Spatial Analysis of Urban Wetland Ecosystem Service Value Changes in Muthurajawela Marsh and Negombo Lagoon, Sri Lanka

January 2022

Athukorala Arachchige Sumudu DARSHANA

Spatial Analysis of Urban Wetland Ecosystem Service Value Changes in Muthurajawela Marsh and Negombo Lagoon, Sri Lanka

A Dissertation Submitted to
the Graduate School of Life and Environmental Sciences,
the University of Tsukuba
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in Science
(Doctoral Program in Geoenvironmental Sciences)

Athukorala Arachchige Sumudu DARSHANA

Abstract

The Muthurajawela Marsh and Negombo Lagoon (MMNL), the biggest coastal saltwater peat bog in Sri Lanka, is located in the Colombo Metropolitan Region (CMR), the country's capital and the location of the MMNL. During the past two decades, the CMR has grown very rapidly; the MMNL's natural environment and the combined wetland ecosystem services they provided (flood attenuation, industrial wastewater treatment, agriculture production, and support to downstream fisheries) are now in danger. Therefore, the state of the MMNL and the trajectory of Land Use/Cover (LUC) change should be evaluated urgently before more irreparable ecological damage occurs.

The main objectives of this study are to project future LUC and wetland ecosystem services value (ESV) changes in the MMNL and to explain their implications for future wetland landscape conservation and urban planning. Geospatial data, tools, and techniques such as Remote Sensing (RS), socio-economic and filed data, Geographic Information System (GIS), the Land Change Modeler (LCM), and ESV coefficients have been used to (1) calculate the LUC and ESV changes from 1997 to 2017; (2) examine the driving force of urbanization and spatial drivers for LUC change and (3) predict the future LUC and ESV changes from 2017 to 2030 based on two scenarios. Scenario 1 is Business As Usual (BAU), based on the continued expansion of LUC pattern changes from 2007 to 2017 in all areas, including marshland, mangrove, and protected areas. Scenario 2 is the Ecological Protection scenario (EP), based on the trends of LUC changes from 2007 to 2017, but with the complete protection of two protected areas and with a 20% reduction in the current urban pressure on the MMNL.

The results revealed that the spatial and socio-economic elements of the rapid urbanization of the MMNL had been the main driver of the transformation of its natural environment over the past 20 years. This is indicated by a substantial expansion of settlements (+70%) and a considerable decrease of marshland and mangrove cover (-28% and -42%, respectively). The MMNL's urbanization has been driven by interrelated socio-economic and biophysical factors. The spatial drivers that impact LUC change patterns include distance to road, distance to growth node, distance to lagoon, distance to the protected area, elevation, and slope.

The LUC changes between 1997 to 2017 considerably impaired the total ESV of the MMNL. The results revealed that from 1997 to 2017, the overall ESV of the MMNL has declined by United States Dollar (USD) 8.96 million/year (Sri Lankan Rupees (LKR) 1642 million/year), or about 33%, primarily due to the loss of mangrove and marshland from urban (settlement) expansion. Under the BAU scenario, it would continue to decrease by about USD 6.01 million/year (LKR 1101 million/year), or about 34%, in 2030. However, under the EP scenario, the decrease would only be about USD 4.79 million/year (LKR 878 million/year) or about 27% Among the ecosystem services of the MMNL that have been, and would be, affected the most are flood attenuation, industrial wastewater treatment, agriculture production, and support to downstream fisheries (fish breeding and nursery). Overall, between the two scenarios, the EP scenario is the more desirable scenario for the sustainability of the MMNL. The urban wetland environment and the wetland ecosystem services of the MMNL are immensely significant in accomplishing many vital roles to the city drawlers in the CMR; hence, they should be considered by local government planners and decision-makers.

From the scientific approach, this study has provided insight into the past and future wetland landscape and ESV change in the MMNL, and research methods and techniques related to LUC change modeling and the monitoring of ESV change. Notably, this study has used the LCM to calibrate the LUC change model, measured the LUC modeling accuracy, and investigated the ESV changes in the Grama Niladhari (GN) division level in the context of landscape conservation and urban planning.

Key words: Wetland ecosystem; Urban wetland; Wetland ecosystem services; Muthurajawela marsh; Negombo lagoon; Sustainability; Land change modeling; Scenario modeling

Contents

List of Tables

List of Figures

List of Photos

Acronyms/Abbreviations

MMNL - Muthurajawela Marsh and Negombo Lagoon

CMR - Colombo Metropolitan Region

LUC - Land Use/Cover

ESV - Ecosystem Services Value

RS - Remote Sensing

GIS - Geographic Information System

LCM - Land Change Modeler

BAU - Business As Usual

EP - Ecological Protection

DEM - Digital Elevation Model

USD - United States Dollar

LKR - Sri Lankan Rupees

SDGs - Sustainable Development Goals

ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer

TM – Thematic Mapper

OLI – Operational Land Imager

GN – Grama Niladhari

IMF – International Monetary Fund

CPI - Consumer Price Index

CE - Conversion Equivalent

DS - Divisional Secretary

PA – Protected Area

MLP NN - Multi-Layer Perception Neural Network

FoM - Figure of Merit

SSPs - Shared Socio-economic Pathways

Chapter 1

Introduction

1.1 Background of the study

Wetland ecosystems provide a wide range of valuable ecosystem services, such as flood control, pollution control, water conservation, and climate regulation (Ghermandi et al., 2016; Sinclair *et al.*, 2021). They feature prominently in the United Nations' Sustainable Development Goals (SDGs) and targets (https://sdgs.un.org/goals). In urban areas, urban wetland ecosystems play important roles, providing ecosystem services that contribute to the maintenance and sustainability of urban ecological environment and the overall safety and livability of urban regions (Tong *et al.*, 2007; Huang *et al.*, 2019; Assefa et al., 2021). However, anthropogenic activities such as industrialization, agricultural expansion, and urbanization have changed, diminished, or destroyed most wetlands in recent decades (Wu et al., 2017; Kharazmi *et al.*, 2018), including urban wetland ecosystems (Athukorala *et al.*, 2021).

In this study, I examined the impacts of urbanization on the natural landscape and ecosystem services of the Muthurajawela Marsh and Negombo Lagoon (MMNL), an important urban wetland ecosystem and one of the top priority wetlands in Sri Lanka. Here, I used settlement expansion as a proxy indicator of urbanization, where settlement is a land use/cover (LUC) class that includes low-intensity and high-intensity urban areas, industrial zones, transportation hubs, airports, home gardens, asphalt areas, and residential areas. Owing to its geographical and biophysical characteristics, the MMNL is a source of valuable ecosystem services, such as flood attenuation, water purification, carbon sequestration, and fish breeding and nursery (Emerton and Kekulandala, 2003; National Wetland Directory of Sri Lanka, 2006).

However, because of rapid and uncontrolled urbanization that has led to the loss of natural cover (Subasinghe *et al*., 2016; Athukorala *et al.*, 2021), this study hypothesize that these ecosystem services, including the ecosystem service value (ESV) of the MMNL have been affected. Among the major challenges that local government planners and decision-makers and other concerned groups and individuals are facing today is how the MMNL's curve of continuous ecological degradation can be flattened. The goal of this study is to help inform landscape and urban planning towards this context and for the sustainability of the MMNL in general.

In previous studies, the concept of ecosystem services has been included in spatiotemporal monitoring and assessments of the impacts of urbanization in many parts of the world, both in non-wetland urban regions (Estoque and Murayama, 2016; Sun *et al.*, 2018; Zhou, Tian and Jiang, 2018; Dai *et al.*, 2020; He *et al.*, 2021) and in urban wetland regions (Tong *et al.*, 2007; Assefa et al., 2021). Advances in geospatial technology, including the increasing availability of Earth observation (remote sensing) data at various spatial and temporal resolutions, have helped to improve social-ecological monitoring and assessments. Furthermore, the development of land change models has helped researchers to project future LUC changes and explore different scenarios (Swetnam *et al.*, 2011; Estoque and Murayama, 2012, 2016; Yirsaw *et al.*, 2017; Sun *et al.*, 2018). This information could be useful for landscape conservation, urban development planning, and policy implementation for the wise use and protection of the remaining wetland ecosystem.

1.2 Literature Review

This study aimed to analyze the LUC change of the MMNL and its impact on its combined ecosystem services. RS data were important in classifying the LUC maps for the study area, which this study heavily relied on. A brief review of literature related to the LUC change studies and the wetland ecosystem services studies is presented.

Wetland ecosystems are our natural wealth, and they provide free services worth trillions of dollars per year (Costanza *et al.*, 1997, *Ramsar*, 2015). Among the pioneer researchers of ecosystem services are Costanza et al., 1997. They categorized the global biome into 16 ecosystems (including wetlands) and 17 service functions and then assessed the ecosystem service value (ESV). Literature shows that monitoring the LUC change is critical for investigating the potential impact of landscape changes on the ecosystem services of a given area (Estoque and Murayama, 2012; Su *et al.*, 2012). For example, Joy and Paul, 2021 studied the economic value and status of the ecosystem services in the Ashtamudi wetland area in Kerala, India. They found the total wetland economic value was United States Dollars (USD) 424 million in 2017. The growing body of literature indicates that scenario-based urban LUC changes modeling and calculating the future ESV play a significant role in giving insights to the policymakers and urban planners.

Several studies have been conducted to investigate various aspects of the MMNL. For example, Athukorala *et al.*, 2021 have studied the impacts of urbanization on the MMNL, emphasizing implications for landscape planning towards a sustainable urban ecosystem. Jayathilake and Chandrasekara, 2015 have investigated the variations of avifaunal diversity concerning land use modifications in the Negombo estuary. Emerton and Kekulandala, 2003 have assessed the economic value of the Muthurajawela Marsh. Bambaradeniya *et al.*,2002 have studied the biodiversity status in the Muthurajawela wetland sanctuary. However, I am not aware of any study that monitored the past-present changes and/or projected the future changes in the ecosystem services and ESV of the MMNL based on Earth observation data and geospatial techniques.

1.3 Remaining challenge

There are no studies that have monitored the past-present changes and/or projected future changes in wetland ecosystem services and Ecosystem Service Value (ESV) of the MMNL based on remote sensing and geospatial techniques.

1.4 Research objectives

The primary objective of this research was to assess changes in the ESV of the MMNL based on LUC changes over the past two decades (1997–2017) using Earth observation data. Considering two plausible scenarios, namely a business-as-usual (BAU) scenario and ecological protection (EP) scenario, and using a spatially explicit land change model, this study simulated future (2030) LUC changes in the area and estimated potential consequent future changes in the ESV of the MMNL. This study discussed the implications of the results in the context of the MMNL's sustainability.

1.5 Study area

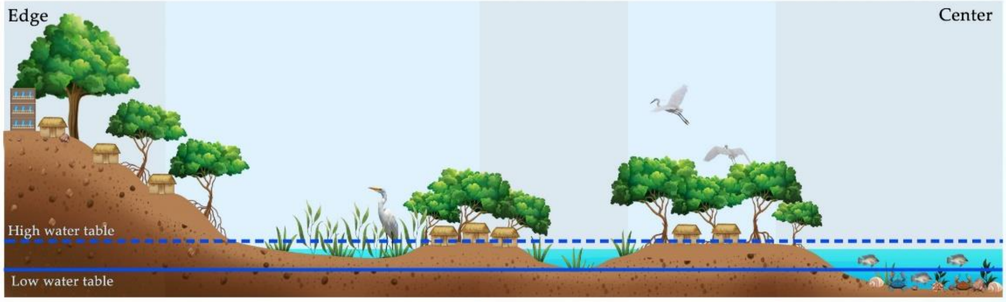
Figure 1-1 shows a cross-section of the MMNL, classified into five ecological zones, each with a description of the level of anthropogenic activities, water conditions, soil groups, vegetation types, and some ecosystem services. The MMNL is situated on the western coastal plain of Sri Lanka, within the Colombo Metropolitan Region (Figure 1-2). It has a total area of approximately 134 km^2 (Athukorala *et al*., 2021). In 1996, the Government of Sri Lanka designated the northern section of the MMNL as a wetland sanctuary (Muthurajawela Sanctuary) owing to its high ecological and biological significance (National Wetland Directory of Sri Lanka, 2006) (Figure 1-2, PA1). In 2006, another protected area was designated by the government (Muthurajawela Environmental Protection Area) for ecosystem services, including flood control (Central Environment Authority, Sri Lanka) (Figure 1-2, PA2) (more details - Appendix 1).

The Negombo Lagoon is linked to the Indian Ocean by a single narrow opening at the northern end of the channel segment (Figure 1-2). The Muthurajawela Marsh stretches southward from the lagoon, forming the largest coastal peat bog in the country (Athukorala *et al., 2021*). The elevation range is approximately from –13 to 44 m above sea level. This urban wetland ecosystem receives plenty of rainwater from the southwest monsoon. Annual average rainfall ranges from 2000 to 2500 mm, and annual average temperatures are from 22.5 ^{0}C to 25.0 ^{0}C (Department of Meteorology, Sri Lanka).

The marsh plant vegetations are in their final stages of succession, leading to dry land formation (National Wetland Directory of Sri Lanka, 2006). In the MMNL, 194 species of flora have been recorded under seven major plant communities—marsh, reed swamp, short grassland, shrubland, lentic, stream bank, and mangrove swamp. For species of fauna, 40 fishes (4 of which are endemic and nationally endangered), 14 amphibians, 31 reptiles, 102 birds (1 endemic and 19 winter migratory birds), and 22 mammals have also been recorded (National Wetland Directory of Sri Lanka, 2006). The aquatic resources are abundant in phytoplankton, phosphors, and algae, all of which are essential components in the food web of various organisms (Environmental Profile of Muthurajawela and Negombo Lagoon, 1991).

Today, the sustainability of this valuable urban wetland ecosystem is under threat from the growing pressure of urbanization. Flattening the MMNL's curve of continuous ecological degradation is important, not only as a research endeavor but also as a landscape and urban planning priority.

Wetland Cross Section – Muthurajawela Marsh and Negombo Lagoon



	Upland Zone	Marsh Zone	Wet Meadow Zone	Mangrove Zone	Aquatic Zone - (Negombo Lagoon)
Anthropogenic activities	High	Moderate	Moderate	Moderate	Moderate
Water	Low	Seasonally/intermittently inundated	Seasonally/ intermittently inundated	Seasonally/ permanently inundated	Permanently inundated (Negombo lagoon)
Soil group	Alluvial soil, latosol, and regosol	Bog and half-bog soil, latosol and regosol, beach and dune sands	Bog and half-bog soil, regosol, beach and dune sands	Bog and half-bog soil	None
Vegetation	Characterized by upland forests, brush land, and mangrove	Characterized by shrubs, sedge, marsh plant and mangrove	Characterized by sedges, grasses and herbs, and mangrove	Characterized by mangrove	Limited
Ecosystem services	Carbon sequestration, and firewood	Carbon sequestration, flood attenuation, and agriculture production	Carbon sequestration, flood attenuation, and leisure and recreation	Carbon sequestration, flood attenuation, and fish breeding and nursery	Fishing, flood attenuation, and leisure and recreation

Figure 1-1. Graphical illustration of the cross-section of the MMNL, divided into five zones (aquatic, mangrove, wet meadow, marsh, and upland). These zones are further characterized based on anthropogenic activities, water level, soil group, vegetation, and ecosystem services. Source: National Wetland Directory of Sri Lanka, 2006, Environmental Profile of Muthurajawela and Negombo Lagoon, 1991, and Athukorala *et al*., 2021.

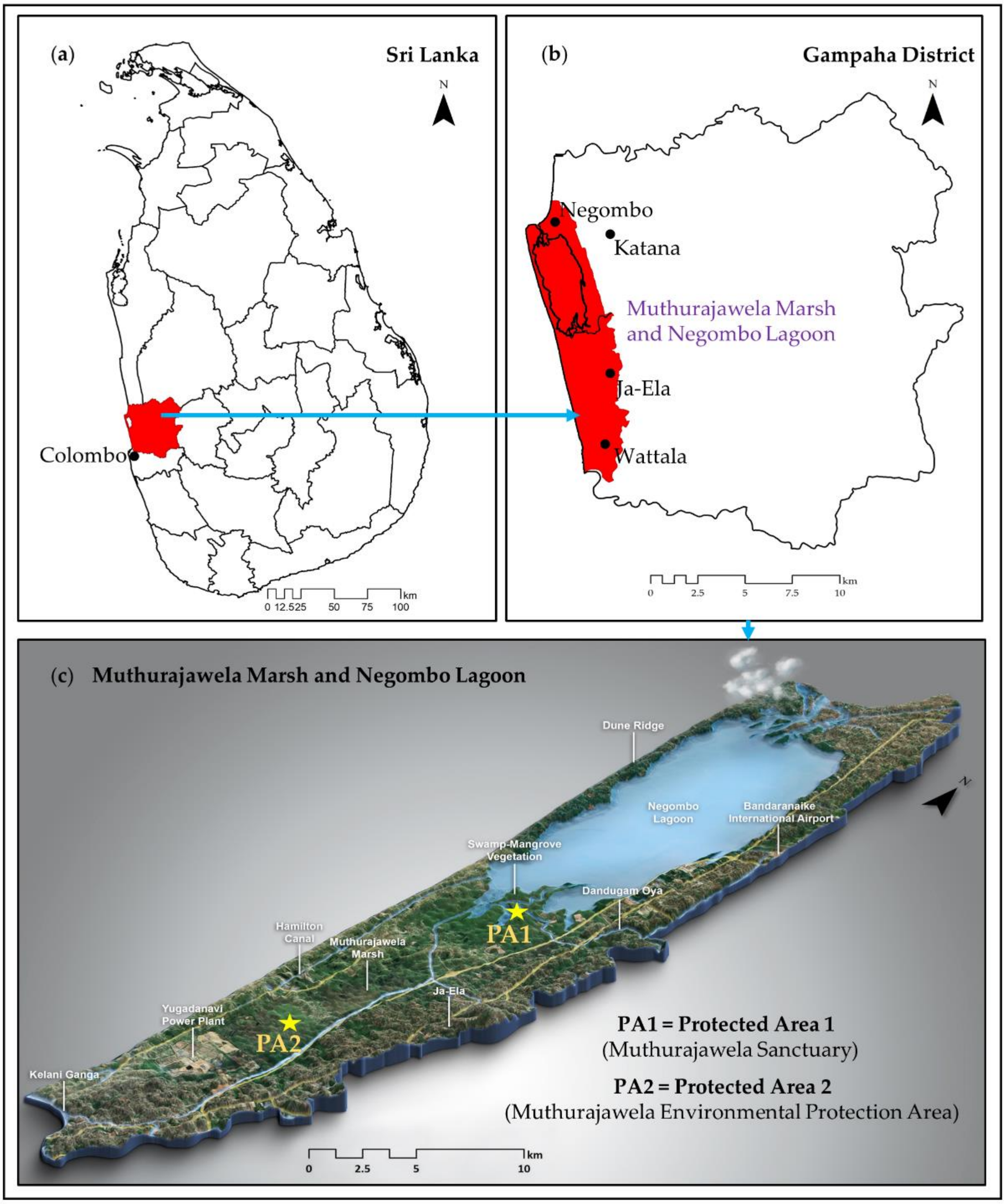


Figure 1-2. Location of the MMNL. (**a**) Map of Sri Lanka, (**b**) Gampaha District, and (**c**) a 3D map of the MMNL produced using a 30 m digital elevation model (ASTER). The Google Earth image was acquired on 17 February 2017.

Chapter 2

LUC and ESV changes in the MMNL (1997-2017)

2.1 Introduction

Advances in geospatial technology, including geographic information systems (GIS) and remote sensing, have greatly improved the monitoring of landscape changes over space and time (Estoque and Murayama, 2012; Su *et al.*, 2012). Today, information derived from these advancements provides important input to landscape planning and decision-making in many contexts, biodiversity conservation, and sustainable urbanization (Athukorala *et al.*, 2021).

Monitoring and evaluating LUC changes and their impact on wetland ecosystem services can help landscape conservation and urban planning (Athukorala *et al.*, 2021). In the LUC monitoring, spatially and temporally consistent LUC maps are required. However, spatially and temporally consistent LUC maps are not easily available in developing countries like Sri Lanka. Wetland-related LUC maps are extremely lacking. This is one of the most critical issues for research in studies involving the spatiotemporal LUC change. The availability of RS data and the necessary tools and technics in data processing has helped to solve such issues.

This chapter presents the assessment of the spatial-temporal changes of LUC in the MMNL from 1997 to 2017 using RS data and GIS techniques. The changes in the ESV in the MMNL were calculated based on the classified LUC maps.

2.2 Data collection

In the absence of spatially and temporally consistent LUC maps of the MMNL, this study relied on multi-temporal medium resolution images (Table 2-1). Two Landsat TM and one Landsat OLI images were collected and processed to assess the spatio-temporal LUC changes in the MMNL for 1997-2007 and 2007 to 2017. These time periods were selected to capture the trend of LUC change caused by the rapid urbanization of the MMNL in recent decades.

This study estimated the ESV changes of the MMNL, ten ecosystem services were considered, and ESV coefficients were transferred from an earlier study in the MMNL (Emerton and Kekulandala, 2003). This study converted the ESV coefficients, which were originally expressed in Sri Lankan Rupee (LKR) (2003 price level), into 2020 USD/ha/year.

The GN division level boundaries were used to estimate the spatial distribution of the ESV in the GN division level in the MMNL.

Table 2-1 Data collection

Data types	Date	Provider	Usage
Satellite data			
Landsat 5 TM	1997-02-07 2007-01-02	The United States Geological Survey (USGS)	LUC change analysis
Landsat 8 OLI	2017-01-13		
Vector data			
Boundaries (GN Level)	2000		Spatial analysis
Value coefficient of each ecosystem service	2003	Emerton and Kakulandala's study	To calculate ESV
Monetary values	**2003 and 2020**	**IMF**	**To transfer LKR-USD**

TM – Thematic Mapper; **OLI** – Operational Land Imager; **GN** – Grama Niladhari; **IMF** – International Monetary Fund; **LKR** – Sri Lankan Rupees; and **USD** – United States Dollars

2.3 Methods

2.3.1 LUC Change Analysis

This study used three LUC maps in this study (1997, 2007, and 2017). This study classified these LUC maps from cloud-free Landsat images (https://earthexplorer.usgs.gov/) captured on 7 February 1997, 2 January 2007, and 13 January 2017, using a supervised classification method, employing the maximum likelihood algorithm (Estoque and Murayama, 2013; Hou et al., 2016; Zhang et al., 2017).

The LUC classification system included four classes, namely marshland, mangrove, settlement, and water. The marshland class included seasonally and intermittently flooded areas, abandoned paddy lands, agricultural lands, marsh plant vegetation, trees, grassland and scrub, peat and bog soil areas, and other cropland areas. The mangrove class included seasonally and intermittently flooded areas with mangroves. The settlement class included low-intensity and high-intensity urban areas, industrial zones, transportation hubs, airports, home gardens, asphalt areas, and residential areas. The water class included the lagoon and other bodies of water such as canals, streams, and ponds.

The accuracy of each LUC map was assessed using 400 reference points generated using a random sampling technique. Google Earth images were used as sources of reference data for 2007 and 2017, while topographic maps of Sri Lanka were used as sources of reference data for 1997.

2.3.2 Calculation of LUC changes in the MMNL

This study calculated the loss (*L*) and gain (*G*) areas and rates for each LUC class using Equations (1) and (2), respectively.

$$\text{L/G area} = A_b - A_a \quad (1)$$

$$\text{L/G rate (\%)} = (A_b - A_a)/A_a \times 100 \quad (2)$$

where, L/G area refers to the area that each class lost or gained (ha). L/G rate refers to the percentage of loss or gain (%) of each class area. A_a and A_b are the beginning and the end values of each class, respectively.

2.3.3 Monitoring ESV Changes

This study estimated the past changes in the ESV of the MMNL (1997–2017), as well as the potential future changes based on the BAU and EP scenarios (2017–2030). This study considered 10 ecosystem services, namely flood attenuation, industrial wastewater treatment, agriculture production, support to downstream fisheries (fish breeding and nursery), firewood, fishing (fisheries production), leisure and recreation, domestic sewage treatment, freshwater supplies for the local population, and carbon sequestration (Table 2-2).

I sourced the needed ESV coefficients from an earlier study in the MMNL (Emerton and Kekulandala, 2003). This study converted the ESV coefficients, which were originally expressed in Sri Lankan Rupee (LKR)/year (2003 price level), into 2020 USD/ha/year equivalents (Equation (3)). To do this, I first expressed the coefficients into 2003 LKR/ha/year, and then converted these 2003 values to the 2020 price level, taking into account inflation. This study used a deflator based on the average consumer price index (CPI, a measure of inflation) in 2003 (44.838) and 2020 (135.367) from https://www.imf.org/en/Home. Subsequently, this study took the average USD–LKR conversion equivalent (CE) in 2020 (I USD = 183.23 LKR) from https://www.cbsl.gov.lk and converted the derived 2020 LKR values to 2020 USD equivalents.

$$\text{ESV (2020 USD)} = \frac{\left(\text{ESV LKR 2003} \times \frac{\text{2020 CPI}}{\text{2003 CPI}}\right)}{\text{2020 CE}} \qquad (3)$$

Table 2-2. Values of the ecosystem services considered in this study. Source of original values: Emerton and Kekulandala, 2003

Ecosystem services	ESV coefficients (2020 USD/ha/year)
Flood attenuation	2607.43
Industrial wastewater treatment	871.69
Agriculture production	162.67
Support to downstream fisheries (fish breeding and nursery)	107.41
Firewood	42.75
Fishing (fisheries production)	33.62
Leisure and recreation	28.36
Domestic sewage treatment	23.20
Freshwater supplies for local population	20.30
Carbon sequestration	4.19

Using the ESV coefficients in Table 2-2, this study estimated the ESV of the MMNL in 1997, 2007, and 2017 following Equation (4) and Equation (5):

$$ESV_f = \sum_{k=1}^{n} A_k \times VC_f \quad (4)$$

$$ESV = \sum_{k=1}^{n} \sum_{f=1}^{m} A_k \times VC_f \quad (5)$$

where, ESV_f and ESV refer to the value of ecosystem service f and the ecosystem service value of the MMNL, respectively. A_k refers to the area (ha) of LUC class k, VC_f refers to the ESV coefficient of ecosystem service f (USD/ha/year) for LUC class k, and n and m refer to the number of LUC classes and ecosystem services considered, respectively. This study considered two LUC classes (marshland and mangrove) and 10 ecosystem services (Table 2-2).

2.3.4 Calculation of ESV in the Grama Niladhari (GN) divisions

This study also mapped the spatial distribution of the 99 Grama Niladhari (GN) divisions that cover the entire MMNL with their respective ESVs. GN divisions are the smallest administrative divisions in Sri Lanka. To do this, first, I conducted a zonal analysis (tabulate area) to determine the LUC composition and extent in each GN division in 1997, 2007, and 2017 using the polygon boundaries of the GN divisions as zones and the LUC maps as inputs. Second, this study estimated the ESV of each GN division using Equation (4) and Equation (5).

2.4 Results

2.4.1 LUC changes (1997-2017)

The overall accuracy was 86.50%, 84.25%, and 84.50% for the 1997, 2007, and 2017 LUC maps, respectively (for confusion matrices of the classified LUC maps of the MMNL- Appendix 2). Over the past 20 years, the MMNL's landscape has undergone considerable changes (Figure 2-1). In 1997, the MMNL had a marshland and mangrove area of 4242 ha and 2637 ha, respectively (Figure 2-2). However, in 2017, their extent decreased to 3058 ha and 1523 ha, equivalent to a 28% and 42% decrease, respectively. By contrast, the area of the settlement has expanded rapidly over the past two decades at the expense of the MMNL's marshlands and mangroves, with 3368 ha in 1997 and 5741 ha in 2017, i.e., equivalent to a 70% increase.

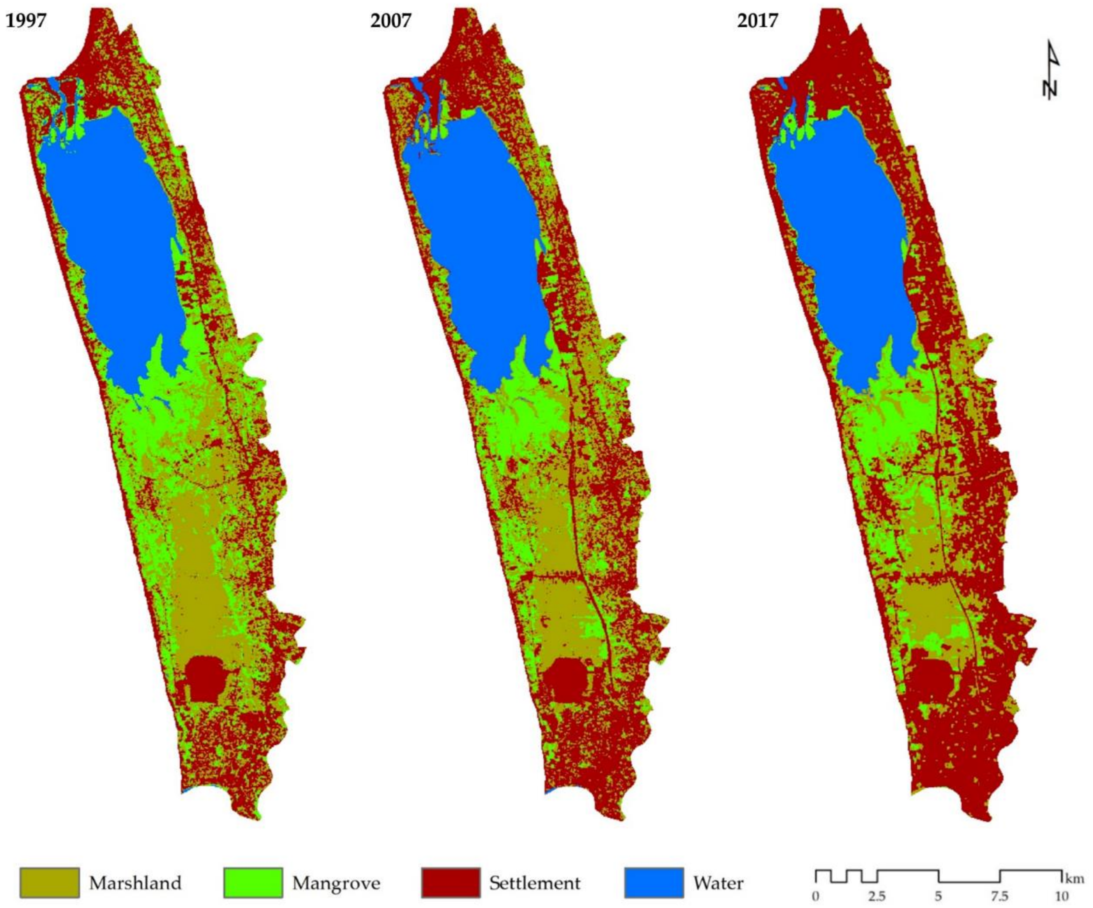


Figure 2-1. LUC maps of the MMNL in 1997, 2007 and 2017.

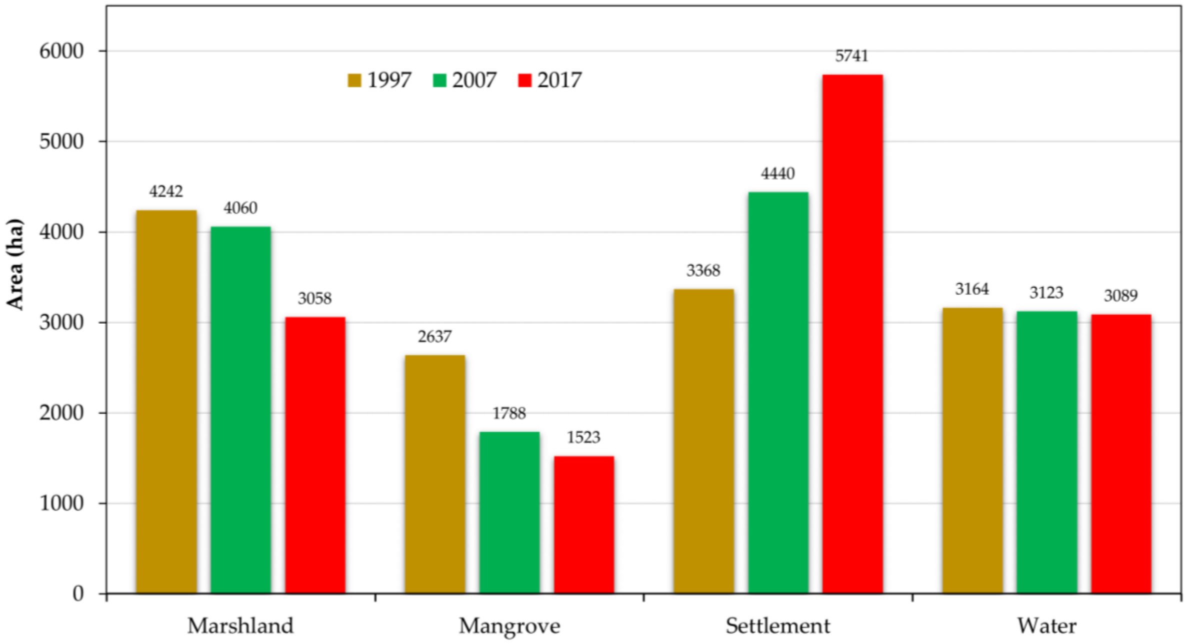


Figure 2-2. LUC changes in the MMNL (1997–2017).

2.4.2 Loss/Gain of the MMNL

Table 2-3 shows the loss/gain of the LUC classes in the MMNL in terms of area and rate. The results revealed that the mangrove class had a net decrease of 1114 ha (42%) from 1997 to 2017, respectively. The marshland class had a net reduction of 1184 ha (28%). By contrast, the settlement class had a net increase of 2373 ha (70%).

Table 2-3. Loss/Gain of the MMNL (1997-2017).

	1997 (ha)	2017 (ha)	L/G area (ha)	L/G rate (%)
Marshland	4242	3058	−1184	−27.90
Mangrove	2637	1523	−1114	−42.26
Settlement	3368	5741	2373	70.47
Water	3164	3089	−75	−2.38

2.4.3 ESV changes in the MMNL (1997-2017)

As a consequence of the significant loss of marshland and mangrove due to urbanization (settlement expansion), the ESV of the MMNL decreased by USD 8.96 million/year, from USD 26.84 million/year in 1997 to 17.88 million/year in 2017, i.e., equivalent to a 33% decrease (Table 2-4). Among the ecosystem services considered, flood attenuation, industrial wastewater treatment, agriculture production, and support to downstream fisheries (fish breeding and nursery) were the top services that were affected the most. Altogether, they accounted for over 95% of the total decrease. The ESV loss of flood attenuation accounted for 67% (USD 6.0 million/year).

Table 2-4. ESV changes in the MMNL (1997-2017).

Ecosystem services	**USD million/year**						
	1997	**2007**	**2017**	**Changes**			
				1997–2007	**% of 1997**	**2007–2017**	**% of 2007**
Flood attenuation	17.94	15.25	11.94	–2.69	–14.99	–3.31	–21.70
Industrial wastewater treatment	6.00	5.10	4.00	–0.90	–15.00	–1.10	–21.57
Agriculture production	1.12	0.95	0.75	–0.17	–15.18	–0.20	–21.05
Support to downstream fisheries (fish breeding and nursery)	0.74	0.63	0.49	–0.11	–14.86	–0.14	–22.22
Firewood	0.29	0.25	0.20	–0.04	–13.79	–0.05	–20.00
Fishing (fisheries production)	0.23	0.20	0.15	–0.03	–13.04	–0.05	–25.00
Leisure and recreation	0.19	0.17	0.13	–0.02	–10.53	–0.04	–23.53
Domestic sewage treatment	0.16	0.13	0.11	–0.03	–18.75	–0.02	–15.38
Freshwater supplies for local population	0.14	0.12	0.09	–0.02	–14.29	–0.03	–25.00
Carbon sequestration	0.03	0.03	0.02	0.00	0.00	–0.01	–33.33
Total	**26.84**	**22.83**	**17.88**	**–4.01**		**–4.95**	

2.4.4 ESV and Its Changes across the GN Divisions

Figure 2-3 shows the spatial distribution of the GN divisions in the MMNL with their respective ESVs in three time points. Of the 99 divisions, only three had a positive change between 1997 and 2017, and these are Katunayaka North (143), Munnakkarai North (156A), and Siriwardana Pedesa (156C) (Appendix A3). The top five ESV-losing divisions over the past 20 years were Kerawalapitiya (171), Pattiyawala (167B), Ambalammulla (146), Bolawalana (157), and Mahabage (178). Overall, this GN division-level ESV monitoring can help in landscape and urban planning.

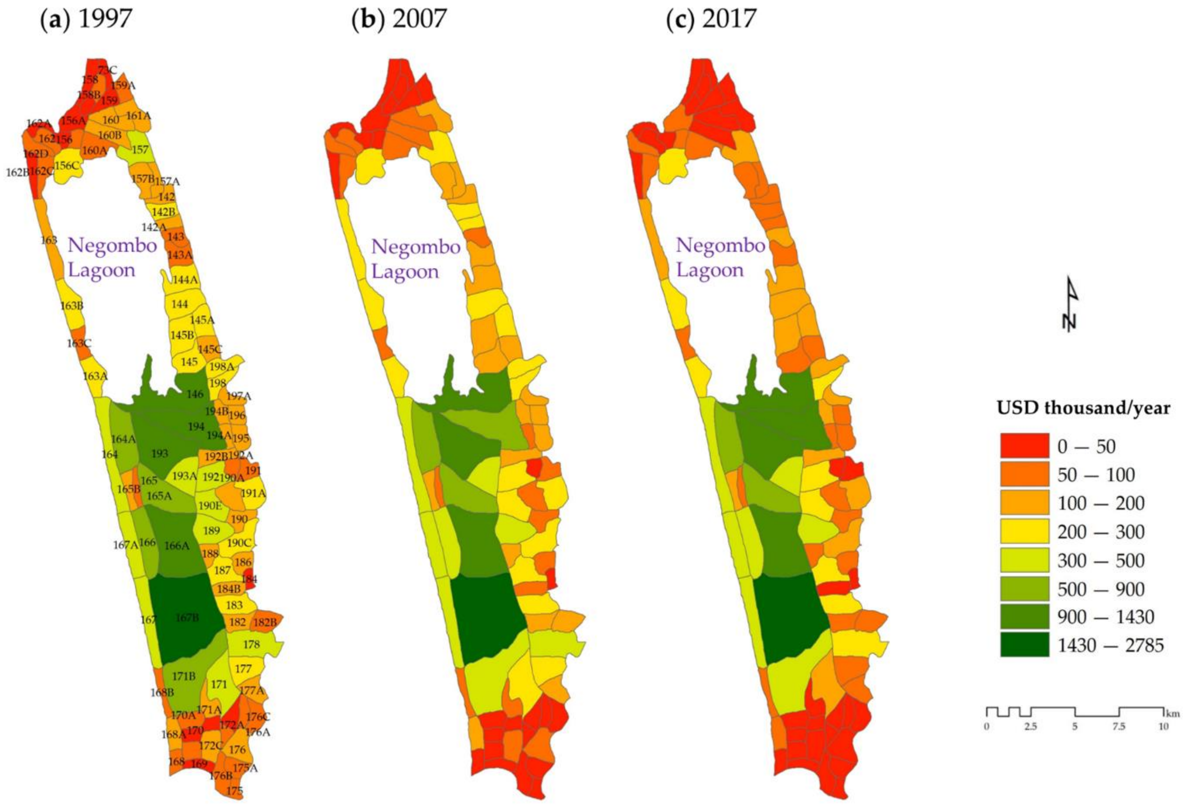


Figure 2-3. GN divisions in the MMNL with their respective ESVs (1997-2017). The numbers and letters on the 1997 map refer to the GN codes as presented in Appendix 3.

2.5 Discussion

2.5.1 Landscape transformation of the MMNL (1997-2017)

The MMNL is an important urban wetland ecosystem in Sri Lanka owing to its biodiverse ecosystem that is home to numerous wildlife, water habitat species, and migratory birds (Muthurajawela marsh and negombo lagoon conservation master plan, 1994), besides the various ecosystem services it provides (National Wetland Directory of Sri Lanka, 2006). The findings showed that the landscape of this highly valuable UWE had been transformed dramatically over the past two decades, losing considerable expanses of its marshland and mangrove cover due to rapid, unplanned, and uncontrolled urbanization (settlement expansion) (Figures 2-1 and 2-2).

Urbanization, led by socio-economic and biophysical factors, has altered and is still altering the MMNL landscape. If this wetland change trend continues, it may adversely impact the ecosystem services, biodiversity, and aesthetic value of the area. There are indications of an infilling urban growth pattern in the MMNL (Figure 2-1) and clear signs of illegal settlements inside the wetland area. The uncontrolled urban expansion of the CMR and its effects on landscape changes have caused many socio-economic and ecological problems, as well as an overall degradation of the natural environment in the study area.

Today, the MMNL has been fragmented into four parts owing to settlements, the construction of the main road and the Colombo-Katunayake Expressway, and the area experiencing a ribbon type-development during the 2007-2017 period. This expressway runs along the marshland, and a small piece of the Negombo lagoon can be clearly identified in the classified maps, especially in 2007 and 2017 (Figure 2-1). Using urban wetland modelling, Zubair *et al.*, 2017 found that two of the main watersheds had increased, but subsequently decreased in one due to urban expansion. These findings generally support this study results on the effects of human intervention, as indicated in previous research (Estoque and Murayama, 2012).

Availability and reclamation of natural wetland areas according to environment-friendly policies and enforcement of regulations are crucial to the protection and conservation of the MMNL. Restoration of wetland vegetation is vital, particularly in the highly populated areas of the GN divisions. A top-to-bottom approach should be adopted to ensure judicious use of wetland to ensure its protection and sustainability. Generally, wetland areas play an essential role in mitigating the urban heat island effect (Athukorala and Murayama, 2020). The MMNL is situated in the CMR which covers a considerable area. Conserving this highly valuable wetland will promote the cooling effect for better living conditions for the city dwellers of the CMR. Therefore, the protection and sustainability of the wetland should be promoted systematically by policymakers and urban planners.

In general, settlement expansion can be correlated with the rapid population growth in the MMNL. It is important to note that the MMNL is located in the Gampaha District of Sri Lanka, the second most populous district in Sri Lanka after the Colombo District. Rural-urban migration due to the establishment of Export Processing Zones (viz. Biyagama, Katunayake) in the Gampaha District (Abeywardene *et al.*, 1994) contributed to the higher population growth during the 1990s. Job opportunities in these Export Processing Zones provided better living conditions for the migrants. Given the decline in agricultural productivity in the country's dry regions, the Government had encouraged rural-urban migration to reduce poverty (Kelegama and Corea, 2004). In particular, post-war policies and development projects in the CMR resulted in the country's industrial capital becoming an important driver of the rapid urban growth of the CMR after 2009 (Hogg, 2011). Figure 2-4 projects continuous growth in four Divisional Secretary (DS) divisions in the study area from 1981 to 2051. The dramatic increase in the urban population of four DS divisions in the study area is expected to continue in the future. From 1997 to 2017, the population of the study area increased by 15.51%, and the population density of the Wattala and Ja-Ela DS divisions was higher than that of Katana and Negombo, indicating high urban pressure radiating from the capital of Colombo and the core of the Gampaha District (Figure 2-1). However, the Negombo DS division should not be ignored because this DS division has a significant effect on the wetland's northern part (Figure 2-1), which has been impacted by rapid population growth leading to residential (including illegal settlements) and non-residential developments in industrial and commercial sectors. This rapid urban development of the MMNL and its subsequent wetland landscape changes have created many socio-ecological problems (Photograph 2-1).

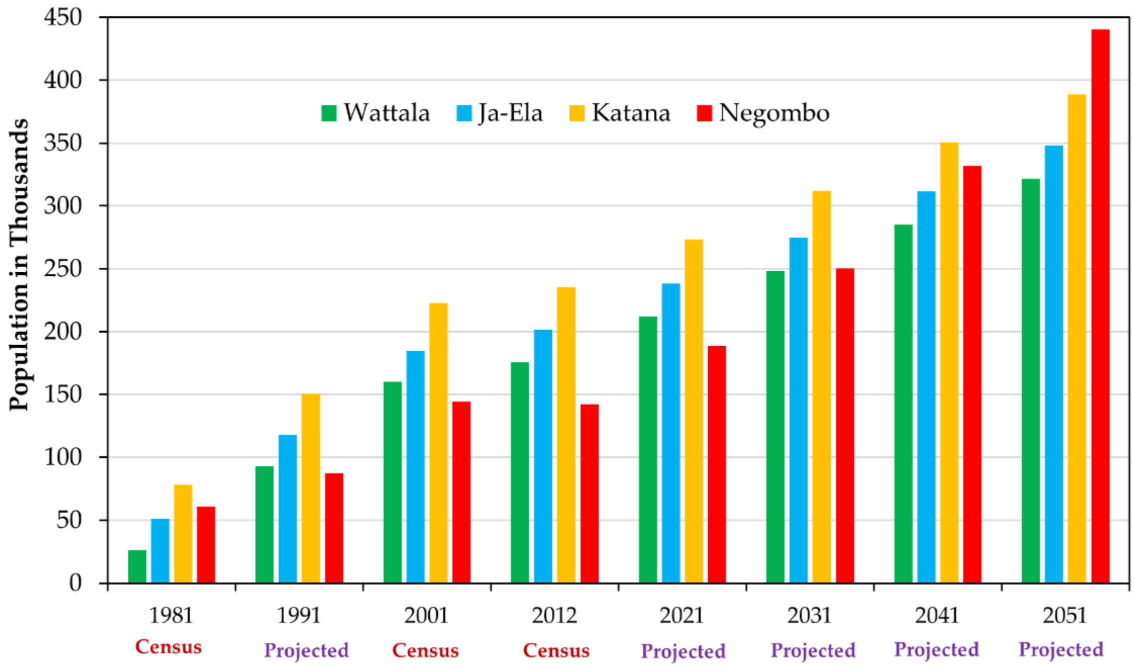


Figure 2-4. Projected population trend for Wattala, Ja-Ela, Katana and Negombo DS divisions of Gampaha District. The population data for 1981, 2001 and 2012 were sourced from the Department of Census and Statistics-Sri Lanka. The 1991 population was projected using growth rates of 5.1%, 2.6%, 2.1%, and 6.9%, Wattala, Ja-Ela, Katana, and Negombo, respectively. From 2021 to 2051, growth rates were projected using growth rates of 0.87%, 0.83%, 0.51%, and -0.13% for Wattala, Ja-Ela, Katana, and Negombo, respectively.

Photograph 2-1. Some fieldwork photos of the MMNL: (a) Human encroachment in Negombo Lagoon area, (b) Illegal settlements in the study area, (c) Dumping of garbage into the lagoon, and (d) Human activities inside the Muthurajawela marshland. Source: Athukorala, D. 2017.

2.5.2 ESV changes in the MMNL (1997-2017)

The MMNL is among the 12 priority wetlands in Sri Lanka. The presence of two protected areas within the MMNL (Appendix 1) is a direct manifestation of its ecological significance. However, the findings indicate that the sustainability of the MMNL is now in jeopardy; hence, urgent action has to be taken, landscape and urban planning wise.

In the early 2000s, in a seminal study that identified and quantified the ecosystem services of the MMNL, it was reported that the area had been experiencing intense and growing pressure from urbanization (Emerton and Kekulandala, 2003). It had been observed that (i) wetland resources had been harvested at high and often unsustainable levels; (ii) lands were being rapidly reclaimed and modified for agricultural, commercial, and residential purposes; and (iii) heavy loads of industrial and domestic wastes were being discharged untreated into the MMNL. With all of these happening, the said study concluded that the MMNL has seriously degraded over time.

Nearly two decades have passed since the conduct of the said study, but the MMNL's curve of continuous ecological degradation has not been flattened out; instead, the degradation of this valuable urban wetland ecosystem has continued as indicated by findings of this study. For example, between 2007 and 2017, the MMNL lost another 1002 ha of marshland and 265 ha of mangrove (Figure 2-2). Between 1997 and 2007, these values were 182 ha and 849 ha, respectively. By contrast, another 1301 ha of natural cover were converted into settlement between 2007 and 2017. This value was even higher than during the 1997–2007 period (1072 ha). Consequently, the ESV of the MMNL has decreased by USD 8.96 million/year over the past 20 years (USD 4.01 million/year between 1997 and 2007, and USD 4.95 million/year between 2007 and 2017) (Table 2-4). Flood attenuation and industrial wastewater treatments were among the ecosystems that were greatly affected.

The MMNL has long been seen as having prime potential for industrial and urban development, but at the same time, it is considered as a coastal wetland ecosystem of high biodiversity and ecological significance (Emerton and Kekulandala, 2003; National Wetland Directory of Sri Lanka, 2006; Athukorala *et al.*, 2021). The findings indicate that while urbanization has been continuing at an unprecedented rate, the conservation of this critical urban wetland ecosystem has been neglected. One important earlier observation that remains valid until today is that there seems to be little appreciation of either the economic value attached to the conservation of the MMNL or the high and far-reaching economic costs arising from its degradation (Emerton and Kekulandala, 2003). Decisions regarding how land and resources should be used have been based on development initiatives that favor the modification of the wetland for short-term economic gain over long-term benefits and the conservation and sustainability of the MMNL (Emerton and Kekulandala, 2003). In fact, the loss of natural cover due to settlement expansion has been observed even within the boundaries of the PAs (Figures 2-1 and Appendix 1).

2.6 Summary

This study examined the impacts of urbanization on the Muthurajawela Marsh and Negombo Lagoon (MMNL), an important urban wetland ecosystem in Sri Lanka owing to the valuable ecosystem services it provides. The results show that a substantial expansion of its settlements (+70%) and a considerable decrease in the extent of its marshland and mangrove forests (-28% and -42%, respectively). The findings also revealed that most of the observed LUC changes occurred in areas close to roads and growth nodes (viz. Negombo, Ja-Ela, and Wattala), resulting in landscape fragmentation and infill urban expansion. Due to rapid urbanization (settlement expansion from 1997 to 2017), the area of the MMNL's marshland and mangrove had decreased by 1184 ha and 1114 ha, respectively. Consequently, its ESV had decreased by USD 8.96 million/year (33%).

Overall, this study concludes that in order to ensure the sustainability of the MMNL which is a highly valuable UWE, there is an urgent need for forward-looking landscape and urban planning that could promote environmentally-conscious urban development in the area.

Chapter 3

Future LUC and ESV changes in the MMNL (2030)

3.1 Introduction

The assessment of spatio-temporal changes in the natural landscape helps to understand the environmental impacts of urbanization (Estoque and Murayama, 2012). Urban LUC change is among the most significant factors affecting ecosystem services, including urban wetland ecosystem services.

Due to urbanization, the complexity of LUC change requires tools and techniques that will show the impact of future LUC change based on spatio-temporal pattern change. During the past decades, various land change models have been developed and implemented. The development of land change models has helped researchers project future LUC changes and explore different scenarios (Estoque and Murayama, 2012).

Many studies have shown that LUC change analysis plays a significant role in the estimation of ESV change. This chapter presents the modeling of future LUC change in the MMNL (2030), using Land Change Modeler (LCM) in the TerrSet software. Based on projected LUC changes, the future ESV changes in the MMNL were calculated.

3.2 Data preparation

The main data set used in the future LUC changes modeling in the MMNL were the three LUC maps in 1997, 2007, and 2017 presented in Chapter 2 (Figure 2-1) and the six spatial variables for LUC change shown in Figure 3-1. The six spatial variables were classified using ArcGIS 10.5 and then converted to the TerrSet file format (.rst) for the modeling process. The value coefficient of each ecosystem service was applied from Chapter 2 (Table 2-2). As in Chapter 2, the GN level boundaries were used to analyze spatiotemporal changes in the GN level in the MMNL.

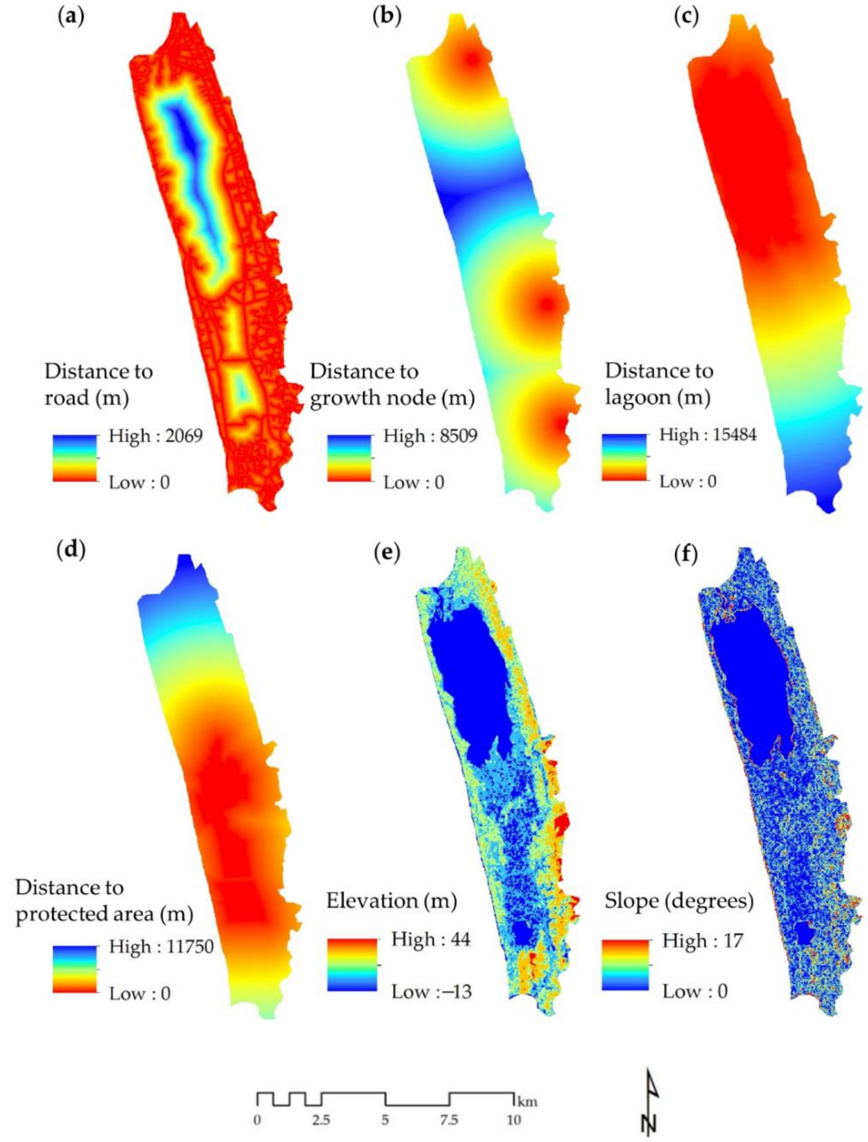


Figure 3-1. Spatial variables used in the modeling of LUC transition potential maps: (a) distance to road, (b) distance to growth node, (c) distance to lagoon, (d) distance to protected area, (e) elevation, and (f) slope.

3.3 Methods

3.3.1 Model Calibration and Validation

This study used the Land Change Modeler (LCM) (Eastman J.R., 2016; Mas *et al.*, 2014; Eastman and Toledano, 2018), which is available in geospatial monitoring and modeling software called TerrSet (https://clarklabs.org/terrset/), to simulate future LUC changes in the area and examine potential future impacts of urbanization on the natural landscape and ecosystem services of the MMNL (2017–2030). To do this, first calibrated the model by simulating the observed LUC changes between 2007 and 2017. This study considered two LUC transitions: (i) marshland to settlement and (ii) mangrove to settlement. This study used the Markov chain algorithm (Eastman J.R., 2016; Mas *et al.*, 2014) to derive a transition matrix that contained the rate or proportion of the area of a particular LUC class that would persist (non-change) or transition to another class (change) from 2007 to 2017 (in this case, these were from marshland to settlement and from mangrove to settlement).

To spatialize the projected quantities of LUC changes from the two transitions considered, this study used six spatial variables (variables that I hypothesized to have influenced LUC change patterns in the area) and the multi-layer perception neural network (MLP NN) algorithm (Eastman J.R., 2016; Mas *et al.*, 2014) to model two transition potential maps (one for each transition). These variables included distance to road, distance to growth nodes, distance to the lagoon, distance to the protected areas, elevation, and slope (Figure 3-1). They were identified and selected based on the literature (Ansari and Golabi, 2019; Ghosh and Das, 2020; Peng *et al.*, 2020; Zhang *et al.*, 2021), knowledge of the study area, and the availability of data. The same set of spatial variables was used for both transitions.

To simulate the LUC changes between 2007 and 2017, this study ran the model (LCM) with the following inputs: 1997 and 2007 LUC maps, the six spatial variables for each transition (for the modeling of transition potential maps using the MLP NN algorithm), and a transition matrix for the 2007–2017 period (derived using Markov chain based on the 1997 and 2007 LUC transitions). The output was a simulated LUC map in 2017 that depicted the projected LUC changes from 2007 based on the two LUC transitions considered (marshland to settlement and mangrove to settlement).

This study validated the simulation result by calculating the figure of merit (FoM) statistic (Pontius *et al.*, 2008; Estoque and Murayama, 2012, 2014) for each transition. The FoM was derived based on a three-map comparison technique: LUC 2007 (observed), LUC 2017 (observed), and LUC 2017 (simulated). More specifically, it was derived by taking the ratio of the intersection (H) of the observed change between 2007 and 2017 (H and M) and simulated change between 2007 and 2017 (H and F) to the union of the observed change and simulated change (Equation (6)).

$$FoM = \frac{H}{(H + M + F)} \times 100 \quad (6)$$

In Equation (6), H (hits) refers to the quantity of observed change pixels that were simulated as change. M (misses) refers to the quantity of observed change pixels that were simulated as non-change. F (false alarms) refers to the quantity of observed non-change pixels that were simulated as change.

3.3.2 Scenario-based LUC Change Simulation

The trajectory (quantity and spatial pattern) of future LUC changes generally depends on various factors, such as future changes in various socioeconomic indicators (including development policy-related) and biophysical conditions in the area. In this context, a scenario analysis might be useful as scenarios are aimed at forward-looking adaptive development planning and decision making (Costanza *et al.*, 2015; Estoque *et al.*, 2019). In fact, scenario analysis has become a useful technique in land change and sustainability research (Estoque and Murayama, 2016; Kubiszewski *et al.*, 2017; DasGupta *et al.*, 2019; Chen *et al.*, 2020; Johnson *et al.*, 2021). Scenario analysis is a structured process of exploring and evaluating plausible alternative futures (Costanza *et al.*, 2015; Estoque *et al.*, 2019).

In this study, I projected the future impacts of urbanization (2017–2030) on the natural landscape and ecosystem services of the MMNL. This study considered two plausible development scenarios: a business as usual (BAU) scenario and an environment protection (EP) scenario.

In the BAU scenario, I allowed the model (LCM) to project and simulate future LUC changes in the MMNL based on the past rates (Markov transition matrix based on the 2007 and 2017 LUC maps) and spatial pattern (transition potential maps) of LUC changes as per the two transitions considered (marshland to settlement and mangrove to settlement). In a recent study, it has been shown that settlements have also been expanding and encroaching into the protected areas (PAs) (Athukorala *et al.*, 2021). In this scenario, I did not introduce any spatial constraints, allowing the observed LUC change pattern to continue. To run the scenario, I used the 2007 and 2017 LUC maps (Figure 2-1) and the six spatial variables (Figure 3-1) as inputs and considered 2030 as the end time (year) of the simulation.

In the EP scenario, I used the same data inputs as in the BAU scenario, but I also introduced some plausible policy and development-related assumptions. More specifically, I was interested in the potential impacts of urbanization on the ecosystem services of the MNNL under a scenario in which (i) the urbanization rate would slow down by 20%, and (ii) the two protected areas (PAs) in the area would be completely protected. To do this, first, I revised the Markov transition matrix by withholding (deducting) 20% of the proportion of the area of marshland and mangrove that would transition to settlement by 2030. Second, I introduced a spatial constraint disallowing LUC change to occur in the two PAs. The 20% rate is based on a previous study (Estoque and Murayama, 2014), and my assumption was that the rate (20%) is not that stringent, meaning plausible at given circumstances (e.g., protection of the protected areas, implementation of land use zoning, no illegal settlements, etc.).

3.3.3 Future ESV changes in GN level in the MMNL (2030)

This study mapped the spatial distribution of the 99 Grama Niladhari (GN) divisions that cover the entire MMNL with their respective ESVs. To do this, first, this study conducted a zonal analysis (tabulate area) to determine the LUC composition and extent in each GN division in 2030 BAU, and 2030 EP using the polygon boundaries of the GN divisions as zones and the LUC maps as inputs. Second, this study estimated the ESV of each GN division using Equation (4) and Equation (5).

3.4 Results

3.4.1 LUC Change Model Validation

LUC change modeling focused on assessing the impacts of urbanization as proxied by settlement expansion on the natural landscape and ecosystem services of the MMNL. Two transitions were considered, namely marshland to settlement and mangrove to settlement, with the FoM being used to validate the LUC change modeling results (section 3.3.1). The validation results revealed that the marshland to settlement transition had a FoM of 45.4%, whereas the mangrove to settlement transition had 29.5%. These FoM values are within the range of FoM values reported in other LUC change modeling studies. For example, in their LUC change modeling in connection with ecosystem services, Estoque and Murayama, 2012 recorded an FoM of 43%. In their LUC change modeling in the context of flooding, Johnson *et al.*, 2021 had an FoM of 20%. In an earlier seminal review of FoM applications in the validation of LUC change modeling studies, Pontius *et al.*, 2008 reported an FoM value range of 1%−59%.

3.4.2 Projected Changes in LUC (2017–2030)

Under the BAU scenario, by 2030, the area of marshland and mangrove in the MMNL would decrease by 1329 ha and 213 ha, respectively, whereas the area of settlement would increase by 1542 ha (Figure 3-2, Table 3-1). By contrast, under the EP scenario in which urban expansion rate (settlement expansion) would slow down by 20% (section 3.3.2), the decrease in the area of marshland and mangrove would be much lower at 1063 ha and 171 ha, respectively. In this scenario, the area of settlement would increase by 1234 ha.

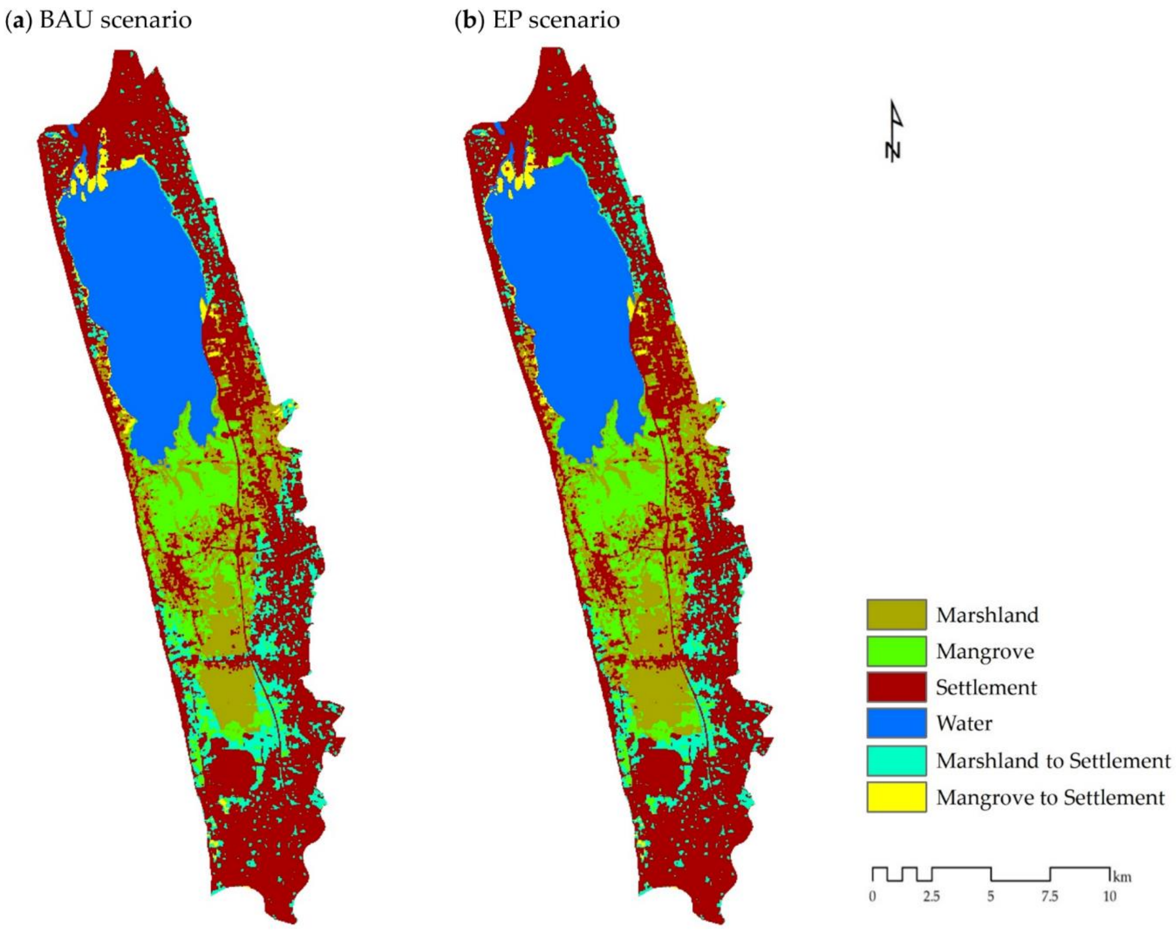


Figure 3-2. Projected LUC changes in the MMNL under the BAU and EP scenarios (2030).

Table 3-1. Future LUC changes in the MMNL (2030).

LUC class	2017	2030 BAU	2030 EP	Changes			
				2017–2030 BAU	% of 2017	2017–2030 EP	% of 2017
Marshland	3058.47	1729.89	1995.66	–1328.58	–43.44	–1062.81	–34.75
Mangrove	1522.98	1309.5	1352.07	–213.48	–14.02	–170.91	–11.22
Settlement	5741.10	7283.16	6974.82	1542.06	26.86	1233.72	21.49

3.4.3 Projected Changes in ESV (2017–2030)

As a consequence of the projected loss of marshland and mangrove by 2030, the ESV of the MMNL would also decrease (Table 3-2). Under the BAU scenario, the MMNL's ESV would decrease by USD 6.01 million/year, i.e., equivalent to a 34% decrease relative to 2017 (Table 3-2). Under the EP scenario, the decrease would be much less at USD 4.79 million/year, i.e., equivalent to a 27% decrease relative to 2017.

Table 3-2. Future ESV changes in the MMNL (2030).

Ecosystem services	2017–2030 (BAU)			2017–2030 (EP)		
	Million USD/year	**% of 2017**	**% of total decrease**	**Million USD/year**	**% of 2017**	**% of total decrease**
Flood attenuation	−4.02	−33.67	66.89	−3.21	−26.88	67.01
Industrial wastewater treatment	−1.35	−33.75	22.46	−1.08	−27.00	22.55
Agriculture production	−0.26	−34.67	4.33	−0.21	−28.00	4.38
Support to downstream fisheries (fish breeding and nursery)	−0.16	−32.65	2.66	−0.13	−26.53	2.71
Firewood	−0.07	−35.00	1.16	−0.05	−25.00	1.04
Fishing (fisheries production)	−0.05	−33.33	0.83	−0.03	−20.00	0.63
Leisure and recreation	−0.04	−30.77	0.67	−0.03	−23.08	0.63
Domestic sewage treatment	−0.04	−36.36	0.67	−0.03	−27.27	0.63
Freshwater supplies for local population	−0.02	−22.22	0.33	−0.02	−22.22	0.42
Carbon sequestration	0.00	0.00	0.00	0.00	0.00	0.00
Total	**−6.01**		**100.00**	**−4.79**		**100.00**

3.4.4 Future ESV and Its Changes across the GN Divisions

Figure 3-3 shows the spatial distribution of the GN divisions in the MMNL with their respective ESVs in three time points. In both scenarios (BAU and EP), the projected top five ESV-losing divisions were Pattiyawala (167B), Balagala (171B), Kunjawatta (166A), Siriwardana Pedesa (156C), and Mahabage (178). Overall, this GN division-level ESV monitoring can help in landscape and urban planning. For example, the projected top ESV-losing divisions should be given particular attention.

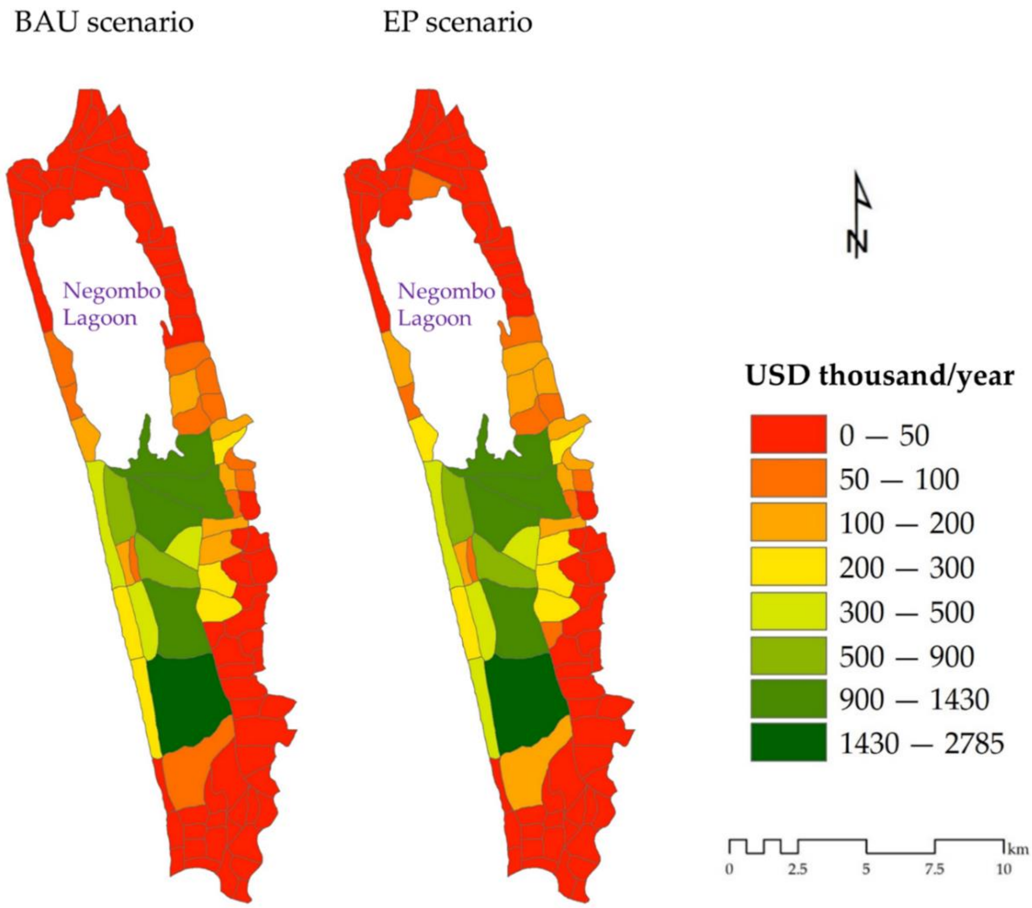


Figure 3-3. GN divisions in the MMNL with their respective ESVs (2030). The ESV of each GN division is presented in Appendix A3.

3.5 Discussion

Results have also shown that the future (2030) condition of the MMNL can be expected to be worse if the recent (2007–2017) rate and spatial pattern of urbanization (settlement expansion) continues (BAU scenario). It is because the projected ESV loss under this scenario between 2017 and 2030 (USD 6.01 million/year) (Table 3-2) would be greater than the ESV loss in the past decade (2007–2017, USD 4.95 million/year) (Table 2-4). This also means that the future of the MMNL will be much worse if the threat of marshland and mangrove loss due to urbanization grows and intensifies. Nonetheless, this study also demonstrates that under the EP scenario, while the continuous decline of the MMNL's ESV cannot be fully stopped, the rate of loss could be slowed down (USD 4.79 million/year) (Table 3-2). Hence, between the two scenarios, the EP scenario is the more desirable one for the MMNL.

This study considered only two basic scenarios, and thus, the exploration of other more complex plausible scenarios can be considered for future research. Examples of more complex scenarios include those that incorporate future trajectories of relevant socioeconomic indicators, such as population growth, changes in economic, land use, and environmental conditions, as well as future development priorities and policy targets. The shared socioeconomic pathways (SSPs) are examples of such scenarios, though they are designed for a global scale analysis (O'Neill *et al.*, 2017; Popp *et al.*, 2017; Riahi *et al.*, 2017). The adaption of these pathways to local-level analysis could be a future research direction. Other scenarios could focus more on conservation storylines (Sun *et al.*, 2018) or other more complex and stringent versions of the EP scenario.

Nonetheless, despite their simplicity, the inclusion of two basic scenarios in the analysis helped us demonstrate that, for the sustainability of the MMNL, it is still possible to flatten its curve of continuous ecological degradation. In fact, the simple full protection of the PAs inside the MMNL (EP scenario) could make a significant positive contribution. Furthermore, with the use of a monitoring scheme built on a state-of-the-art geospatial technique (including GIS, remote sensing, and scenario-based land change modeling) and the concept of ecosystem services, this study also makes important methodological and empirical contributions.

In fact, the economic value of wetland goods and services is rarely factored into LUC change decisions in the MMNL (Emerton and Kekulandala, 2003). This study offers a basic template that can be adopted and improved in future studies and/or considered in landscape and urban planning for the MMNL. In general, the valuation and monitoring of ecosystem services across space and time have many potential uses, including raising of awareness and interest, national income and well-being accounts, specific policy analyses, urban and regional planning, payment for ecosystem services, full cost accounting, and common asset trusts (Costanza *et al.*, 2014, 2017; Estoque and Murayama, 2016). I argue that the MMNL can benefit from landscape and urban planning that considers the concept of ecosystem services.

3.6 Summary

This study proposes a framework for evaluating the future LUC changes in the wetland ecosystem services in the MMNL, Sri Lanka, discovering their implications, and making policies to protect this valuable urban wetland ecosystem.

The EP scenario will show wetland ecosystem services improved more efficiently than the BAU scenario in the MMNL. Wetland management strategies and environmental engineering measures should be considered to improve said WESs, not only in the highest-ESV GN divisions, but also in the moderate and low-ESV GN divisions. Ensuring sustainable and effective mangrove rehabilitation activities in specific areas, participatory monitoring and evaluation, and community-based management are all practical approaches for protecting the long-term wetland and their combined wetland ecosystem services; and establishing urban boundaries and protecting areas of natural and semi-natural habitats, can also be adapted to control urban growth in the MMNL. Finally, this research identified the potential effects of past and future LUC changes on the wetland ecosystem services provided by the MMNL in Sri Lanka and provided some critical insights to protect the area.

Chapter 4

Conclusions

The MMNL is an important urban wetland ecosystem in Sri Lanka, but its sustainability is now in jeopardy due to rapid and uncontrolled urbanization. Swift action must be taken in order to save this valuable urban wetland ecosystem. In this study, to help inform sustainable landscape and urban planning, this study examined the impacts of urbanization on the natural landscape and ecosystem services of the MMNL over the past 20 years (1997–2017). This study also projected landscape and ESV changes by 2030 under two plausible scenarios. I found that, due to rapid urbanization (settlement expansion equivalent to 70% from 1997 to 2017), the area of the MMNL's marshland and mangrove had decreased by 1184 ha and 1114 ha, respectively. Consequently, its ESV had decreased by USD 8.96 million/year (33%). If the current rate and spatial pattern of urbanization (2007–2017) continued in the future (BAU scenario), another 1329 ha of marshland and 213 ha of mangrove would be lost by 2030. The projected loss in ESV would be USD 6.01 million/year (34%).

However, if the urbanization rate slowed down by 20% and the PAs were completely protected (EP scenario), the future loss of marshland and mangrove would only be around 1063 ha and 171 ha, respectively. The projected loss in ESV would be lower at USD 4.79 million/year (27%). Between the two scenarios, the EP scenario would be the more desirable one that should be considered by local government planners and decision-makers. The past, present, and future ESV maps of the GN divisions produced in this study can be used to identify hotspots. For future research, other more complex and stringent plausible scenarios need to be explored to help flatten the MMNL's curve of continuous ecological degradation. Overall, the results of this study can help provide landscape and urban planners with information useful to the sustainability of the MMNL. The approach employed is also adaptable and applicable to other urban wetland ecosystems in the country and the rest of the world.

Acknowledgement

I would like to offer my sincere gratitude to my supervisor Prof. Dr. Bunkei MATSUSHITA, Division of Spatial Information Science, Graduate school of Life and Environmental Science, University of Tsukuba for the excellent supervision and guidance.

My sincerest thanks and deepest gratitude also go to Prof. Emeritus Dr. Yuji MURAYAMA, Prof. Dr. Takehiro MORIMOTO, and Prof. Dr. Kenlo Nishida NASAHARA, members of the thesis advisory committee, for their valuable comments and suggestions that helped me improve this study.

I offer my deepest gratitude to Dr. Ronald C. Estoque for his support & encouragement given me to complete this study successfully.

I am also thankful to Mr. Malinda Siriwardhana for his continuous support in numerous ways during the research periods.

I offer my deepest gratitude to secretaries of Negombo, Wattala, Kadana and Ja- Ela DS Divisions.

My special thanks are due to my colleagues, staff of the Division of Spatial Information Science, staff of the Graduate School of Life and Environmental Sciences for supporting me during the study period.

Finally, I am thankful to my loving parents and my family members, M.P.S. Perera, for all sacrifices, inspiration and kindness.

References

Abeywardene, J., Alwis, R. de, Jayasena, A., Jayaweera, S., & Sanmugam, and T. (1994). Export processing zones in Sri Lanka: Economic impact and social issues. Centre for Women's Research, Sri Lanka.

Ansari, A., & Golabi, M. H. (2019). Prediction of spatial land use changes based on LCM in a GIS environment for Desert Wetlands – A case study: Meighan Wetland, Iran. *International Soil and Water Conservation Research*, *7*(1), 64–70.

Assefa, W. W., Eneyew, B. G., & Wondie, A. (2021). The impacts of land-use and land-cover change on wetland ecosystem service values in peri-urban and urban area of Bahir Dar City, Upper Blue Nile Basin, Northwestern Ethiopia. *Ecological Processes*, *10*(1), 1-18.

Athukorala, D., Estoque, R. C., Murayama, Y., & Matsushita, B. (2021). Impacts of urbanization on the Muthurajawela Marsh and Negombo Lagoon, Sri Lanka: Implications for landscape planning towards a sustainable urban wetland ecosystem. *Remote Sensing*, *13*(2), 316.

Athukorala, D., & Murayama, Y. (2020). Spatial Variation of Land Use/Cover Composition and Impact on Surface Urban Heat Island in a Tropical Sub-Saharan City of Accra, Ghana. *Sustainability*, *12*(19), 7953.

Bambaradeniya, C. N., Ekanayake, S. P., Kekulandala, L. D. C. B., Samarawickrama, V. A. P., Ratnayake, N. D., & Fernando, R. H. S. S. (2002). An assessment of the status of biodiversity in the Muthurajawela wetland sanctuary. *Occasional Papers of IUCN Sri Lanka*, *3*, 48.

Central Environment Authority, Sri Lanka. Available at: http://www.cea.lk/web/?option=com_content&view=article&layout=edit&id=1155 (Accessed: 14 June 2021).

Chen, G., Li, X., Liu, X., Chen, Y., Liang, X., Leng, J., Xu, X., Liao, W., Wu, Q. and Huang, K., (2020). Global projections of future urban land expansion under shared socioeconomic pathways. *Nature communications*, *11*(1), pp.1-12.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., and Belt, M.V.D., (1997). The value of the world's ecosystem services and natural capital. *nature*, *387*(6630), pp.253-260

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S. and Turner, R.K., (2014). Changes in the global value of ecosystem services. *Global environmental change*, *26*, pp.152-158.

Costanza, R.; Kubiszewski, I.; Cork, S.; Atkins, P. W. B. W. B.; Bean, A.; Diamond, A.; Grigg, N.; Korb, W.; Logg-Scarvell, J.; Navis, and R.; Patrick, K., (2015). Scenarios for Australia in 2050. *Journal of. Future. Studies, 19*, 49–76.

Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S. and Grasso, M., (2017). Twenty years of ecosystem services: how far have we come and how far do we still need to go?. *Ecosystem services*, *28*, pp.1-16

Dai, X., Wang, L., Huang, C., Fang, L., Wang, S., & Wang, L. (2020). Spatio-temporal variations of ecosystem services in the urban agglomerations in the middle reaches of the Yangtze River, China. *Ecological Indicators*, *115*, 106394.

DasGupta, R., Hashimoto, S., Okuro, T., & Basu, M. (2019). Scenario-based land change modelling in the Indian Sundarban delta: an exploratory analysis of plausible alternative regional futures. *Sustainability Science*, *14*(1), 221-240.

Department of Census and Statistics-Sri Lanka. Available at: http://www.statistics.gov.lk/ (Accessed: 3 May 2020).

Department of Meteorology, Sri Lanka. Available at: https://www.meteo.gov.lk/index.php?lang=en (Accessed: 15 June 2021).

Eastman, J. R., & Toledano, J. (2018). A short presentation of the Land Change Modeler (LCM). In *Geomatic approaches for modeling land change scenarios* (pp. 499-505). Springer, Cham.

Emerton, L., & Kekulandala, B. (2003). Assessment of the Economic Value of Muthurajawela Wetland. *IUCN—The World Conservation Union, Sri Lanka Country Office and Regional Environmental Economics Programme Asia, Colombo*.

Environmental Profile of Muthurajawela and Negombo Lagoon (1991). Greater Colombo Economic Commision, Euroconsult, The Netherlands.

Estoque, R.C., Gomi, K., Togawa, T., Ooba, M., Hijioka, Y., Akiyama, C.M., Nakamura, S., Yoshioka, A. and Kuroda, K., (2019). Scenario-based land abandonment projections: Method, application and implications. *Science of the Total Environment*, *692*, pp.903-916.

Estoque, R.C., Ooba, M., Avitabile, V., Hijioka, Y., DasGupta, R., Togawa, T. and Murayama, Y., (2019). The future of Southeast Asia's forests. *Nature communications*, *10*(1), pp.1-12.

Estoque, R. C., and Murayama, Y. (2012). Examining the potential impact of land use/cover changes on the ecosystem services of Baguio city, the Philippines: a scenario-based analysis. *Applied Geography*, *35*(1-2), 316-326.

Estoque, R. C., and Murayama, Y. (2013). Landscape pattern and ecosystem service value changes: Implications for environmental sustainability planning for the rapidly urbanizing summer capital of the Philippines. *Landscape and urban planning*, *116*, 60-72.

Estoque, R. C., and Murayama, Y. (2014). Measuring sustainability based upon various perspectives: a case study of a hill station in Southeast Asia. *Ambio*, *43*(7), 943-956.

Estoque, R. C., and Murayama, Y. (2016). Quantifying landscape pattern and ecosystem service value changes in four rapidly urbanizing hill stations of Southeast Asia. *Landscape Ecology*, *31*(7), 1481-1507.

Ghermandi, A., Sheela, A. M., and Justus, J. (2016). Integrating similarity analysis and ecosystem service value transfer: Results from a tropical coastal wetland in India. *Ecosystem services*, *22*, 73-82.

Ghosh, S., and Das, A. (2020). Wetland conversion risk assessment of East Kolkata Wetland: A Ramsar site using random forest and support vector machine model. *Journal of Cleaner Production*, *275*, 123475.

He, Y., Wang, W., Chen, Y., and Yan, H. (2021). Assessing spatio-temporal patterns and driving force of ecosystem service value in the main urban area of Guangzhou. *Scientific Reports*, *11*(1), 1-18.

Hogg, C. L. (2011). Sri Lanka : Prospects for Reform and Reconciliation, Available at: http://www.adb.org/documents/books/ado/2011/ado2011-sri.pdf.

Ramsar Homepage. Available at: https://www.ramsar.org/ (Accessed: 7 September 2018).

Hou, H., Estoque, R. C., and Murayama, Y. (2016). Spatiotemporal analysis of urban growth in three African capital cities: A grid-cell-based analysis using remote sensing data. *Journal of African Earth Sciences*, *123*, 381-391.

Huang, Q., Zhao, X., He, C., Yin, D., and Meng, S. (2019). Impacts of urban expansion on wetland ecosystem services in the context of hosting the Winter Olympics: a scenario simulation in the Guanting Reservoir Basin, China. *Regional Environmental Change*, *19*(8), 2365-2379.

Eastman, J. R. (2016). TerrSet geospatial monitoring and modeling system. *Clark University: Worcester, MA, USA*, 345-389.

Jayathilake, M. B., and Chandrasekara, W. U. (2015). Variation of avifaunal diversity in relation to land-use modifications around a tropical estuary, the Negombo estuary in Sri Lanka. *Journal of Asia-Pacific Biodiversity*, *8*(1), 72-82.

Johnson, B. A., Estoque, R. C., Li, X., Kumar, P., Dasgupta, R., Avtar, R., and Magcale-Macandog, D. B. (2021). High-resolution urban change modeling and flood exposure estimation at a national scale using open geospatial data: A case study of the Philippines. *Computers, Environment and*

Urban Systems, *90*, 101704.

Joy, N. M., and Paul, S. K. (2021). Analysis of the Economic Value and Status of the Ecosystem Services Provided by the Ashtamudi Wetland Region, a Ramsar Site in Kerala. *Journal of the Indian Society of Remote Sensing*, *49*(4), 897-912.

Kelegama, S., and Corea, G. (2004), *Economic Policy in Sri Lanka: Issues and Debates*. SAGE Publications. Available at: https://books.google.co.jp/books?id=vTOJiGQ2mLIC.

Kharazmi, R., Tavili, A., Rahdari, M. R., Chaban, L., Panidi, E., and Rodrigo-Comino, J. (2018). Monitoring and assessment of seasonal land cover changes using remote sensing: a 30-year (1987–2016) case study of Hamoun Wetland, Iran. *Environmental monitoring and assessment*, *190*(6), 1-23.

Kubiszewski, I., Costanza, R., Anderson, S., and Sutton, P. (2017). The future value of ecosystem services: Global scenarios and national implications. *Ecosystem Services*, *26*, 289–301.

Mas, J. F., Kolb, M., Paegelow, M., Olmedo, M. T. C., & Houet, T. (2014). Inductive pattern-based land use/cover change models: A comparison of four software packages. *Environmental Modelling & Software*, *51*, 94-111.

Muthurajawela marsh and negombo lagoon: conservation master plan, (1994). Central Environmental Authority, Sri Lanka.

National Wetland Directory of Sri Lanka (2006). The Central Environmental Authority Colombo, Sri Lanka.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., and Solecki, W., (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global environmental change*, *42*, pp.169-180.

Peng, K., Jiang, W., Deng, Y., Liu, Y., Wu, Z., and Chen, Z. (2020). Simulating wetland changes under different scenarios based on integrating the random forest and CLUE-S models: A case study of

Wuhan Urban Agglomeration. *Ecological Indicators*, *117*, 106671.

Pontius, R.G., Boersma, W., Castella, J.C., Clarke, K., de Nijs, T., Dietzel, C., Duan, Z., Fotsing, E., Goldstein, N., Kok, K. and Koomen, E., Lippitt, C.D., McConnell, W., Sood, A.M., Pijanowski, B., Pithadia, S., Sweeney, S., Trung, T.N., Veldkamp, A.T., and Verburg, P.H., (2008). Comparing the input, output, and validation maps for several models of land change. *The Annals of Regional Science*, *42*(1), pp.11-37.

Popp, A.; Calvin, K.; Fujimori, S.; Havlik, P.; Humpenöder, F.; Stehfest, E.; Bodirsky, B. L.; Dietrich, J. P.; Doelmann, J. C.; Gusti, M.; Hasegawa, T.; Kyle, P.; Obersteiner, M.; Tabeau, A.; Takahashi, K.; Valin, H.; Waldhoff, S.; Weindl, I.; Wise, M.; Kriegler, E.; Lotze-Campen, H.; Fricko, O.; Riahi, K.; and Vuuren, D. P. va. (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, *42*, 331-345.

Riahi, K.; van Vuuren, D. P.; Kriegler, E.; Edmonds, J.; O'Neill, B. C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; Lutz, W.; Popp, A.; Cuaresma, J. C.; KC, S.; Leimbach, M.; Jiang, L.; Kram, T.; Rao, S.; Emmerling, J.; Ebi, K.; Hasegawa, T.; Havlik, P.; Humpenöder, F.; Da Silva, L. A.; Smith, S.; Stehfest, E.; Bosetti, V.; Eom, J.; Gernaat, D.; Masui, T.; Rogelj, J.; Strefler, J.; Drouet, L.; Krey, V.; Luderer, G.; Harmsen, M.; Takahashi, K.; Baumstark, L.; Doelman, J. C.; Kainuma, M.; Klimont, Z.; Marangoni, G.; Lotze-Campen, H.; Obersteiner, M.; Tabeau, A.; and Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global environmental change*, *42*, 153-168.

Sinclair, M., Sagar, M. V., Knudsen, C., Sabu, J., and Ghermandi, A. (2021). Economic appraisal of ecosystem services and restoration scenarios in a tropical coastal Ramsar wetland in India. *Ecosystem Services*, *47*, 101236.

Su, S., Xiao, R., Jiang, Z., and Zhang, Y. (2012). Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. *Applied Geography*, *34*, 295-

305.

Subasinghe, S., Estoque, R. C., and Murayama, Y. (2016). Spatiotemporal analysis of urban growth using GIS and remote sensing: A case study of the Colombo Metropolitan Area, Sri Lanka. *ISPRS international journal of geo-information*, *5*(11), 197.

Sun, X., Crittenden, J. C., Li, F., Lu, Z., and Dou, X. (2018). Urban expansion simulation and the spatio-temporal changes of ecosystem services, a case study in Atlanta Metropolitan area, USA. *Science of the Total Environment*, *622*, 974-987.

Sustainable Development Goals. Available at: https://sdgs.un.org/goals (Accessed: 23 September 2021).

Swetnam, R. D.; Fisher, B.; Mbilinyi, B. P.; Munishi, P. K. T.; Willcock, S.; Ricketts, T.; Mwakalila, S.; Balmford, A.; Burgess, N. D.; Marshall, A. R.; and Lewis, S. L. (2011). Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. *Journal of environmental management*, *92*(3), 563-574.

Tong, C., Feagin, R. A., Lu, J., Zhang, X., Zhu, X., Wang, W., and He, W. (2007). Ecosystem service values and restoration in the urban Sanyang wetland of Wenzhou, China. *Ecological engineering*, *29*(3), 249-258.

Wu, W. T., Zhou, Y. X., and Tian, B. (2017). Coastal wetlands facing climate change and anthropogenic activities: A remote sensing analysis and modelling application. *Ocean & Coastal Management*, *138*, 1-10.

Yirsaw, E., Wu, W., Shi, X., Temesgen, H., and Bekele, B. (2017). Land use/land cover change modeling and the prediction of subsequent changes in ecosystem service values in a coastal area of China, the Su-Xi-Chang Region. *Sustainability*, *9*(7), 1204.

Zhang, X., Estoque, R. C., and Murayama, Y. (2017). An urban heat island study in Nanchang City, China based on land surface temperature and social-ecological variables. *Sustainable cities and society*, *32*, 557-568.

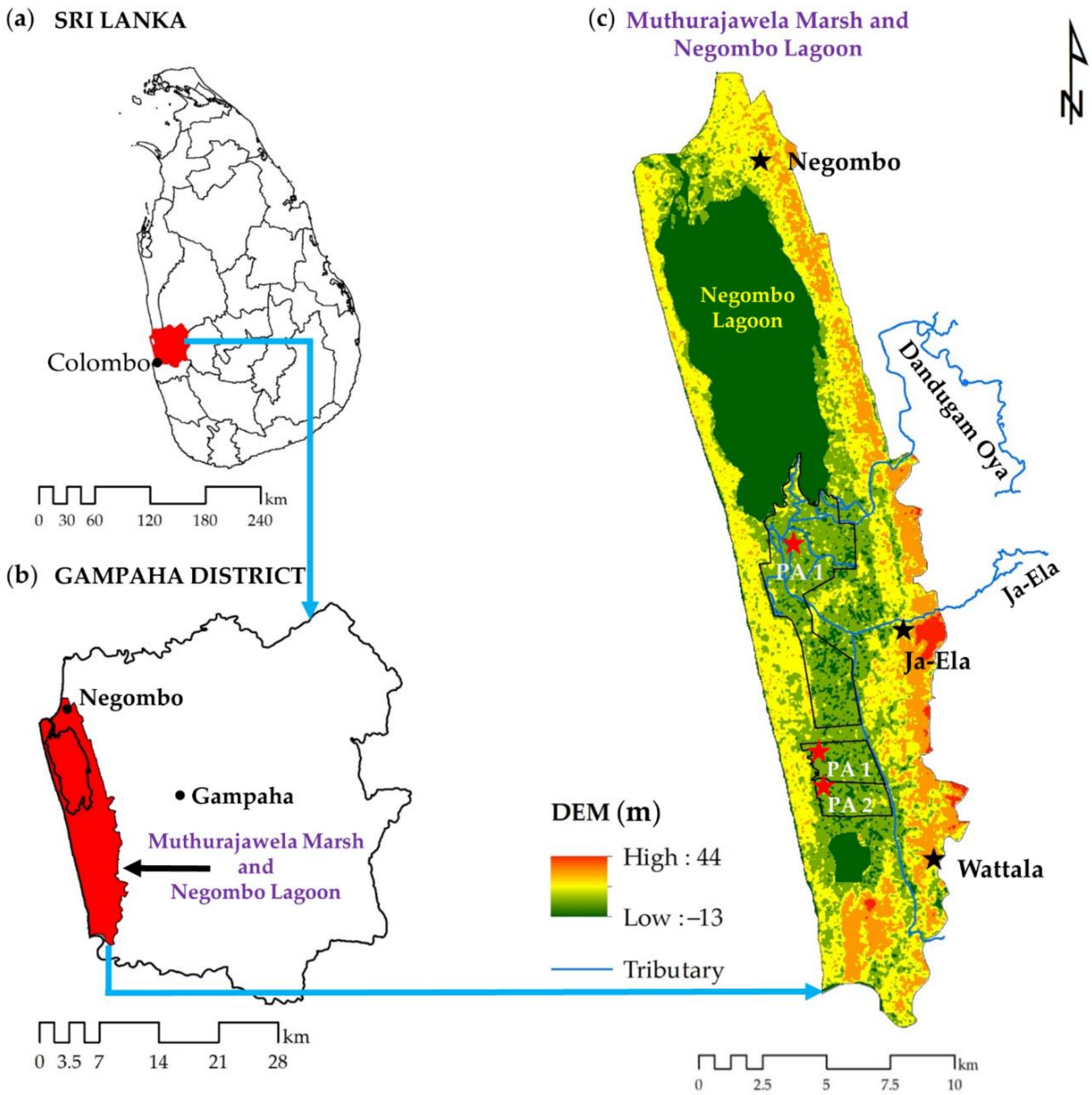
Zhang, Z., Hu, B., Jiang, W., and Qiu, H. (2021). Identification and scenario prediction of degree of wetland damage in Guangxi based on the CA-Markov model. *Ecological Indicators*, *127*, 107764.

Zhou, D., Tian, Y., and Jiang, G. (2018). Spatio-temporal investigation of the interactive relationship between urbanization and ecosystem services: Case study of the Jingjinji urban agglomeration, China. *Ecological indicators*, *95*, 152-164.

Zubair, O. A., Ji, W., and Weilert, T. E. (2017). Modeling the impact of urban landscape change on urban wetlands using similarity weighted instance-based machine learning and Markov model. *Sustainability*, *9*(12), 2223.

Appendices

Appendix 1. Location of the study area: (**a**) map of Sri Lanka; (**b**) Gampaha District; and (**c**) Muthurajawela marsh and Negombo Lagoon. PA 1 = Protected area 1 (Muthurajawela Sanctuary). PA 2 = Protected area 2 (Muthurajawela Environmental Protection Area).



Appendix 2. Confusion matrices of the classified LUC maps of the MMNL.

Classified data	Reference data				Total	User's accuracy (%)
	Marshland	Mangrove	Water	Settlement		
(a) 1997						
Marshland	101	8	4	7	120	84.17
Mangrove	8	85	5	4	102	83.33
Water	6	4	73	1	84	86.90
Settlement	4	3	0	87	94	92.55
Total	119	100	82	99	400	
Producer's accuracy (%)	84.87	85.00	89.02	87.88		
Overall accuracy (%) = 86.50						
(b) 2007						
Marshland	83	7	5	8	103	80.58
Mangrove	9	83	6	7	105	79.05
Water	5	6	78	1	90	86.67
Settlement	6	1	2	93	102	91.18
Total	103	97	91	109	400	
Producer's accuracy (%)	80.58	85.57	85.71	85.32		
Overall accuracy (%) = 84.25						
(c) 2017						
Marshland	89	9	3	8	109	81.65
Mangrove	8	78	5	6	97	80.41
Water	4	7	68	1	80	85.00
Settlement	5	2	4	103	114	90.35
Total	106	96	80	118	400	
Producer's accuracy (%)	83.96	81.25	85.00	87.29		
Overall accuracy (%) = 84.50						

Appendix 3. ESV and its changes at the GN division level. Note: The GN code is linked with Figure 2-3.

GN code	GN name	ESV (USD thousand/year)						
		1997	2007	2017	2030 BAU	2030 EP	Change	
							2017–2030 BAU	2017–2030 EP
190A	Weligampitiya North	167.40	78.90	52.60	1.00	1.00	51.60	51.60
191A	Ja-Ela	279.00	241.20	131.40	0.60	0.60	130.80	130.80
165B	Pulluhena	171.30	168.20	133.80	133.80	133.80	0.00	0.00
175	Telangapatha	62.20	39.40	12.40	0.00	0.00	12.40	12.40
169	Hekitta	57.70	17.30	4.80	0.00	0.00	4.80	4.80
175A	Evariwatta	90.80	47.70	10.90	0.01	0.09	10.89	10.81
176B	Galwetiya	70.50	25.20	3.90	0.02	0.06	3.88	3.84
168	Palliyawatta South	64.10	32.70	34.10	0.01	0.08	34.08	34.02
169A	Kurunduhena	72.70	42.00	8.10	0.01	0.00	8.09	8.09
172C	Nayakakanda South	136.60	75.80	29.20	0.00	0.00	29.20	29.20
170	Thimbirigasyaya	49.20	26.50	1.30	0.00	0.00	1.30	1.30
176	Wattala	140.00	71.20	13.10	0.00	0.00	13.10	13.10
172	Hendala South	60.90	11.60	7.10	0.00	0.00	7.10	7.10
168A	Palliyawatta North	154.70	127.60	86.60	0.00	0.00	86.60	86.60
172B	Nayakakanda North	41.70	29.50	9.00	0.00	0.00	9.00	9.00
170A	Elakanda	76.80	35.00	6.40	0.00	0.00	6.40	6.40
176C	Welikadamulla	103.40	43.90	7.80	0.00	0.00	7.80	7.80
172A	Hendala North	50.00	19.60	9.10	0.00	0.00	9.10	9.10
176A	Mabola	60.90	35.10	18.20	0.00	0.00	18.20	18.20
171A	Matagoda	134.30	64.50	35.10	0.02	0.00	35.08	35.09
177A	Kerangapokuna	151.20	129.90	84.10	0.00	0.90	84.10	83.20
168B	Dikovita	115.60	100.00	83.20	24.50	25.60	58.70	57.60
177	Mattumagala	244.20	214.90	60.20	3.00	3.00	57.20	57.20
171	Kerawalapitiya	500.10	243.80	136.50	16.20	16.20	120.30	120.30
178	Mahabage	445.60	391.90	224.60	29.50	29.50	195.10	195.10
171B	Balagala	607.50	468.60	412.10	54.60	104.20	357.50	307.90
182	Welisara	194.60	146.70	83.60	29.30	29.30	54.30	54.30
182B	Elehiwatta	118.50	131.70	58.80	0.00	0.00	58.80	58.80
183	Nagoda	321.70	238.30	166.80	27.70	27.70	139.10	139.10
184B	Uswatta	153.00	86.40	39.50	1.20	1.90	38.30	37.60
167	Uswetakeiyawa	391.80	397.40	314.90	245.80	280.50	69.10	34.40
167B	Pattiyawala	2785.40	2548.70	2493.10	1916.50	2278.10	576.60	215.00
184	Kandana West	28.40	20.90	4.30	0.00	0.00	4.30	4.30
187	Nedurupitiya	316.70	245.40	166.60	17.10	17.10	149.50	149.50
186	Rilavulla	127.10	111.40	42.70	3.50	3.50	39.20	39.20
188	Kalaeliya	171.00	142.80	94.70	19.00	38.40	75.70	56.30
190C	Kapuwatta	302.70	233.90	118.00	4.10	4.10	113.90	113.90
189	Wewala	428.10	368.10	297.90	183.30	224.90	114.60	73.00
167A	Paranambalama	407.20	371.30	324.40	174.40	234.40	150.00	90.00
190	Weligampitiya South	153.90	80.70	55.20	1.10	1.10	54.10	54.10
166	Nugape	594.10	541.90	448.80	439.30	448.80	9.50	0.00

166A	Kunjawatta	1658.50	1529.00	1458.80	1139.90	1198.00	318.90	260.80
190E	Indivitiya	383.40	263.40	255.90	170.70	211.20	85.20	44.70
165	Bopitiya	102.70	78.00	47.50	47.50	47.50	0.00	0.00
165A	Bopitiyathuduwa	887.70	780.10	796.20	703.00	708.30	93.20	87.90
192	Thudella West	379.30	288.10	209.60	116.30	176.90	93.30	32.70
192A	Thudella South	65.40	39.00	14.90	0.00	0.00	14.90	14.90
191	Kanuwana	88.60	76.70	14.30	0.00	0.00	14.30	14.30
193A	Delathura East	462.40	334.80	326.60	326.60	326.60	0.00	0.00
192B	Thudella North	194.70	178.60	127.20	105.40	111.20	21.80	16.00
194A	Dehiyagatha South	123.30	105.90	93.60	55.80	85.90	37.80	7.70
195	Kudahakapola South	163.40	119.40	63.80	4.10	18.20	59.70	45.60
193	Delathura West	1453.00	1415.20	1368.50	1358.50	1368.50	10.00	0.00
196	Kudahakapola North	167.50	137.00	97.80	54.80	74.40	43.00	23.40
164A	Maha Pamunugama	837.30	839.30	752.60	736.10	736.10	16.50	16.50
194	Dandugama	1090.30	952.30	1076.70	896.30	893.40	180.40	183.30
194B	Dehiyagatha North	158.60	147.90	120.10	120.10	120.10	0.00	0.00
164	Pamunugama	532.00	521.40	464.90	460.00	464.10	4.90	0.80
197A	Udammita South	159.50	156.10	109.00	94.60	107.90	14.40	1.10
198	Alawathupitiya	227.40	224.20	205.20	196.80	205.20	8.40	0.00
163A	Kepungoda	218.00	289.90	188.00	140.30	181.90	47.70	6.10
198A	Dambaduraya	285.30	259.10	160.50	160.50	160.50	0.00	0.00
146	Ambalammulla	1425.80	1263.20	1159.50	1079.40	1159.50	80.1000	0.0000
145	Bandarawatta West	308.80	169.50	92.90	91.90	91.80	1.00	1.10
145C	Bandarawatta East	167.50	175.20	89.90	85.10	89.90	4.80	0.00
163C	Settappaduwa	102.90	109.80	73.10	48.40	48.40	24.70	24.70
145B	Mookalangamuwa West	305.80	177.70	122.00	120.10	122.00	1.90	0.00
145A	Mookalangamuwa East	273.90	212.90	137.40	72.80	131.50	64.60	5.90
144	Liyanagemulla South	244.80	200.60	134.10	70.50	108.50	63.60	25.60
163B	Dungalpitiya	258.10	258.70	172.10	58.60	104.90	113.50	67.20
144A	Liyanagemulla North	293.60	189.30	127.70	34.60	50.40	93.10	77.30
143A	Katunayaka South	81.20	140.40	63.20	0.00	0.90	63.20	62.30
143	Katunayaka North	60.80	82.50	132.10	0.00	0.00	132.09	132.09
142A	Kurana Katunayaka South	213.20	215.50	58.40	0.00	0.00	58.40	58.40
142B	Kurana Katunayaka Central	265.70	256.50	80.20	0.00	0.00	80.19	80.19
163	Thalahena	179.30	218.50	111.60	0.01	0.02	111.58	111.57
142	Kurana Katunayaka North	133.60	145.80	90.30	0.00	0.00	90.30	90.30
157B	Kurana West	196.90	150.70	45.30	0.01	0.02	45.28	45.27
157A	Kurana East	133.10	135.50	75.50	0.09	0.02	75.41	75.48
162C	Pitipana Southeast	107.60	110.00	49.90	0.00	0.00	49.90	49.90

162B	Pitipana South - West	54.40	54.00	8.90	0.00	0.00	8.90	8.90
156C	Siriwardana Pedesa	233.60	221.10	240.50	0.00	0.00	240.50	240.50
156	Munnakkarai	18.30	2.00	10.50	0.10	0.00	10.49	10.49
160A	Thaladoowa	82.80	85.30	70.30	0.00	42.80	70.29	27.50
162D	Pitipana Central	99.70	94.30	77.30	0.00	0.00	77.30	77.30
157	Bolawalana	376.00	299.30	147.00	0.00	0.30	147.00	146.70
156B	Munnakkarai East	61.00	48.10	58.90	0.00	26.40	58.90	32.50
162	Pitipana North	108.00	102.80	31.50	0.00	0.00	31.50	31.50
162A	Doowa	33.70	39.10	29.10	0.05	0.01	29.05	29.09
160B	Udayarthoppuwa South	161.40	89.00	12.40	0.00	0.30	12.40	12.10
160	Udayarthoppuwa	122.50	71.90	1.20	0.00	0.30	1.20	0.90
156A	Munnakkarai North	32.30	54.60	71.20	0.00	11.20	71.20	60.00
161A	Angurukaramulla	209.30	124.60	3.90	0.00	0.00	3.90	3.90
158A	Wella Weediya South	10.70	9.60	1.20	0.00	0.00	1.20	1.20
159	Periyamulla	47.30	29.20	6.70	0.00	0.00	6.70	6.70
158	Wella Weediya	12.50	12.30	5.00	0.00	0.00	5.00	5.00
73C	Kudapaduwa South	45.20	38.00	6.20	0.00	0.00	6.20	6.20
158B	Wella Weediya East	63.70	29.90	0.20	0.00	0.00	0.20	0.20
159A	Hunupitiya	74.70	28.70	2.00	0.00	0.00	2.00	2.00