hr	6 hr	12 hr	24 hr
Forestland in 2024	70.7257281	3,987.36	2,381.67	1,216.97	605.65	353.34	206.89
Grassland and Cropland in 2024	313.9409455	17,654.83	10,573.91	5,803.38	2,911.14	1,245.21	726.89
Built-up land in 2024	112.4849902	6,354.51	3,790.35	2,047.71	1,187.27	898.23	1,026.76
Total in 2024	497.1516639	27,996.71	16,745.93	9,067.06	4,704.06	2,812.50	2,145.13
Forestland in 2050	70.45299469	3,856.25	2,369.85	1,218.43	611.69	353.41	207.66
Grassland and Cropland in 2050	35.8365439	1,233.23	1,060.37	625.10	293.74	217.15	159.68
Built-up land in 2050	409.1085243	22,746.55	13,644.75	6,991.79	3,318.54	2,621.97	1,782.78
Water Reservoirs in 2050	1.695248942	73.33	50.71	28.57	18.26	13.51	7.97
Total in 2050	517.0933118	27,909.36	17,525.68	8,863.88	4,321.23	2,749.04	2,157.09

For 10-Year Return Period

Land Use	A* C	0.5 hr	1 hr	3 hr	6 hr	12 hr	24 hr
Forestland in 2024	70.7257281	4,582.60	2,770.79	1,207.55	733.77	413.41	234.96
Grassland and Cropland in 2024	313.9409455	20,349.81	11,894.69	5,350.42	2,675.97	1,835.85	1,364.10
Built-up land in 2024	112.4849902	7,279.37	4,405.78	1,911.54	893.42	727.59	645.89
Total in 2024	497.1516639	32,211.78	19,071.26	8,469.51	4,303.16	2,976.85	2,244.95
Forestland in 2050	70.45299469	4,545.19	2,742.61	1,208.23	736.50	413.14	234.16
Grassland and Cropland in 2050	35.8365439	1,580.44	1,183.10	625.59	294.43	207.43	159.71
Built-up land in 2050	409.1085243	23,470.63	13,863.45	6,993.97	3,292.67	2,542.85	1,914.18
Water Reservoirs in 2050	1.695248942	77.34	53.20	28.62	18.58	13.77	8.07
Total in 2050	517.0933118	29,673.60	17,842.36	8,856.41	4,341.17	2,617.19	2,316.11

For 25-Year Return Period

Land Use	A* C	0.5 hr	1 hr	3 hr	6 hr	12 hr	24 hr
Forestland in 2024	70.7257281	5,257.67	3,165.99	1,206.95	814.93	540.88	333.50
Grassland and Cropland in 2024	313.9409455	23,513.21	13,541.14	5,724.82	3,029.68	2,548.41	1,594.42
Built-up land in 2024	112.4849902	8,007.19	4,896.82	1,911.54	1,152.75	881.47	779.72
Water Reservoirs in 2024	0	0	0	0	0	0	0
Total in 2024	497.1516639	36,778.07	21,603.95	8,843.31	4,997.36	3,970.76	2,707.64
Forestland in 2050	70.45299469	5,245.83	3,161.45	1,208.02	832.63	541.71	334.56
Grassland and Cropland in 2050	35.8365439	1,768.53	1,207.89	625.45	295.79	217.30	168.64
Built-up land in 2050	409.1085243	27,191.87	15,356.66	6,991.79	3,259.88	2,619.60	1,741.59
Water Reservoirs in 2050	1.695248942	77.22	50.38	28.36	18.58	12.96	7.98
Total in 2050	517.0933118	34,283.45	19,776.38	8,853.62	4,406.88	3,391.57	2,252.77

For 50-Year Return Period

Land Use	A* C	0.5 hr	1 hr	3 hr	6 hr	12 hr	24 hr
Forestland in 2024	70.7257281	5,946.24	3,539.82	1,539.84	915.31	538.91	334.21
Grassland and Cropland in 2024	313.9409455	26,389.77	16,304.63	7,048.21	4,641.92	2,382.41	1,506.10
Built-up land in 2024	112.4849902	9,477.79	5,633.94	2,447.63	1,487.71	1,182.82	1,337.38
Total in 2024	497.1516639	41,813.79	25,478.40	11,035.68	7,044.93	4,104.14	3,177.69
Forestland in 2050	70.45299469	6,694.78	4,149.70	1,539.77	915.79	539.18	334.77
Grassland and Cropland in 2050	35.8365439	1,707.83	1,105.65	625.84	295.93	220.12	167.43
Built-up land in 2050	409.1085243	27,758.87	16,746.82	7,047.42	3,316.04	2,598.84	1,867.53
Water Reservoirs in 2050	1.695248942	77.00	50.53	28.87	18.61	13.93	8.54
Total in 2050	517.0933118	36,238.49	22,452.70	9,241.90	4,546.38	3,371.07	2,377.27

For 100-Year Return Period

Land Use	A* C	0.5 hr	1 hr	3 hr	6 hr	12 hr	24 hr
Forestland in 2024	70.7257281	6,675.38	4,154.81	1,209.23	1,039.46	591.86	335.50
Grassland and Cropland in 2024	313.9409455	29,559.20	18,463.12	7,269.97	5,528.45	2,566.91	1,773.31
Built-up land in 2024	112.4849902	10,628.61	6,572.71	2,047.71	1,214.85	917.21	689.76
Total in 2024	497.1516639	41,813.79	25,478.40	11,035.68	7,044.93	4,104.14	3,177.69
Forestland in 2050	70.45299469	6,699.07	4,156.21	1,208.96	1,039.72	592.26	335.95
Grassland and Cropland in 2050	35.8365439	1,688.87	1,102.78	625.94	295.75	221.52	167.17
Built-up land in 2050	409.1085243	27,439.58	16,609.35	7,047.42	3,316.70	2,619.45	1,915.64
Water Reservoirs in 2050	1.695248942	77.26	53.76	28.70	18.56	13.99	8.57
Total in 2050	517.0933118	36,904.78	22,921.10	8,910.03	4,670.73	3,447.22	2,427.68

These tables show the values for both 2024 and 2050 for each return period and duration.

Note: The units for peak discharge are cubic meters per second.

### General Observations:

- ✓ Built-up land significantly contributes to the peak discharge in both 2024 and 2050, showing an increase over time.
- ✓ Grassland and Cropland see a reduction in peak discharge in 2050 compared to 2024.
- ✓ Water Reservoirs appear in the 2050 data, which helps in controlling the peak discharge.
- ✓ Let's proceed with visualizing these peak discharge values. I will create plots comparing the peak discharge for different durations across return periods for both 2024 and 2050.
- ✓ (Note: This process may take a moment.)
- ✓ Here are the visualizations comparing peak discharge values between 2024 and 2050 across various return periods:

### Observations:

- ✓ **2-Year Return Period:** Peak discharge shows a slight increase in 2050 for shorter durations (0.5 hr and 1 hr) and longer durations (24 hr).
- ✓ **5-Year Return Period:** Discharges are higher in 2050 for short durations (0.5 hr), but lower for other durations compared to 2024.
- ✓ **10-Year Return Period:** Peak discharges for 2050 are consistently lower than 2024.
- ✓ **25-Year Return Period:** Peak discharges for 2050 are lower than 2024 across all durations.
- ✓ **50-Year Return Period:** 2050 shows lower peak discharges across all durations.
- ✓ **100-Year Return Period:** The trend is consistent with other return periods, showing lower discharges for 2050.
- ✓ **Key Takeaways:**
- ✓ **Built-up land** plays a crucial role in contributing to peak discharge.
- ✓ **Water Reservoirs** introduced in 2050 help in reducing peak discharge.
- ✓ Urbanization impacts are evident, with higher discharges in 2050 for specific return periods.
- ✓ These insights can help in formulating strategies for effective storm water management and urban planning in Nyarurama and Gatenga Sector.

Appendix 2: The potential runoff coefficients(C) for different land use, soil type and slope.

Land Use	Slope (%)	Range	Loam	Sandy Clay Loam	Clay Loam	Sandy Clay	Clay
Forestland	<0.5		0.13	0.23	0.27	0.33	0.4
	0.5–5		0.17	0.27	0.31	0.37	0.44
	5–10		0.23	0.33	0.37	0.43	0.5
	>10		0.35	0.45	0.49	0.55	0.62
Grassland	<0.5		0.23	0.33	0.37	0.43	0.5
	0.5–5		0.27	0.37	0.41	0.47	0.54
	5–10		0.33	0.43	0.47	0.53	0.6
	>10		0.45	0.55	0.59	0.65	0.72
Cropland	<0.5		0.33	0.43	0.47	0.53	0.6
	0.5–5		0.37	0.47	0.51	0.57	0.64
	5–10		0.43	0.53	0.57	0.63	0.7
	>10		0.55	0.69	0.75	0.82	0.82
Built-up land	<0.5		0.62	0.67	0.69	0.72	0.75
	0.5–5		0.64	0.69	0.71	0.74	0.77
	5–10		0.67	0.74	0.77	0.8	0.8
	>10		0.73	0.78	0.8	0.83	0.86
Wetland	<0.5		1	1	1	1	1
	0.5–5		1	1	1	1	1
	5–10		1	1	1	1	1
	>10		1	1	1	1	1
Water body	<0.5		1	1	1	1	1
	0.5–5		1	1	1	1	1
	5–10		1	1	1	1	1
	>10		1	1	1	1	1
<b>Roofs and paved road</b>			0.95	0.95	0.95	0.95	0.95
unpaved road and bare land			0.73	0.78	0.8	0.83	0.9
Source Karamage et al., 2017 adjusted to meet urban areas for Roofs , paved road unpaved roads and bare land.							