Urban wetland vulnerability analysis in the City of Kigali - A case of Upper Nyabugogo Wetland

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DOI: 10.29322/IJSRP.13.06.2023.p13839
http://dx.doi.org/10.29322/IJSRP.13.06.2023.p13839

Paper Received Date: 12th May 2023
Paper Acceptance Date: 14th June 2023
Paper Publication Date: 21st June 2023

Abstract- The vulnerability of urban wetlands is examined in this study. Data were collected using Driver-Pressure-State-Impact-Response Framework (DPSIR). Indicators were categorized into IPCC components of vulnerabilities namely exposure, sensitivity, and resilience. Analytic Hierarchy Process (AHP) was used to weight indicators, but particular attention was given to expert's judgment. To produce maps of IPPC vulnerability components and the final map of wetland vulnerability, Weighted Linear Combination (WLC) was utilized. The results showed that the majority of the wetland area, more than half (54%) is exposed to medium, high, and very high levels of vulnerability. Additionally, more 58% of the Nyabugogo urban wetland area has medium to high sensitivity to climate change and human activities, with 13% of the area classified as having a very high sensitivity to wetland vulnerability. Only a small proportion (less than 5%) have a high or very high resilience to disturbances or negative impacts. The final wetland vulnerability map generated showed that 138 ha (43%) of the area is in medium to very high vulnerability, with highly or very highly vulnerable areas occupied by anthropogenic activities such as human settlements, Nyabugogo car parking, and central businesses that are prone to flooding. The very high class of wetland vulnerability (WVI) includes 220 houses, and 628 houses are in the high class of WVI. The validation of wetland vulnerability map classes was performed using Google Earth imagery, Esri satellite imagery of 2023, and field verification to ensure the map's classification was accurate and reliable. The result of this study is crucial in restoration of this wetland for flood control in the City of Kigali as it will enable urban planners and policymakers to strategically design and implement green infrastructure solutions to enhance the wetland's ability to absorb and retain water during flood events.

Key Words- City of Kigali, Flood control, Urban wetlands, Weighted Linear Combination, Wetland vulnerability.

I. Introduction

Urban wetlands can play a critical role in flood mitigation by reducing the impact of heavy rainfall and storms [1]. Urban wetlands can play a crucial role in the creation of sponge cities by acting as natural "sponges" that can absorb and store large amounts of water during times of heavy rainfall [2]. This can help reduce the risk of flooding downstream and can help protect infrastructure and communities. In addition to storing water, wetlands can also slow down the movement of water, allowing it to be absorbed into the ground more slowly [3]. This can help reduce the intensity and speed of floodwaters, reducing their erosive power and allowing them to be more easily absorbed into the soil. Wetlands can also help reduce the risk of flash flooding by providing a natural buffer zone between urban areas and nearby rivers or streams [4]. When heavy rains occur, wetlands can absorb and store water, reducing the amount of water that flows downstream and reducing the risk of flooding. Reductions in wetland size and capacity to provide ecosystem services increase the vulnerability of adjacent areas by diminishing the capacity of wetlands to trap, hold, and decelerate flooding in the aftermath of a flood occurrence [5]. Green infrastructure methods, including permeable pavement, stormwater wetlands, and rain gardens, are integrated infrastructure systems that utilize natural ecosystems to mitigate flooding while simultaneously enhancing resilience to natural hazards for both society and the environment [6]. These types of green infrastructure solutions are becoming more prevalent in urban regions. Thus, in order to effectively use urban wetlands for flood mitigation, it is important to protect and manage these ecosystems in a sustainable way[7]. Furthermore, Wetland vulnerability assessment is a critical tool for ecosystem restoration efforts that could be used in wetland restoration using that use natural-based adaptation strategies[8]. It may help to identify vulnerable areas, select appropriate adaptation strategies, monitor progress, and engage stakeholders in the restoration process, ultimately leading to more effective and sustainable ecosystem restoration outcomes [9]. GIS (Geographic Information System) and remote sensing are crucial tools in wetland vulnerability assessment because they allow for the collection, processing, and analysis of spatial data related to wetland characteristics and the surrounding environment [10]. These technologies provide a comprehensive understanding of the changes and trends occurring in wetlands over time, which is essential for effective management and conservation [11].

Urban wetlands in Rwanda are facing significant threats from human activities such as urbanization, land-use changes, and pollution [12]. As the country continues to develop and urbanize, wetlands are often drained and filled to make way for housing and infrastructure, leading to the loss of important ecosystem services [13]. The vulnerability of urban wetlands in Rwanda is a growing concern, as their degradation can have significant impacts on both the environment and human well-being. In September 2021, a master plan for the urban wetlands of Kigali was released. The plan identified that 15.76 square kilometers, which accounts for 20% of the total area of Kigali (730 square kilometers), had been designated as wetlands and marshlands that required restoration due to the encroachment of human and industrial activities. Hence, the wetland vulnerability assessment activity is a crucial stage in supporting the government of Rwanda's restoration initiatives. It provides valuable information that is used to develop effective restoration plans and identify potential threats to the wetlands.

With the increase of flooding in Kigali as a result of climate change and low rate of city's sponginess[14], Nyabugogo wetland is very crucial for floods control in Kigali city. However, Nyabugogo wetland is one of the urban wetlands in Rwanda that is highly vulnerable to degradation and loss due to various human activities [15]. The wetland is threatened by urbanization, pollution, overfishing, and invasive species. Urbanization is putting pressure on the wetland's ability to provide ecosystem services, while pollution from industrial and household waste, as well as agricultural runoff, can harm the plants and animals that depend on it [16].

Overall, these threats highlight the urgent need for effective management and conservation strategies to protect Nyabugogo wetland and ensure its sustainability. Furthermore, in order to effectively use Nyabugogo urban wetland as part of sponge city initiatives, it is important to protect and manage its ecosystems in a sustainable way.

Therefore, there is a need for more comprehensive and integrated approaches to analyses wetland vulnerability in order to identify the most appropriate restoration techniques, such as the reintroduction of native species, hydrological restoration, or sediment management. Wetland vulnerability assessments can help prioritize wetlands for restoration based on their level of vulnerability and potential ecological benefits, allowing for the allocation of resources where they are most needed. The objective of this study is to employ geospatial technologies to evaluate the vulnerability of urban wetlands as nature-based solutions for wetland restoration to support the sponge city and flood mitigation services provided by these wetlands.

II. METHODOLOGY

2.1. Study area description

Nyabugogo wetland is located in the city of Kigali, the capital of Rwanda, in East Africa (Figure 1). The part of our study area Wetland covers an area of 322 hectares and is situated at coordinates 1°51'53.14"S and 30°05'26.41"E [17]. It is situated in the Nyabugogo catchment, which is part of the larger Nyabarongo River Basin. The wetland is bounded by the Nyabarongo River to the South , the Nyabugogo River to the North, the Kigali-Gicumbi road to the East, and the Kigali-Huye to the south [18].

The Nyabugogo catchment, like the rest of Rwanda, experiences a tropical climate with moderate temperatures. The average annual precipitation in the area falls within the range of 992 mm to 1128 mm, while the average annual evapotranspiration ranges from 503 mm to 1050 mm [19]. The elevation of the Nyabugogo wetland is generally low, as it is located in a river basin. The exact elevation varies across the wetland, but it is typically at or below the level of the surrounding land. The soil in the wetland is mainly composed of organic matter and is generally characterized as peat soil.

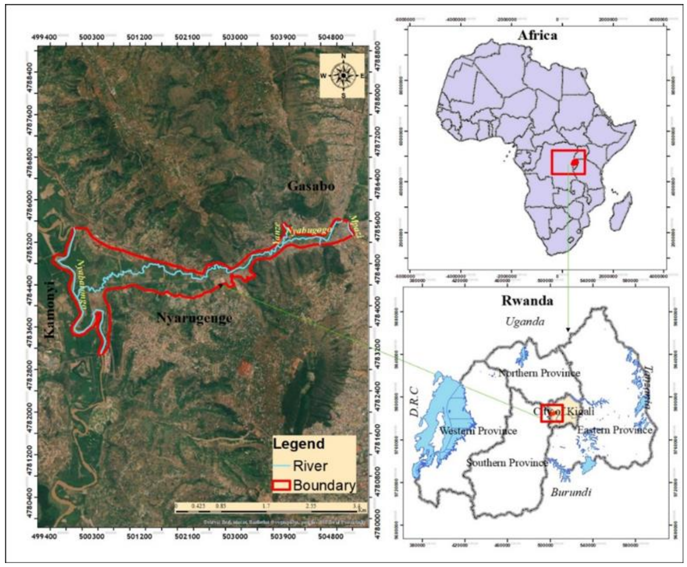

Figure 1: Location Map

The wetland is characterized by a mosaic of different vegetation types, including papyrus swamps, reed beds, open water, and seasonally flooded grasslands [15]. These different habitats support a rich diversity of flora and fauna, including several species of waterbirds, frogs, and fish. The wetland also provides important ecosystem services such as water filtration, flood control, and carbon sequestration [20]. In recent years, the population in the surrounding area has increased due to urbanization and development [21]. This has put additional pressure on the wetland and has led to increased pollution and encroachment [22].

2.2. Data used and sources

Wetland vulnerability assessment involves considering various variables that can affect the condition and resilience of wetland ecosystems. These variables were broadly classified into three components of vulnerability which are exposure, sensitivity, and resilience (adaptive capacity) [23]. Exposure or threats refer to external factors that can negatively impact wetland ecosystems, such as human activities and climate change [24]. Examples of drivers include urbanization, climate change (drought), and social economic status. Sensitivity refers to the specific mechanisms through which drivers impact wetlands [25]. These can include physical alterations to wetland habitats, changes in hydrology, and changes in biotic communities. For example, land use change can lead to the loss of wetland habitat, increased runoff and erosion, and the introduction of non-native species. Resilience factors refer to the characteristics of wetlands that enable them to withstand and recover from external pressures [26]. These factors include wetland vegetation composition, soil type and quality, and hydrology. Wetlands that are larger, more connected, and have more diverse plant communities are generally more resilient to external pressures than smaller or fragmented wetlands with less diverse plant communities.

Table 1 Data source[22]

Domain/Vulnerability component	Indicator/criterion	Earth observation data and source
Exposure	Land development	Land use /land cover: https://scihub.copernicus.eu/dhus/#/home
	Population growth	Population pressure: WorldPop Gridded data 1km resolution (https://www.worldpop.org/doi/10.52 58/SOTON/WP00004)
	Land Degradation	http://geoportal.icpac.net/layers/
	Climate change	Rainfall data (Meteo Rwanda)
	Urbanization	Sentinel data https://scihub.copernicus.eu/dhus/#/home
Sensitivity	Ecosystem Services	Land use/Land cover: Groot et al., 2012
	NDVI	Vegetation Index (NDVI) Sentinel data https://scihub.copernicus.eu/dhus/#/home
	Wetness Index	Normalized Difference Water Index (MNDWI): Sentinel data https://scihub.copernicus.eu/dhus/#/home
Resilience/Adaptive capacity	TWI	Digital Elevation Model (DEM) https://earthexplorer.usgs.gov/
	NDVI	Sentinel data https://scihub.copernicus.eu/dhus/#/home
	Turbidity	https://app.climateengine.org/climateEngine
	Chlorophyll concentration	https://app.climateengine.org/climateEngine

2.3. Procedures and data analysis

2.3.1 Framework for wetland vulnerability analysis

Assessing the vulnerability of wetlands requires the collection and analysis of both spatial and non-spatial data, which has been a challenge in the past [27]. However, with the increasing availability and affordability of Earth Observation (EO) data and efficient geo-spatial data processing techniques, wetland vulnerability assessment is entering a new phase of advancement. Nevertheless, it is important to combine EO data with local knowledge and in situ data to ensure relevant outputs. This study used weighted linear combination to find the exposure, sensitivity, resilience, and wetland vulnerability map. Indicators here refers to and individual factor or criterion while domains refer to a group of criteria or factors[28].

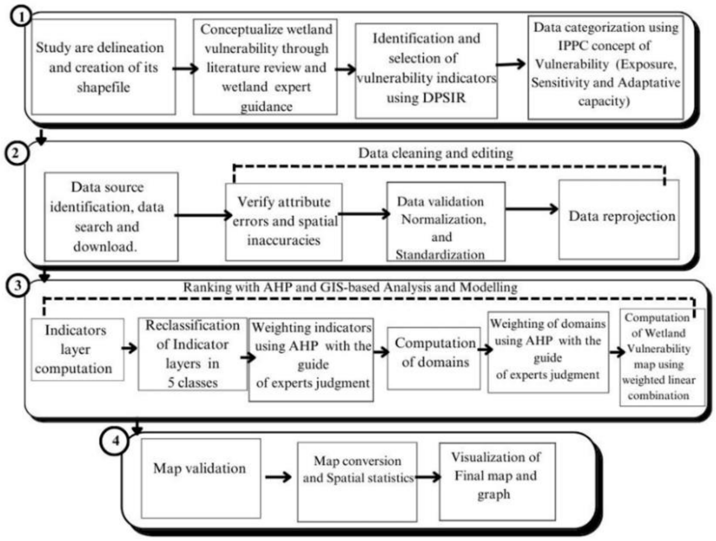

Figure 2. Framework for wetland vulnerability analysis

2.3.2 Computation of indicators

To find geospatial layers that represent wetland vulnerability indicators, GIS and Remote sensing data were downloaded from different platforms mentioned in Table 1. Using ArcGIS 10.4 Software formulae were applied to calculate indicators. However, some indicators were downloaded already computed.

2.3.3 Weights and influence on Vulnerability

A methodology using Analytic Hierarchy Process (AHP) weights based on the level of influence to vulnerability was used for assessing wetland vulnerability. AHP is a multi-criteria decision-making method that allows for the systematic evaluation of complex systems by breaking them down into hierarchical structures and assigning weights to different criteria based on their relative importance [29]. The weighting process in which criteria were assigned importance was completed through the use of the Analytical Hierarchy Process (AHP) with the guidance of wetland experts who provided their expert input. Table 2 summarizes the weight provided of each individual indicator and the domain.

Table 2: Weighting of factors and domains

Domain (Vulnerability components)		Weight of individual factor (%)	Rank of individual factor	Domain weights (%)	Rank of Domains
Exposure	Land use/cover	51.5	1	60.1	1
	Population growth	24.4	2		
	Climate change (Pmm)	13.2	3		
	Wetland land degradation	7.4	4		
	Built-up index (NDBI)	3.6	5		
Sensitivity	Ecosystem services	76.1	1	22.1	2
	Wetness index (MNDWI)	15.8	2		
	Wetland vegetation (NDVI)	8.2	3		
Resilience	Wetland vegetation (NDVI)	62.4	1	17.8	3
	Chlorophyll concentration	19.0	2		
	Topographic Wetness Index (TWI)	12.4	3		
	Turbidity	6.2	4		

For exposure: Consistency Ratio (CR)= 3.9%, for sensitivity: CR = 0.1%, for resilience, CR = 4.1%, for Domains: CR= 3%

2.3.4 Re-classification of factors based on Vulnerability

The re-classification of factors was based on the classification of vulnerability (Table 3) regarding their susceptibility or exposure to harm or damage. A combination of Google Earth imagery and field verification was used to validate the wetland classes on the Wetland Vulnerability Map. This approach ensured that the map's classification was accurate and reliable.

Table 3: Vulnerability classes

Vulnerability	Description regarding factor	Score
Very low	Minimally contributes to wetland vulnerability	1
Low	Contributes lowly to the wetland vulnerability	2
Medium	Somewhat contribute to wetland vulnerability	3
High	Contributes highly to wetland vulnerability	4
Very High	Contributes very highly to wetland vulnerability	5

2.3.5 Computations of wetland vulnerability components

2.3.5.1 Exposure Map

This refers to a map that shows the extent to which wetlands are exposed to certain threats. It can be created by calculating the exposure level using variables such as land use land cover, population, and land degradation, and then combining these variables into a spatial map. The following formula (1) is used in the processing of the exposure map using variables: $\boldsymbol{Exposure\ Map = \sum W * Exposure\ factor}$. The weight (**W) represents** the relative importance of each factor in the overall vulnerability of the wetland.

2.3.5.2 Sensitivity Map

The result of the Sensitivity Map indicates the relative sensitivity of different areas within the wetland system to the factors (such as land use change, water quality, etc.) considered in the assessment. The following formula is used in the process: $\boldsymbol{Sensitivity\ Map = \sum W * Sensitivity\ factor}$. The formula involves summing up the product of the weight assigned to each factor (W) and the sensitivity score assigned to each factor (Sensitivity factor).

2.3.5.3 Resilience Map

Resilience refers to the ability of a wetland system to withstand and recover from disturbances or stressors. Areas with high resilience are better able to recover from disturbances and are therefore less vulnerable to degradation or loss. To elaborate the resilience, map the formula below is used: $\boldsymbol{Resilience\ Map = \sum W * Resilience\ factor}$.

2.3.5.4 Wetland Vulnerability I Map

The Wetland Vulnerability Map is a composite map that is created using Weighted Linear Combination. The three maps namely exposure map, sensitivity map, and resilience map are combined to provide a comprehensive assessment of wetland vulnerability by integrating information on the exposure, sensitivity, and resilience of the wetland system to stressors. To calculate the vulnerability index, we took into account the impact of each domain, including Exposure, Sensitivity, and Resilience. This was accomplished by assigning weights to each domain based on their contribution to the overall vulnerability of the wetland (Table 2).

III. Results and Discussions

The obtained results from the all the afore-mentioned steps are discussed below.

3.1 Exposure

In the context of wetland vulnerability assessment, "wetland exposure" refers to the degree to which a wetland is likely to be affected by various stressors, such as changes in temperature, precipitation, water quality, land use, and human activities [5]. It takes into account both the sensitivity of the wetland to these stressors and the magnitude and frequency of their occurrence in the surrounding area [30], [31]. Wetland exposure is a key factor in determining the overall vulnerability of a wetland to future changes and can help prioritize conservation and management actions to reduce potential impacts.

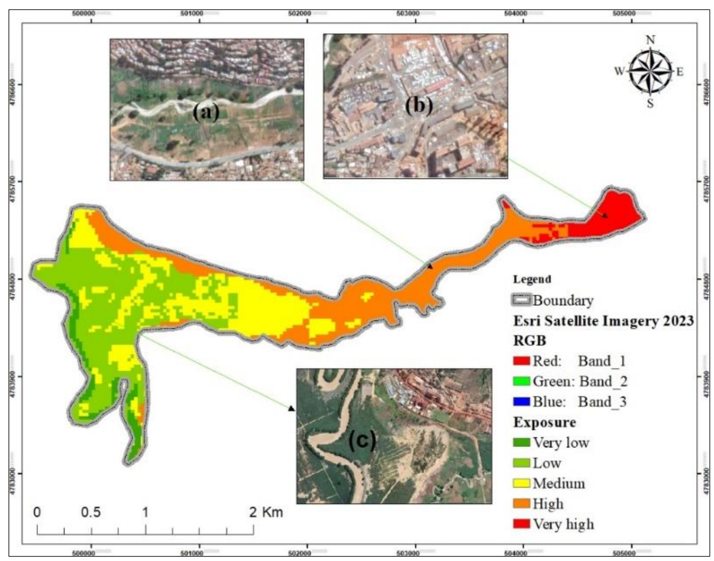

Figure 3: Exposure of wetland to various activities

The results in Figure 3 show that the wetland areas vary in their exposure to various activities. Nyabugogo wetland (Fig. 3(a)) is currently exposed to various activities, primarily related to land use and human activities such as settlement (Fig. 3 (b)) and agriculture (Fig. 3 (c)). These activities have the potential to impact the functioning of the wetland ecosystem as well as the associated services that it provides. Referring to Table 4, the Nyabugogo wetland exhibits an exposure to vulnerability pattern where more than half (54%) of its area is exposed to medium, high, and very high levels of vulnerability. This may be due to a variety of factors, such as land use change, climate change, pollution, and human activities. The medium, high, and very high exposure may be a concern as wetlands provide important ecosystem services such as water purification, carbon sequestration, and wildlife habitat. On the other hand, 46% of the area is characterized by a very low to low level of vulnerability. However, it is important to note that even low exposure can still have adverse effects on wetland ecosystems.

Table 4: Exposure calculations

Grid code	Exposure	Area in (Ha)	Percentage (%)
1	Very low	15	5
2	Low	132	41
3	Medium	56	17
4	High	97	30
5	Very high	22	7
Total		322	100

The results highlight the need for effective management and conservation efforts to ensure the long-term health and sustainability of wetlands, especially those in high and very high exposure to vulnerability.

3.2 Sensitivity

Figure 3 provides information on the sensitivity of Nyabugogo urban wetland to climate change and anthropogenic activities, as classified into five different grid codes based on their level of sensitivity. The results show that a majority of the wetland area 185.75 Ha (approximately 58%) has a medium to high sensitivity to climate change and anthropogenic activities, with around 110.91 Ha (35%) of the area classified as having a medium sensitivity and 74.84 Ha (23%) classified as having a high sensitivity. The portion of 41.51 Ha, which corresponds to 13% of the Nyabugogo urban wetland area, is classified as having a "very high" sensitivity to wetland vulnerability. The remaining area has a lower sensitivity, with around 40.15 Ha (12%) classified as very low and 53.95 Ha (17%) classified as low sensitivity.

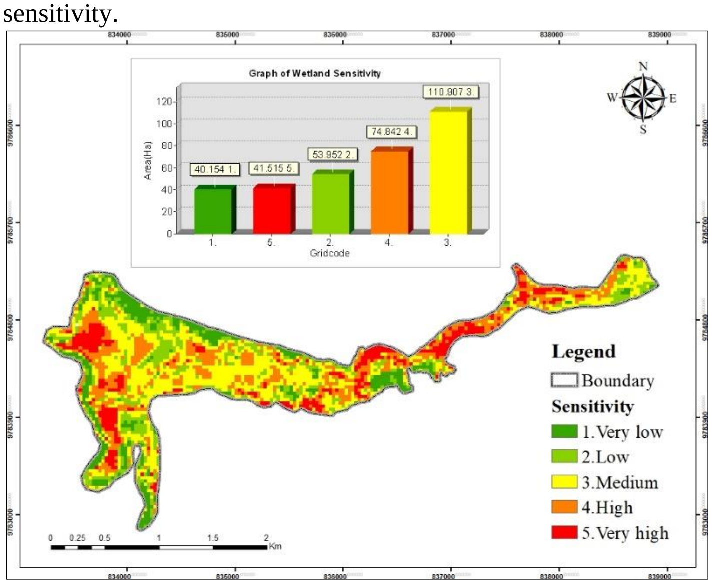

Figure 3: Wetland sensitivity

Wetlands with very high sensitivity are often characterized by delicate ecological balances and unique hydrological regimes, which can be easily disrupted by changes in water levels or quality, as well as changes in land use patterns [32]. The consequences of this disruption can be severe, including loss of habitat for sensitive species, changes in water quality and quantity, and reduced ability to provide important ecosystem services such as flood control, water purification, and carbon sequestration.

Understanding the sensitivity of wetlands is important for identifying areas that may require conservation or restoration efforts, as well as for informing land use planning and management decisions. For example, wetlands with high sensitivity to climate change may require specific management interventions to mitigate the impacts of changing precipitation patterns or sea level rise [3]. Similarly, wetlands with high sensitivity to human activities may require protection or restoration efforts to prevent degradation or loss of ecosystem services.

3.3 Resilience

Resilience is the capacity of a system, in this case, the Nyabugogo urban wetland, to withstand disturbances or changes and recover quickly. The resilience of a wetland is related to its ability to maintain its structure, function, and ecological processes despite various stressors [33].

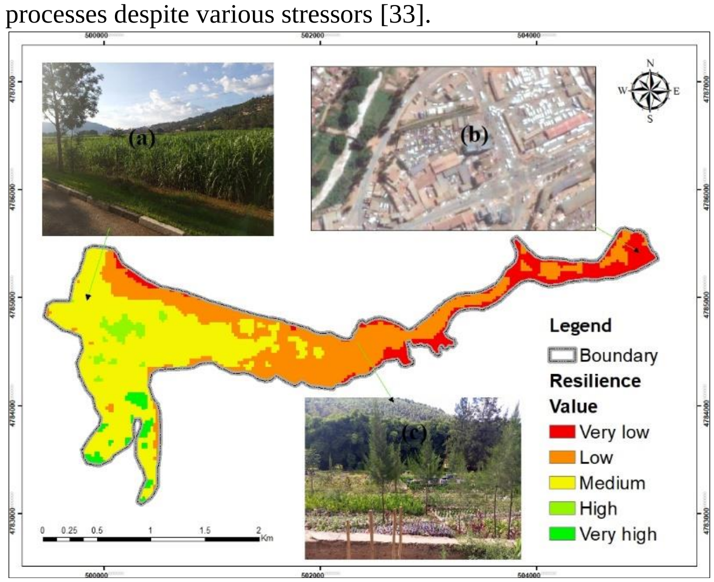

Figure 4: Wetland resilience

The data in Table 5 shows that the majority of the wetland area, which is approximately 80%, has medium to low resilience. The fact that only a small proportion of the wetland area (less than 5%) has high or very high resilience indicates that there are limited areas within the wetland that can withstand disturbances or recover quickly from negative impacts. This highlights the need for appropriate management and conservation measures to improve the overall resilience of the Nyabugogo urban wetland.

Table 5: Resilience classes

Grid code	Class	Area in (Ha)	%
1	Very low	48.36	15
2	Low	112.08	35
3	Medium	146.05	45
4	High	7.64	2
5	Very high	7.53	3
Total		322	100

The encroached area of Nyabugogo wetland, as indicated in Figure 4(a,b,c), has been identified as less resilient due to the various human activities taking place in that region. The presence of activities such as settlements, car parking, and central businesses in the wetland makes it more vulnerable to flooding and reduces its capacity to perform vital ecological functions such as water purification, nutrient cycling, and habitat provision. As argued by Zhang et al. (2019), A crucial indicator of how well wetlands respond to climate change is their hydrologic resilience, or their capacity to absorb disturbances and return to their pre-disturbance hydrological function. Therefore, the reduced resilience of the wetland in the encroached area highlights the need for urgent action to address the threats posed by human activities and restore the wetland's natural state to improve its ability to provide critical ecosystem services.

3.4 Wetland Vulnerability

The Wetland Vulnerability map (Figure 5) was produced using Weighted Linear Combination by summing up the product of exposure, sensitivity, and resilience maps with their weights.

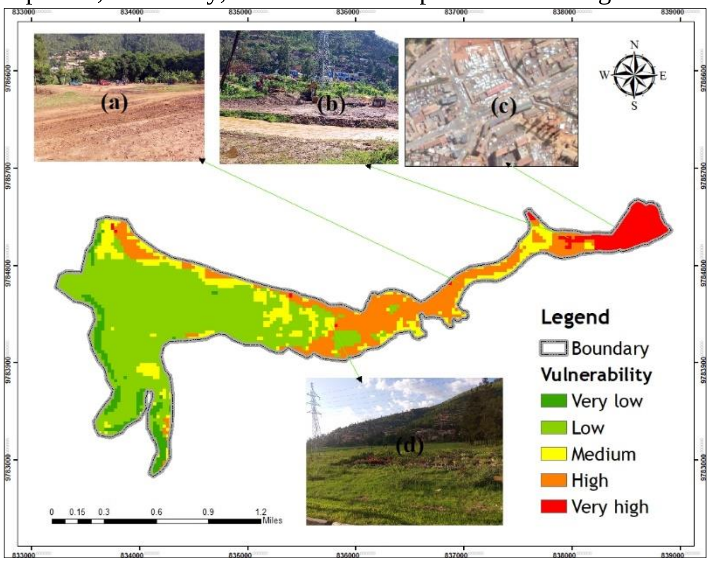

Figure 5: Wetland Vulnerability

The table 6 provided summarizes the wetland vulnerability of Nyabugogo Urban wetland based on the vulnerability classes of very low, low, medium, high, and very high. The table shows that a majority of the wetland falls into the low to very low vulnerability (57%) followed by very high, high, and medium vulnerability (43%). Of the areas with high and very high vulnerability, they are being utilized for various activities, including human settlements, Nyabugogo Car parking, and central businesses (Fig. 5 (c)). Based on the remote sensing data analysis, it has been revealed that there are 220 houses in the very high class of wetland vulnerability (WVI) and 628 houses in the high class of WVI. Moreover, the data underscores the existence of other facilities like a playground, driving school, car parking, and petrol stations in these areas, which can potentially have adverse impacts on the wetland ecosystem, such as pollution and habitat fragmentation.

The findings of Bayizere et al. (2022) also shed light on the detrimental impact of urbanization on Nyabugogo wetland, highlighting the significant degradation of water quality in the area as a result of human activity. In a study conducted by Akumu et al. (2018), it was also noted that a considerable number of wetland types with high vulnerability in the study area were negatively affected by human stressors.

Table 6: Vulnerability classes

Grid code	Class	Area in (Ha)	Percentage (%)
1	Very low	15.08	5
2	Low	165.51	52
3	Medium	48.07	15
4	High	68.08	21
5	Very high	22.25	7

This information can be used to guide wetland management strategies. For example, wetland areas classified as high vulnerability could be given priority for conservation and restoration efforts. On the other hand, wetlands classified as very low vulnerability could be considered less critical and may not require the same level of conservation efforts.

Overall, the Wetland Vulnerability map is a valuable tool for wetland management and conservation efforts, as it provides a clear and detailed picture of the state of different wetland areas. The map and the associated vulnerability assessment can guide decision-making processes related to wetland management, including conservation, restoration, and development activities, ensuring that wetlands are managed sustainably for the benefit of both people and the environment. Moreover, the Wetland Vulnerability map is a crucial component in the implementation of a sponge city approach for flood control [2]. By identifying areas of high vulnerability within wetlands, urban planners and policymakers can strategically design and implement green infrastructure solutions to enhance the wetland's ability to absorb and retain water during flood events.

IV. Conclusion

In conclusion, the results of the wetland vulnerability assessment of Nyabugogo urban wetland highlight the need for effective management and conservation efforts to ensure the long-term sustainability of wetlands, especially those in high and very high exposure to vulnerability. The wetland areas vary in their exposure to various activities, with the majority of the wetlands being exposed to some degree of vulnerability. The sensitivity of the wetlands to climate change and anthropogenic activities indicates that a significant portion of the wetlands may require specific management interventions to mitigate the impacts of changing environmental stressors. Finally, the low resilience of the wetland areas emphasizes the importance of developing measures to enhance the ability of the wetland to withstand disturbances or recover quickly from negative impacts. This study can facilitate the implementation of ecosystem-based restoration measures that aim to enhance the wetlands' capacity for flood control in sponge city components. Therefore, utilizing geospatial tools to assess wetland vulnerability is crucial for the restoration and preservation of these vital ecosystems

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