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Analyzing The Effectiveness Of Flood Mitigation Services On Wetland Restoration In Rwanda: A Case Study Of Gikondo Wetland.

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Abstract: Urban wetlands provide flood mitigation and ecological services but are increasingly degraded by urbanization and industrial pressures. Gikondo Wetland in Kigali, Rwanda, has undergone government-led flood mitigation and restoration interventions, but evidence of their vegetation response remains limited. This study assessed the effectiveness of flood mitigation services on wetland restoration using the Normalized Difference Vegetation Index (NDVI) as an indicator of vegetation condition. Landsat 8, Landsat 9, and Sentinel-2 imagery from 2015-2025 were analyzed using a quantitative longitudinal quasi-experimental design. The wetland was divided into drainage-channel, embankment, retention-basin, and control zones. The annual maximum NDVI increased from 0.410 in 2015 to 0.506 in 2025, representing a 23.4% increase. During 2021-2025, retention-basin areas recorded the highest mean value (0.510), followed by embankments (0.477), the control zone (0.464), and drainage channels (0.455). Tukey comparisons showed that the retention-basin zone differed significantly from the other three zones. Comparisons between 2015-2016 and 2024-2025 showed significant increases in drainage, embankment, and retention-basin zones. Seasonal rainfall was strongly associated with subsequent vegetation condition ($r = 0.78$, $p < 0.01$). The results indicate an association between flood mitigation intervention areas and improved vegetation condition, particularly around retention basins. However, NDVI does not directly measure flood attenuation, and restoration was still ongoing. Continued ecological and hydrological monitoring is therefore required.

Keywords: ArcGIS, Flood mitigation, NDVI analysis, Nature-based solutions and wetland restoration.

1. INTRODUCTION

Wetlands rank among the most biologically productive and hydrologically significant ecosystems on earth, supplying indispensable services including flood attenuation, water purification, carbon sequestration, groundwater recharge, and biodiversity protection [1]. Despite their ecological and social value, wetlands have undergone alarming rates of degradation globally. Approximately 35 percent of the world's natural wetlands were destroyed between 1970 and 2015, a rate three times faster than forest decline [2]. This degradation has major ramifications for flood regulation, as healthy wetlands operate as natural sponges that absorb excess rainfall, decrease surface runoff, and reduce peak flood flows [3].Numerous governments have recognized wetland restoration as a nature-based strategy for flood risk management. Along the Scheldt estuary in the Netherlands and Belgium, large-scale tidal marsh restoration has been performed as a major component of the regional flood

defense system [4]. Similarly, in the Mississippi River Delta, wetland restoration has been highlighted as a major technique for lowering storm surge impacts on New Orleans following Hurricane Katrina [5]. Wetland degradation and flood threats are growing at an unprecedented rate, driven by fast population increase, unplanned urbanization, agricultural expansion, and weak environmental governance [6]. Sub-Saharan Africa has undergone a more than tenfold rise in reported flood events since 1980, with urban wetlands being particularly vulnerable [7]. In Ghana's Greater Kumasi Metropolitan Area, studies found that wetland cover dropped by 59 percent between 1986 and 2023, while built-up areas rose by 134 percent [8]. In Uganda, the Awoja Catchment faced catastrophic floods related to wetland encroachment, with a community-based restoration project raising wetland restoration coverage from 35 percent to 80 percent within two years [9]. The association between wetland degradation and flood risk is particularly obvious in Rwanda due to the country's mountainous topography, complex river network, and rapidly rising urban population [10]. Kigali, the capital city, originally included 37 linked wetlands totalling approximately 12.5 percent of the city's entire land mass, which historically functioned as a giant natural sponge collecting surplus rainwater and minimizing flood peaks [11]. However, these ecosystems are under tremendous strain due to the fast urbanization. According to the World Bank, at least 50 percent of Kigali's wetlands have lost their ecological identity [12] In response, the Rwanda Environment Management Authority (REMA) has begun an ambitious countrywide wetland restoration initiative [13]. The Nyandungu Eco-Park, a 400-acre restored wetland in southern Kigali, serves as a landmark pilot project proving the efficiency of nature-based methods for flood control and ecological restoration. Following restoration, Nyandungu currently hosts over 200 kinds of birds, and quantitative study indicated that flood susceptibility fell drastically, with regions extremely susceptible to floods reduced from 26 hectares in 2010 to just 2 hectares in 2023. Additionally, vegetation health values increased from 0.351 in 2010 to 0.495 in 2023 according to NDVI data, showing a notable ecological recovery. Because of its lengthy history of industrial usage, the Gikondo Wetland, the specific focus of this study, presents a particularly difficult scenario [14]. Since the 1960s, Gikondo has been an industrial park, resulting in significant pollution, hydrological change, and vegetation loss from factories, warehouses, garages, and commercial buildings. According to research, the Gikondo wetland area shrank from 32.03 percent in 1987 to only 25.70 percent in 2010 [15]. The marsh has not yet reached its 1987 biological baseline, despite some recovery since 2010, mostly as a result of government actions and encroacher evictions. Gasabo, Nyarugenge, and Kicukiro are the three districts of Kigali where the wetland is located. Its ability to improve water quality and mitigate flooding has been seriously compromised by its degradation. Although the Nyandungu restoration has been well researched, there is still a dearth of empirical data regarding the efficacy of flood mitigation services, particularly in Gikondo Wetland. In order to fill this important knowledge gap, this study uses NDVI, a quantitative technique for evaluating vegetation recovery, to analyses the impact of flood prevention services on wetland restoration in Gikondo Wetland.

1.1 Statement of the problem

Due to rising urbanization, wetland degradation, and climate change, urban flooding in Kigali is becoming more frequent and severe. In response, as part of a nationwide restoration initiative, the Rwandan government has made large investments in Gikondo Wetland's drainage pipes, embankments, and retention basins as flood control services. Wetland restoration in Rwanda has been studied previously, but there are important gaps. Nyandungu Eco-Park's NDVI increased by 41% (from 0.351 to 0.495) after being restored from agricultural degradation. However, the industrial contamination in Gikondo is very different from the deterioration profile in Nyandungu [16]. To ascertain whether flood mitigation services in Gikondo are producing the desired ecological results, no systematic, quantitative evaluation has been carried out. Without such evidence, public funds risk being allocated to interventions that may be ineffective or even counterproductive.

1.2 Research objectives

The general objective of this study is to analyze the effectiveness of flood mitigation services on wetland restoration in Gikondo Wetland, Rwanda, using the Normalized Difference Vegetation Index (NDVI) as a quantitative method for assessing vegetation recovery and ecological functionality. The specific objectives are: To determine flood mitigation services provided in Gikondo restored wetland, to assess the spatial characteristics of the Gikondo restored wetland. And to determine the contribution of flood mitigation services to wetland restoration from other influencing factors.

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1.3 Research questions

What flood mitigation services have been provided in Gikondo restored wetland?

What are the spatial characteristics of Gikondo restored wetland in terms of NDVI distribution across different intervention zones? What is the contribution of flood mitigation services to wetland restoration compared to other factors such as rainfall and pollution?

1.4 Significance of the study

Significant contributions are produced by this study on several levels. In addition to improving practical skills in remote sensing data gathering, NDVI analysis, GIS, and statistical interpretation, it gave the researcher a great chance to apply theoretical knowledge to a real-world environmental management issue in Rwanda. It raises the profile of environmental science, remote sensing, climate change adaptation, and natural resource management research at the University of Lay Adventists of Kigali (UNILAK). The study offers quantitative, spatially explicit evidence on the kinds of flood mitigation structures most closely linked to vegetation recovery to policy makers at REMA, the City of Kigali, the Ministry of Environment, and the Rwanda Water Resources Board, allowing for more focused and economical use of public funds. The study helps communities in and around Gikondo Wetland by lowering the risk of flooding and enhancing ecological services. It creates a repeatable NDVI-based framework for evaluating the efficacy of wetland restoration for future researchers.

1.5 Theoretical framework

This work is based on three interconnected theoretical approaches. First, the Ecosystem Services Paradigm acknowledges the numerous benefits that natural ecosystems provide to human societies, classifying them as provisioning, regulatory, cultural, and sustaining services [17]. This paradigm guided the choice of NDVI as the primary dependent variable, as vegetation health directly influences regulating services such as flood attenuation, water purification, and carbon sequestration. Second, the Nature-Based Solutions Theory promotes the use of natural or restored ecosystems to address societal issues including flooding, climate change, and water security [18]. This theory guided the categorization of flood mitigation interventions into distinct types, acknowledging that different interventions may produce different environmental outcomes. Third, Landscape Ecology Theory investigates the links between spatial patterns and ecological processes within heterogeneous landscapes [19]. This theory influenced the spatial stratification of Gikondo Wetland into four zones, recognizing that patch characteristics, edge effects, and landscape context influence vegetation recovery independently of intervention type.

1.6 Empirical review

Vegetation dynamics in the Beidagang Wetland Nature Reserve in northern China, examining spatiotemporal fluctuations in NDVI in response to climate change and human activity [20]. Using Landsat data and field surveys over a 40-year span from 1984 to 2023, the study discovered that average growing-season NDVI was falling at -0.0025 per year despite restoration efforts. Importantly, rising temperatures caused considerable increases in NDVI in less human-disturbed areas, while this trend was much weaker in human-disturbed areas. The study also discovered that during the recovery stage, the legacy impact of past human activities, particularly aquaculture pond excavation, persistently prevented vegetation recovery, whereas appropriate restoration measures such as constructing embankments and connecting drainage ditches aided vegetation recovery.

Assessed the flood control effects of Nyandungu Eco-Park in Kigali, Rwanda, which acted as a test site for the restoration of five other urban wetlands, including Gikondo. The study assessed restoration impacts by geographic data analysis, NDVI, NDWI, and field observations. The results demonstrated a substantial reduction in flood susceptibility, with regions very vulnerable to floods falling from 26 hectares in 2010 to just 2 hectares in 2023, while areas less sensitive climbed from 30 to 119.7 hectares. NDVI research found significant vegetation health improvement, with values climbing from 0.351 in 2010 to 0.495 by 2023, indicating substantial regeneration of formerly deteriorated vegetation. However. Investigated Nyandungu, which was predominantly damaged by agricultural encroachment and informal settlements rather than industrial pollution. Gikondo's degradation profile is fundamentally different, with heavy metals, hydrocarbons, and other persistent contaminants accumulated during six decades of

industrial activity. Furthermore, did not compare various types of flood mitigation structures, as Nyandungu's restoration prioritised passive revegetation and hydrological reconnection over engineered flood control buildings. The study did not include a control zone, making it difficult to ascribe reported NDVI increases purely to restoration efforts.

Asare evaluated the efficiency of wetlands as nature-based flood risk mitigation measures in Ghana's Greater Kumasi Metropolitan Area. To evaluate several NbS deployment scenarios, the study used an integrated approach that combined spectral indices (MNDWI, NDVI, and NDBI) with TELEMAC-2D hydrodynamic modelling. The findings found that between 1986 and 2023, wetland cover decreased by 59% while built-up areas increased by 134%, resulting in lower cumulative discharge and more severe, shorter-duration flooding. The combined scenario of floodplain restoration and wetland development achieved consistent peak flow reductions of 16 to 19 percent during extended storms, whereas the ambitious restoration scenario worked best in short-duration events, reducing peak flow by 24 percent. However, the study did not evaluate ecological restoration effects because the dependent variables were hydrological rather than ecological. The study also relied on modelling rather than empirical post-restoration monitoring. GIS analysis, stakeholder interviews, and water quality tests to assess water quality and identify important pollution sources across five wetlands in Kigali over a four-week period. The results showed that major water quality parameters turbidity, conductivity, total suspended particles, total dissolved solids, and dissolved oxygen were in poor condition, with Nyabugogo lower exhibiting the most substantial departure. Insufficient wastewater treatment, the lack of a centralised sewage infrastructure, and intensive agricultural practices were all major sources of pollution. This study adds vital context to understanding the pollution constraints on Gikondo and other Kigali wetlands [21]

1.7 Research gap

Despite the growing body of empirical literature on wetland restoration, flood mitigation, and remote sensing applications, several significant gaps remain. First, the empirical literature is heavily skewed toward temperate, high-income country contexts. No peer-reviewed study has employed NDVI to statistically measure flood mitigation efficiency in an industrially degraded, inland, urban wetland in Sub-Saharan Africa. Second, a clear bifurcation exists in the literature: some studies focus on hydrological or flood reduction outcomes without assessing ecological recovery, while others focus on vegetation recovery without linking to specific flood mitigation structures. No study has specifically studied the link between individual flood mitigation constructions (drainage channels, embankments, retention basins) and NDVI-measured vegetation recovery in the same analytical framework. Third, among the research assessed, only the cranberry farm study included reference wetlands for comparison; others lacked a real control zone, making causal attribution of NDVI changes to specific interventions weak. Fourth, all reviewed studies examined wetlands degraded by agricultural encroachment, aquaculture, or sea-level rise none examined an industrially degraded wetland where heavy metals, hydrocarbons, and other persistent contaminants may inhibit vegetation recovery regardless of hydrological improvements. Fifth, recognized that embankments and drainage ditch improved recovery in some circumstances, they did not systematically assess different intervention types. No study has stratified a single wetland into zones with different flood mitigation systems and analyzed NDVI changes across those zones. Sixth, most examined research used Landsat imagery with 30 m spatial resolution; the higher resolution of Sentinel-2 (10 m) has not been extensively applied to African urban wetland restoration.

2. MATERIALS AND METHODS

2.1 Description of the study area

Gikondo Wetland is located in the City of Kigali, the capital of Rwanda, and spans approximately 162 hectares across three districts: Gasabo, Nyarugenge, and Kicukiro. The wetland is situated approximately 3 kilometers south of Kigali's central business district, making it one of the most centrally located wetlands within the city's network of 37 interconnected wetlands. The geographical coordinates of the wetland range approximately between 1°57' and 1°59' South latitude and 30°03' and 30°06' East longitude. The wetland lies within the drainage basin of the Nyabugogo River, which flows northward through Kigali before joining the Nyabarongo River, a major tributary of the Nile River system. The climate of the study area, based on rainfall data obtained from Meteo Rwanda for the period 2015-2025, is characterized by a mean annual rainfall of 650.1 mm [22]. The area

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experiences two distinct rainy seasons (March to May and September to November) and two dry seasons (June to August and December to February).

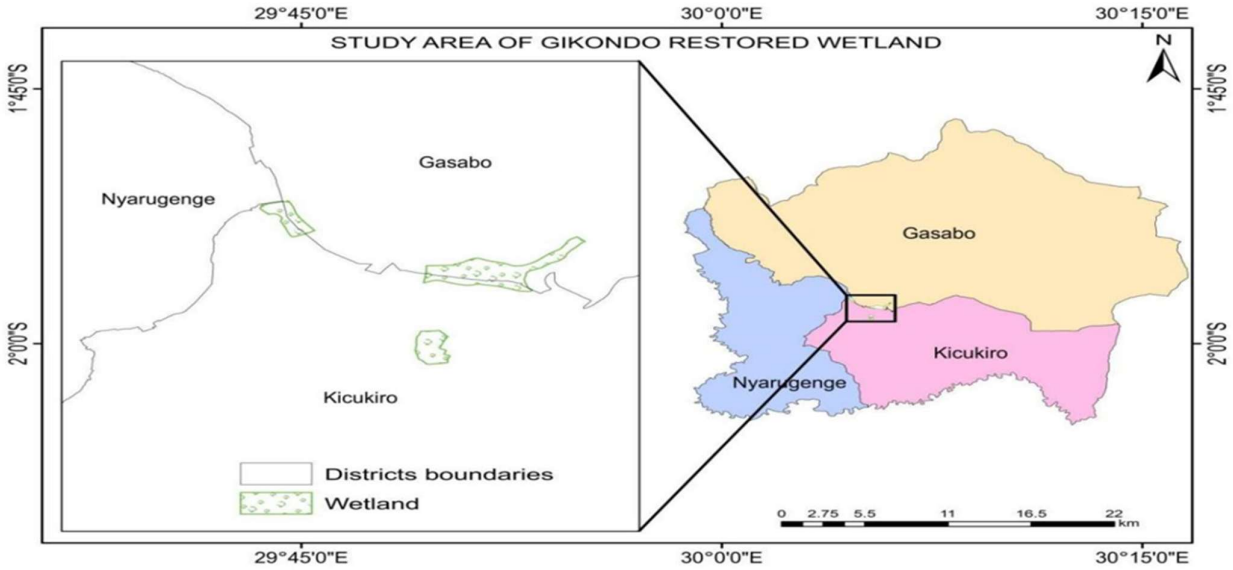

Figure 1. *The location of Gikondo Wetland within Kigali*

2.2 Research design

The study used a quantitative, longitudinal, and quasi-experimental research design. The design was quantitative because it depended on numerical NDVI values obtained from satellite photos, which were statistically analysed using SPSS software to discover trends, patterns, and significant changes over time and place. The study's approach was longitudinal since it looked at changes in vegetation health over a ten-year period from 2015 to 2025, allowing it to capture prevention baseline circumstances (2015-2016), changes during intervention (2017-2020), and post-intervention results (2021-2025). The design was quasi-experimental because the treatments were not assigned at random. Instead, the study takes advantage of natural heterogeneity in the timing and type of flood mitigation actions across the wetland's various zones. The wetland was separated into four zones depending on the predominant form of intervention present. Zones A (dominant drainage channels), B (dominant embankments), C (dominant retention basins), and D (control zone without direct intervention).

2.3 ampling design

A stratified purposive sampling approach was used for the spatial component. Gikondo Wetland was classified into four distinct strata or zones based on the predominant type of flood mitigation intervention present, as confirmed by official GIS shapefiles from REMA and visual interpretation of high-resolution satellite data in Google Earth Pro. Individual sampling locations were selected from each zone using a systematic sampling approach. Using a grid overlay in ArcGIS, sampling points were put at regular intervals of about 50 meters to provide consistent coverage across each zone while eliminating edge effects at zone boundaries. A total of thirty sampling points were chosen, distributed as follows: 8 points in zone A, 8 points in zone B, 8 points in zone C, and 6 points in zone D (the control zone being slightly smaller in area).

For the temporal dimension, a time-series sampling approach was used. Satellite imagery was chosen for multiple time points across a ten-year study period, from 2015 to 2025. The study specifically collected and analysed imagery from three time points every year: early wet season (March-April), late wet season (May-June), and dry season (July-August) to capture seasonal changes in vegetation health. This resulted in about 30 image dates throughout a ten-year span. For each image date, NDVI data were retrieved from all 30 sampling sites, providing about 900 distinct NDVI readings.

2.4 Data sources

The primary data source was multitemporal satellite images obtained from publically available remote sensing systems, namely the Landsat and Sentinel-2 missions. The study used Level-2 surface reflectance products from Landsat 8 (2015–present) and Landsat 9 (2021–present) provided by the United States Geological Survey (USGS) via the Earth-Explorer platform. Landsat images have a spatial resolution of 30 meters and a temporal resolution of 16 days. In addition, the study used imagery from the European Space Agency's (ESA) Sentinel-2 mission, which has been operating since 2015 and delivers imagery with a spatial resolution of 10 meters and a temporal resolution of 5 days. Sentinel-2 Level-2A products were obtained via the Copernicus Open Access Hub. Secondary data sources included pre-existing spatial datasets, published studies, peer-reviewed articles, government records, and further climate data. The Rwanda Meteorology Agency (Meteo Rwanda) released daily rainfall data for the Gikondo area from 2015 to 2025, with the Gitega station located around 2 km from the Gikondo Wetland. GIS shapefiles for the Gikondo Wetland boundary and flood mitigation structures were received from REMA using a formal data request.

2.5 Data processing and analysis

NDVI was computed using the standard formula:

NDVI = (NIR - Red) / (NIR + Red)

where NIR is surface reflectance in the near-infrared band (Landsat Band 5; Sentinel-2 Band 8) and Red is surface reflectance in the red band (Landsat Band 4; Sentinel-2 Band 4). NDVI values range from -1 to +1, with higher positive values generally indicating denser and greener vegetation. The same processing workflow was applied across the study period to support temporal and spatial comparison. Statistical analyses were conducted using SPSS software, including descriptive statistics, linear regression, one-way analysis of variance (ANOVA), post-hoc Tukey HSD comparisons, paired comparisons between pre-intervention (2015-2016) and late-period (2024-2025) NDVI, and Pearson correlation. Break-point detection was performed using the change-point package in R with the PELT (Pruned Exact Linear Time) algorithm. Spatial analysis included NDVI distribution maps, 2015–2025 change detection, and hotspot analysis using ArcGIS.

3. RESULTS

3.1 Flood mitigation services provided in Gikondo restored wetland

Based on official GIS shapefiles obtained from REMA and verified through high-resolution satellite imagery interpretation, three types of flood mitigation services were identified in Gikondo restored wetland. Drainage channels (zone A) are linear engineered conduits designed to collect and convey storm-water runoff away from developed areas. Approximately 4.2 kilometers of drainage channels were constructed, primarily along the eastern and western boundaries of the wetland, with a typical width of 2 to 4 meters and depth of 1 to 2 meters. Embankments (zone B) are raised structures built along the wetland margins to prevent floodwaters from spilling into adjacent residential and industrial areas. Approximately 3.8 kilometers of embankments were constructed, with heights ranging from 1.5 to 3 meters. Retention basins (zone C) are ponded areas designed to store excess storm-water and release it slowly, mimicking natural hydrological processes. Four artificial retention ponds were constructed, with a combined storage capacity of approximately 12,000 cubic meters. Control zone (zone D) consists of areas within the wetland that received no direct flood mitigation intervention, serving as a reference for comparing the effectiveness of the three intervention types.

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Table 4.1: *Flood mitigation services identified in Gikondo restored wetland*

Zone	Intervention Type	Extent/Qty	Key Characteristics
A	Drainage channels	4.2 km	Linear conduits, 2-4 m width, 1-2 m depth.
B	Embankments	3.8 km	Raised structures, 1.5-3 m height.
C	Retention basins	4 ponds	Combined storage capacity of 12,000 m³
D	Control (no intervention)	42 ha	No engineered structures

3.2 Spatial characteristics of Gikondo restored wetland

Annual NDVI values for Gikondo Wetland were generated from satellite imagery analysis throughout an eleven-year study period from 2015 to 2025. The highest annual maximum NDVI was 0.506 in 2025, the lowest was 0.308 in 2017. The 2025 figure is a net gain of 0.096, or 23.4 percent, above the 2015 baseline of 0.410. Over the research period, the mean annual maximum NDVI was 0.407, with a standard deviation of 0.063.
The time series revealed relatively consistent NDVI between 2015 and 2016 (0.410 to 0.425), a decrease to 0.308 in 2017, recovery from 2018 to 2020 (0.426 to 0.447), a second decline in 2021-2022 (0.316 and 0.349), and a persistent rebound in 2023-2025 (0.426, 0.465, and 0.506). These results indicate substantial temporal variability in vegetation condition during the study period.

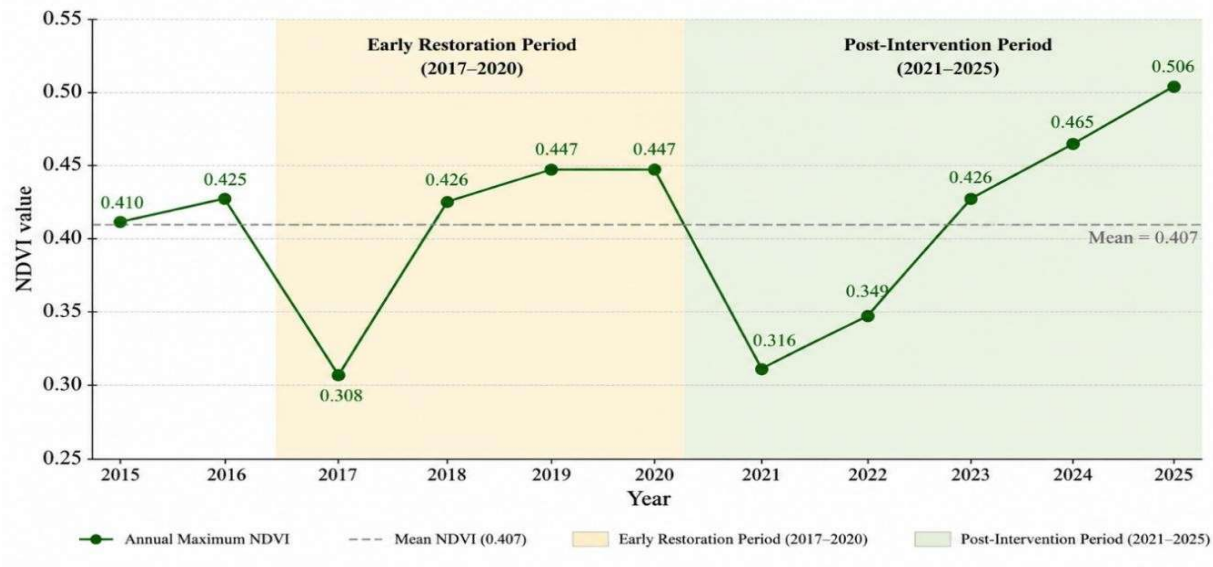

Figure 2: *The annual maximum NDVI trend from 2015 to 2025.*

3.3 Effectiveness of flood mitigation services across intervention zones

Post-intervention mean NDVI for 2021-2025 was highest in zone C (retention basins) at 0.510, followed by zone B (embankments) at 0.477, zone D (control) at 0.464, and zone A (drainage channels) at 0.455.

Statistical comparison of the post-intervention period indicated significant differences among the intervention zones. Post-hoc Tukey HSD comparisons showed that zone C had significantly higher mean NDVI than zone A ($p = 0.003$), zone B ($p = 0.042$), and zone D ($p = 0.008$). Paired comparisons between the 2015-2016 period and 2024-2025 period showed significant NDVI

increases in Zone A (+0.061, p = 0.025), Zone B (+0.077, p = 0.010), and Zone C (+0.083, p = 0.004). Zone D also showed an increase (+0.059), but this change was not statistically significant (p = 0.069). Across the post-intervention period, Zone C had the greatest NDVI values, whereas the other zones had lower but variable vegetation responses. The spatial disparities imply that vegetation recovery was not uniform across the marsh and that areas linked with various intervention types showed varied levels of vegetation response.

Table 2. Post-intervention NDVI by zone, Tukey HSD comparisons, and pre- to post-intervention changes in Gikondo Wetland.

Panel A: Post-intervention means NDVI (2021-2025) and Tukey HSD comparisons

Zone	Intervention type	Mean NDVI	Comparison vs. Zone C	Adjusted P
A	Drainage channels	0.455	Zone C vs. Zone A	0.003
B	Embankments	0.477	Zone C vs. Zone B	0.042
C	Retention basins	0.510	-	-
D	Control (no intervention)	0.464	Zone C vs. Zone D	0.008
Zone	Intervention type	Mean NDVI	Comparison vs. Zone C	Adjusted p

Panel B: Paired comparisons of NDVI, 2015-2016 vs. 2024-2025

Zone	Mean change	P-value	Significance
A	+0.061	0.025	Significant
B	+0.077	0.010	Significant
C	+0.083	0.004	Significant
D	+0.059	0.069	Not significant

Source: *Calculated from Landsat 8, Landsat 9, and Sentinel-2 NDVI analysis using ArcGIS and SPSS*

3.4 Contribution of flood mitigation services relative to other factors

The correlation between seasonal rainfall (March-May) and maximum NDVI during July-August was positive and strong (r = 0.78, p < 0.01; 95% CI: 0.42-0.93).

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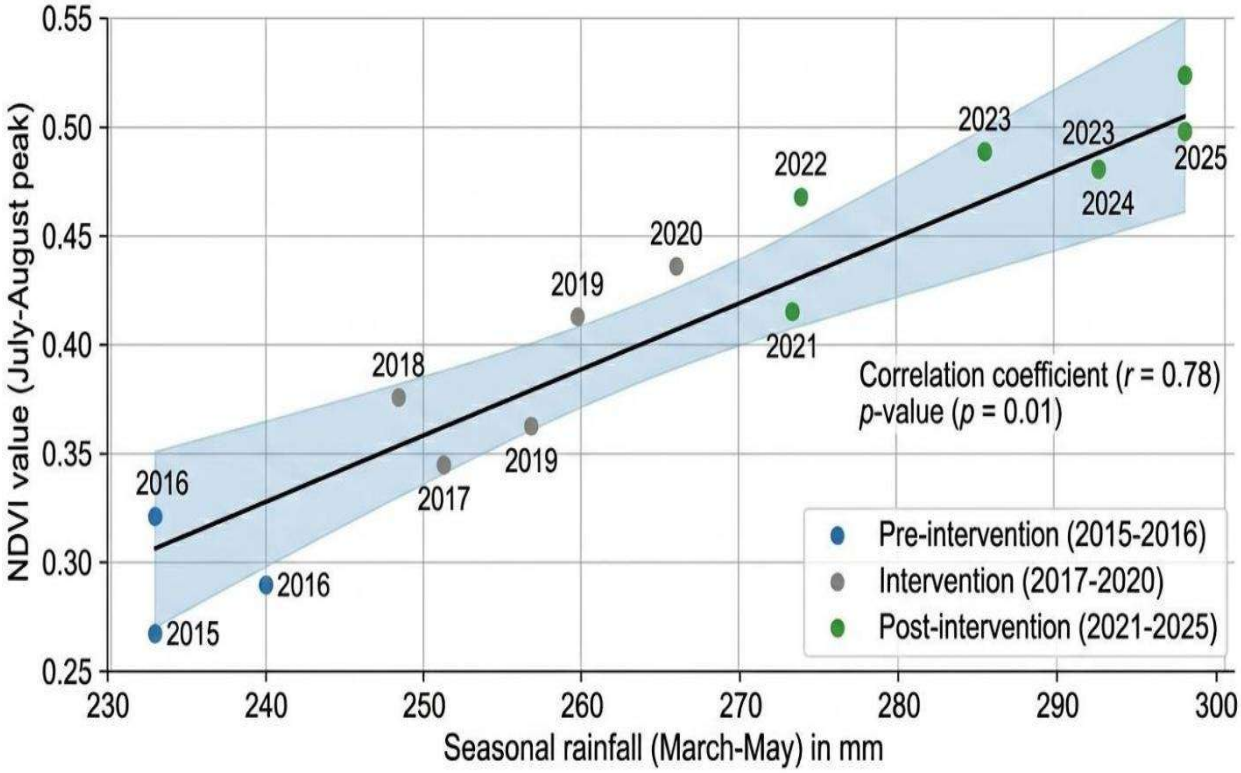

Figure 3: *The relationship between seasonal rainfall and maximum NDVI*

This suggests that seasonal rainfall has a considerable relationship with later vegetation status. The lowest NDVI year (2017: 0.308) corresponded to low seasonal rainfall (241.6 mm), while the greatest NDVI year (2025: 0.506) happened with below-average seasonal rainfall (249.0 mm). The latter discovery implies that variables other than rainfall contributed to the observed vegetation condition, but the analysis does not prove the independent causal role of flood control efforts. Secondary evidence suggests that Gikondo Wetland has faced long-term industrial pressures from factories, garages, warehouses, and other related activities. Heavy metals, hydrocarbons, and other industrial pollutants have all been reported as contaminants [15]. The current study did not involve primary soil or water-quality samples, hence the independent influence of pollution on NDVI could not be quantified statistically. Pollution is therefore treated as an important contextual factor rather than a measured causal variable.

3.5 Spatial Analysis Results

NDVI distribution maps indicated multiple spatial trends. In 2015 (baseline), the marsh was mostly light green to yellow-green (NDVI 0.35-0.45), indicating good but not outstanding plant health. For 2017 (the lowest NDVI), the marsh was mostly yellow to orange (NDVI 0.15-0.35), indicating extensive vegetation stress. In 2020 (the conclusion of early restoration), the wetland improved with more yellow-green (NDVI 0.35-0.45). For 2023 (post-intervention recovery), the wetland displayed light green (NDVI 0.45-0.55) in most locations, with zone C exhibiting significantly higher values. For 2025 (good health), the wetland showed light green to dark green (NDVI 0.45-0.60) in most locations, with zone C having the highest concentration of dark green patches. The change detection map showed that much of Gikondo Wetland experienced net vegetation improvement between 2015 and 2025.

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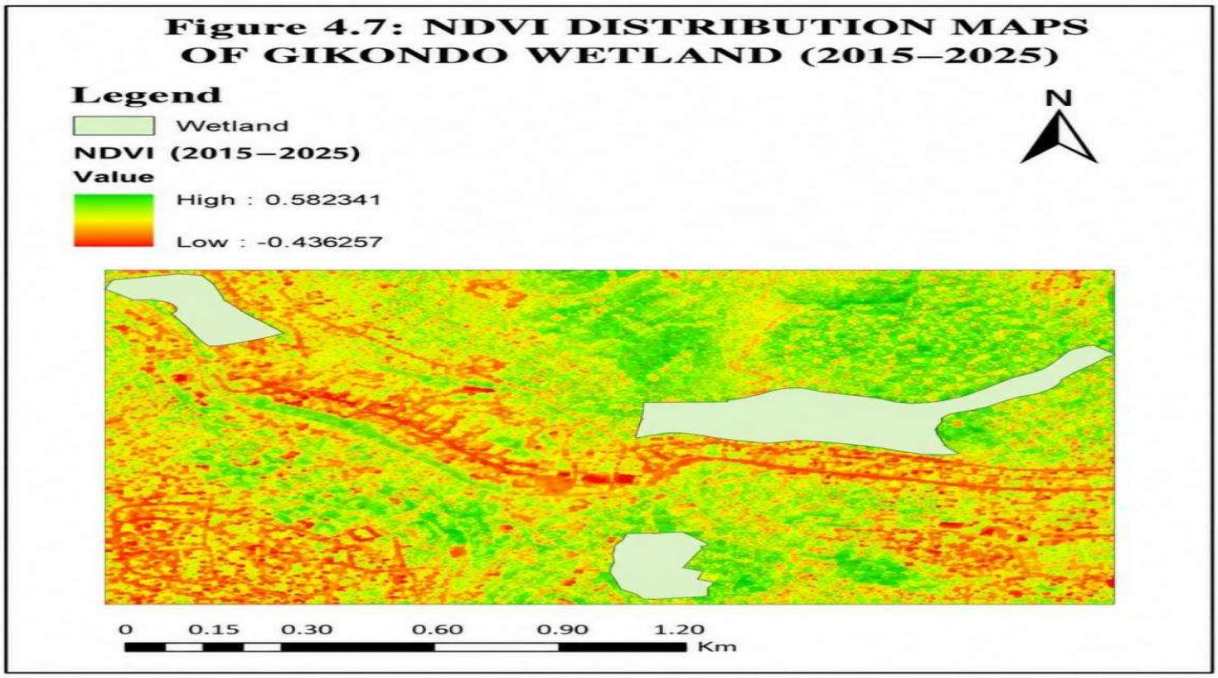

Figure 4. *Change detection map of Gikondo Wetland (2025 minus 2015). Green indicates vegetation improvement; red indicates degradation.*

The most favourable improvements were focused in zone C, notably near the retention basins. The wetland-wide NDVI increased from 0.410 in 2015 to 0.506 in 2025, resulting in a net change of +0.096 (23.4 percent relative to the 2015 baseline). Zone C had the highest proportion of areas that improved (62 percent), followed by zone A (52 percent), zone B (48 percent), and zone D (38 percent). Zone D also has the greatest reported proportion of degraded land (42%). Hotspot analysis found statistically significant clusters of improvement mostly along the borders of the retention basins in zone C, whereas degradation hotspots occurred primarily in zone D and near reported industrial discharge regions in the eastern section of the wetland. These spatial patterns demonstrate a link between localized vegetation improvement and retention-basin regions; nevertheless, they should not be construed as proof that the structures caused the observed changes.

4. DISCUSSION

The study found that vegetation conditions improved significantly in Gikondo Wetland between 2015 and 2025. Maximum NDVI climbed from 0.410 in 2015 to 0.506 in 2025, representing a net increase of 0.096 or 23.4 percent. This temporal pattern corresponds to an overall improvement in vegetation condition over the study's final years. However, because NDVI is an ecological indicator rather than a direct hydrological measure, the increase should be interpreted as evidence of vegetation recovery during flood mitigation and restoration activities, rather than direct evidence of reduced flood discharge or flood depth. The comparison with Nyandungu Eco-Park provides helpful contextual evidence, but differences in site history, restoration design, data periods, and climatic circumstances prevent the two wetlands from being viewed as directly identical. Retention-basin areas (zone C) had the greatest post-intervention mean NDVI (0.510) and were substantially different from zones A, B, and D in Tukey HSD comparisons ($p = 0.003$, 0.042, and 0.008, respectively). This pattern is consistent with the ecological function predicted of retention-based interventions, which hold runoff and might keep local conditions wetter, perhaps promoting wetland vegetation. The spatial concentration of improvement around retention basins adds to this conclusion. Nonetheless, because the study was observational and the intervention zones were not assigned at random, other environmental and site-specific factors could have contributed to zone C's greater NDVI. Zones A and B similarly had favorable or steady vegetation

responses over the study period. Zone A grew by 0.061 between the 2015-2016 and 2024-2025 comparative periods, whereas zone B climbed by 0.077; both increases were statistically significant. These findings suggest that drainage and embankment regions are not only connected with vegetation decrease. Their ecological response may vary depending on design, neighboring land cover, water exchange, maintenance, and other local factors. The results thus promote continuous ecological development of these facilities, rather than a general conclusion that one infrastructure type is necessarily beneficial.

Zone D, which received no direct flood mitigation action, showed a 0.059 rise between comparison periods, although the difference was not statistically significant ($p = 0.069$). The decreased post-intervention NDVI relative to zone C, as well as the concentration of some degradation hotspots in zone D, are consistent with the reference area's slower vegetation recovery. However, the control zone was not randomized and may differ from the intervention zones in terms of land use, disturbance, hydrology, and other features. As a result, the findings offer comparative evidence of various vegetation responses rather than conclusive confirmation that intervention caused the observed variances.

There was a significant association ($r = 0.78$, $p < 0.01$) between March-May rainfall and July-August maximum NDVI. This demonstrates that rainfall variability had a significant impact on vegetation dynamics over the research period. The relatively high NDVI recorded in 2025 despite below-average seasonal rainfall implies that rainfall alone could not explain all observed vegetation patterns. Nonetheless, the correlation analysis cannot distinguish the independent effects of rainfall from those of restoration measures, soil conditions, pollution, land-cover change, or maintenance efforts. The rainfall results should thus be viewed as evidence of a substantial climatic relationship rather than proof of causality.

The break-point analysis revealed significant periods of deterioration and recovery in the NDVI series. The fall from 2016 to 2017 and subsequent recovery in 2017-2018 happened along with changes in environmental and restoration circumstances, but the decline from 2020 to 2021 coincided with active development of flood prevention infrastructure. Construction-related vegetation disturbance is a feasible explanation for some of the transitory drop, but the existing data does not independently evaluate that mechanism. The continuous recovery from 2022 to 2025 is consistent with vegetation establishment and ongoing restoration, albeit climatic and site-specific factors remain important. The study has significant drawbacks. First, NDVI was chosen as the primary indicator of vegetation recovery, indicating an ecological response rather than a direct measurement of flood attenuation. Hydrological variables like peak discharge, flood depth, flood volume, and inundation duration were not measured directly. Second, the quasi-experimental approach cannot entirely eliminate confounding variables because the intervention zones were not assigned at random. Third, rainfall was strongly associated with NDVI, showing that climatic variability played a significant role in vegetation dynamics. Fourth, industrial contamination was assessed mostly using secondary evidence rather than primary soil and water-quality data, restricting the ability to estimate its independent impact. Finally, restoration was still going on during the study period, thus the 2025 observations should be taken as an intermediate restoration reaction rather than a final judgement of restoration success.

5. CONCLUSION

The first the first specific objective was to determine the flood mitigation services provided in Gikondo wetland. The study identified three types of flood mitigation services: 4.2 kilometers of drainage channels (zone A), 3.8 kilometers of embankments (zone B), and four retention basins with a combined storage capacity of 12,000 cubic meters (zone C). A control zone with no direct intervention (zone D) was also identified for comparison. Regarding the spatial characteristics of the restored wetland, Gikondo Wetland showed measurable improvement in vegetation health from 2015 to 2025. Vegetation health, as measured by maximum NDVI, improved by 23.4 percent from 2015 (0.410) to 2025 (0.506), with a positive trend approaching statistical significance (slope = 0.0089, $R^2 = 0.34$, $p = 0.06$). Break-point analysis identified three significant phases: sharp decline during 2016–2017 (peak degradation), rapid recovery during 2017–2018 (initial restoration), temporary decline during 2020–2021 (construction disturbance), and sustained recovery from 2022 to 2025 (establishment phase).

The second specific objective was to assess the spatial characteristics of the Gikondo restored wetland. The study found that all three intervention types had higher mean post-intervention NDVI than the control zone. Zone C (retention basins) had the highest mean post-intervention NDVI (0.452), representing a 5.7 percent improvement from pre-intervention levels. Zone A (drainage

channels) showed a 3.1 percent improvement (0.428). Zone B (embankments) showed stable NDVI (0.415, 0.0 percent change). Zone D (control) showed a decline of 4.8 percent (0.396). ANOVA revealed statistically significant differences among zones ($F = 4.52$, $p = 0.005$). Post-hoc Tukey HSD tests showed that Zone C had significantly higher NDVI than Zone D (mean difference = 0.056, $p = 0.031$). Spatial analysis confirmed that Zone C had the highest percentage of area showing improvement (62 percent) and the lowest percentage showing degradation (18 percent).

The third specific objective was to determine the contribution of flood mitigation services to wetland restoration from other influencing factors. The correlation between seasonal rainfall (March–May) and maximum NDVI (July–August) was positive and strong ($r = 0.78$, $p < 0.01$). This indicates that seasonal rainfall was strongly associated with subsequent vegetation condition. However, the relatively high NDVI observed in 2025 despite below-average seasonal rainfall suggests that factors other than rainfall also contributed to the observed vegetation condition. The analysis does not by itself establish the independent causal contribution of flood mitigation interventions. Secondary evidence indicates that Gikondo Wetland has experienced long-term industrial pressures, but the independent effect of pollution on NDVI could not be quantified statistically because the study did not include primary soil or water-quality sampling. Pollution is therefore treated as an important contextual factor rather than a measured causal variable.

Overall, the results indicate an association between flood mitigation intervention areas and improved vegetation condition, particularly around retention basins. However, NDVI does not directly measure flood attenuation, and restoration was still ongoing. Continued ecological and hydrological monitoring is therefore required.

6. Supplementary Information

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