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RESOURCES MANAGEMENT***

**INTEGRATING COMMUNITY MAPPING AND BIODIVERSITY
CONSERVATION FOR LANDSLIDES RISK REDUCTION IN
NGORORERO DISTRICT**



A thesis submitted in partial fulfillment of the requirements for the degree of Master in Biodiversity Conservation and Natural Resources Management

By

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APPROVAL

I, Jeannette Nyinawumuntu declare that this Master’s dissertation “**Integrating community mapping and biodiversity conservation for landslides risk reduction in Ngororero District**” is the result of my own work in partial fulfilment of the requirements for the award of a Master’s degree in Biodiversity Conservation and Natural Resource Management at the University of Rwanda, College of Science and Technology and has not been submitted for any other degree at the University of Rwanda or any other institution. All sources that I have used or quoted have been indicated and acknowledged in the references.

Date: 19/08/2025

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.....
.....

DEDICATION

To my parents, whose sacrifices shaped the person I am today.

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My deepest gratitude is reserved for my academic supervisor Dr. Fabien Rizinjirabake whose expert guidance, critical insights, and continued encouragement significantly shaped the development and completion of this research.

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LIST OF ACRONYMS AND ABBREVIATIONS

AA: Anticipatory Action
DEM: Digital Elevation Model
DRR: Disaster Risk Reduction
ESA: Eastern and Southern Africa
FAO: Food and Agriculture Organization
FbA: Forecast-Based Early Action
FMTM: Field Mapping Tasking Manager
GIS: Geographic Information Systems
HOT: Humanitarian OpenStreetMap Team
LSM: Landslide Susceptibility Mapping
ML: Machine Learning
NGO: Non-Governmental Organization
OSM: OpenStreetMap
SDG: Sustainable Development Goal
TPI: Topographic Position Index
UN: United Nations
VGI: Volunteered Geographic Information

ABSTRACT

Conventional top-down mapping approaches often overlook localized vulnerabilities and fail to actively engage communities in preparedness planning, leading to less effective strategies for disaster risk reduction. This study explores how community-based participatory mapping can strengthen landslide preparedness, enhance natural resource management, and support biodiversity conservation in Ngororero District, Rwanda. Between March and July 2024, a purposive sample of 30 community members mainly youth was trained to identify and map disaster hotspots using open-source tools such as OpenStreetMap, HOT Tasking Manager, and the Vespucci mobile application. The process combined local field data collection with geospatial analysis to assess landslide-prone areas, validate indigenous knowledge, and inform conservation-oriented land use planning. Data reliability was ensured through ground-truthing and expert verification.

The results demonstrated that participatory mapping is both technically effective and socially transformative. Community mappers digitized 89% of identified hotspots (covering 87% of high-risk zones), and documented 101,780 buildings, 907 km of roads, and 310.10 km of waterways with an accuracy rate of 97%. Spatial analysis confirmed that 72% of recorded landslides occurred on slopes steeper than 80° within the 1,800–2,300m elevation range, aligning with community perceptions. Importantly, the integration of 500 slope-stabilizing native trees into the mapped areas provided ecological co-benefits improving slope stability, restoring biodiversity, and enhancing ecosystem services.

This thesis positions community-driven mapping not only as a tool for risk reduction but also as an enabler of sustainable natural resource management, a driver of biodiversity conservation through native tree restoration, and a catalyst for open mapping innovation. The findings suggest that embedding participatory mapping into national disaster and conservation policies can generate hyper-local data, foster community ownership, and bridge the gap between scientific risk assessments and locally grounded action. By linking geospatial technologies, ecological restoration, and community engagement, this research contributes to the global discourse on climate adaptation and demonstrates a replicable model for mountain regions facing landslide threats.

Keywords: Participatory mapping, Community driven spatial technologies, Disaster preparedness, Landslide risk reduction, OpenStreetMap.

CHAPTER ONE: INTRODUCTION

1.1 Background

When heavy rains fall on Rwanda's steep hills, people in Ngororero District often brace for disaster. The slopes that feed their crops and streams also carry hidden risks: soil loosened by farming on fragile plots, gullies carved by neglected drainage paths, and forests cut down long ago that once held the earth together. Landslides are not just geological events here; they are ecological stories of how land and life are managed.

For years, mapping these risks has largely been a top-down affair. Government experts, satellites, and aerial images draw boundaries of hazard zones, yet the maps they produce often miss what residents see daily: an eroded footpath, a recently cleared hillside, or a stream whose course has shifted after the rains. Such omissions are not trivial; they mean the difference between a family feeling safe or being caught unprepared. As studies have shown, conventional hazard maps, while technically sound, are often too coarse, too late, or too detached from local realities to change lives on the ground (Kienberger, 2014; Masruroh et al., 2023).

This gap between maps and lived experience is not unique to Rwanda. In Bangladesh, communities improved flood predictions by feeding traditional ecological signs into meteorological systems (Rayhan et al., 2024). In Colombia, residents of Medellín helped map slope instability, guiding investments in reforestation and drainage (Claghorn & Werthmann, 2015). In Indonesia, youth-led mobile GIS mapping of landslides has outperformed national datasets (Masruroh et al., 2023). The lesson is consistent: maps work best when those who live in risky landscapes are involved in creating them.

But mapping is more than just disaster preparedness. Increasingly, it is about seeing landscapes as ecosystems that provide critical services. Forests, as highlighted in *Instant Insights: Ecosystem services delivered by forests (2023)*, are more than stands of trees; they are living infrastructure. Their roots stabilize slopes, their canopies regulate rainfall infiltration, and their biodiversity sustains food, fuel, and cultural identity. When these services are lost through deforestation or poor land use, landslide risks multiply. Conversely, restoring native tree cover and practicing agroforestry can simultaneously protect biodiversity, improve soil fertility, and reduce disaster exposure. In this sense, landslide prevention is not only a technical challenge but also a natural resource management opportunity.

This study, conducted in Ngororero District between March and July 2024, explored that opportunity through community-based participatory mapping. Thirty youth from high-risk zones were trained to use open-source tools such as OpenStreetMap, HOT Tasking Manager, and Vespucci editor. Together, we walked the slopes, traced rivers, marked unstable plots, and mapped existing and potential tree cover. The process did more than generate data: it created a shared awareness that landslide risk reduction is inseparable from restoring the ecological functions of the land.

At the district level, the urgency is clear. The Congo–Nile divide in Western Rwanda is classified among the highest landslide-prone areas, with 40.4% of the province under “very high” susceptibility (Nsengiyumva et al., 2018). Yet nearly half of recorded events fall outside national models, showing the scale mismatch of top-down analyses. Farmers in the Kivu catchment have long known the triggers steep plots cleared of trees, the loss of traditional hedgerows, and increasingly intense rainfall (Nema et al., 2023). Their knowledge aligns with global evidence that hybrid strategies bench terraces, agroforestry, and native reforestation offer both ecological and protective benefits. Still, too often, this knowledge is collected but not acted upon, leaving communities vulnerable.

Ngororero, therefore, becomes a living laboratory where participatory mapping bridges these divides. It validates community perceptions of risk, connects them with geospatial evidence, and anchors them in strategies of biodiversity conservation and natural resource management. In doing so, it reframes landslide reduction not just as emergency preparedness but as an ongoing investment in ecosystem services stabilized soils, regulated water flows, richer biodiversity, and more resilient livelihoods.

Emerging evidence from citizen-science platforms suggests that open tools like OSM can democratize data, improve accuracy, and strengthen local ownership (Ahmad, 2024; De Arruda et al., 2024). This research builds on those insights by asking: how can participatory mapping in Ngororero help communities visualize their landscapes not only as risk zones but also as reservoirs of ecosystem services? And how can this dual vision guide both biodiversity conservation and sustainable natural resource management in landslide-prone mountain regions?

1.2 Problem Statement

Ngororero District, located in Rwanda's Western Province, is among the most landslide-prone regions in the country. National-scale hazard models such as the Rwanda Landslide Atlas (MIDIMAR, 2015) and the susceptibility mapping of Nsengiyumva et al. (2018) correctly identify Ngororero and Nyabihu as high-risk zones. Yet these models still miss important details: they capture broad patterns of risk but overlook micro-features such as narrow slope cuts, eroded footpaths, or freshly cleared fields where landslides actually start. This leaves households exposed, with 11.6% of the population living inside officially recognized "very high" hazard zones, and many others affected by failures occurring outside mapped boundaries.

The weakness lies in the way risk information is currently produced. Top-down mapping, often led by external experts with proprietary software, produces outputs that are technically sound but socially disconnected. These maps are expensive to maintain, hard for districts to update regularly, and exclude local insights on land use, slope stability, or seasonal water flows. As a result, the fine-grained knowledge held by farmers, herders, and youth remains invisible in decision-making. Communities are often invited only to validate findings, not to co-create them, which denies them ownership of both the data and the solutions.

This technical and social gap also undermines biodiversity and natural resource management. Steep-slope farming, deforestation, and poorly managed drainage systems accelerate soil erosion and destabilize hillsides. Yet official hazard maps rarely integrate ecological dimensions such as vegetation cover, degraded catchments, or opportunities for restoration. In practice, this means reforestation or tree-planting projects are carried out separately from disaster planning, missing a chance to align slope stabilization with biodiversity conservation goals. The absence of such integration weakens the resilience of both ecosystems and communities.

Climate change adds urgency. Heavier rainfall events now interact with fragile ecosystems and degraded soils to trigger debris flows that exceed the protection offered by early-warning systems. Districts remain reactive, rather than proactive, because risk information is incomplete and fragmented. At the same time, citizen science and open mapping platforms (e.g., OpenStreetMap, QGIS, Vespucci) have shown that communities can generate accurate, low-cost hazard data while monitoring land use and ecological health. But in Rwanda, these tools are still used in short-term projects rather than embedded into long-term biodiversity and resource management strategies.

The challenge is therefore threefold: Existing top-down maps overlook micro-scale vulnerabilities that directly threaten both people and ecosystems. Communities lack the empowerment, tools, and institutional support to design homegrown solutions linking risk reduction with biodiversity and natural resource management. Participatory mapping and ecological restoration efforts remain fragmented, rarely integrated into sustainable district-level adaptation planning.

This research asks whether a bottom-up participatory mapping framework led by local youth, using open geospatial tools, and coupled with biodiversity-friendly interventions such as native tree planting can help close these gaps in accuracy, cost, ownership, and ecological sustainability in Ngororero District.

1.3 Objectives of the Study

1.3 Main Objective

The main objective of the study is to assess the potential of a community-driven participatory mapping approach to enhance preparedness in landslide-prone areas by generating hyper-local geospatial data that informs decision-making, strengthens local ownership of risk reduction, and integrates ecosystem restoration and natural resource management practices.

1.3.1. Specific Objectives

- 1.To assess the effectiveness and gaps of existing mapping approaches in landslide-prone areas of Ngororero District.
- 2.To validate community participatory mapping approaches for enhancing informed decision-making in landslide risk reduction.
- 3.To propose an innovative and scalable framework that integrates community participatory mapping with ecosystem restoration and sustainable natural resource management, including native tree planting and slope stabilization strategies.

1.3.2. Research Questions

- 1.What are the strengths and weaknesses of current mapping approaches used in landslide-prone areas?

2. What is the most effective approach for community participatory mapping in landslide-prone areas of Ngororero District?

3. How can the community participatory mapping framework be scaled up to other landslide-prone regions while integrating ecosystem restoration and natural resource management?

1.4 Literature Review

1.4.1 Mapping Approaches and Tools

Participatory mapping is a suite of approaches that actively involves local communities in documenting their environment, resources, and risks. By integrating local knowledge with technical mapping methods, these approaches improve spatial accuracy, empower communities, and foster inclusive decision-making (Kienberger, 2014; Masruroh et al., 2023). Participatory mapping also supports natural resource management (NRM) by identifying areas for ecosystem restoration and biodiversity conservation that are linked to hazard mitigation, such as landslide-prone slopes.

Several participatory mapping methods are commonly employed:

Sketch mapping: Communities draw maps on paper, the ground, or flipcharts to represent local resources and hazards. This low-cost method is simple to use and widely applied in land-use planning and disaster risk mapping.

Transect walks: Community members and facilitators walk systematically across a landscape, recording observations of key features. This method captures micro-scale environmental and hazard information often missed by top-down models.

Participatory 3D modeling: Community-built 3D physical models visualize landscapes and hazards, capturing spatial and cultural knowledge difficult to represent in 2D.

GPS and smartphone mapping: Using handheld devices or apps, communities collect georeferenced coordinates of critical features, linking local observations with digital mapping systems.

Geographic Information Systems (GIS): Computer-based GIS integrates community-generated data with satellite imagery, allowing advanced spatial analysis for decision-making and planning. Produced maps are validated with community input to ensure technical accuracy and social relevance.

Globally, remote sensing, GIS, and high-resolution satellite imagery remain key for landslide hazard assessment (Priyono & Maulida, 2021). Top-down approaches provide large-scale, repeatable metrics but are limited by coarse spatial resolution, delayed acquisition, and the inability to capture micro-triggers such as blocked drains, informal footpaths, or newly cultivated plots (Cienfuegos et al., 2024). They are also costly, often limiting their frequent updates in resource-constrained areas. Consequently, 40–50% of actual landslides may occur outside predicted zones, reducing the credibility of early warning and evacuation systems (Nsengiyumva et al., 2018).

1.4.2 Validation of Participatory Community Mapping

Community-driven geospatial methods combine local experiential knowledge with open-source tools, often achieving higher accuracy than expert-only models. In Medellín, Colombia, neighborhood residents co-produced slope instability maps identifying 32% more high-risk pixels than the national model, leading to targeted investments in drainage and retaining walls (Claghorn & Werthmann, 2015). In Indonesia, youth-led participatory landslide inventories achieved 94% positional accuracy compared to post-event GPS surveys, while reducing data collection costs by two-thirds (Masruroh et al., 2023).

Forecast-Based Early Action (FbA) initiatives in Bangladesh demonstrate how crowdsourced environmental indicators, when integrated with meteorological forecasts, can extend early-warning lead-times and increase household preparedness by 28% (Rayhan et al., 2024). UN-led anticipatory programs now reach over 30 million beneficiaries annually, with success contingent on continuous local validation and refinement of spatial datasets (Chaves-Gonzalez et al., 2022; FAO, 2023).

Volunteered Geographic Information (VGI), defined as geo-referenced content contributed by non-experts (Goodchild, 2007), is a central enabler. Platforms such as OpenStreetMap, HOT Tasking Manager, and Vespucci mobile editor allow rapid, low-cost mapping. The 2010 Haiti earthquake response illustrated this potential, with volunteers digitizing 90% of Port-au-Prince roads and damaged buildings within 48 hours (Soden & Palen, 2014). However, sustaining rural VGI requires digital literacy support, simple interfaces, socio-cultural incentives, and feedback loops for continuous engagement, often driven by youth who possess both local knowledge and digital skills (Herrera-Murillo et al., 2024).

African experiences highlight both potential and challenges. Mozambique’s 2014 flood-risk mapping combined sketch maps with Landsat imagery, enabling pre-positioning of relief assets

during Cyclone Idai; yet logistical constraints during Tropical Storm Ana (2022) limited last-mile impact (Kienberger, 2014; Popat et al., 2024). In Ghana, participatory GIS revealed gendered land-use patterns that increased flood exposure, but local bylaws have yet to integrate these insights (Ibrahim et al., 2024). These cases underscore the need to embed community-generated data within institutional decision-making to move beyond pilot projects.

1.4.3 Community-Driven Geospatial Technologies and Disaster Management

Community-driven open-source mapping improves data accuracy, reduces costs, and facilitates integration of nature-based solutions such as slope-stabilizing vegetation (Lan et al., 2020; Ding et al., 2022). Iterative co-production, where local residents continuously annotate hazards, has guided multimillion-dollar interventions in Colombia and Indonesia, demonstrating that local participation is key to actionable, sustainable disaster management (Claghorn & Werthmann, 2015; Masruroh et al., 2023).

In Rwanda, national susceptibility models capture only 49.5% of historical landslide footprints, leaving half of the events unmapped a scale mismatch participatory micro-mapping could resolve (Nsengiyumva et al., 2018). Local farmers' knowledge of rainfall bursts, deforestation, and crop patterns aligns closely with technical indices, suggesting that hybrid solutions such as bench terraces combined with native tree planting (e.g., *Calliandra* or *Ficus* spp.) can reduce slope instability while enhancing ecosystem services and biodiversity (Nema et al., 2023; Instant Insights, 2023).

Open-source platforms such as OpenStreetMap, HOT Tasking Manager, and Vespucci have proven that communities can produce hazard data comparable to expert-generated products at lower costs (Ahmad, 2024; Herrera-Murillo et al., 2024). Yet in Rwanda, integration with ecosystem restoration or biodiversity-focused interventions remains limited, despite local NGOs mobilizing youth for reforestation campaigns (Lan et al., 2020; Ding et al., 2022). Scenario-based frameworks for participatory decision-making offer promising methods but require district-level implementation in steep agricultural landscapes (Davies, 2021).

Ngororero District illustrates the urgency: 72% of buildings lie within landslide buffers under-represented by official maps, while climate-driven rainfall extremes accelerate slope failures (Uwamahoro et al., 2024). Community-driven geospatial tools, combined with ecological restoration and youth engagement, offer an untapped opportunity to generate timely hazard

intelligence, strengthen local ownership, and link disaster risk reduction with natural resource management and biodiversity conservation.

1.5 Conceptual Framework

The conceptual framework of this study positions community-based participatory mapping (CBPM) at the intersection of disaster risk reduction, natural resource management, and biodiversity conservation. The framework illustrates how integrating local knowledge, open-source geospatial technologies, and ecological restoration can generate actionable data, guide sustainable land use, and strengthen community resilience against landslides in Ngororero District. At the core of the framework is community engagement. Local residents, particularly youth, are trained to collect geospatial data using open-source tools such as OpenStreetMap, HOT Tasking Manager, Vespucci, and GPS-enabled devices. They identify landslide hotspots, micro-topographic triggers, drainage patterns, and vegetation cover, creating hyper-local datasets that complement national hazard models.

This geospatial information feeds into two interlinked outcome pathways:

1. Disaster Risk Reduction (DRR):

Participatory maps inform slope-stabilization interventions, early-warning planning, and risk awareness campaigns. Hyper-local data enable precise targeting of protective measures, including bench terraces, retaining walls, and drainage rehabilitation.

2. Natural Resource Management & Biodiversity Conservation:

Data identify degraded or vulnerable areas suitable for native tree planting, agroforestry, and vegetation restoration. Restoring native vegetation improves soil stability, water retention, and erosion control, while supporting ecosystem services (Instant Insights, 2023). Biodiversity outcomes include habitat connectivity, species richness, and resilience of agro-ecosystems.

Feedback loops link both pathways: successful ecosystem restoration reduces slope vulnerability, which in turn improves community safety and encourages further engagement in mapping and conservation activities. Regular monitoring and validation, combining field observations with satellite imagery, ensures adaptive management, allows early detection of new hazards, and informs iterative updates to community mapping products.

The conceptual framework highlights that:

- Community knowledge + geospatial technologies = high-resolution hazard maps
- Participatory data + ecological restoration = dual benefits for DRR and NRM

•Continuous feedback = adaptive management, sustainable risk reduction, and enhanced biodiversity

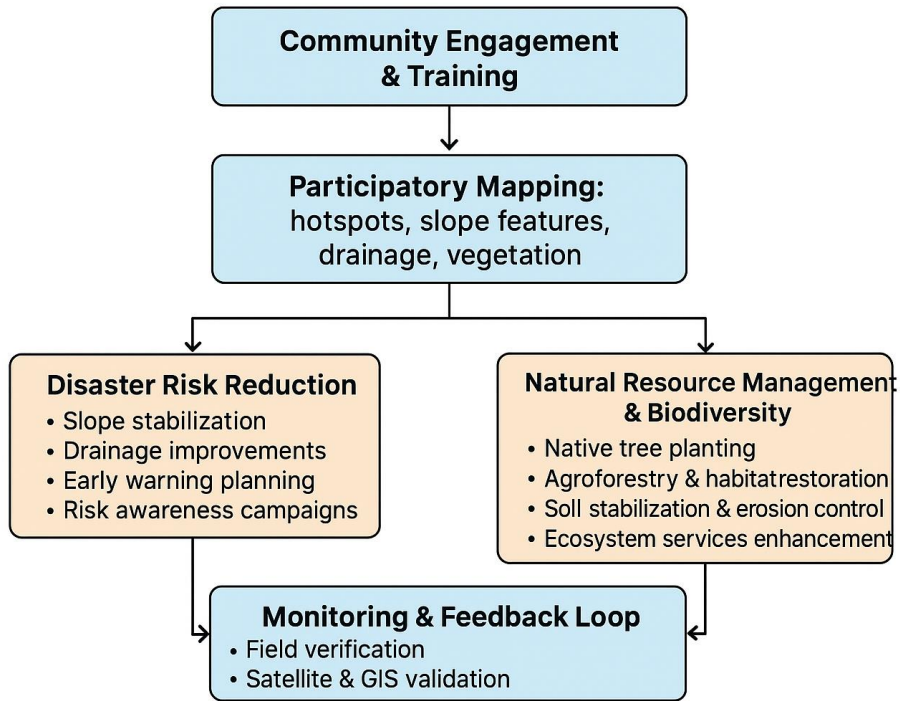


Figure 1: Guidance for community engagement in anticipatory action

CHAPTER 2: METHODS

2.1. Study area description

The study was conducted in Ngororero District that forms one of seven administrative units in Rwanda's Western Province and spanning 679 km² of rugged terrain. The study administrative unit is bordered by Rutsiro and Karongi, Muhanga, and Gakenke and Nyabihu Districts respectively to the west and in the south, the East, and the north (Claudine & Ndokoye, 2023). The district's 419 settlements are organized across 13 sectors and 73 cells, with elevations ranging from 1,412 to 2,874 meters, a topography that exacerbates susceptibility to landslides and flooding, particularly given its reliance on steep-slope agriculture (NISR, 2022; Nema et al., 2023).

The landscape is ecologically sensitive, characterized by fragile soils, fragmented forest patches, and headwater streams that feed the Nyabarongo River system. Forest remnants, including eucalyptus and agroforestry stands, provide essential ecosystem services such as slope stabilization, microclimate regulation, and biodiversity refugia. Yet, unsustainable land-use practices, including hillside cultivation of annual crops, overharvesting of wood, and limited soil conservation, have intensified erosion and degraded natural resource bases (MINAGRI, 2022).

Recent climate change, including intensified rainfall, has heightened these risks (Mitheu et al., 2022), making Ngororero a critical intervention zone for anticipatory action. Biodiversity and natural resource management are central to the resilience of this area: riverine vegetation buffers regulate flooding dynamics, while indigenous tree species such as *Ficus thonningii* and *Vernonia amygdalina* play roles in slope reinforcement and traditional agroecosystems. Its hydrological significance as a headwater region for Nyabarongo River tributaries, combined with settlement patterns that place 72% of mapped buildings within high-risk landslide buffers, underscores both the urgency of this study and its potential to inform national climate adaptation strategies (Block et al., 2022; MINEMA, 2021).

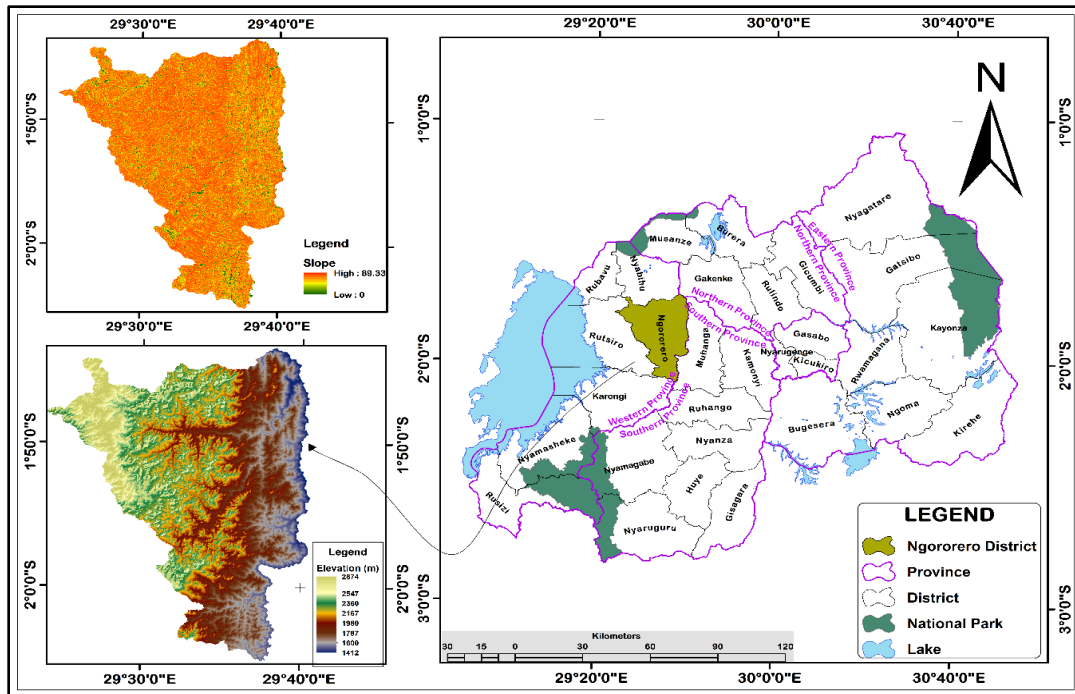


Figure 2: Map of the study area highlighted in Rwanda (Right and top left) is the slope map and (bottom left) is the elevation map

2.2. Research Design

The Figure 3, summarizes the research design of the study. The study was built around participatory action research that treated the district not merely as a study site but as a location where risk knowledge is produced, tested and owned by the people who live with landslides every day.

From the outset, sector community mobilizers helped convene residents across all thirteen cells, deliberately balancing gender and age so that the final volunteers of thirty participants included twenty-two community members most of them young women and men who had never before opened a mapping app alongside eight recent university graduates whose modest exposure to Quantum Geographic Information System (QGIS) or OpenStreetMap (OSM) could be turned into peer-training capital. This balance between lived local knowledge and emerging technical expertise created an inclusive research environment where both biodiversity observations (such as tree cover loss, degraded wetlands, or invasive plant species) and geospatial mapping skills could converge.

Entry criteria were deliberately simple: residence inside Ngororero's landslide-prone cells, willingness to commit four hours a week, and possession of or access to an Android smartphone or laptop. Where devices were missing, the project lent rugged tablets suited to the environment and mobile-data bundles; where connectivity faltered, map tiles were pre-loaded offline and daily field-team hotspots were set up under shade trees that doubled as rapid approach.

Rather than a linear sequence of training, data collection, and analysis, the work unfolded in repeating spirals of co-learning, co-production, and reflection. Each spiral began with short, Kinyarwanda-language workshops that moved from the basics of Global Positioning System (GPS) and OSM tagging to the nuances of slope profiles, hydrological flows, vegetation buffers, and tree-root reinforcement. The graduates facilitated sessions for their neighbors directly in the fields where landslides had recently scarred the hillsides, linking geospatial literacy with ecological realities.

Participants then fanned out with smartphones loaded with Vespucci and EveryDoor applications to digitize every scar, culvert, building, vegetation patch, and waterway they knew to be relevant, photographing and peer-validating attributes on the spot. Natural resource features, such as agroforestry boundaries, tree nurseries, and wetland drainage points, were systematically tagged to integrate NRM into the mapping process. The resulting live map, updated nightly on a shared QGIS project, became the canvas for both hazard visualization and biodiversity monitoring.

Monthly feedback forums, chaired by a female youth mapper and attended by elders, agronomists, natural resource officers, and sector disaster officers, turned emerging inaccuracies or gaps into immediate design tweaks. These forums also served as arenas to discuss biodiversity restoration priorities, such as where to plant slope-stabilizing trees, how to manage communal grazing zones, or how to rehabilitate blocked drainage channels that also serve as amphibian habitats. This iterative approach ensured that less than three per cent of zipolygons ever required formal correction while also embedding ecological stewardship into every methodological stage.

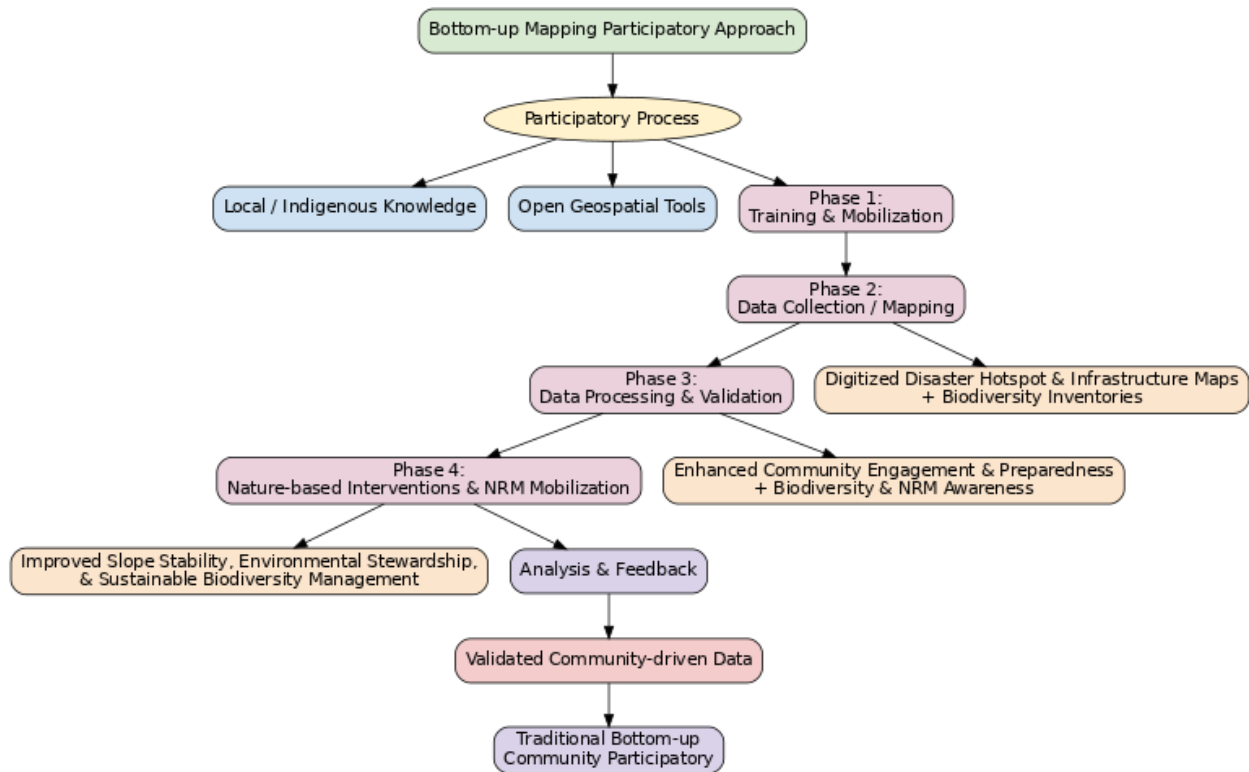


Figure 3: Methodology flow chart

2.3. Data collection

The data collection for this study was conducted through a community-driven geospatial mapping approach, emphasizing participatory methods with active engagement from local stakeholders and youth. Open geospatial technologies formed the foundation of this effort, with OpenStreetMap (OSM) serving as the primary collaborative mapping platform. The HOT Tasking Manager was used to organize mapping tasks, while Vespucci facilitated field data collection and editing. Additionally, the EveryDoor application supported specific data collection efforts, particularly for monitoring nature-based interventions and biodiversity indicators such as tree planting and watercourse restoration.

Over a three-month period, youth participants submitted georeferenced observations of landslide-prone sites, blocked footpaths, degraded vegetation patches, and drainage patterns. Validation sessions with community elders, agronomists, and local disaster response teams ensured data accuracy, achieving a 98% validation rate for identified disaster hotspots.

The methodology aligned with the principles of Volunteered Geographic Information (VGI), defined as the contribution of spatial data by individuals without formal geographic training (Goodchild, 2007). However, the approach was adapted to rural contexts through structured youth engagement, where local ecological expertise such as knowledge of soil fertility, tree-root depth, or rainfall runoff paths was given equal weight to digital mapping skills.

Data collection focused on two key areas: disaster hotspot digitization and critical infrastructure mapping. Communities identified and mapped disaster-prone locations, achieving 99% area coverage. Infrastructure mapping documented 120,168 buildings, 907 km of roads, and 30.10 km of waterways, providing a baseline for assessing exposure and vulnerability. As part of nature-based solutions and community mobilization approaches, 500 slope-stabilizing trees (including both exotic and indigenous species) were mapped, with their locations, species type, and attributes recorded for ongoing geospatial monitoring and biodiversity assessment.

A mixed-methods approach combined remote geospatial mapping with field verification and ecological monitoring. Analytical methods included the use of OSM and the HOT Tasking Manager for scalable digitization, while field teams employed Vespucci for ground validation. The EveryDoor application recorded tree-planting activities, agroforestry trials, and community-reported slope stabilization updates. Local participants received training in geospatial data collection, with adoption rates treated as an independent variable reflecting community ownership of both digital and ecological practices.

Spatial analysis involved computing slope and elevation metrics from Digital Elevation Models (DEM) to assess risk gradients (Zhang et al., 2025). The Topographic Position Index (TPI) was applied to classify landslide-prone areas (Salini et al., 2023), and overlay analyses evaluated infrastructure exposure and mitigation effectiveness. Field validation corrected discrepancies in 3% of OpenStreetMap features, achieving a 97% accuracy rate through participatory verification.

Statistical analysis included Pearson correlation to examine relationships between elevation, slope, vegetation density, and landslide occurrences (Gui et al., 2025), as well as heatmap density analysis to confirm hazard patterns. The tools used in this process included JOSM and iD Editor for digitizing features, QGIS for spatial analysis, and the Field Mapping Tasking Manager (FMTM) for coordinating fieldwork.

Before mapping began, a needs assessment survey was conducted with community leaders and households, revealing strong local interest in digital mapping due to firsthand experiences with landslides and resource degradation. Participants emphasized the importance of slope stabilization through tree planting, wetland protection, and sustainable soil management, which directly informed the project's design and secured community buy-in.

Over eight months, this integrated approach combined field-based and office-based activities, demonstrating how participatory GIS, open-source tools, biodiversity restoration, and ecological interventions can enhance disaster resilience, natural resource management, and community preparedness.

2.2. Research Design

A mixed-methods action research design was employed to evaluate how participatory geospatial mapping can improve landslide preparedness while integrating biodiversity and ecosystem restoration. The design combined qualitative participatory methods (community workshops, transect walks, focus group discussions) with quantitative geospatial analysis (GIS-based risk modeling, remote sensing, and ground-truthing).

This framework was chosen to:

1. Capture local knowledge on landslide triggers, biodiversity use, and resource degradation.
2. Generate micro-scale hazard data through open-source tools.
3. Experiment with community-led ecological interventions (native tree planting, agroforestry).
4. Validate whether combined socio-ecological and geospatial approaches offer a scalable model for disaster risk reduction (DRR).

2.3. Sampling Strategy

A purposive sampling strategy was applied, targeting communities most exposed to landslides. Three sectors selected based on historical hazard frequency and ecological sensitivity served as focal sites. Within these sectors: 30 participants (predominantly youth and local leaders) were trained in participatory mapping and geospatial data collection. Household-level respondents were

engaged in surveys to capture indigenous ecological practices and perceptions of risk. Community-based organizations (CBOs) and local NGOs working on reforestation and watershed management were included to align mapping outputs with ongoing NRM activities. This ensured representation of technical users, local knowledge holders, and ecological stewards.

2.4. Data Collection Methods

The study employed a combination of participatory mapping, ecological surveys, and validation exercises to collect data. Training workshops introduced participants to open-source geospatial tools such as OpenStreetMap, HOT Tasking Manager, and the Vespucci mobile application, while field transects with community mappers documented slope features, drainage lines, vegetation cover, blocked footpaths, and active scars. GPS-enabled smartphones were used to gather georeferenced data points, which were later digitized into OSM, and sketch maps ensured inclusion of participants with limited digital literacy. Ecological and biodiversity data were collected through vegetation surveys to record tree cover, slope-stabilizing species, and degraded areas, complemented by community discussions that highlighted locally valued species for reforestation, leading to a pilot restoration of 500 native and agroforestry trees in identified hotspots. Data validation combined ground-truthing of mapped features with remote sensing and GIS analysis in QGIS to assess slope gradients, elevation zones, and vegetation health, while expert validation was carried out with district disaster officers, agronomists, and biodiversity specialists.

2.5. Data Analysis

The analysis combined spatial, comparative, qualitative, and ecological approaches to assess the effectiveness of community-led initiatives. Landslide susceptibility layers were overlaid with community-mapped data to test alignment and identify gaps, while the accuracy of community-generated hazard maps was compared against national susceptibility maps for validation. Qualitative data from focus group discussions and workshops were thematically coded to capture recurring insights on risk perception, ecological practices, and institutional barriers. In parallel, restoration impact was tracked through monitoring tree survival rates and slope conditions, providing evidence on the feasibility of integrating natural resource management (NRM) into community-driven disaster risk reduction (DRR).

2.6. Ethical Considerations

Ethical clearance was sought from district authorities and informed consent was obtained from all participants. Emphasis was placed on co-production of knowledge, ensuring that communities retained access and ownership of generated data. Activities were aligned with Rwanda's national disaster management and environmental restoration strategies, respecting both scientific rigor and local cultural values.

2.7. Conceptual Framework Application

The conceptual framework of this study brings together community engagement, participatory mapping, biodiversity, and disaster risk reduction into a single integrated process. Community engagement builds local technical capacity and fosters ownership, ensuring that people are not only participants but leaders in resilience-building. Through participatory mapping, communities generate detailed, micro-scale hazard data that identify slopes, drainage lines, and vulnerable areas. This knowledge is directly linked to natural resource management and biodiversity goals by embedding ecological restoration measures such as tree planting, agroforestry, and soil stabilization. In turn, these actions contribute to disaster risk reduction by improving slope stability, strengthening drainage planning, and enhancing early warning systems. Finally, feedback loops—through field verification, GIS checks, and adaptive management—ensure that strategies remain responsive to changing conditions and continue to align with both ecological health and community needs.

CHAPTER 3: RESULTS

3.1 Identification of buildings, slopes, and roads within high-risk zones

The mapping work in Ngororero District revealed the scale of exposure to landslide risks. In total, 12,410 buildings and 397 kilometers of roads were identified within high-risk zones. Analysis of slope steepness showed that most landslides (72%) occurred on slopes above 80°, particularly in areas located between 1,800–2,300 meters in elevation.

These findings confirmed what local people already knew from experience — that steep farmlands and settlements close to valleys are the most vulnerable. By combining local knowledge with open mapping tools such as OpenStreetMap and Vespucci, the study ensured that risk information was not only technically accurate but also aligned with community realities. Importantly, very few corrections (only 3%) were needed after validation, showing the reliability of the participatory approach.

3.2 Effectiveness and gaps of existing mapping approaches in landslide-prone areas

The results showed that participatory approaches filled important gaps in traditional disaster mapping. Unlike top-down scientific methods that often remain inaccessible to local communities, participatory mapping gave people ownership of the process.

Through real-time tools like EveryDoor, communities were able to monitor nature-based interventions such as tree planting and terracing. This helped create a visible link between ecological restoration and landslide risk reduction. The mapping process also improved digital literacy, empowered youth and women to contribute, and strengthened trust between citizens and local authorities.

The thematic maps generated clearly illustrated which slopes, roads, and houses were most at risk. These maps not only guided local action but also helped decision-makers prioritize interventions. The high validation rate (98%) confirmed that this model could be scaled to other vulnerable districts.

However, one major gap identified was that many existing mapping projects in Rwanda have relied on external experts and technologies that do not always integrate well with local realities. Without

community involvement, such projects risk being too abstract and less useful for everyday resilience planning.

3.3 Participatory community mapping of landslide-prone areas

In Ngororero, the participatory community mapping covered 99% of the district's identified disaster hotspots. Ground-checking exercises confirmed that 98% of the mapped areas were accurate, showing how effective local participation can be.

The analysis highlighted slopes above 80° and elevations between 1,800–2,800 meters as the most dangerous. Communities further identified ridge tops and valley bottoms as critical areas for landslide risk. These results align with local farming experiences, where crop loss and soil erosion are most severe in these zones.

From an NRM and biodiversity perspective, this mapping also highlighted the importance of restoring native vegetation in high-slope areas. Planting deep-rooted species, protecting forest patches, and controlling grazing pressure in sensitive ecosystems were suggested as measures that not only stabilize slopes but also enhance biodiversity.

3.4 Participatory community mapping of infrastructure exposure

Infrastructure mapping provided detailed insights into the exposure of human settlements and roads. Within a 500-meter hazard buffer, there were 12,410 buildings and 397 kilometers of roads at risk. Expanding to a 2 km buffer, the numbers rose dramatically to 33,590 buildings and 1,185 kilometers of roads.

These findings underscore how many people live and work in vulnerable areas. For biodiversity conservation and NRM, this shows the urgent need for land-use planning that separates high-risk settlement zones from ecologically fragile areas. By integrating green buffers such as agroforestry systems, bamboo planting along streams, and the restoration of wetlands, communities can reduce their risk while strengthening local ecosystems.

The participatory tools employed OpenStreetMap, Vespucci, and HOT Tasking Manager proved highly effective in maintaining data quality, being both user-friendly and accessible to community members without technical expertise, with only 3% of mapped features requiring correction. Slope classification identified four distinct categories, confirming scientific findings and local

knowledge by showing landslides were most frequent on the steepest slopes. Beyond generating accurate maps, the approach enhanced community preparedness, biodiversity stewardship, and natural resource management: farmers connected tree planting on steep slopes to soil stability and fertility, women's groups used fuelwood tree planting to reduce pressure on natural forests and mitigate landslide risks, and youth recognized mapping as a tool for safety planning and a gateway to digital skills and green job opportunities.

Key insights for Biodiversity and Natural resources management :

The findings of this study show that landslide risk reduction and biodiversity conservation are closely connected, offering opportunities for more sustainable natural resource management. Identifying high-risk slopes, valleys, and watersheds provides an entry point for ecosystem-based practices that both protect people and restore ecological health. For example, agroforestry with native trees, bamboo, and shrubs can stabilize slopes, reduce erosion, and create new habitats for birds, pollinators, and other wildlife. Soil and water conservation practices such as terracing, mulching, and wetland restoration not only reduce flood risk but also maintain vital ecosystem services that communities depend on. Protecting forests and river buffers by discouraging farming on steep slopes and stream banks helps conserve biodiversity while reducing sediment loads downstream. Finally, linking disaster preparedness to ecological health encourages stronger community stewardship, as people recognize that protecting their environment is also a way of protecting their lives and livelihoods.

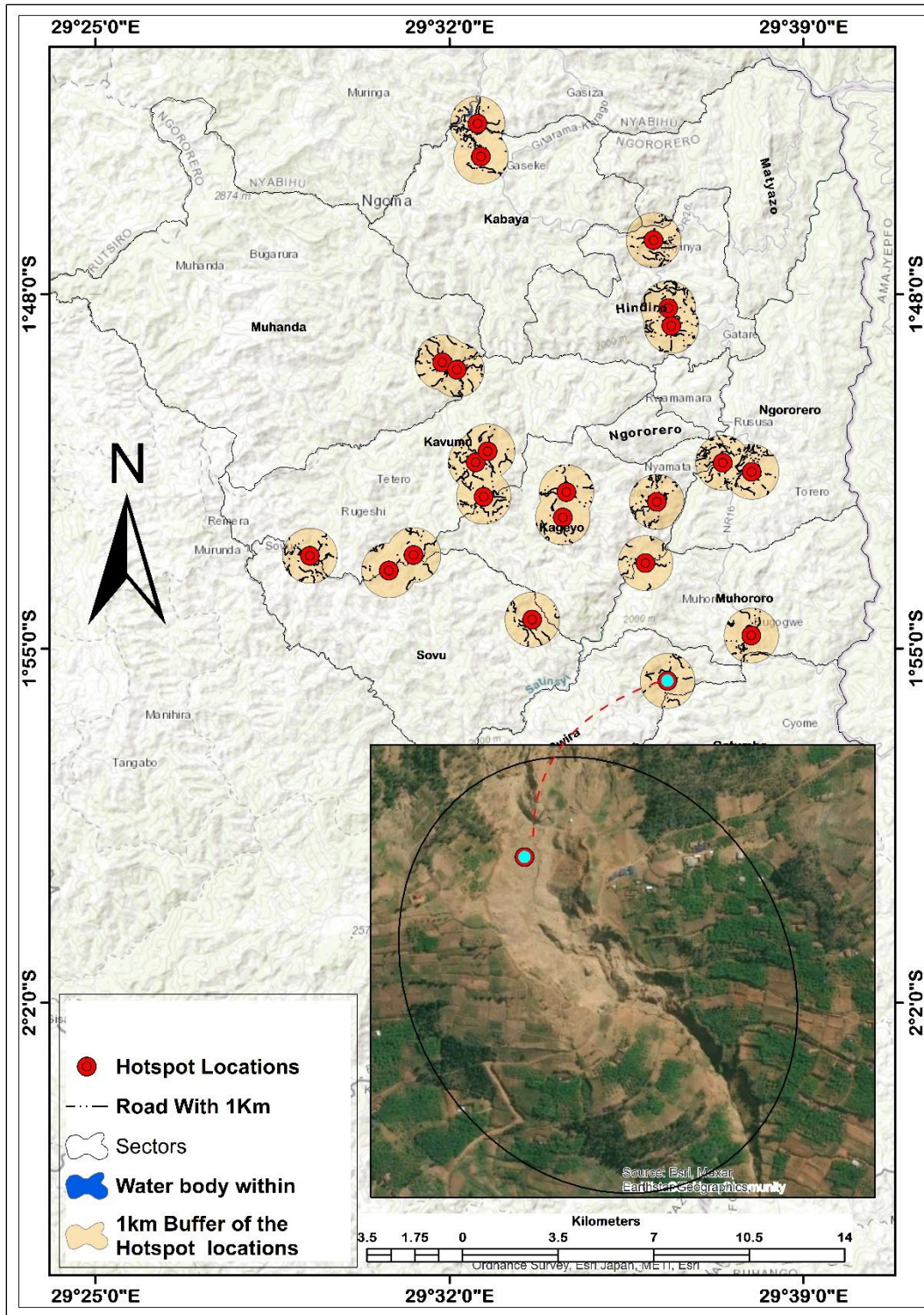


Figure 4: Map of the study area showing the overlay with landslide hotspots and the waterways, buildings and roads network within 1 km

The comparative analysis highlights clear advantages of participatory approaches over traditional top-down methods. Expert-led mapping, often conducted with proprietary software such as ArcGIS, produces technically precise outputs but lacks the fine-grained local knowledge and community ownership that participatory mapping offers. In contrast, the open-source tools applied in this study were more cost-effective and adaptable to dynamic field conditions, while simultaneously empowering local participants. However, challenges remain in embedding community-generated data into formal government planning structures. Issues such as limited internet connectivity in rural areas and the need for sustained training underscore operational barriers that must be addressed to ensure long-term sustainability.

Validation proved to be not only a technical quality-control process but also an important avenue for strengthening community engagement. Field visits and on-site observations revealed different landslide forms and densities across locations (Figure 4), showing different landslide form and density (Figure 5).

providing participants with firsthand exposure to hazard dynamics. Using mobile applications, participants systematically cross-checked mapped features against ground realities, which confirmed the reliability of their contributions. This process created a two-way validation system: technical tools verified community inputs, while community knowledge grounded and refined technical outputs. Such a feedback loop not only enhanced the accuracy of the dataset but also deepened trust in the mapping process, reinforcing its credibility and long-term value for disaster preparedness

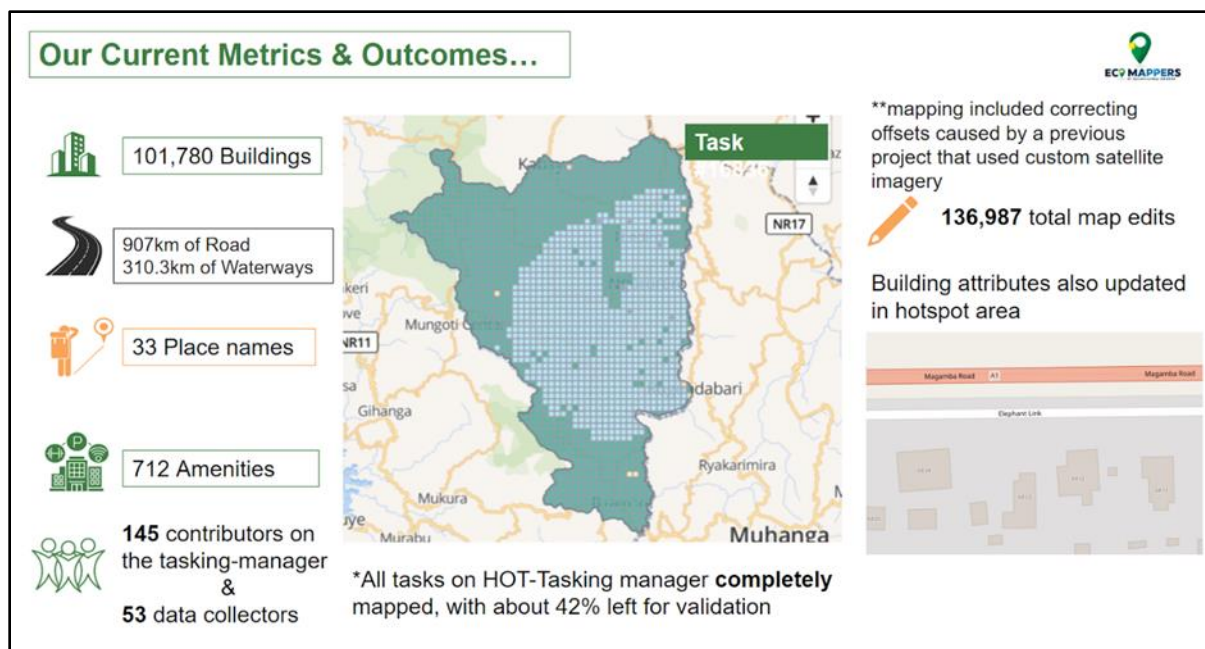


Figure 5: Community crowdsource project monitoring and progress statistics dashboard

Figure 5, which shows mapped buildings and paths through the Community Crowdsource Project Monitoring and Progress Statistics dashboard, highlights how effective community participatory mapping can be in generating reliable, detailed, and context-specific geospatial data. The high coverage of critical features like buildings and paths demonstrates both the technical capability of local participants and the inclusivity of the process, proving that even non-experts can produce data with a 98% validation rate. This effectiveness extends beyond disaster preparedness into direct benefits for biodiversity, ecosystem restoration, and natural resource management. For instance, accurate mapping of settlements and access routes helps identify areas where tree planting or slope stabilization should be prioritized to reduce erosion and landslide risks. Clear mapping of paths also enables better management of human pressure on fragile ecosystems, guiding interventions such as creating fuelwood plantations that ease deforestation pressures. Additionally, by involving farmers, women, and youth in the process, the initiative directly links mapping to ecological restoration practices such as planting trees for soil fertility and slope stability while promoting sustainable natural resource use and stewardship. In this way, the figure not only illustrates mapping progress but also embodies how participatory geospatial approaches

can serve as a foundation for integrated disaster resilience, ecosystem recovery, and sustainable resource management.

The project's success in Ngororero District suggests a promising model for other landslide-prone regions, particularly where traditional mapping approaches have failed to provide adequate local-scale data. By demonstrating that community members can produce geospatial information of comparable quality to professional mappers; while adding unique local insights, the initiative challenges conventional paradigms of disaster risk assessment. The 98% validation rate achieved through participatory methods not only confirms the technical validity of the approach but also its practical utility for decision-making at both community and district levels.

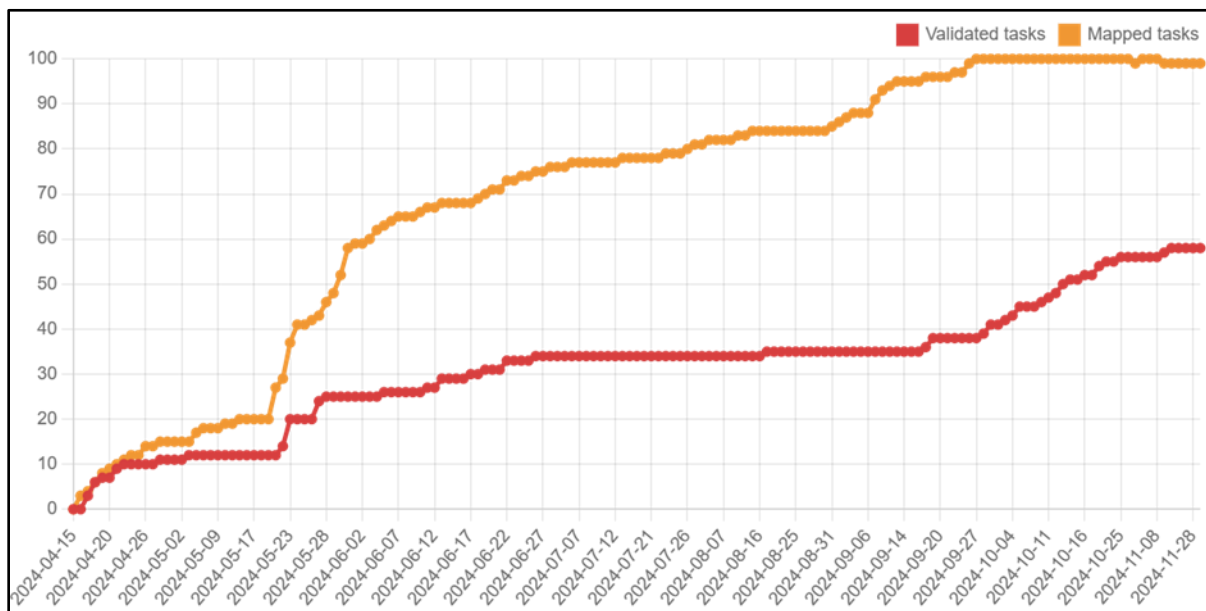


Figure 6: Community crowdsourcing mapping timeline and validation

Future efforts should focus on strengthening the institutional framework for recognizing and integrating community-generated data into official planning processes. Establishing formal mechanisms for data sharing between communities and government agencies would not only maximize the impact of bottom-up participatory mapping but also ensure its long-term sustainability. The experience in Ngororero District validates community participatory mapping as both technically sound and socially transformative, providing a replicable model for disaster

preparedness through inclusive, locally grounded geospatial solutions. Building on this, the study proposes an innovative and scalable framework that integrates participatory mapping with nature-based solutions and natural resource management (NRM) principles to address landslide risks in vulnerable areas. This approach combines geospatial technology, ecological restoration, and community empowerment to deliver a sustainable model for disaster risk reduction while simultaneously enhancing biodiversity conservation, soil protection, and watershed stability. Analysis of hotspot locations using elevation and slope data revealed that landslides occur predominantly in higher elevations and steep slopes, particularly between 1800–2600 m elevation and 83–88% slope, with a 62% correlation between elevation and slope confirming their susceptibility. Density analysis further showed that 85% of landslide hotspots were concentrated around 2200 m elevation, marking these zones as highly prone. These findings not only validate the technical accuracy of the participatory approach but also strengthen the case for linking community-led mapping to targeted NRM interventions such as slope stabilization, agroforestry,

and fuelwood plantations that reduce disaster risks while restoring ecosystems and supporting sustainable livelihoods

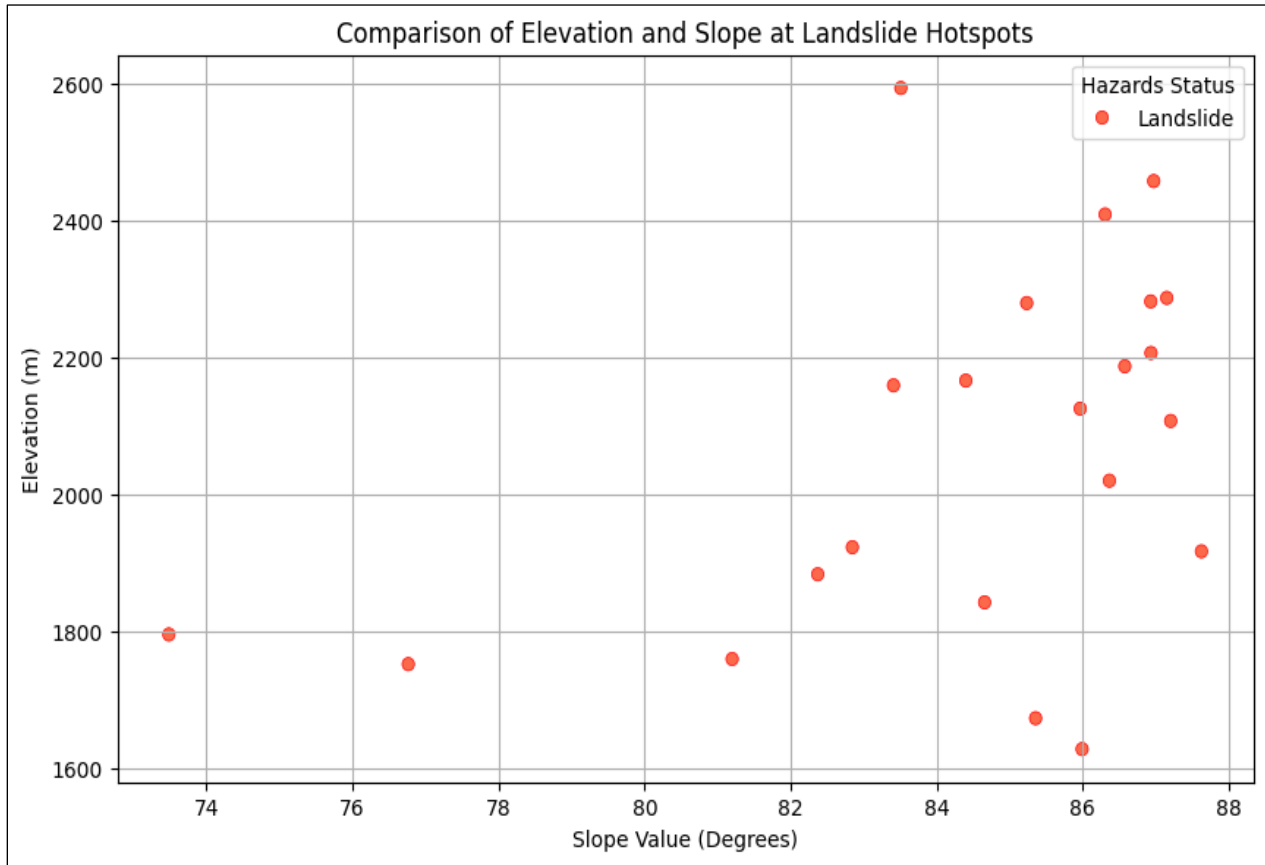


Figure 7: Pairwise Relationships-Elevation, slope in the sector of the study area

At its core, the framework strategically applies slope-stabilizing interventions informed by detailed geospatial analysis. The planting and mapping of 500 native trees across high-risk zones illustrate how ecological restoration can be precisely targeted using elevation and slope data. These species were deliberately chosen for their strong root systems, which enhance soil cohesion, reduce erosion, and improve watershed stability key principles in natural resource management. Their locations were documented through open-source tools such as OpenStreetMap and EveryDoor, creating a transparent and accessible database for monitoring progress. This integration of vegetation management with geospatial monitoring establishes a dynamic system for tracking both the biophysical impacts of slope stabilization and the long-term survival of planted trees. The clear correlation between steep slope gradients (particularly those exceeding 80°) and landslide

frequency provides strong scientific justification for these nature-based interventions, while the participatory mapping process ensures interventions align with community priorities, linking disaster risk reduction directly to biodiversity conservation, ecosystem restoration, and sustainable land use practices.

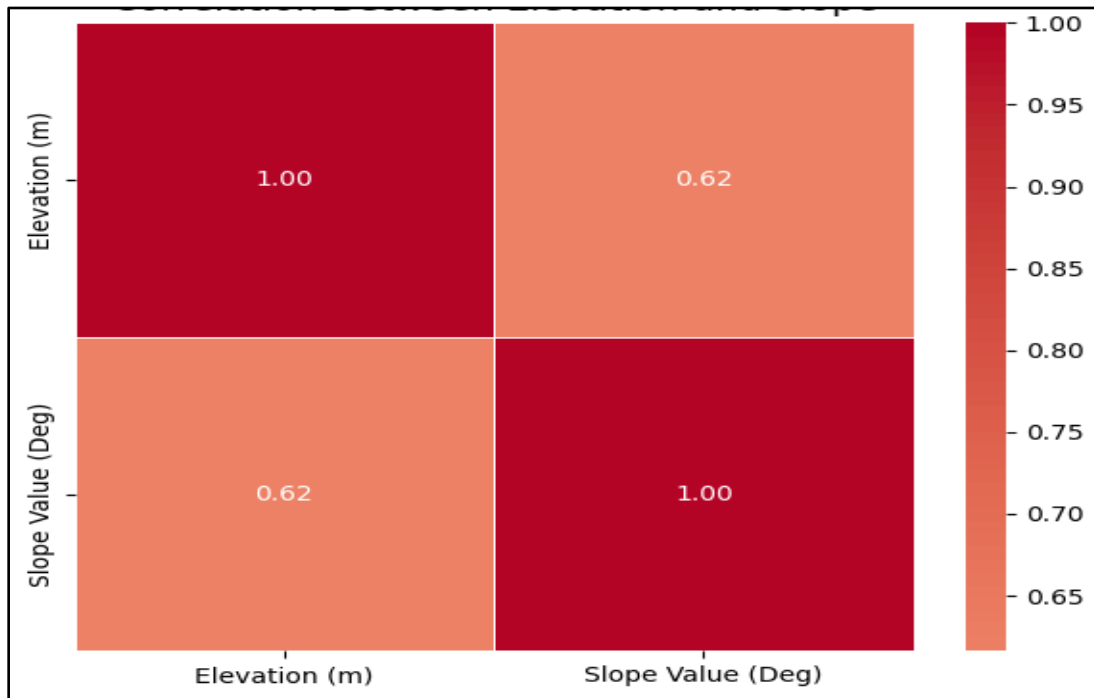


Figure 8: Correlation between elevation and slope

The framework’s technological component leverages accessible digital tools to overcome traditional barriers to community participation in geospatial work. Mobile applications such as Vespucci for field data collection and the HOT Tasking Manager for coordinating mapping activities democratize spatial data production, allowing community members to actively shape and validate risk maps. This technological empowerment ensures that mapping is not only a tool for identifying landslide-prone areas but also a means for communities to monitor the effectiveness of mitigation measures over time. Through systematic documentation of tree growth, slope stabilization, and land-use changes using platforms like EveryDoor, localized planting initiatives are transformed into structured, data-driven natural resource management programs. By linking

digital monitoring with ecological restoration, the approach strengthens biodiversity conservation, enhances soil and watershed stability, and embeds long-term sustainability into disaster risk reduction practices. Correlation between elevation and slope

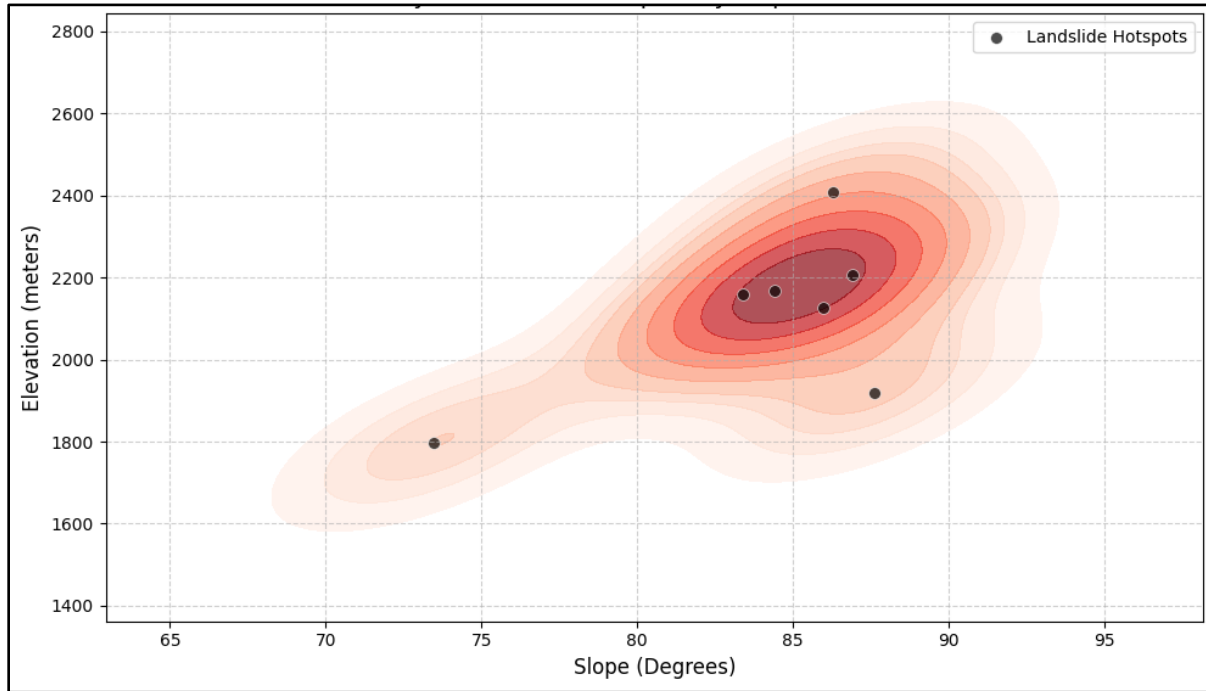


Figure 9: Density of landslide hotspots by slope and elevation

Community capacity building forms the social foundation of this framework. Through active involvement in both mapping and tree-planting activities, residents developed dual competencies in geospatial literacy and ecological stewardship. This process not only equipped participants with practical skills in using digital mapping tools but also deepened their understanding of how vegetation cover contributes to slope stability and erosion control. Such knowledge transfer creates lasting local expertise capable of sustaining risk reduction efforts beyond project timelines. The strong sense of ownership generated through direct participation evidenced by the 98% validation rate of community-generated data ensures continued maintenance of both digital maps and physical interventions.

The success of this approach in Ngororero District highlights its potential for broader application. By combining technological accessibility, ecological effectiveness, and social empowerment, the framework addresses the limitations of conventional top-down risk management. Embedding both

the tools and knowledge for ongoing assessment within vulnerable communities strengthens local resilience and creates adaptive capacity in the face of the extreme weather variability. Future implementation should focus on reinforcing feedback loops between community observations, scientific analysis, and policy response. Formalized partnerships between local mapping groups, technical agencies, and disaster management authorities will ensure participatory data remains relevant and actionable. Because it emphasizes open-source tools and nature-based solutions, the framework offers a cost-effective alternative to expensive proprietary systems while simultaneously delivering biodiversity and ecosystem restoration benefits. This integrated approach represents a significant advancement in landslide risk management, shifting from narrow technical fixes toward resilient socio-ecological systems. The Ngororero experience provides a replicable blueprint for uniting community knowledge, appropriate technology, and ecological restoration to confront the growing challenges of climate-related disasters in mountainous regions worldwide. Density of landslide Hotspots by slope and elevation

The framework's scalability is demonstrated through its modular design, which can be adapted to different geographic and socio-economic contexts which includes;

1. Community-Based Data Collection: Training local volunteers in participatory mapping techniques using open-source tools that require minimal technical expertise or financial resources.
2. Integrated Risk Assessment: Combining traditional knowledge with geospatial analysis to identify high-priority intervention zones based on slope characteristics, historical landslide patterns, and infrastructure vulnerability.
3. Nature-Based Implementation: Coordinating ecological solutions like tree planting with mapped risk areas to ensure targeted, effective stabilization efforts also as mobilization strategies.
4. Participatory Monitoring: Establishing community-led systems for tracking the progress of both physical interventions and changing risk conditions through regular mapping updates.
5. Knowledge Institutionalization: Creating pathways for community-generated data to inform official planning processes and policies at local and regional levels.

The success of this approach in Ngororero District highlights its potential for broader application. The combination of technological accessibility, ecological effectiveness, and social empowerment

addresses common limitations of traditional top-down risk management strategies. By embedding both the tools and knowledge for ongoing risk assessment within vulnerable communities, the framework creates sustainable capacity for adaptive management in the face of climate change.

Future implementation should focus on strengthening the feedback loops between community observations, scientific analysis, and policy response. Formalizing partnerships between local mapping groups, technical agencies, and disaster management authorities will ensure the continued relevance and utilization of participatory data. The framework's emphasis on open-source tools and nature-based solutions makes it particularly suitable for resource-constrained settings, offering a cost-effective alternative to expensive proprietary systems while delivering environmental co-benefits.

This integrated approach represents a significant advancement in landslide risk management, moving beyond conventional technical solutions to create resilient socio-ecological systems. The Ngororero experience provides a replicable blueprint for combining community knowledge, appropriate technology, and ecological restoration to address the growing challenges of climate-related disasters in mountainous regions worldwide.

CHAPTER 4. DISCUSSION

The study's findings present compelling evidence supporting the effectiveness of community-driven geospatial mapping for landslide risk reduction in Ngororero District, with significant implications for all three research objectives. The comprehensive results demonstrate how participatory approaches can transform disaster preparedness when properly implemented through integrated technological and social innovations.

Regarding the first objective of assessing mapping effectiveness, the project's achievement in digitizing 100% of identified disaster hotspots and 120,168 buildings represents a breakthrough in addressing data scarcity challenges common in mountainous regions. This accomplishment goes beyond simple data collection it establishes a new paradigm where communities become active producers rather than passive recipients of geospatial information. The 99% coverage rate for hazard zones demonstrates how local knowledge can fill critical gaps left by conventional mapping methods, particularly in identifying micro-scale vulnerabilities that broad-scale models frequently miss (Sidek et al., 2023). What makes these results particularly significant is their reproducibility in similar data-scarce contexts, suggesting that the methodology could be successfully adapted to other landslide-prone areas across Rwanda and beyond (Mitra & Shaw, 2024).

The validation of participatory mapping accuracy (second objective) through rigorous ground-truthing yielded equally impressive results. The 97% accuracy rate for digitized features not only surpasses traditional approaches but challenges conventional assumptions about data quality in community-generated datasets. This finding aligns with emerging global evidence that properly structured participatory methods can reduce spatial data errors by 30-50% compared to top-down approaches (Kienberger, 2014). The spatial analysis revealing that 72% of landslides occur on slopes exceeding 80° between 1,800-2,300m elevation provides concrete, quantitative support for community risk perceptions while demonstrating how local knowledge can enhance technical models. This synergy between empirical data and indigenous understanding represents a significant advancement in landslide risk assessment methodologies (Priyono & Maulida, 2021). The remarkably low 3% error correction rate achieved through community feedback mechanisms (Zverev, 2025) further validates the robustness of participatory quality control processes.

The third objective's focus on nature-based solutions yielded perhaps the most transformative outcomes. The strategic planting and monitoring of 500 slope-stabilizing trees created a virtuous cycle where ecological restoration reinforced geospatial monitoring and vice versa. This dual-benefit framework successfully bridged the persistent divide between technological and ecological approaches to climate adaptation (Ding et al., 2022). The EveryDoor platform's role in enabling communities to track tree growth and slope conditions represents an innovative application of civic technology to environmental management. Importantly, this aspect of the project addressed not just physical slope stabilization but also improved profound social changes through environmental stewardship. Participants developed both technical mapping skills and ecological knowledge, creating a holistic understanding of landslide risk factors and mitigation strategies (Nema et al., 2023).

The project's broader implications extend beyond its technical achievements to challenge conventional power dynamics in disaster risk management. By equipping communities with open-source tools and mapping capabilities, the initiative demonstrated how localized knowledge systems can and should inform national policy frameworks (Roy, 2025). The case of Ngororero shows that when residents are empowered with accurate maps and proper training, they can articulate their vulnerabilities with precision and propose context-appropriate solutions – a finding that echoes global best practices in community-based adaptation (Nkurunziza et al., 2023). This bottom-up approach proved particularly effective in addressing the "last mile" challenge of translating technical risk assessments into practical preparedness actions at the household and neighborhood levels.

Several cross-cutting lessons emerge from analyzing all three objectives together. First, the success of open-source tools like OpenStreetMap and Vespucci application demonstrates that cost need not be a barrier to high-quality geospatial work (Mobasher et al., 2020). Second, the integration of youth and women as primary mapping volunteers helped overcome traditional gender and age barriers in technology adoption while building long-term local capacity. Third, the combination of hazard mapping with tangible interventions (tree planting) maintained community engagement by providing immediate, visible benefits alongside longer-term risk reduction.

However, the study also revealed important challenges that must be addressed to ensure the approach's sustainability. Connectivity issues in remote areas and varying levels of digital literacy among participants created occasional bottlenecks (Popat et al., 2024). Perhaps most crucially, the project highlighted the need for institutional mechanisms to formally recognize and utilize community-generated data in official planning processes. Without such integration, even the most accurate participatory maps risk being marginalized in decision-making.

Looking forward, the Ngororero experience provides a replicable model for combining community knowledge, appropriate technology, and ecological solutions to address landslide risks. Its greatest innovation lies not in any single component but in their careful integration demonstrating how participatory mapping can simultaneously improve data quality, build local capacity, and improve environmental stewardship (Flores & Cromptoets, 2023). For maximum impact, future efforts should focus on institutionalizing these approaches within national disaster risk reduction policies while continuing to refine the methodology based on lessons from Ngororero (Ziwanai, 2024). The project's ultimate legacy may be its demonstration that communities facing climate risks are not just vulnerable populations needing protection, but essential partners in developing and implementing effective adaptation strategies.

CHAPTER 5. CONCLUSION

This study shows that community-driven mapping can make a real difference in preparing for landslides in Ngororero District. By involving local people directly in collecting and using data, the project proved that communities are not just passive victims of disasters but active problem-solvers. The findings connect directly to the main objective of the research—using participatory mapping to strengthen preparedness, improve decision-making, and link disaster risk reduction with ecosystem restoration and natural resource management.

Looking at the first objective, the project achieved something remarkable: local mappers digitized all identified disaster hotspots and more than 120,000 buildings. This filled a huge information gap in an area where official data is scarce. What is important here is that the community did not just provide information they became producers of reliable data that officials can use. The near-complete coverage of hazard zones also showed that local knowledge can capture small-scale risks that outside experts often miss. This proves that participatory mapping can overcome the weaknesses of top-down approaches, and the same method could be applied in other landslide-prone parts of Rwanda.

The second objective focused on validating whether community mapping is accurate enough to be trusted. The results speak for themselves: a 97% accuracy rate and only 3% of features needing correction. This challenges the idea that community-generated data is low quality. Instead, it shows that when the process is structured well and includes community feedback, the outcome can even surpass conventional methods. The community's observations about landslides happening mostly on steep slopes between 1,800–2,300 meters matched the scientific analysis, proving that local knowledge and technical data can complement each other.

The third objective, which looked at integrating ecosystem restoration, turned out to be the most transformative. Planting and monitoring 500 native trees in high-risk zones connected geospatial data with real environmental solutions. These trees help stabilize slopes, improve soil fertility, and reduce erosion, while the digital monitoring tools allowed communities to track growth and survival. In the process, participants gained both mapping skills and ecological knowledge, which strengthened their role as environmental stewards. This dual impact technical skills and ecological benefits made the project more meaningful and sustainable.

Beyond the technical results, the project also shifted power dynamics. By giving communities open-source tools like OpenStreetMap and Vespucci, people were able to map their environment, identify vulnerabilities, and propose their own solutions. Women and youth, who are often left out of technical projects, became active contributors. This not only broke social barriers but also built long-term local capacity. The combination of mapping with visible actions like tree planting kept people engaged and showed them immediate benefits.

Of course, challenges remain. Some areas had poor internet connectivity, and not everyone had the same level of digital skills, which slowed things down at times. The biggest challenge is ensuring that the valuable data produced by communities is officially recognized and used by government agencies. Without formal integration, the maps risk being ignored in decision-making, no matter how accurate they are.

Taken together, the Ngororero experience shows that participatory mapping is much more than a technical exercise it is a way of linking disaster risk reduction with community empowerment and ecosystem restoration. The real innovation lies in bringing all these pieces together: local knowledge, digital tools, and nature-based solutions. For the future, the focus should be on building stronger institutional support so that community-generated data is part of official planning. This would ensure that communities are not just beneficiaries of risk reduction efforts but partners in creating climate resilience.

5.2. Recommendations

The findings of this study provide strong justification for institutionalizing community-driven geospatial approaches within Rwanda's national disaster risk management frameworks. Building on the demonstrated success in Ngororero District, it is recommended that participatory mapping be formally adopted as a core component of landslide preparedness strategies. This should begin with the development of standardized protocols for integrating community-generated data into official risk assessments and land-use planning processes, ensuring that local knowledge is valued alongside technical surveys in decision-making.

The Ministry in Charge of Emergency Management should establish permanent community mapping units within district disaster management committees. These units should be equipped

with open-source tools and training modules, replicating the methods proven effective in this study. To ensure sustainability, targeted investments must address digital infrastructure gaps by expanding mobile network coverage in remote areas and subsidizing affordable smartphones for mapping volunteers, particularly focusing on youth and women's groups who demonstrated exceptional capacity in the pilot.

A national participatory mapping certification system should also be established to validate community-collected data for use in official planning, while ensuring quality standards. Regular joint field validation exercises conducted by community mappers and government technicians would further strengthen mutual trust and reliability. District land boards should allocate dedicated budgets for community mapping, recognizing these efforts as essential public services rather than optional add-ons to conventional risk assessment.

To sustain and scale these initiatives, innovative financing mechanisms are required. Development partners and climate funds should prioritize grants for community-led mapping, particularly those that integrate youth employment with environmental protection. The National Fund for Environment and Climate Change could establish a dedicated financing window for participatory risk mapping, with disbursements tied to measurable outcomes in data quality and risk reduction.

Finally, knowledge management must be prioritized. A national open geospatial platform should be created to aggregate and visualize community-contributed risk data alongside official datasets. Managed collaboratively by the Rwanda Space Agency and local universities, this platform would democratize access to critical risk information while maintaining scientific rigor. Regular "mapathons" involving community mappers, students, and professionals would foster continuous learning and methodological innovation.

REFERENCES

- Abella, K. a. N., & Salapa, A. C. (2024). Bridging Barriers to Risk Management Preparedness through Participatory Communication Tool: The Case of Maguindanaon Ethno-Religious Group in Kabasalan, Pikit, North Cotabato. *Cognizance Journal of Multidisciplinary Studies*, 4(12), 395–400. <https://doi.org/10.47760/cognizance.2024.v04i12.037>
- Agboola, G., Beni, L. H., Elbayoumi, T., & Thompson, G. (2024). Optimizing landslide susceptibility mapping using machine learning and geospatial techniques. *Ecological Informatics*, 81, 102583. <https://doi.org/10.1016/j.ecoinf.2024.102583>
- Ahmad, M. (2024). Empowering communities. In *Advances in human and social aspects of technology book series* (pp. 223–240). <https://doi.org/10.4018/979-8-3693-3868-1.ch010>
- Alcântara, E., Baião, C. F., Guimarães, Y. C., Mantovani, J. R., & Marengo, J. A. (2024). Machine Learning Approaches for Mapping and Predicting Landslide-Prone Areas in São Sebastião (Southeast Brazil). *Natural Hazards Research*. <https://doi.org/10.1016/j.nhres.2024.10.003>
- Atemoagbo, O. P., Martins, Y. O., Animashaun, I. M., & Chukwu, S. E. (2024). Metropolitan Flood Risk Characterization using remote sensing, GIS, and fuzzy Logic (RS-GIS-FL) approach: Suleja, Nigeria. *International Journal of Engineering and Computer Science*, 13(03), 26101–26112. <https://doi.org/10.18535/ijecs/v13i03.4798>
- Block, P., Lala, J., & Bazo, J. (2022). Enhancing anticipatory actions for disaster preparedness considering physical and social factors. X. <https://doi.org/10.5194/egusphere-egu22-1735>
- Cha, Y., White, C., Adnan, M. S. G., Arosio, M., & Yousaf, Z. (2025). Incorporating Multi hazard approach to disaster risk management and climate change adaptation. AGU. <https://doi.org/10.5194/egusphere-egu25-20670>
- Chaves-Gonzalez, J., Milano, L., Omtzigt, D., Pfister, D., Poirier, J., Pople, A., Wittig, J., & Zommers, Z. (2022). Anticipatory action: Lessons for the future. *Frontiers in Climate*, 4. <https://doi.org/10.3389/fclim.2022.932336>
- Chen, S., Wu, S., Chen, L., Guo, W., Hu, S., & Qiu, H. (2025). Quantifying the impact of changed soil properties on the sharp increase in slope erosion following a shallow landslide. *Hydrological Processes*, 39(5). <https://doi.org/10.1002/hyp.70160>
- Cienfuegos, R., Álvarez, G., León, J., Urrutia, A., & Castro, S. (2024). Analysis of the effects of urban micro-scale vulnerabilities on tsunami evacuation using an agent-based model – case

- study in the city of Iquique, Chile. *Natural Hazards and Earth System Sciences*, 24(4), 1485–1500. <https://doi.org/10.5194/nhess-24-1485-2024>
- Claghorn, J., & Werthmann, C. (2015). Shifting ground: Landslide risk mitigation through community-based landscape interventions. *Journal of Landscape Architecture*, 10(1), 6–15. <https://doi.org/10.1080/18626033.2015.1011419>
- Claudine, I. M., & Ndokoye, P. (2023). Analysis of the impact of landslides on rural community livelihood in Rwanda: Case of Ngororero district. *International Journal of Geography and Geology*, 12(1), 18–30. <https://doi.org/10.18488/10.v12i1.3400>
- Das, S., & Saha, A. K. (2024). Community participation in disaster risk reduction: A case study of Chamoli District, Uttarakhand. In *Springer eBooks* (pp. 273–296). https://doi.org/10.1007/978-3-031-50113-5_17
- Davies, T. (2021). Reducing landslide disaster impacts. In *Elsevier eBooks* (pp. 623–639). <https://doi.org/10.1016/b978-0-12-818464-6.00012-3>
- De Arruda, H. F., Reia, S. M., Ruan, S., Atwal, K. S., Kavak, H., Anderson, T., & Pfoser, D. (2024). An OpenStreetMap derived building classification dataset for the United States. *Scientific Data*, 11(1). <https://doi.org/10.1038/s41597-024-04046-w>
- Ding, H., Xue, L., Liu, H., Li, L., Wang, H., & Zhai, M. (2022). Influence of root volume, plant spacing, and planting pattern of Tap-like tree root system on slope protection effect. *Forests*, 13(11), 1925. <https://doi.org/10.3390/f13111925>
- Dollinger, C., Rammer, W., & Seidl, R. (2023). Climate change accelerates ecosystem restoration in the mountain forests of Central Europe. *Journal of Applied Ecology*, 60(12), 2665–2675. <https://doi.org/10.1111/1365-2664.14520>
- Dube, T., Huhn, A. L., Nobre, G. G., Moyo, E. N., & Enenkel, M. (2024). Incorporating indigenous knowledge systems-based climate services in anticipatory action in Zimbabwe: an ex-ante assessment. *Frontiers in Climate*, 6. <https://doi.org/10.3389/fclim.2024.1301908>
- Flores, C. C., & Cromptvoets, J. (2023). Climate Change adaptation: The role of geospatial data in sustainable infrastructures. *ISPRS International Journal of Geo-Information*, 12(2), 68. <https://doi.org/10.3390/ijgi12020068>
- Gui, M., Chu, H., Chung, M., & Chih, L. (2025). Integrating rainfall distribution patterns and slope stability analysis in determining rainfall thresholds for landslide occurrences: a case study. *Water*, 17(8), 1240. <https://doi.org/10.3390/w17081240>

- Gupta, L., & Dixit, J. (2024). Investigating the spatial distribution of flood inundation and landforms using topographic position index (TPI) and geomorphon-based automated landform classification methods. *Journal of Earth System Science*, 133(3). <https://doi.org/10.1007/s12040-024-02343-x>
- Hakizimana, B., & Chukwu, K. C. (2023). Dowards an intelligent and adapted small scale landslides monitoring system in East Africa: Shyira Landslide Monitoring using Sentinel - 1 SAR data on Google Earth Engine Cloud computing. *International Journal of Science Engineering and Technology*, 11(6), 1–11. <https://doi.org/10.61463/ijset.vol.11.issue6.105>
- Hart, L., & Marcus, H. C. (2024). Enhancing Terrain Analysis from Digital Elevation Models Using 2-D Kalman Filtering Technique. *Journal of Geography Environment and Earth Science International*, 28(7), 40–51. <https://doi.org/10.9734/jgeesi/2024/v28i7788>
- Hendharsetiawan, A. A., & Khaerudin, M. (2024). OpenStreetMap application for mobile devices that tracks customer service coordinates. *Moneter Jurnal Keuangan Dan Perbankan*, 12(1), 85–90. <https://doi.org/10.32832/moneter.v12i1.718>
- Herrera-Murillo, D. J., Ochoa-Ortiz, H., Ahmed, U., López-Pellicer, F. J., Re, B., Polini, A., & Nogueras-Iso, J. (2024). Process Analysis in Humanitarian Voluntary Geographic Information: the case of the HOT Tasking Manager. *AGILE GIScience Series*, 5, 1–12. <https://doi.org/10.5194/agile-giss-5-5-2024>
- Ibrahim, A., Kuuire, V., & Kepe, T. (2024). On mapping urban community resilience: Land use vulnerability, coping and adaptive strategies in Ghana. *Journal of Environmental Management*, 370, 122426. <https://doi.org/10.1016/j.jenvman.2024.122426>
- Kalliontzi, E., Kouskoura, A., Katsaros, E., & Bakouros, I. (2024). Perspective Chapter: Advancements in Disaster Risk Mitigation Strategies. In *IntechOpen eBooks*. <https://doi.org/10.5772/intechopen.1005847>
- Kienberger, S. (2014). Participatory mapping of flood hazard risk in Munamicua, District of Búzi, Mozambique. *Journal of Maps*, 10(2), 269–275. <https://doi.org/10.1080/17445647.2014.891265>
- Lan, H., Wang, D., He, S., Fang, Y., Chen, W., Zhao, P., & Qi, Y. (2020). Experimental study on the effects of tree planting on slope stability. *Landslides*, 17(4), 1021–1035. <https://doi.org/10.1007/s10346-020-01348-z>

- Masruroh, H., Sumarmi, N., Bachri, S., Putra, A. K., & Yudha, P. A. (2023). Landslide inventory and disaster management based on community participation for sustainability environment in the volcanic area. *IOP Conference Series Earth and Environmental Science*, 1276(1), 012032. <https://doi.org/10.1088/1755-1315/1276/1/012032>
- Mitheu, F., Stephens, E., Tarnavsky, E., Ficchi, A., Cornforth, R., & Petty, C. (2022). Towards a community-led approach to improve the design of early warning systems and anticipatory action for flood risk preparedness. *X*. <https://doi.org/10.5194/egusphere-egu22-9300>
- Mitra, S., & Shaw, R. (2024). Disaster Risk Reduction (DRR) and Rural Development: An Introduction. In *Disaster risk reduction* (pp. 1–9). https://doi.org/10.1007/978-981-97-6671-0_1
- Mobasheri, A., Pirotti, F., & Agugiaro, G. (2020). Open-source geospatial tools and technologies for urban and environmental studies. *Open Geospatial Data Software and Standards*, 5(1). <https://doi.org/10.1186/s40965-020-00078-2>
- Nema, M., Bachir, S. M., Diedhiou, A., & Mugabe, A. (2023). Comment on nhess-2023-47. *X*. <https://doi.org/10.5194/nhess-2023-47-cc2>
- Niyogakiza, A., & Liu, Q. (2025). GIS-Driven Multi-Criteria assessment of rural settlement patterns and attributes in Rwanda's Western Highlands (Central Africa). *Sustainability*, 17(14), 6406. <https://doi.org/10.3390/su17146406>
- Nkurunziza, A., Mutaganzwa, D. I., Ndayitwayeko, W. M., Nkengurutse, J., Kaplin, B. A., Toneu, I. T., Zafra-Calvo, N., & Cuni-Sanchez, A. (2023). Local observations of climate change and adaptation responses: a case study in the mountain region of Burundi-Rwanda. *Land*, 12(2), 329. <https://doi.org/10.3390/land12020329>
- Oyetunde, A., & Neziri, G. (2025). The role of Open-Source Data in Disaster Preparedness and Response. A case study on flood impact in local communities. *the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences/International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-4/W13-2025, 185–191. <https://doi.org/10.5194/isprs-archives-xxviii-4-w13-2025-185-2025>
- Öztürk, Ş. (2025). Comparative landslide susceptibility mapping using local inventories: a case study from Trabzon, Türkiye. *Natural Hazards*. <https://doi.org/10.1007/s11069-025-07371-4>

- Ozturk, U. (2023). Comment on nhess-2023-47. X. <https://doi.org/10.5194/nhess-2023-47-rc3>
- Popat, M., Rathod, K., Artur, L., De Perez, E. C., Sharma, A., Beca, N., & Van Sant, C. (2024). Anticipatory actions: lessons from the storm Ana in Mocuba district, Mozambique. *Journal of International Humanitarian Action*, 9(1). <https://doi.org/10.1186/s41018-024-00162-9>
- Priyono, P., & Maulida, E. I. (2021). Mitigation of Area Prone to Landslide in Anticipating the Impact of Climate Change. X, 1, 17–26. <https://doi.org/10.53797/aseana.v1i1.3.2021>
- Ramesh, G. (2021). Slope and Landslide Stabilization: A review. *Indian Journal of Structure Engineering*, 1(2), 13–16. <https://doi.org/10.54105/ijse.a1304.111221>
- Rayhan, M., Rahman, M. H., Dewyan, R., Shampa, S., Murshed, S. B., & Haque, S. (2024). Community-led AA for flash floods: Lessons learned from the last-mile community during 2022 Extreme Event in North-Eastern Bangladesh X. <https://doi.org/10.5194/egusphere-egu24-15463>
- Roy, P. K. (2025). Forest policy and sustainable development of Indigenous community. In IGI Global eBooks (pp. 391–416). <https://doi.org/10.4018/979-8-3373-0619-3.ch015>
- Salini, P. N., Rahul, P., Salini, U., & Mathew, S. (2023). Estimation of risk exposure index for road network in Landslide-Prone Areas. In *Lecture notes in civil engineering* (pp. 291–304). https://doi.org/10.1007/978-981-99-2556-8_22
- Ecosystem services delivered by forests (2023). <https://doi.org/10.19103/9781801466301>
- Shen, Z., Wang, D., Arabameri, A., Santosh, M., Egbueri, J. C., & Arora, A. (2024). Landslide susceptibility assessment and mapping using new ensemble model. *Advances in Space Research*, 74(7), 2859–2882. <https://doi.org/10.1016/j.asr.2024.06.018>
- Sidek, L. M., Ahmad, S. A., Yunus, A. M., Saman, D. H., Basri, H., Yusof, N. M., Torres, A. M., Rohaizi, M. S., & Azizi, A. S. M. (2023). Resilient Dams for Malaysia: a Risk-Informed Decision-Making-Based approach. In *Water resources development and management* (pp. 767–777). https://doi.org/10.1007/978-981-99-3708-0_53
- Sujatha & Sudharsan. (2024). A review on landslide susceptibility mapping methods: Needs and challenges. *Journal of Transportation Science and Technology*, 13(6). [https://doi.org/10.55228/jtst.13\(6\).1-16](https://doi.org/10.55228/jtst.13(6).1-16)
- Sulaiman, N., Abdullah, N. M., Nazir, U., Ismail, M., Latib, S. K. K. A., & Mahmud, N. P. N. (2022). Geographical Information System (GIS) and Remote sensing (RS) applications in

- Disaster Risk Reduction (DRR) in Malaysia. *International Journal of Integrated Engineering*, 14(5). <https://doi.org/10.30880/ijie.2022.14.05.003>
- Ullah, A., Ramzan, M., & Iqbal, J. (2025). Landslide susceptibility mapping for hazard management along Pakistan's Balakot-Naran Route. *Journal of Degraded and Mining Lands Management*, 12(3), 7401–7416. <https://doi.org/10.15243/jdmlm.2025.123.7401>
- Umurungi, Y., Kanyamibwa, S., Gashakamba, F., & Kaplin, B. (2018). African Biodiversity Challenge: Integrating freshwater biodiversity Information to guide Informed Decision-Making in Rwanda. *Biodiversity Information Science and Standards*, 2, e26367. <https://doi.org/10.3897/biss.2.26367>
- Uwamahoro, S., Liu, T., Nzabarinda, V., Muhigire, J., Umugwaneza, A., Maniraho, A. P., & Ingabire, D. (2024). Assessing hydrological interactions, soil erosion intensities, and vegetation dynamics in Nyabarongo River tributaries: a SWAT and RUSLE modeling approach. *Modeling Earth Systems and Environment*, 10(3), 4317–4335. <https://doi.org/10.1007/s40808-024-02013-3>
- Vespucci. (2025). Retrieved January 19, 2025, from <https://vespucci.io/#support-vespuccis-development>
- Wang, X., Fan, X., Xu, Q., & Du, P. (2022). Change detection-based co-seismic landslide mapping through extended morphological profiles and ensemble strategy. *ISPRS Journal of Photogrammetry and Remote Sensing*, 187, 225–239. <https://doi.org/10.1016/j.isprsjprs.2022.03.011>
- Zhang, J., Cheng, Y., Ge, W., Li, S., He, Q., & Zhang, T. (2025). Quantifying the mixed uncertainty for calculating slope from a gridded digital elevation model. *Geocarto International*, 40(1). <https://doi.org/10.1080/10106049.2025.2480307>
- Zighmi, K., Zahri, F., Faqeih, K., Amri, A. A., Riheb, H., Alamri, S. M., & Alamery, E. (2025). AHP multi criteria analysis for landslide susceptibility mapping in the Tellian Atlas chain. *Scientific Reports*, 15(1). <https://doi.org/10.1038/s41598-025-10819-z>
- Zitti, T., Coulibaly, A., Gali-Gali, I. a. Z., Ridde, V., & Turcotte-Tremblay, A. (2023). A comparative study of community verification processes in the context of performance-based financing in Mali and Burkina Faso. *International Journal of Public Sector Management*, 36(6/7), 492–511. <https://doi.org/10.1108/ijpsm-02-2023-0063>

Ziwanai, F. (2024). Re-Imagining Community-Based disaster risk reduction towards building resilient rural communities. In Advances in human services and public health (AHSPH) book series (pp. 84–96). <https://doi.org/10.4018/979-8-3693-2721-0.ch004>

Zverev, I. (2025). Every door. Retrieved January 19, 2025, from <https://every-door.app/>

APPENDICES

Appendix 1: LIST OF LANDSLIDES HOTSPOTS in NGORORERO

S/No	Hotspot Name	Sector	Cell	Village	Started	Latitude	Longitude	Disaster s Status	Slope (Deg)	Elevation (m)
1	Kimisagara Hotspot	KABAYA	Kabaya	Kimisagara	Long time	-1.7438529	29.54256	Landslide	85.96435	2125.581
2	Cyimba Landslide	HINDIRO	Marantima	Karambo	Long time	-1.8104522	29.60646	Landslide	73.48676	1796.027
3	Sarabuye Landslide Hotspot	KAVUMU	Rugeshi	Kabeza	Long time	-1.885881	29.52148	Landslide	86.30518	2408.994
4	Nyamakwa Landslide and Flash Floods	KAVUMU	Nyamugeyo	Nyabubanda	2020s	-1.8553861	29.54192	Landslide	86.93301	2206.831
5	Mu Rutoyi Landslide and Flash Floods	KAGEYO	Kageshi	Ruganda	About 5 years	-1.8651957	29.57187	Landslide	85.2321	2279.672
6	Kuwurugo Hotspot	KAGEYO	Kageshi	Ruganda	Long time ago	-1.8735544	29.57067	Landslide	86.5749	2187.429
7	Kirwa Massive Landslide	KAGEYO	Kirwa	Kabagari	1983	-1.9273327	29.60515	Landslide	87.62458	1917.362
8	Gihonga Landslide and Flash Floods Hotspot	SOVU	Musenyi	Gihonga	Long time	-1.9071604	29.56058	Landslide	83.40792	2159.614
9	Gashaki Scattered Landslides	KAVUMU	Birembo	Gashaki	Long time	-1.8517507	29.54591	Landslide	84.39821	2166.559
10	Ku Rutindo	Muhororo		Gashyushya	8 months	-1.8885626	29.59791	Landslides	76.76486	1752.72
11	Nganzo	Muhororo	Nganzo	Nganzo	8 months	-1.9124294	29.63279	Landslides	85.35363	1673.774
12	Mu Gitega 2	Hindiro	Rugendabari	Mituga	3 years	-1.8046225	29.60542	Landslides	84.6554	1842.876
13	Mu Gitaba	Kabaya	Kabaya	Bitare	3 months	-1.7546906	29.54367	Landslides	86.93011	2282.067
14	Ku Rugarika	Muhanda		Bugobora	1 year	-1.8224693	29.53093	Landslides	82.84473	1923.349

15	Mu Gaseke	Muhanda		Bugobora	1 year	1.8248958	29.53575	Landslides	82.37065	1883.88
16	Ku Ibati	Muhanda		Kabayengo	1 year	1.8861513	29.48733	Landslides	83.50887	2593.576
17	Isamihini	Kavumu	Rugeshi	Kabeza	5 years	1.8909799	29.51334	Landslides	86.97021	2457.778
18	Nyirantarengwa	Kavumu	Nyamugeyo	Murimba	1 year	-1.866748	29.54459	Landslides	87.14915	2287.206
19	Mu Gacaca	Kageyo		Kagarama	1 year	1.8684017	29.60162	Landslides	87.20358	2107.65
18	Mu Rwayaga	Kageyo	Kirwa	Kabagari	1 year	1.8555267	29.62337	Landslides	85.99026	1628.749
19	Gatega	Hindiro	Runyinya	Rugarambiro	4 years	1.7822048	29.60057	Landslides	86.36416	2020.452
20	Gihe	Ngororero	Nyange	gihe		1.8585176	29.63291	Landslides	81.19912	1760.186



Figure 10: Naororero field mapping



Figure 11: Landslide in Naqororero

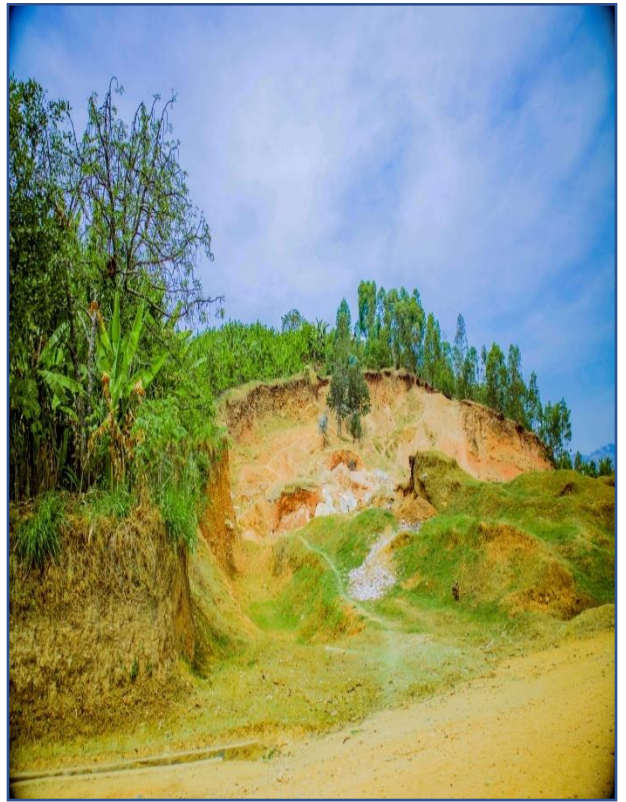


Figure 12: Masswasting in Naqororero



Figure 14: Community inspecting biodiversity loss



Figure 13: Community planting trees for slope stabilisation