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Land Cover Change Assessment, Prediction Modelling, and Ecosystem Service Implications in Lubigi Wetland, Kampala, Uganda

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Abstract

Urbanization and agricultural expansion often result in the degradation of natural wetlands, leading to significant ecological impacts. This study explored the dynamics of land cover changes and their implications on ecosystem services in Lubigi Wetland, Kampala, Uganda. The objectives were to assess the dynamics of land cover changes between 1999 and 2022, predict future land cover scenarios for 2030, and identify the ecosystem services under threat due to wetland degradation. Sentinel-2 and Landsat imagery were processed using ArcGIS and the Land Change Modeler (LCM) to assess land cover transitions. Multi-Layer Perceptron (MLP) neural network and Markov Chain analysis were employed to model future land cover scenarios. Land cover transitions were quantitatively calculated in terms of gains, losses, and net change. Regression analysis was used to identify key drivers of wetland degradation. The ecosystem services evaluated were categorized into regulating, provisioning, cultural, and supporting services. The findings reveal significant land cover changes in Lubigi Wetland from 1999 to 2022, with built-up areas increasing by 1140.60% from 10.74 km^2 in 1999 to 122.5 km^2 in 2022, while wetland areas decreased by 49.5%, from 453.54 km^2 to 228.96 km^2. By 2030, built-up areas are predicted to expand further to 279 km^2, and wetland areas are projected to shrink to 200 km^2. The loss of wetland area has had a profound impact on ecosystem services, particularly in flood regulation, water quality, and biodiversity support, all of which have been significantly degraded due to increasing anthropogenic pressures. The results suggest that population growth and urban expansion are major drivers of wetland degradation, and urgent conservation measures are necessary to mitigate further damage. The MLP neural network demonstrated an accuracy rate of 87.64%, supporting its use in land cover change modelling. The study concludes that without intervention, the continued expansion of anthropogenic land cover will exacerbate the loss of critical ecosystem services, further threatening the ecological stability of Lubigi Wetland.

Keywords

Land Change Modeler, Land Use Land Cover, Markov Chain, Multi-Layer Perceptron, Wetland degradation, Remote sensing, Lubigi Wetland, Kampala, Uganda

1. Introduction

Wetlands are among the most productive ecosystems globally, providing provisioning, regulating, supporting, and cultural services that sustain biodiversity and human well-being [1] [2]. They play critical roles in flood regulation, water purification, climate mitigation, and carbon storage [3] [4]. Despite their importance, wetlands have been degraded worldwide due to urban expansion, agriculture, and infrastructure development [5] [6].

In Africa, wetlands are increasingly threatened by unsustainable land use practices and weak policy enforcement [7] [8]. Uganda, with wetlands covering approximately 13% of its total land area, has experienced significant wetland losses, estimated at 2% annually [9] [10]. The Lubigi Wetland, located in northwestern Kampala, exemplifies this trend. Once a critical ecological buffer, it has been increasingly encroached upon by settlements, agriculture, and industrial activities [11] [12].

Previous studies on Lubigi have documented ecological functions [11], land use pressures [13] [14], and biodiversity values [15], but comprehensive analyses integrating historical land cover change, predictive modelling, and ecosystem service implications remain limited. Advances in remote sensing and predictive modelling now allow for robust assessments of land cover dynamics and future trajectories [3] [16] [17].

This study aimed to:

1. Assess historical land cover changes in Lubigi Wetland between 1999 and 2022.
2. Predict land cover scenarios for 2030 using a Multi-Layer Perceptron neural network and Markov Chain analysis.
3. Evaluate the implications of land cover change on wetland ecosystem services.

2. Literature Review

Wetlands contributed disproportionately to global ecosystem services despite covering only a small fraction of the Earth's surface [2] [4]. They supported biodiversity, stored carbon, and provided flood regulation, water purification, and food security [1] [18]. However, population growth, agriculture, and urban development were identified as major drivers of wetland degradation worldwide [5]-[7].

In Africa, wetland resources were under increasing pressure from irrigation projects, land reclamation, and weak institutional frameworks [8] [19]. Studies highlighted their economic value [8] and vulnerability to unsustainable exploitation [10]. The Ramsar Convention provided guidelines for sustainable wetland management [17] [20], but implementation across many African countries, including Uganda, remained inadequate [21] [22].

In Uganda, wetlands covered about 13% of the country and played critical ecological and socio-economic roles [9]. Despite this, degradation was accelerating, particularly around urban centers like Kampala [13] [14]. The Lubigi Wetland, located within the Kampala-Mukono corridor, had been reported to be heavily encroached upon by agriculture, settlement, and industrial development [11] [12] [15]. Such degradation reduced its capacity to regulate floods, purify water, and support biodiversity [11] [14] [15].

Remote sensing and Earth Observation tools had increasingly been applied to assess land cover changes and wetland dynamics [3] [6] [16]. Object-oriented classification and satellite-based monitoring demonstrated strong potential in capturing wetland loss trends [3] [16]. Prediction models, including neural networks and Markov Chain analysis, had been successfully applied to project land cover changes under different scenarios [23] [24]. Nevertheless, few studies integrated these methods with ecosystem service assessment to guide policy and urban planning [12] [25] [26].

3. Materials and Methods

3.1. Study Area

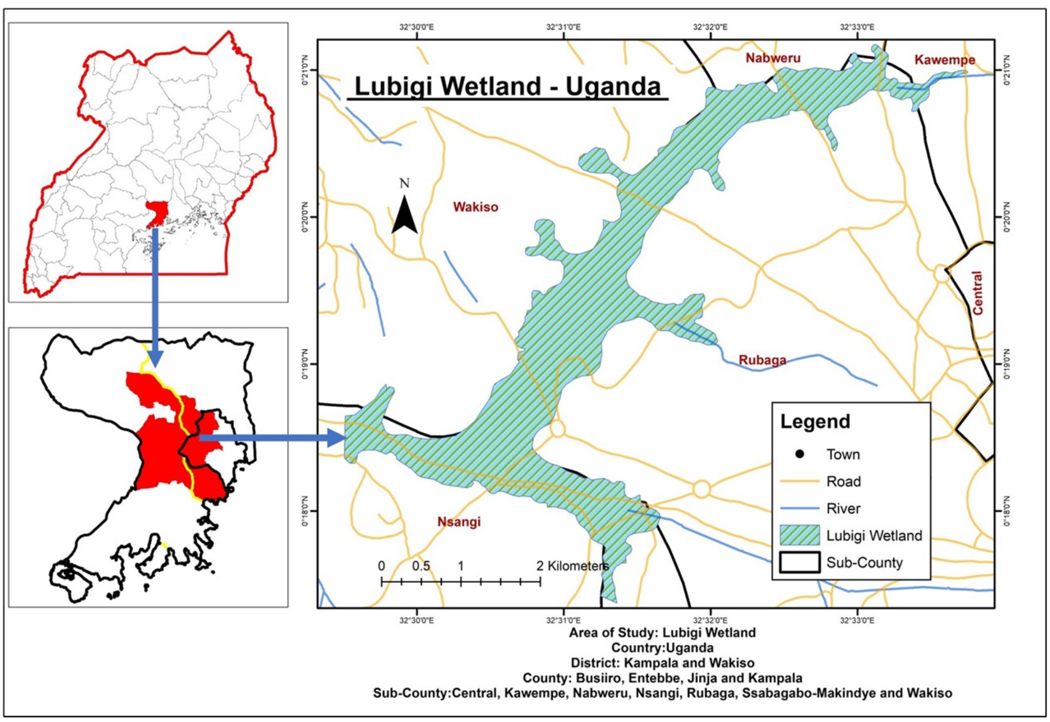

Figure 1. Study area map (Source: Waswa, 2021).

The study area as shown in **Figure 1** focused on Lubigi Wetland, located in north-western Kampala, Uganda. The wetland formed part of the greater Lake Victoria Basin and provided ecological services such as flood regulation, water purification, and habitat for biodiversity [9] [11]. However, the wetland had been increasingly encroached upon by settlements, agriculture, and industrial activities [13] [14]. The methodology employed is shown in **Figure 2**.

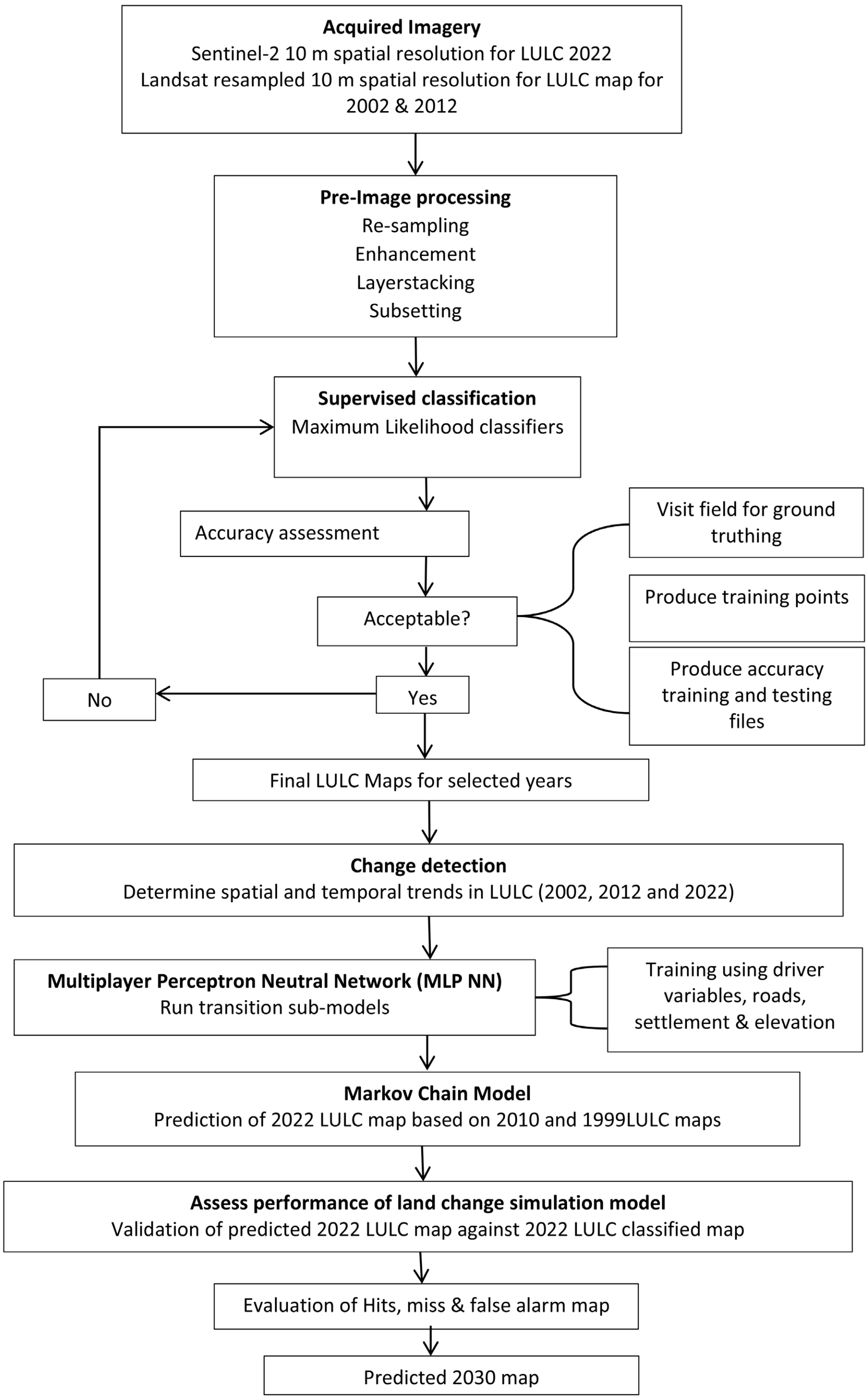

Figure 2. Methodology flowchart (Source: Waswa, 2021).

3.2. Data Sources

Satellite imagery from Landsat (1999, 2010) and Sentinel-2 (2022) were used to analyze land cover dynamics. Landsat images with a spatial resolution of 30 m were resampled to 10 m to match Sentinel-2 resolution. Ancillary data included population statistics from Uganda Bureau of Statistics and secondary literature on wetland dynamics [9] [26].

3.3. Image Processing and Classification

Preprocessing included geometric and radiometric corrections. Land cover maps were generated using the Maximum Likelihood Classification algorithm, which had been widely applied in wetland and land use studies [3] [6] [16]. Five land cover classes were identified: wetlands, built-up areas, cropland, forest, and water bodies.

3.4. Accuracy Assessment

Accuracy of classification was evaluated using ground control points and high-resolution imagery. A confusion matrix and kappa coefficient were generated to determine classification reliability [27].

3.5. Prediction Modelling

The LULC projection process for 2030 used a transition sub-model structure. The analysis was conducted using logistic regression models and a Multi-Layer Perceptron (MLP) neural network in the Land Change Modeler [23] [24]. Driver variables incorporated into the MLP included road networks, settlement distribution, and elevation, which were selected to represent accessibility, demographic pressure, and physical constraints on land cover change. This structured approach enabled the identification of land cover transitions and persistence between 1999 and 2010, thereby supporting 2030 projections. The main findings show that at least 1905 cells changed land cover classes during this time, but a significant number of cells (25,468) remained in the same land cover class. The sample size for the analysis was 1,905, with a 50% split between training and testing data.

3.6. Ecosystem Service Assessment

Ecosystem services were assessed by linking land cover categories with provisioning, regulating, supporting, and cultural functions [4] [5] [18]. Changes in land cover were analyzed to infer impacts on wetland services such as flood regulation, biodiversity, and carbon storage.

4. Results and Discussion

4.1. Land Cover Change (1999-2022)

The classified land cover maps for 1999, 2010, and 2022 illustrated significant transformations within the Lubigi Wetland (**Figure 3** and **Figure 4**). Between

1999 and 2022, built-up areas expanded from 10.74 km^2 to 122.5 km^2, representing a 1040% increase. Conversely, wetlands declined from 453.54 km^2 to 228.96 km^2, a loss of nearly 50%. Cropland expanded significantly, while forest and water bodies remained relatively stable.

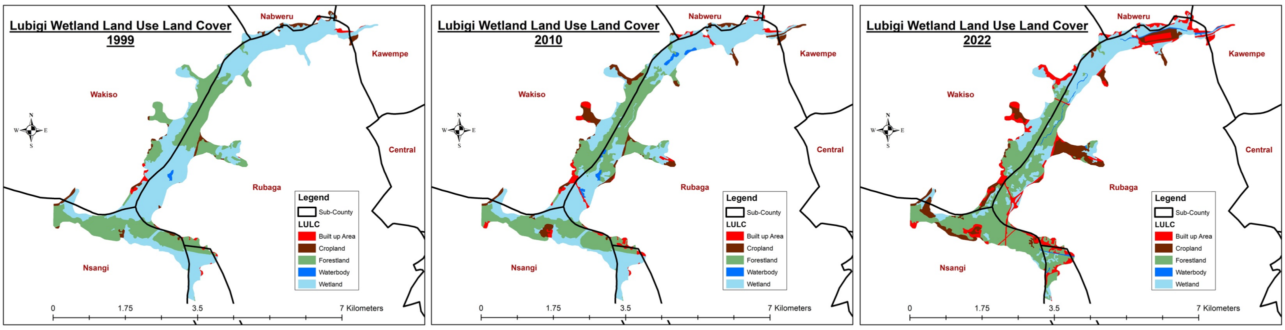

Figure 3. Spatial distribution of land cover in Lubigi wetland (1999-2022).

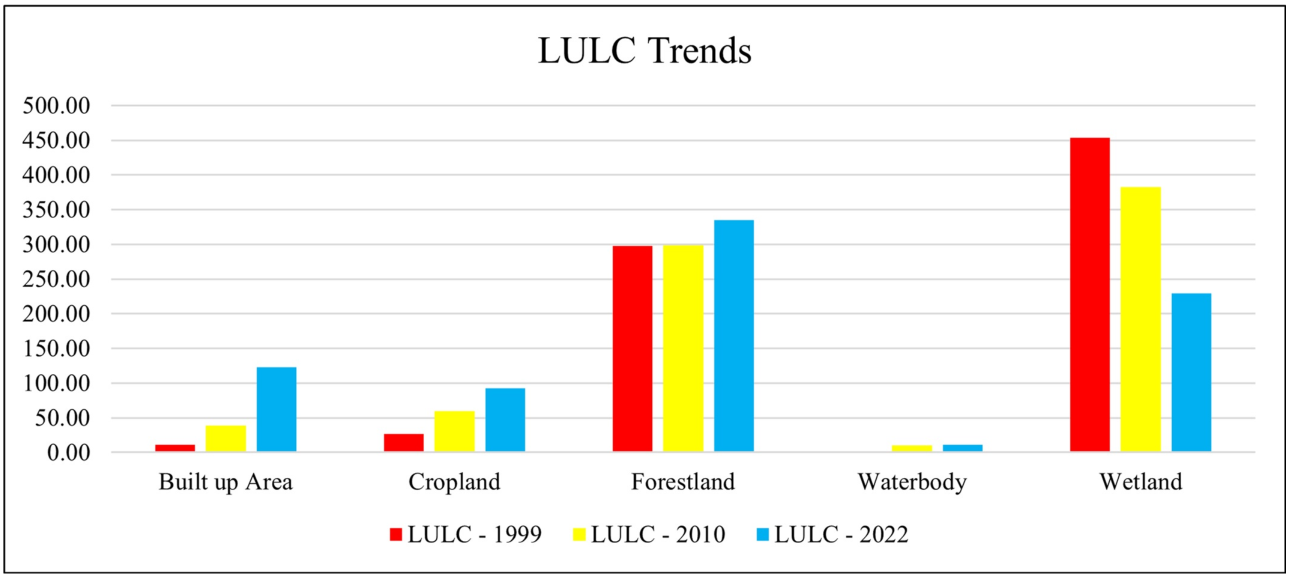

Figure 4. Trends in land use and land cover change in km^2 for Lubigi wetland (1999-2022).

Table 1. Land use and land cover change in km^2 of Lubigi wetland (1999-2022).

LULC	1999	2010	2022
Built up Area	10.74	38.80	122.50
Cropland	26.68	60.02	92.88
Forestland	297.35	298.83	334.83
Waterbody	2.05	10.39	11.19
Wetland	453.54	382.33	228.96
Total	790.37	790.37	790.37

The land cover change statistics are summarized in Table 1, which shows the change in each category. Wetlands were the most affected, highlighting the scale of anthropogenic pressure. These results were consistent with earlier studies that identified urban expansion and agriculture as major drivers of wetland degradation in Uganda [11] [14] [15].

4.2. Prediction Modelling (2030 Scenario)

The Land Use and Land Cover (LULC) classes were merged into three categories, namely: Anthropogenic (Built-up Area and Cropland), Forestland, and Wetland (Waterbody and Wetland). This reclassification was undertaken to reduce model complexity and improve predictive performance by minimizing confusion among spectrally similar classes, while still preserving the ecological and socio-economic relevance of key land cover types. Similar aggregation of LULC classes has been applied in previous modelling studies to enhance robustness and interpretability [23]. Grouping Built-up and Cropland into "Anthropogenic" emphasized human-driven land transformations, whereas Forestland and Wetlands were retained as distinct categories due to their ecological importance and vulnerability to degradation. Using this simplified classification, the Multi-Layer Perceptron (MLP) neural network and Markov Chain model projected continued wetland decline and urban expansion by 2030 (**Figure 5**). Built-up areas were expected to reach 279 km^2, while wetlands would shrink further to 200 km^2. The validation demonstrated strong overlap between observed and predicted land cover, with the model achieving an accuracy of 87.64%. This performance aligned with reported applications of similar predictive approaches in land use modelling [6] [24].

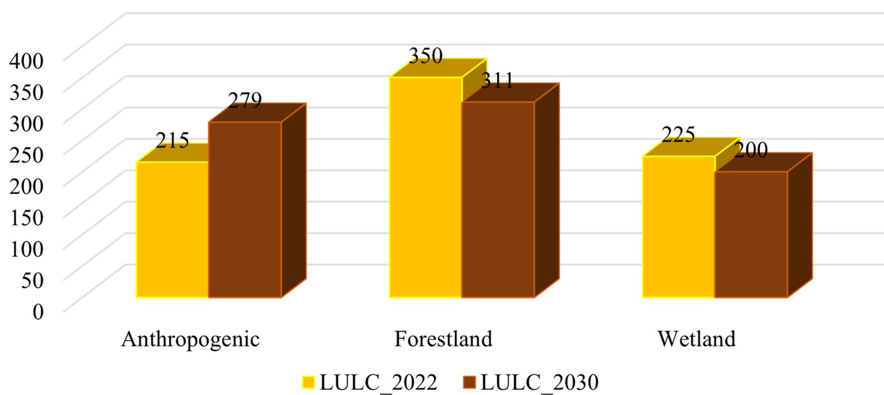

Figure 5. Projected land use land cover changes in km^2 (2022-2030).

These projections indicated that without intervention, wetland loss in Kampala would accelerate, intensifying ecological vulnerability.

4.3. Drivers of Land Cover Change

Regression analysis results (**Table 2**) revealed a strong positive correlation ($r = 0.985$, $p < 0.05$) between population growth and the expansion of built-up areas, based on four paired data points derived from population figures and land cover extent (km^2) for the analyzed years. This indicates demographic pressure as a key driver of wetland degradation [9] [26]. However, the small sample size (n = 4) represents a limitation, and the results should therefore be interpreted with caution. Infrastructure development, road construction, and informal settlements along the Kampala-Mukono corridor further contributed to the observed wetland losses [13] [14].

Table 2. Regression analysis results.

Parameter	Value
Pearson Correlation Coefficient (r)	0.9854
r^2	0.971
P-value	0.01458
Covariance	206522000
Sample Size (n)	4
Statistic	8.1902

4.4. Implications for Ecosystem Services

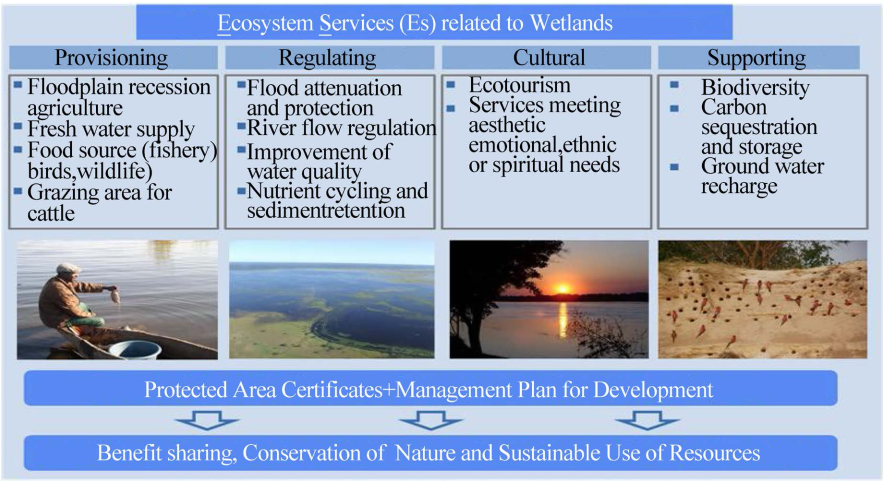

Figure 6. Ecosystem services related to wetland.

Ecosystem services were assessed by linking land cover categories with ecosystem functions using a qualitative matrix approach developed from the literature [4]. The decline in wetland cover had already undermined critical ecosystem services. Flood regulation capacity was reduced, increasing the frequency and severity of urban flooding (**Figure 6**) [11][12]. Water purification and groundwater recharge functions were diminished, contributing to declining water quality in Kampala [4] [18]. The loss of wetland vegetation also reduced carbon sequestration potential, undermining climate change mitigation [1] [2] [12]. Biodiversity support functions were threatened, with field-based studies reporting declines in bird and aquatic species populations [15]. In addition, the degradation of Lubigi Wetland diminished cultural ecosystem services. Recreational opportunities and access to natural green spaces have declined, cultural heritage and spiritual values associated with wetlands are eroding, and the role of wetlands as outdoor learning environments has been weakened, undermining both social well-being and community engagement in conservation [4].

4.5. Comparison with Other Studies

The observed trends in Lubigi were consistent with global wetland loss patterns, where urbanization and agricultural expansion remained the primary drivers [2] [5] [6]. Comparable studies in Greater Cairo [6] and papyrus swamps in East Africa [5] reported similar declines in wetland ecosystem services.

These results reinforced the importance of predictive modelling in anticipating environmental change and informing sustainable urban planning [3] [16] [17].

5. Conclusion and Recommendations

This study demonstrated that Lubigi Wetland experienced rapid land cover changes between 1999 and 2022, with built-up areas expanding more than tenfold while wetland cover declined by nearly half. Prediction modelling indicated that by 2030, built-up areas were expected to increase further to 279 km^2, while wetlands would shrink to 200 km^2. These findings confirmed that urbanization and agricultural encroachment were the main drivers of wetland degradation, strongly correlated with population growth and infrastructure expansion.

The decline in wetland cover had already reduced the wetland's capacity to regulate floods, purify water, support biodiversity, and store carbon. Without timely intervention, ecosystem service losses were expected to intensify, undermining both ecological integrity and human well-being in Kampala.

Based on these findings, the following recommendations were made:

1. Strengthen wetland protection policies: Enforcement of existing legislation and urban planning regulations should be prioritized to curb illegal encroachment.

2. Promote community engagement: Local communities should be involved in wetland management through education and sustainable livelihood alternatives.

3. Integrate predictive modelling into planning: Tools such as MLP and Markov Chain models should inform urban development and conservation strategies.

4. Restore degraded wetland areas: Rehabilitation of buffer zones and reforestation programs could help recover lost ecological functions.

5. Mainstream wetland conservation in development planning: National and local governments should integrate wetland conservation into broader urban development frameworks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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