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Wetland Vulnerability Analysis in the Upper Nyabarongo River

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Abstract—*Wetlands provide crucial ecosystem services such as water purification, flood control, and biodiversity support, yet they face growing vulnerability due to human activities and climate change. This study focuses on the wetland ecosystems in the Upper Nyabarongo River in Rwanda, which are increasingly at risk from disasters such as floods, landslides, and erosion. Using Geographic Information Systems (GIS) and remote sensing techniques, the research investigates the factors contributing to wetland degradation and evaluates the key ecosystem services these wetlands provide. Various environmental indices—such as the Standardized Precipitation Index (SPI), Normalized Difference Built-up Index (NDBI), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Water Index (NDWI)—are employed to assess the environmental pressures on these ecosystems. The results categorize wetland vulnerability into five levels: very high, high, medium, low, and very low, with urban and suburban areas experiencing the highest vulnerability. The findings highlight significant threats from human-induced pressures and climate impacts, underscoring the urgent need for effective conservation strategies. Ultimately, this study aims to enhance regional biodiversity, reduce disaster risks, and promote the sustainability and resilience of wetland ecosystems in the face of environmental change*.

Keywords— *Wetland Vulnerability, GIS and Remote sensing, Environmental Degradation*.

I. INTRODUCTION

The frequency, intensity, and impact of natural hazard events are escalating, leading to an increase in disasters that negatively affect humans, economies, and the environment. Numerous regions worldwide are susceptible to one or more natural hazards. Disasters occur when risk factors such as hazards, vulnerability, and insufficient coping capacities converge in space and time (Nohrstedt, Mazzoleni et al. 2021). Among major ecosystems, wetlands stand out for providing important ecosystem services, including water purification, flood prevention and biodiversity support. However, these ecosystems are increasingly vulnerable to anthropogenic pressures and climate change, which contribute to wetland degradation (Mitsch, Bernal et al. 2015).

Over the last decade, the frequency and severity of natural disasters, particularly those caused by floods and droughts, have significantly increased, resulting in rising human casualties, as well as economic and environmental losses (Kabalisa and Kagambira 2021). Floods are one of the most catastrophic natural disasters, affecting a large portion of the global population. Heavy rainfall over an extended period triggers rivers and streams to overflow, leading to widespread flooding. Although floods are primarily natural events, they can be exacerbated by human activities such as poor land use, improper waste disposal, and deforestation (Devitt, Neal et al. 2023). Floods are among the most common natural disasters, occurring annually in many parts of the world. The consequences of floods include the spread of epidemic diseases, soil erosion, the destruction of wildlife habitats and forests, and significant damage to infrastructure such as buildings, bridges, roads, sewer pipes, power lines, and agricultural land. Flood-affected areas often experience acute shortages of food and drinking water (Jonkman, Curran et al. 2024).

Floods are the most prevalent natural hazards globally, impacting 80% of the world’s population. It is estimated that more than one-third of the world’s land area is flood-prone (Dilley 2005). In the 20th century, floods alone killed 100,000 or more than 1.4 billion people worldwide (Jonkman 2005). There are various types of floods, but the most common are riverine floods and flash floods. According to (Jonkman 2005), riverine floods occur when rivers overflow their usual boundaries, often due to high precipitation levels, snowmelt, or blockages in the flow. Flash floods, on the other hand, result from intense local rainfall, which rapidly raises water levels and poses a significant threat to human life. The short warning time makes flash floods particularly dangerous, and they typically occur in mountainous and urban areas.

In Rwanda, there are 165,000 hectares of wetlands, 7% of the country's total land area, of which 92,000 hectares are used for agriculture. These wetlands play a crucial role in water treatment, purification, and serve as sources of water for lakes and connecting rivers (Mind’je, Mindje et al. 2021). However, they are under threat from human activities such as agricultural production, urbanization, mineral extraction, and infrastructure development. Rwanda is particularly vulnerable to localized floods and landslides due to its dense river network and extensive wetlands, especially in the Nyabarongo catchment area. The country faces significant risks from riverine floods, which cause infrastructure damage, fatalities, injuries, landslides, agricultural losses, soil erosion, and environmental degradation.

The wetlands in Rwanda, especially in the Nyabarongo River, are vital for maintaining regional biodiversity, water quality, and climate regulation. However, rapid urbanization, agricultural expansion, and climate change have placed considerable pressure on these ecosystems (Umugwaneza, Chen et al. 2021). This study focuses on assessing wetland vulnerability in the upper stream Nyabarongo Catchment wetland using GIS and remote sensing data. By integrating

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various indices, such as The Standardized Precipitation Index (SPI), The Normalized Difference Built-up Index (NDBI), The Normalized Difference Vegetation Index

(NDVI), The Normalized Difference Water Index (NDWI), and Land use and Land cover (LULC) change, Population density, Actual land degradation index and Ecosystem services, a comprehensive understanding of the factors contributing to wetland degradation can be obtained. Understanding the vulnerability of wetlands to these threats is crucial for developing effective conservation and management strategies.

II. METHODOLOGY, DATA COLLECTION AND DATA ANALYSIS

II.1. Study area description

The Upper Nyabarongo river is located entirely within Rwanda, spans an area of catchment 3,348 km² of across eight districts: Ngororero, Rutsiro, Muhanga, Karongi,

Nyamagabe, Ruhango, Nyanza, and Huye. This catchment originates on the eastern slopes of the Nyungwe high-altitude rainforest, a fully protected area with minimal human habitation. The western part of the Daraz Basin follows the drainage between the Nile and the Congo Basin. The southern tip of the catchment initially flows eastward, then curves northward, with the overall drainage pattern running from south to north, characterized by a dense dendritic network (Umuhoza, Niu et al. 2024).

The Upper Nyabarongo river, an upstream system, is clearly demarcated with no upstream inflows and an outflow at the confluence of the Nyabarongo River with the Mukungwa River. Notably, depending on the definition used (longest distance), this catchment might contain the source of the Nile River.

A further subdivision of the 3,348 km² Level 1 catchment has been proposed into three Level 2 sub-catchments wetland:

1. Mbirurume Sub-Catchment: Covering 511 km² in Rwanda, this area is drained by the Mbirurume River, which flows through an upland catchment with steep slopes, partly covered by the Nyungwe forest.
2. Rukarara-Mwogo Sub-Catchment wetland: Spanning 1,284 km² in Rwanda, this subcatchment includes the Mwogo River and its tributary, the Rukarara River. It shares similar characteristics with the Mbirurume sub-catchment.
3. Nyabarongo Sub-Catchment wetland: This sub-catchment, covering 1,553 km² in Rwanda, is drained by the upper Nyabarongo River, which forms at the confluence of the Mbirurume and Mwogo rivers. It is similar in nature to the other sub-catchments, featuring a mountain stream that gradually increases in flow as it traverses the hills.

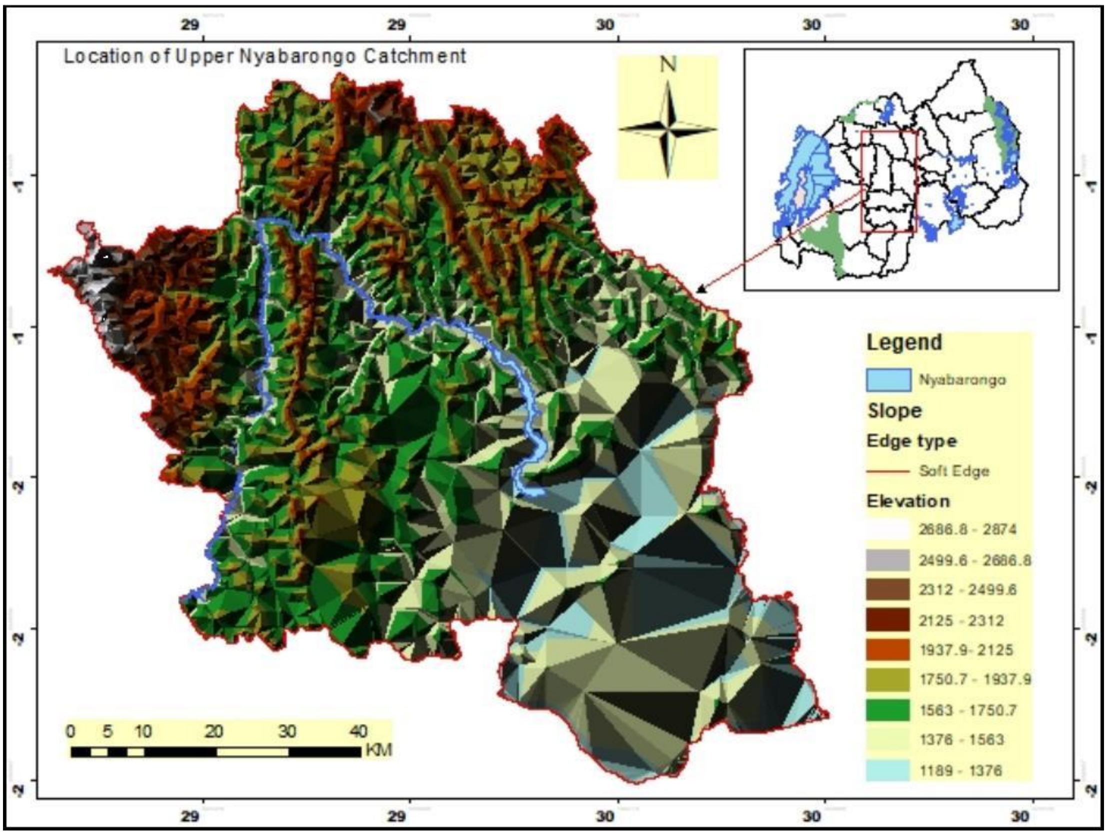

Figure 1. Location of Upper Nyabarongo Wetland

II.2. Data Acquisition and Data Pre-Processing

GIS and Remote sensing are significant for analysis the wetland vulnerability analysis. The data used in this study were acquired from the different website such as Climate

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Engine, ICPAC Geoportal and USGS Earth explorer. GIS 10.8 and GIS Pro were used to analyze and to calculate the different indexes. GIS 10. 8 was used for preparation data of indexes such as NDVI, NDWI, SPI, Population density, LULC, Ecosystem Services and actual land degradation index.

II.2.1. Drought Assessment Using SPI

The Standardized Precipitation Index (SPI) is used to quantify drought conditions over the catchment area. By analyzing precipitation data over a specific period, the SPI provides insight into the frequency and severity of drought events, which directly impact wetland hydrology and health (Livada and Assimakopoulos 2007).

The Standardized Precipitation Index (SPI) was downloaded from Climate engine; https://www.climateengine.org/ .

II.2.2. Urbanization and Settlement Analysis Using NDBI

The Normalized Difference Built-up Index (NDBI) is applied to assess the extent of urbanization and settlement in the catchment area. Increased urbanization leads to habitat loss, pollution, and changes in hydrological patterns, all of which contribute to wetland degradation (Alademomi, Okolie et al. 2022).

Landsat 8 image gained from USGS Earth explorer; https://earthexplorer.usgs.gov/ , were used for calculating NDBI for analysis the vulnerability of wetland.

Formula:

$$NDBI = \frac{Band\ 6 - Band\ 5}{Band\ 6 + Band\ 5}$$

II .2.3. Vegetation Health Using NDVI

The Normalized Difference Vegetation Index (NDVI) is employed to monitor vegetation health within the wetlands. NDVI is a critical indicator of plant vigor and biomass, providing insight into the impacts of land use change and environmental stressors on wetland ecosystems (Alademomi, Okolie et al. 2022). However, to analyze the wetland vulnerability of Upper

Nyabarongo also can use NDVI got from Climate engine; https://www.climateengine.org/ .

Formula;

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

II .2.4. Water Quality Analysis Using NDWI

The Normalized Difference Water Index (NDWI) is used to assess water quality in the catchment area. Changes in NDWI values can indicate alterations in water bodies due to sedimentation, pollution, or other anthropogenic activities affecting wetland health (Alademomi, Okolie et al. 2022). However, NDWI were require for monitoring water quality index was gotten from Climate Engine: https://www.climateengine.org/ .

Formula

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

II .2.5. Land Use and Land Cover (LULC) Analysis

LULC changes are analyzed using satellite imagery to identify trends in land conversion and their impact on wetland ecosystems. The analysis highlights areas of agricultural expansion, deforestation, and urban growth, providing a basis for understanding the drivers of wetland vulnerability. Land use and land cover change was import for monitoring change over time. Data used in this study captured from Esri: https://livingatlas.arcgis.com/landcover/ .

II .2.6. Ecosystem Services and Land Degradation

The study also evaluates ecosystem services provided by the wetlands, such as water purification, carbon sequestration, and biodiversity support. Additionally, land degradation is assessed to understand the cumulative impacts of human activities on wetland sustainability. To access the land degradation data site, click on the link http://geoportal.icpac.net/layers/ .

Table of Price of ecosystem services per US dollars per

Land use and Land cover	Price for Ecosystem Services
Built Up	0
Cloud	0
Trees	14.8
crops	7.4
Bare land	0
Flooded vegetation	14.4
Water Bodies	3.4

Source: (Groot et al., 2012).

TABLE 1. Sources and categorization of WVA datasets and indicator variables

Domain	Indicator variables for wetland vulnerability	Proxy earth observation data	Earth Observation data sources/provider	Years acquired
Drivers (Threats)	Population Growth	Population pressure	Worldpop Gridded data 1km resolution https://www.worldpop.org/doi/10.5258/SOTON/WP00004	Shape file2023
	Climate change	Drought--NDVI/SPI	https://www.climateengine.org/	Shape file 2023
	Urbanization and settlements	Normalized difference Built-up index-NDBI	Sentinel data https://earthexplorer.usgs.gov/	LandSat 8 image 2023
Pressures (Threats)	-Land development	Land Use change Landuse/landcover	http://geoportal.icpac.net/layers/	Shape file 2015
State (Resilience factors)	Wetland water quantity	NDWI	https://www.climateengine.org/	Shape file 2023
	Wetland habitat cover	Normalized Difference Vegetation Index (NDVI)	Climate engine; https://www.climatee	Price of Ecosystem services 2023
	Ecosystem	Price for Ecosystem	(Groot et al., 2012)	Shape file 2023
	Actual Land degradation index	Land degradation index	http://geoportal.icpac.net/layers/	Shape file 2023

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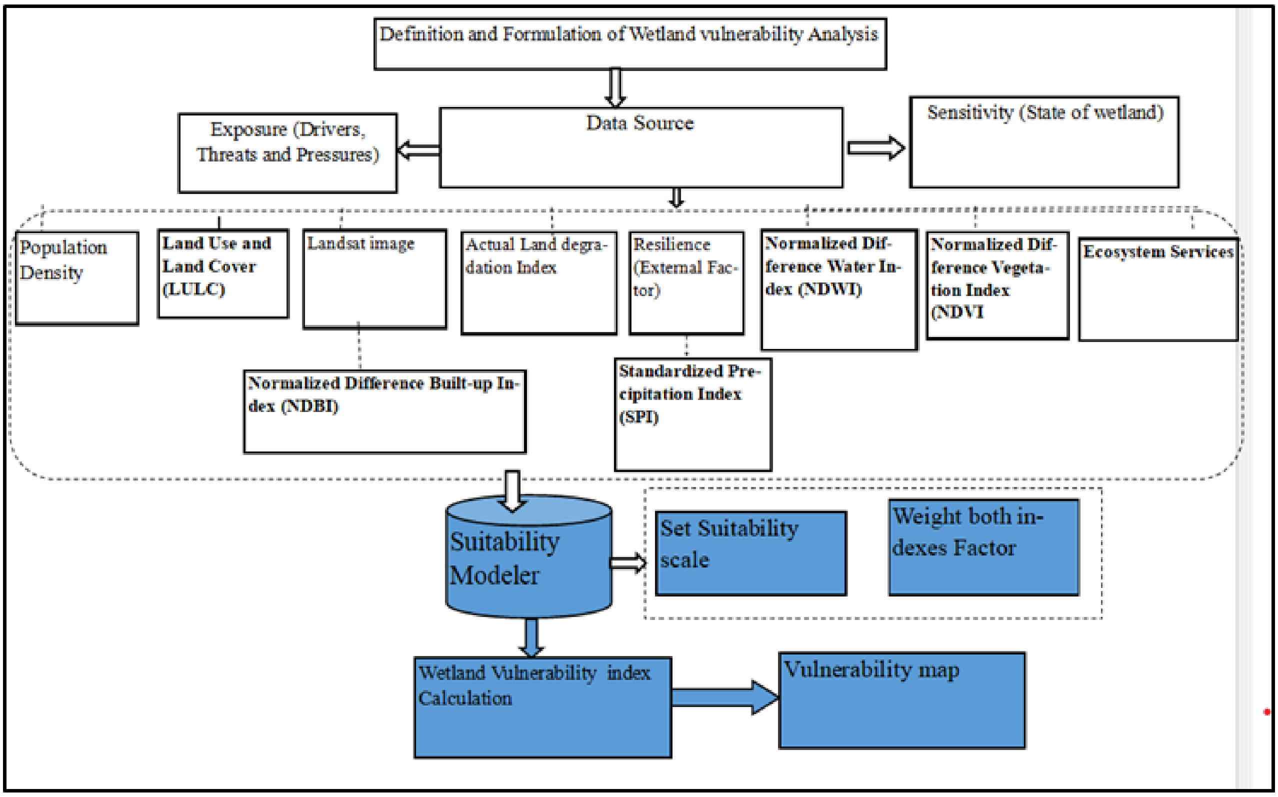

Figure 2. Flowchart of Wetland Vulnerability analysis of DPSIR Framework

III. RESULTS AND DISCUSSION

Analysis of wetland vulnerability combined eight parameters of different index; The Standardized Precipitation Index (SPI), The Normalized Difference Built-up Index (NDBI), The Normalized Difference Vegetation Index (NDVI), The Normalized Difference Water Index (NDWI), Land Use and Land Cover (LULC), Population density, Ecosystem Services and Land Degradation index. However, it's provide the wetland vulnerability index which helps us for getting area prone of wetland degradation. Rapid urbanization, expansion of agriculture, mining activities and development activities also contributes to wetland degradation.

III.1. The wetland vulnerability indexes

III.1.1. The standard Precipitation index (SPI)

The Standardized Precipitation Index (SPI) is a widely used tool for monitoring and analyzing drought conditions. Developed in the early 1990s, the SPI measures the deviation of precipitation from the long-term average for a specific location and time period.

The figure 3 indicate that there is no drought index found on Nyabarongo wetland in Rwanda

III.1.2. The Normalized Difference Built-up Index (NDBI)

The Normalized Difference Built-up Index (NDBI) is a remote sensing index used to identify and quantify built-up areas, such as urban regions, by analyzing satellite imagery. It is particularly useful for monitoring urbanization, land-use changes, and the growth of cities over time. The figure below illustrates that urbanization, and cities extension are carried out in Nyarugenge, Kamonyinyi and Muhanga district.

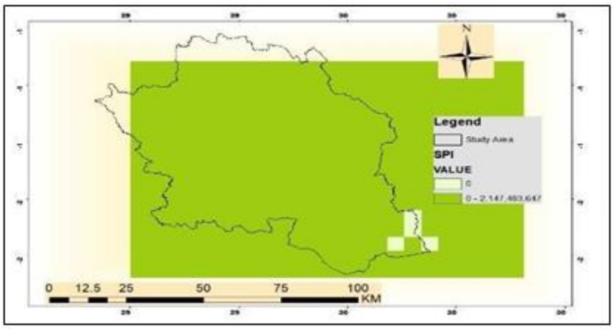

Figure 3. SPI Analysis

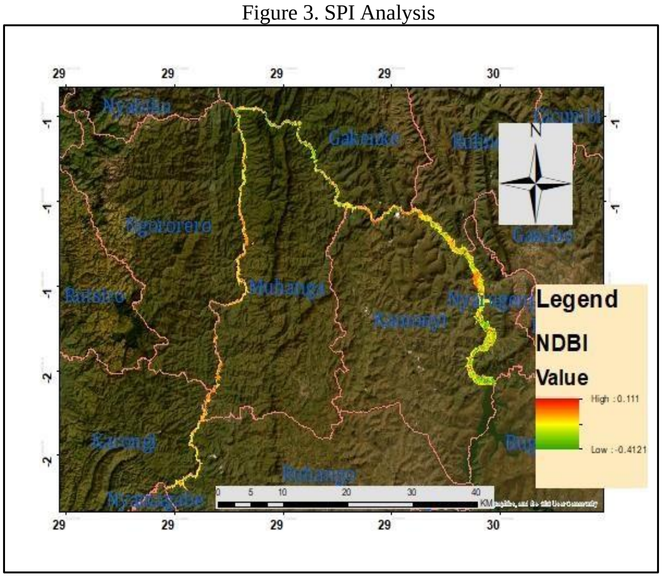

Figure 4. NDBI Analysis

III.1.3. The Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing index that measures the density and health of vegetation by analyzing the difference between the reflectance of near-infrared (NIR) and visible red light from vegetation.

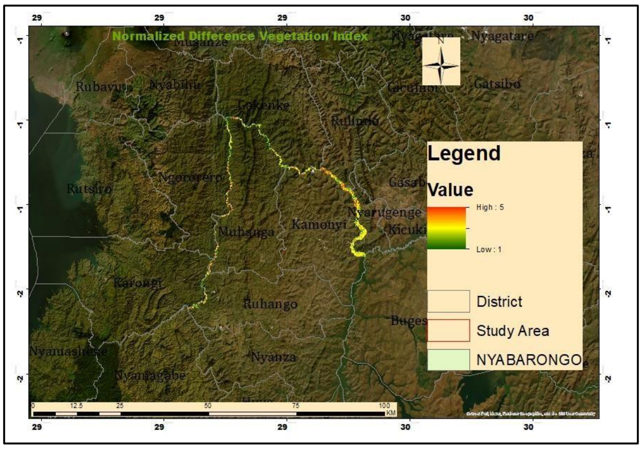

Figure 5. NDVI Analysis

The figure 5 illustrate that potential high degradation of vegetation is found in Part of Nyarugenge, Kamonyi and Muhanga District because of urban sprawl and high population are drives of deterioration of vegetation. The agriculture activities are main cause of degradation of vegetation in Gakenke, Ruhango, Ngororero, Bugesera and Nyamagabe District.

III.1.4. The Normalized Difference Water Index (NDWI)

The Normalized Difference Water Index (NDWI) is a remote sensing index used to identify and monitor water bodies, such as lakes, rivers, and wetlands, from satellite imagery. the blue color indicates an area that has water pollution. The region that have high pollution include Nyarugenge, Kamonyi and Muhanga District are more pollute than other district due industrial activities, Residential areas because the local people dumping home waste into river which triggered water pollution

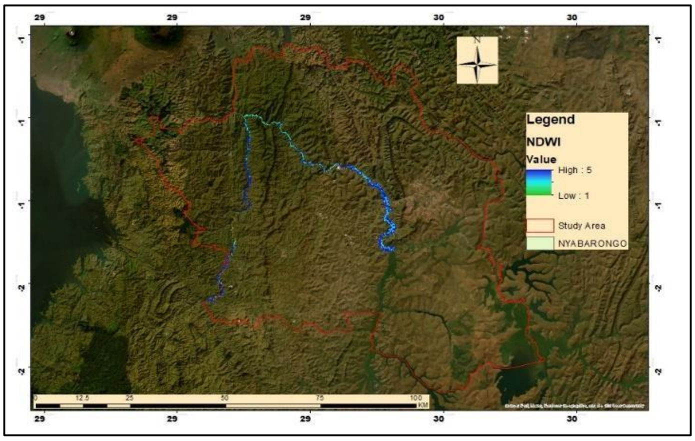

Figure 6. NDWI Analysis

III .1.5. Land Use and Land Cover (LULC) Analysis

Land Use and Land Cover (LULC) analysis is a critical component in wetland vulnerability assessments. It involves examining the types of land use (how land is utilized by humans) and land cover (the physical material on the surface, like vegetation, water, or buildings) in and around wetland areas to understand how these factors contribute to the vulnerability of wetlands. The map below shows area that affected with LULC change at Upper Nyaborongo wetland, the green color demonstrate the area of high affected with change land use.

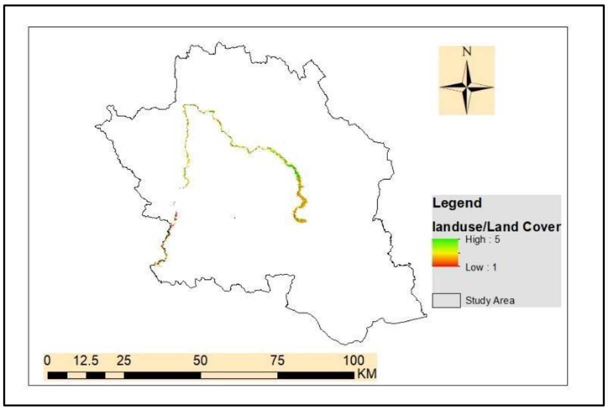

Figure 7. LULC Analysis

III.1.6. Ecosystem Services and Land Degradation

Ecosystem Services and Land Degradation are crucial concepts in the analysis of wetland vulnerability, as they provide insight into both the benefits that wetlands offer to human society and the potential impacts of land degradation on these ecosystems.

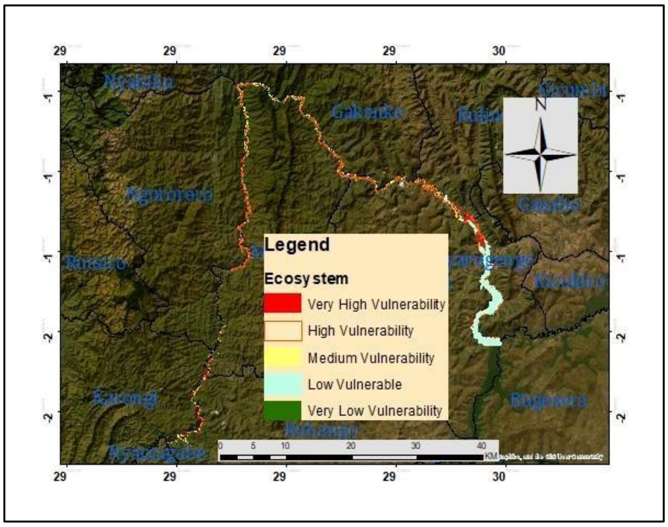

Figure 8. Ecosystem Analysis

The figure 8 indicate that the ecosystem is categorized into five classes; Very high, high, Medium, low and very low vulnerability. Largest Part of Nyabarongo wetland the ecosystem is degraded caused by anthropogenic activities.

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III .1.7. Actual Land degradation index

The actual land degradation index is one fact which driving the wetland degradation in Nyabarongo Wetland. Different types of erosion can remove the soil from top hill to down valley. Urban wetland are more vulnerable other the other parts of wetland. High surface runoff from paved area and building can drives degradation of wetland. Nyarugenge and Kamonyi district are more vulnerable in my study area.

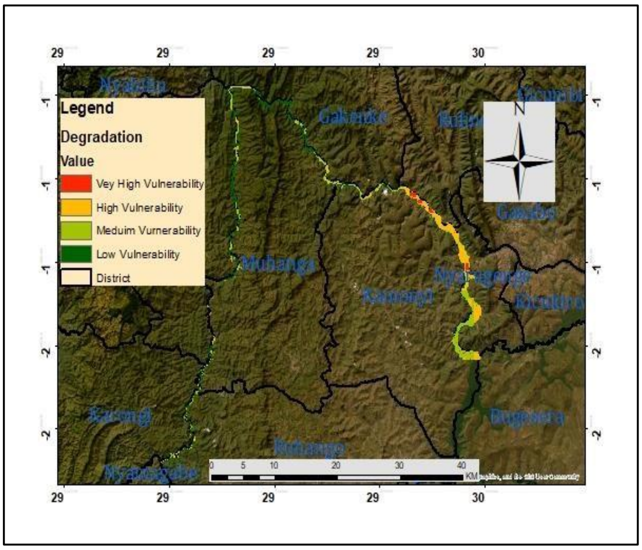
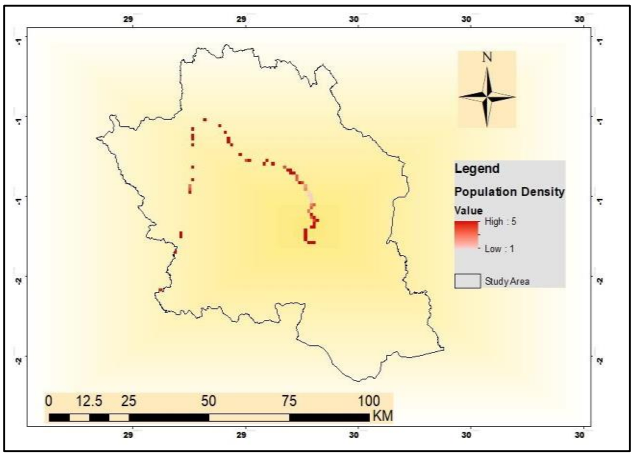


Figure 9. Actual land degradation index analysis

III .1.8 Population Density

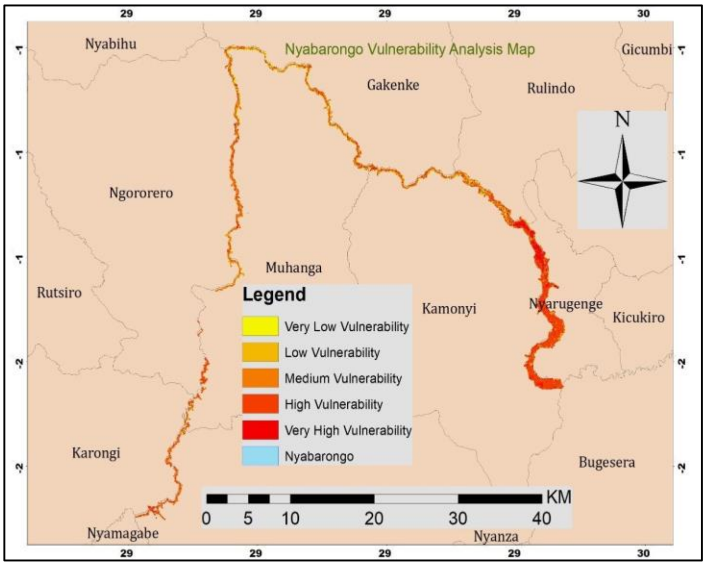
The population density is crucial impact of deterioration of Nyabarongo wetland upper stream.

The urban area has high population density of people that are settled near wetland.



III .2. Nyabarongo Wetland Vulnerability Analysis

This map shows the vulnerability analysis of the upstream Nyabarongo River Wetland in Rwanda. The analysis classifies vulnerability into five categories: Very Low Vulnerability, Low Vulnerability, Medium Vulnerability, High Vulnerability, and Very High Vulnerability. For example, the wetland in Nyarugenge District is highly prone to degradation due to factors like high population density, rapid urbanization, and pollution from residential areas and industries.



In contrast, the upstream Nyabarongo wetland which located in Nyamagabe and Karongi Districts is less vulnerable to degradation, as these areas are largely covered by forests and have less agricultural activity. Nyabarongo Wetland, which is highlighted in light blue, running through multiple regions.

TABLE 2. Classes of Vulnerability analysis, Area in Ha and its Percentage

Vulnerability Analysis	**Area in Ha**	**Percentage**
High Vulnerability	2285.47	34.78
Low Vulnerability	569.97	8.67
Medium Vulnerability	1397.54	21.27
Very High Vulnerability	1409.53	21.45
Very Low Vulnerability	908.19	13.82
Total	6570.70	100

Table 2 shows the classification of wetlands based on their vulnerability levels, with 34.78% categorized as High Vulnerability, 21.45% as Very High Vulnerability, 21.27% as Medium Vulnerability, 8.67% as Low Vulnerability, and 13.83% as Very Low Vulnerability to wetland degradation.

According to table 3, the result indicates that all wetland of upstream Nyabarabango river are cover with 6557.94 total ha. 76.83% of wetland degradation are located in Nyarugenge, Kamonyi and Muhanga District. The medium district affected is Ruhango and Ngorerero district which represent 12.50% of vulnerability index.

Table 3 provides a breakdown of wetland vulnerability by district:

- Nyarugenge District has the highest vulnerability, with 5.20% of wetlands in the Very High Vulnerability category, 11.22% in High Vulnerability, 1.44% in Medium Vulnerability, 0.29% in Very Low Vulnerability, and 2.67% in Low Vulnerability.
- Muhanga District follows, with 6.71% of wetlands classified as High Vulnerability, 3.66% as Very High

Vulnerability, 5.67%, 2.39%, and 6.37% as Medium, Low, and Very Low Vulnerability, respectively.

- Kamonyi District is third, with 11.58% of wetlands in the High Vulnerability category, 8.19% in Very High Vulnerability, 6.09% in Medium Vulnerability, 1.97% in Low Vulnerability, and 3.39% in Very Low Vulnerability.

TABLE 3

District	Vulnerability Analysis	Area in Ha	%
BUGESERA	High Vulnerability	8.52	0.13
BUGESERA	Low Vulnerability	2.55	0.04
BUGESERA	Very High Vulnerability	1.01	0.02
GAKENKE	High Vulnerability	47.49	0.72
GAKENKE	Low Vulnerability	24.88	0.38
GAKENKE	Medium Vulnerability	55.51	0.85
GAKENKE	Very High Vulnerability	46.52	0.71
GAKENKE	Very Low Vulnerability	88.26	1.35
KAMONYI	High Vulnerability	759.42	11.58
KAMONYI	Low Vulnerability	129.12	1.97
KAMONYI	Meduim Vulnerability	399.09	6.09
KAMONYI	Very High Vulnerability	536.93	8.19
KAMONYI	Very Low Vulnerability	222.22	3.39
KARONGI	High Vulnerability	30.17	0.46
KARONGI	Low Vulnerability	3.33	0.05
KARONGI	Meduim Vulnerability	45.67	0.70
KARONGI	Very High Vulnerability	22.47	0.34
KARONGI	Very Low Vulnerability	5.97	0.09
MUHANGA	High Vulnerability	439.83	6.71
MUHANGA	Low Vulnerability	156.85	2.39
MUHANGA	Meduim Vulnerability	371.84	5.67
MUHANGA	Very High Vulnerability	239.99	3.66
MUHANGA	Very Low Vulnerability	417.65	6.37
NGORORERO	High Vulnerability	121.45	1.85
NGORORERO	Low Vulnerability	63.00	0.96
NGORORERO	Meduim Vulnerability	179.32	2.73
NGORORERO	Very High Vulnerability	81.15	1.24
NGORORERO	Very Low Vulnerability	65.42	1.00
NYAMAGABE	High Vulnerability	0.04	0.00
NYAMAGABE	Meduim Vulnerability	0.13	0.00
NYAMAGABE	Very High Vulnerability	0.04	0.00
NYARUGENGE	High Vulnerability	735.82	11.22
NYARUGENGE	Low Vulnerability	175.25	2.67
NYARUGENGE	Meduim Vulnerability	94.26	1.44
NYARUGENGE	Very High Vulnerability	340.89	5.20
NYARUGENGE	Very Low Vulnerability	19.02	0.29
RUHANGO	High Vulnerability	100.19	1.53
RUHANGO	Low Vulnerability	8.57	0.13
RUHANGO	Meduim Vulnerability	170.92	2.61
RUHANGO	Very High Vulnerability	95.30	1.45
RUHANGO	Very Low Vulnerability	33.64	0.51
RULINDO	High Vulnerability	37.93	0.58
RULINDO	Low Vulnerability	5.30	0.08
RULINDO	Meduim Vulnerability	78.23	1.19
RULINDO	Very High Vulnerability	42.41	0.65
RULINDO	Very Low Vulnerability	54.35	0.83
	Total	6557.94	100

High population density, rapid urbanization, and wetland agriculture contribute to the high vulnerability in Kamonyi and Nyarugenge districts. Ruhango District is moderately affected by wetland degradation, while Ngororero District has medium vulnerability due to human activities like mining and agriculture are main triggers.

Finally, Bugesera, Gakenke, Rulindo, Karongi, and Nyamagabe districts have lower wetland vulnerability, with each having less than 1% in the Low Vulnerability category, primarily influenced by agricultural activities.

IV. Conclusion and Recommendations

By conclusion, the Nyabarongo river wetland vulnerability analysis is crucial important for assessing and monitoring wetland degradation for using GIS and Remote sensing data. The seven drives such as NDVI, NDBI, NDWI, Population density, Land use/Land cover change, Ecosystem services and actual land degradation index were use to indicate the level of wetland vulnerable index. The Wetland Vulnerability Index is divided into five categories. very vulnerable, high vulnerable, medium vulnerable, low vulnerable and very low vulnerable. The results prevailed that Nyarugenge, Kamonyi and Muhanga district are the mostly prone wetland the degradation with 76.83%. Followed by Ruhango and Ngororero Districts which represent 12.50% as medium vulnerability index. Other district like Bugesera, Rulindo, Gakenke and Karongi district are at least vulnerability represent only 10.67% of wetland vulnerability.

Recommendations

Strengthen Wetland Protection Policies: There is a need for stronger enforcement of wetland protection regulations to curb encroachment and degradation.

Promote Sustainable Land Use Practices: Encouraging sustainable agricultural practices and responsible urban planning can reduce the pressures on the wetland.

Implement Restoration Projects: Restoration of degraded wetland areas should be prioritized to enhance ecosystem services and biodiversity.

Enhance Monitoring and Research: Continuous monitoring using GIS and remote sensing should be implemented to track changes and guide management actions

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