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ASSESSMENT OF LAND DEGRADATION VULNERABILITY IN MARA WETLANDS BY USING GIS AND REMOTE SENSING

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ASSESSMENT OF LAND DEGRADATION VULNERABILITY IN MARA WETLANDS BY USING GIS AND REMOTE SENSING

By;

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A dissertation submitted in the department of Geospatial Sciences and Technology in Partial fulfillment of the requirements for the award of Bachelor degree of Science in Geographical Information Systems and Remote Sensing at Ardhi University.

Certification

The undersigned certify that they have proof read and hereby recommend for acceptance of a dissertation entitled "Assessment of Land Degradation Vulnerability in Mara Wetlands" in partial fulfillment of the requirements for the award of degree of Bachelor of Science in Geographical Information Systems and Remote Sensing at Ardhi University.

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Declaration and Copyright

I Saled, Baraka M., declare that this dissertation is my own original work and that to the best of my knowledge, it has not been presented to any other University for a similar or any other degree award except where due acknowledgements have been made in the text.

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25458/T.2020

Date……………………………

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Dedication

This work is dedicated to my Mother, Mrs. Saled Liuta, who have been a well-wisher in my educational endeavor.

Abstract

Land degradation is among the most persistence environmental hazard in most of the places, and it becomes a severe problem if proper measures are not taken into consideration. Land degradation is among major threats to sustainability of wetland ecosystems globally. Lack of consistent data for monitoring susceptibility of wetlands to land degradation, has been named as one of limitations for effecting proper measures to counteract degradation in Tanzania. This study attempts to assess and map areas vulnerable to land degradation in the Mara wetlands using GIS and remote sensing technique.

A GIS and remote sensing based multi-criteria analysis was used to estimate potential vulnerability of Mara wetlands to land degradation by utilizing various spatial data including precipitation data, land surface temperature (LST), surface elevation data land use and land cover (LULC) and soil properties data. Criteria were generated for land degradation based on rainfall erosivity, soil erodibility and soil pH, soil moisture index (SMI), and topographic witness index (TWI) spatial factors and indices respeectively.

The results obtained demonstrate wetlands' proneness to land degradation ranges from less to extreme vulnerable. The land degradation vulnerability for 2.15%, 4.37%, 51.88%, and 41.60% of extreme, slight, moderate and less respectively. Generally, areas of the wetlands prone to land degradation have been identified and land degradation vulnerability map have been generated to support decision making processes regarding development of Mara wetlands control and adaptive measures for sustainable environment conservation measures.

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List of Abbreviation and Acronyms

AHP	Analytical Hierarchy Process
DEM	Digital Elevation Model
GIS & RS	Geographic Information System and Remote Sensing
LD	Land Degradation
LDV	Land Degradation Vulnerability
LDVI	Land Degradation Vulnerability Index
LST	Land Surface Temperature
LULC	Land Use Land Cover
LVBC	Lake Victoria Basin Commission
MRB	Mara River Basin
NDVI	Normalized Difference Vegetation Index
NEMC	National Environmental Management Commission
SRTM	Shuttle Radar Topography Mission
TanSIS	Tanzania Soil Information Services
USG	United States Geological Survey
VCI	Vegetation Condition Index

CHAPTER ONE

INTRODUCTION

1.1 Background

Land degradation (LD) is defined as "the continuous reduction or loss of the productivity of the land due to a combination of natural and anthropogenic causes" (UNCCD, 1994). Land degradation is caused by multiple forces, including extreme weather conditions, particularly drought (Chen et al., 2020). It is also caused by human activities that pollute or degrade the quality of soils and land utility (URT, 2017). It negatively affects food production, livelihoods, and the production and provision of other ecosystem goods and services and may accelerate the rate of environmental disaster displacement (Stocking & Murnaghan, 2020).

Moreover, Land is the most important basic natural resource (Sileshi, 2016). It is a dynamic and complex combination of geology, topography, hydrology, soil and flora and fauna, and, it influences every sphere of human activities such as aspects of social, economic, cultural and political development (Duro, 2012). Land is a broad term with many interpretations; for example, as an ecosystem, as a landscape, as an administrative or planning unit, and as a social or cultural concept. Lands are complex systems operating on large spatial and temporal scales that present many challenges to effective management (Lead et al., 2019).

Wetlands are defined as "areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine water the depth of which at low tide does not exceed six meters" (Type et al., 2023). Where by freshwater wetlands provide a very large number of ecosystem services, such as groundwater replenishment, flood protection and nutrient retention, and are biodiversity hotspots (Mombo et al., 2007). Wetlands are primarily responsible for providing ecosystem services to the environment, as they facilitate filtering of water, habitat to terrestrial and aquatic lives and regulation of the climate and weather conditions, the functions which when degraded may not be performed to the fullness (USAID, 2019).

Conversion of freshwater wetlands to agricultural land has historically been a common way of increasing the area of arable land (Kamukala, 2023; Mosha, 1983). In addition to land conversion driven by a rapidly growing population, most of the people in Mara region generally rely on forest resources as cooking fuel sources and support for livestock production, which have contributed to degraded forests, grasslands, and soil and water resources (Bogers, 2007;

URT, 2007). Wetlands and land degradation can affect human health through complex pathways. As land is degraded in some places, food production is reduced, water sources dry up and populations are pressured to move to more hospitable areas (Arhem & Freden, 2014). Around 24% of the world's total geographic area (approximately 3500 million hectares) is severely affected by land degradation (Romshoo, Amin, Sastry, & Parmar, 2020).

Wetlands are natural or artificial ecosystems where water is the main component controlling the environment and its flora and fauna (Omolo et al., 2018). They may be temporary or permanent wetlands, where by Mara wetlands have existed over decades and have may be recognized as a permanent wetland in Tanzania (NELSACCU, 2015). Modeling and assessing the vulnerability of land degradation in the wetlands plays a vital role in land degradation neutrality planning and prioritization processes and in fulfilling targets for wetlands restoration. Assessment of land degradation requires various information such as climate, pedological properties, topography, land use (Pacheco, Fernandes, Valle, Valera, & Pissarra, 2018).

Projected increases in temperature, variability in rainfall, frequency and intensity of heavy rainfall events, and intensity and duration of heat waves and drought events, coupled with high levels of poverty and a reliance on rained agriculture, make the communities around the wetlands particularly vulnerable to climate change (USAID, 2019). Water shortage, poor water quality and environmental degradation has become a threat to human settlement within Mara wetlands and along the Mara River (Omolo et al., 2018). Contiguous increase in population, diversification of agriculture, deforestation, livestock raising, mining industry, and tourism are the driving forces of land degradation, water quality and ecosystem problems for Mara River catchment and the associated wetland areas (URT, 2022).

Wetlands may be lost due to desertification, which may be an impact of either natural or anthropogenic phenomena or both (Ya et al., 2015). When desertification occurs, fertile land becomes unproductive and when the severe conditions are prolonged may likely become deserts (Zorn & Komac, 2013). There is also a need to look the wider context of the rapid and ongoing disappearance and degradation of wetlands globally, and increasingly in Africa (Davidson, 2014, Verhoeven, 2010). About 65% of the African continent's farm land is affected by erosion-induced losses of topsoil and soil nutrients (FAO, 2018) Tanzania is also a victim of soil erosion as in the recent years it has led to an annual loss of 2.3 billion dollars reported due to land degradation in the semi-arid areas (Mwalyosi, 2002).Within the Mara basin in

Tanzania roughly 300 square kilometers of rangeland was lost between 1986 and 2015 (Lake Victoria Basin Commission, 2016).

1.2 Statement of a research problem

Land use and wetland management are important aspects of ensuring sustainability of the natural resources and environment. Various mitigation policies and programs such as, (Environmental, 2018) which indicates the initiatives undertaken and to be implemented to achieve environmental justice have been hindered in local levels. This has been due to the limited availability of the information in location and extent or and proneness of environmental degradation at the grass root levels. Since, some studies have been focused on global and regional scale, there is a need to narrow down the research into local scale being the very prone areas of these aspects. Assessing and mapping the environmental vulnerable aspects such as land degradation is crucial effort for creating awareness and information prior for implementation of various environmental programs, plans and policies.

1.3 Objectives

1.3.1 Main Objective

To assess and map Land Degradation Vulnerability (LDV) in Mara Wetlands.

1.3.2 Specific Objectives

i. To assess the spatial-temporal factors for land degradation in the wetlands.
ii. To establish criteria and determine the relative importance of the factors for land degradation vulnerability in Mara wetlands.
iii. To identify and map the critical areas of land degradation in the wetlands.

1.4 Research questions

This study is intended to answer the following questions;

i. What are the spatial-temporal drivers for land degradation in Mara wetlands?
ii. Do the driving factors for land degradation in Mara wetlands vary in their relative importance?
iii. What is the land degradation vulnerability status of Mara wetlands?

1.5 Scope and limitations of the study

This study focuses on the assessment and mapping of land degradation vulnerability by determining the magnitude and location of the vulnerable areas in the Mara Wetlands basing on Land-use and Land-cover (LULC), precipitation data, Land Surface Temperature (LST), topology and pedology. It utilizes an Analytical Hierarchy Process (AHP) a GIS based multi-criteria analysis to analyze the Land Degradation vulnerability in the Mara wetlands. However other methods which involves direct observation of the field may be used, GIS and remote sensing is cost effective and applicable for large and remote areas which cannot be on reach with field surveys. The results of which will contribute in developing and achieving making informed decisions for sustainable development of the Mara basin and other relevant wetlands in Tanzania and sub-Saharan countries.

Most of the factors used for land degradation vulnerability assessment for this study were very generic and continuous, however the analysis was possible it was challenging to obtain some data and information which could have narrowed the scope of study, since there is inadequate spatial data and information in the region.

1.6 Significance

The findings of this study will be of greater importance for the society as it will provide information to influence sustainable land management and development of the watershed areas.

1.7 Beneficiaries

- National Environmental Management Council (NEMC).

The results of this dissertation may provide the National Environmental Management Council (NEMC) with voluble information describing the areas that are prone to environmental degradation and be able to undertake various precautionary and mitigation measures towards protecting the environment and people's vulnerability to related hazards.

- Lake Victoria Basin Commission (LVBC).

Since LVBC is responsible for managing and maintaining the conditions of the wetlands within the Lake Victoria basin, this study will add value to the (NELSACCU, 2015) and facilitate achieving its goals by having integrated with variety of expert information and recommendation.

- Decision and policy makers.

The government, non-government organizations and private sectors are highly centered on making various informed-decisions (Mathenge et al., 2022). Thus, they may opt to use the results of this study as a base for establishing the decision making process especially on how the wetlands should be managed or invested with safeguarding the environment and achieving satisfaction to the individual persons, society, organization and or a country at large.

- Researchers.

This study will establish a basis for literature review to students, researchers, investigators and environment knowledge providers. It will be a suitable base to narrow the study into evaluating the relationships that may exist between the environment aspects. Researches normally are required to develop problems which arise from the literatures or the actual world environmental setup (Johnston, 2016), which are either fully or partially captured in this study, a valuable criteria for aiding various scientific findings cutting across the environmental aspects such as climate.

- Farmers.

Farmer's needs are to achieve food security and commerce rely on the environment. This study will provide the farmers with information that aims at ensuring they invest in an enviro-friendly agricultural production, for both domestic based producers and financially based producers. For example, to achieve the goals of (Platte et al., 2009), the area suitable for agriculture must be clearly demarcated and managed with the use of appropriate expertise, information and technology.

1.8 Description of the study area

The Mara Wetlands (Figure 1.1) is an extensive swamp in Tanzania at the lower end of the Mara River Basin (MRB) located between longitudes 33°47' E and 35°47' E and latitudes 0°38' S and 1°52' S and covers 13, 750 square kilometers; 65 percent is in Kenya, and 35 percent in Tanzania (Omolo et al., 2018; Foundation, 2017; Mutie et al., 2005;). The Mara Wetlands extends in four administrative boundaries of Tarime, Serengeti, Butiama and Rorya surrounded by the total of 20 villages(USAID, 2019). The Mara Wetlands provides an array of ecosystem services that include provisioning services, regulating services, supporting services and cultural services(URT, 2017).

A number of socio-economic and cultural activities that are taking place in the wetlands includes, mining livestock husbandry, fisheries, tourism, non-timber production, and agriculture and honey production which poses threat to the environment (Platte et al., 2009). Mara wetlands has been experiencing soil erosion condition and water pollution events in the available water resources such as the Mara River which is a major source of water in the region supplying its water to the Lake Victoria (NELSACCU, 2015). Due to persistence of natural and human induced influences the Mara wetlands have suffered from land degradation threats and events from time to time such that in between 2010 and 2017 bushfires and monoculture contributed to famine and drought events in some areas of the Mara wetlands belt (WWF-Kenya, 2017).

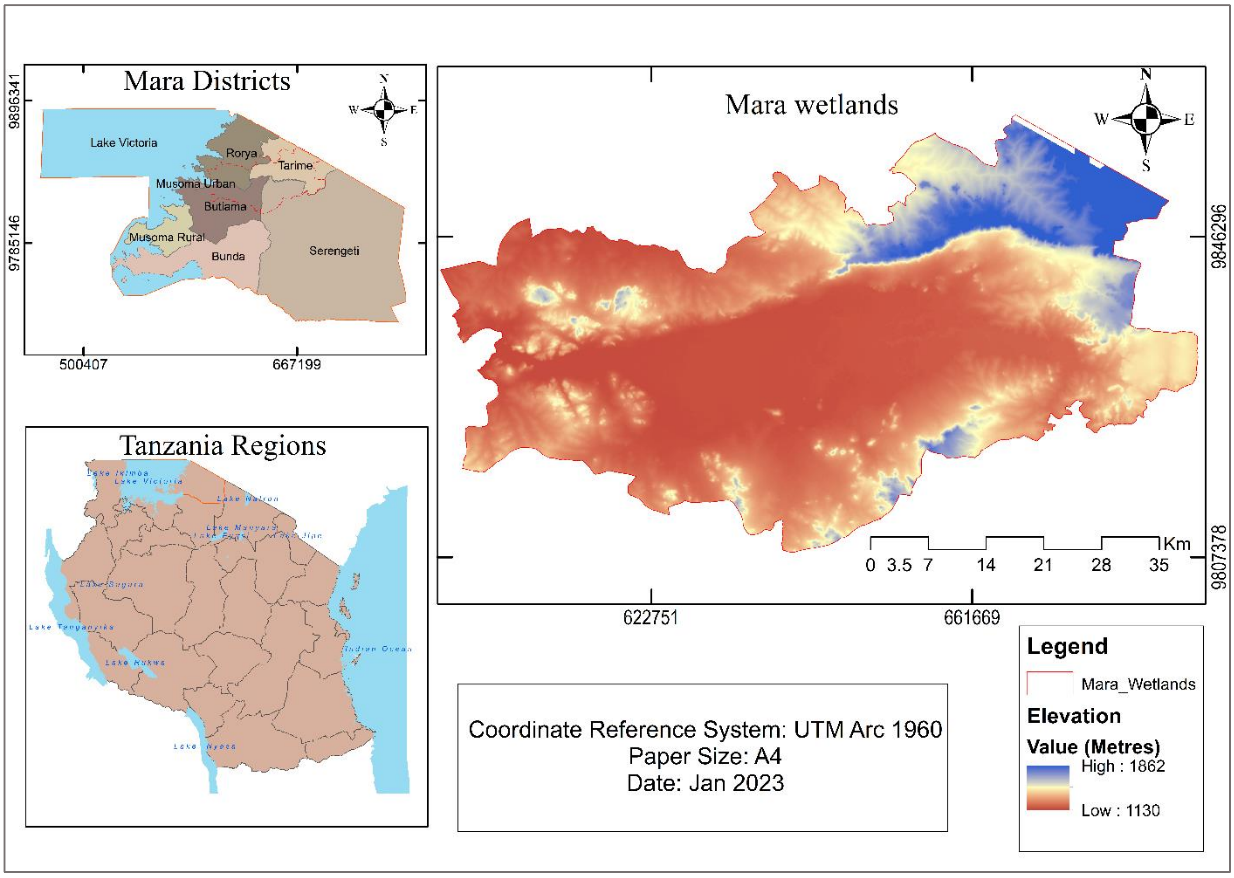


Figure 1. 1: The study area.

CHAPTER TWO

LITERATURE REVIEW

1.4 Overview

This study will be performed by investigating the spatial-temporal indicators to understand the vulnerability of the wetlands to land degradation (Ngandam, Etouna, Nongsi, Mvogo, & Noulaquape, 2016). The parameters to consider includes, climate where rainfall and land surface temperature will be analyzed, terrain, and vegetation and soil parameters (Abebe , Megersa , Quoc, & Duong, 2021).

2.3 Land degradation

Land degradation refers to the deterioration of the quality and productivity of land due to various human and natural factors. (Pacheco, Fernandes, Valle, Valera, & Pissarra, 2018) It can have severe consequences for ecosystems, agriculture, and human livelihoods. The criteria for land degradation can vary depending on the context, but here are some common criteria used to assess land degradation (Romshoo, Amin, Sastry, & Parmar, 2020).

2.4 Types of land degradation

There are four major land degradation types, each type of land can be sectioned by precise sub-set of degradation processes, these are, soil degradation, vegetation degradation, water resource degradation and pollution (Davidson, 2014). However, to identify the land degradation type and process are the most important to be concerned about the vulnerability area of the watershed. Mostly it depends on soil degradation focused on other types of land degradation (Verhoeven, 2010)

2.4.1 Soil degradation

Land degradation of this kind often is associated with the loss of soil fertility, which is the ability of the soil to support healthy plant growth (Stocking & Murnaghan, 2020). Soil fertility can be diminished by factors such as nutrient depletion, soil compaction, and the accumulation of toxic substances. Reduced crop yields or the need for excessive fertilization can indicate degraded land (Abebe , Megersa , Quoc, & Duong, 2021). Also when soil erosion occurs the top layer of soil is removed or displaced by natural processes such as wind or water. It can be accelerated by unsustainable land use practices like deforestation, overgrazing, or improper agricultural practices. Excessive soil erosion is a clear sign of land degradation (Arhem & Freden, 2014).

2.4.2 Vegetation degradation

According to (Clarke et al., 2022)it refers to the compromised condition and growth or healthy of vegetation associated with the changes in the composition, structure and function of particular vegetation cover and surrounding environment. Also (Stocking & Murnaghan, 2020) shows that vegetation is dynamic with the existing environmental problems and dynamist may be remarked with variations in the distribution of vegetation types and changes in the growth and development periods of various plants. The plant growth period frequent observation and measurement is significant for monitoring changes and vegetation dynamics is another field for investment for socio-economic and environmental wellbeing (Ortega-gaucin et al., 2021)

2.4.3 Water resource degradation

This involves ground water table lowering, minimized recharge and increased extraction, the amount of sediment load increased in watercourses and rivers as a result of increased soil erosion in their catchment areas (Gebeyehu, 2019). Reduced water storage capacity due to sedimentation of reservoirs; the ground water resource pollution and surface water pollution to the direct cause of human and animal wastes, agrochemicals, industrial and mining wastes; and increased salt content of surface and ground water resources due to excess salt flushing from irrigated areas (Farinosi et al., 2019; Ortega-gaucin et al., 2021; Zorn & Komac, 2013).

2.5 Causes of land degradation

The cause of land degradation involves multiple causal factors. These are the physical/natural and human induced causes. The relations between the two systems determine the decline of resource management

2.5.1 Natural causes

Land degradation may occur as the impact of natural forces such as climatic changes, volcanic eruption, landslides, flooding events and soil erosion. This factors may alter the whole structure of the soil, water resources, vegetation and impact human livelihood negatively (WWF-Kenya, 2019).

2.5.2 Human induced causes

There are several recognized causes of land degradation being a factor of human-environment relationship, these includes biophysical factors such as inappropriate land use, socio-economic factors such as lack of land management activities, access to markets, infrastructure, land tenure, institutional support income and political factors such as lack of incentives and political instability which hand to mouth agriculture, poverty and illiteracy people are the main causes of land and environmental degradation (Duan et al., 2022; WWF-Kenya, 2017)

2.6 Land degradation process

Land degradation is primarily caused by human activities and natural processes, leading to the loss of soil fertility, vegetation cover, and overall ecosystem health (Kumsa & Assen, 2022). It may start disrupting ecosystems, reducing biodiversity, altering local climate systems. The rampant expansion of cities and improper infrastructure development can lead to soil sealing, and the alteration of natural drainage patterns can disrupt ecosystems, reduce soil fertility, and increase the risk of flooding (Erman et al., 2019). The excessive use of pesticides, herbicides, and fertilizers in agriculture can contaminate soil and water resources. These chemicals can have long-term effects on soil health, microorganisms, and crop productivity (Verma et al., 2013)., as well as uncontrolled grazing by livestock on fragile ecosystems can lead to reduced vegetation cover, disrupted soil structure, and promotes soil erosion, especially in arid and semi-arid regions (Omolo et al., 2018).

2.7 Land degradation control measures

Soil degradation detection and monitoring Addressing land degradation requires sustainable land management practices, reforestation, erosion control measures, proper land-use planning, and the adoption of sustainable agricultural techniques (Businge, 2017).

2.8 Assessment of land degradation

Land degradation may be assessed in various ways, such as measuring trend of the productive capacity of the land or soil (Sileshi, 2016; Tolche et al., 2021). Evaluating the ecosystems complexity, environmental quality as-well-as increased vulnerability of the environment or people to land degradation hazards (Omolo et al., 2018). Either of these may be done using field survey or the application of GIS and remote sensing and become successful (Gebeyehu, 2019).

2.9 Multi-criteria decision support analysis

The GIS and Remote Sensing Multi-criteria Decision Support Analysis method, Analytical Hierarchy Process (AHP) will be employed to support weighing of the utilized parameters and to map the vulnerable areas in the wetland. Analytical Hierarchy Process (AHP) have been adopted to map successfully the ground water potential recharge in various areas as well as in land degradation and soil erosion and land degradation assessments.

2.10 Analytical Hierarchy Process (AHP)

AHP method is a mathematical approach used in multi-criteria decision analysis providing a way to conduct pairwise comparison of the weight of the criteria used based on knowledge of the criteria. It allows to determine consistency of the comparison, Consistency Ratio (CR) and Consistency Index (CI), as in equations (1 and 2) (Saaty, 1980).

$$CI = \frac{\mathrm{K}max - n}{n-1} \quad \text{.............................. (1)}$$

$$CR = \frac{CI}{RI} \quad \text{.................................... (2)}$$

The random index for the pairwise comparison were designed based on the number of elements being compared to establish consistency and uniformity in the assessment, as in *Table 2.1* (Saaty, 1980).

Table 1. 1: The Random Index (RI) Table.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.58	1.58

Where; *RI* is Random Index, *CR* is consistency ratio, *CI* is the consistency index, *n* is the number of elements being compared in the matrix and Kmax is the principal Eigen-value of the matrix.

2.11 Land degradation assessment factors

2.11.1 Soil types

It's important to note that certain soil types may be more prone to specific types of land degradation depending on their inherent properties and how they are managed.

1. Sandy soils: Sandy soils have larger particles and low water-holding capacity. They are prone to erosion by wind and water due to their loose structure (B.Humberto and L.Rattan, 2008). Sandy soils are susceptible to nutrient leaching as water easily drains through them, leading to reduced soil fertility and nutrient depletion. Without proper management practices such as irrigation and organic matter addition, sandy soils can experience land degradation, decreased crop productivity, and increased vulnerability to drought (Zorn & Komac, 2013).

2. Clay soils, have smaller particles and high water-holding capacity. They can be highly fertile but are prone to compaction when overloaded (Mohamed et al., 2020). Compacted clay soils have poor drainage and limited root penetration, leading to waterlogging and decreased aeration (Hasab et al., 2020). They may be managed well through practices of proper tillage and soil amendment, clay soils can suffer from reduced productivity, poor crop establishment, and increased vulnerability to flooding(Gebeyehu, 2019).
3. Loam soils: are a balanced mixture of sand, silt, and clay particles. They typically have good water-holding capacity, adequate drainage, and are fertile and are generally more resilient to erosion compared to sandy or clay soils(Ortega-gaucin et al., 2021; The World Bank Office, 2012; WWF-Kenya, 2017). However, poor land management practices like overgrazing, intensive agriculture without proper soil conservation measures, or excessive use of chemical inputs can still lead to land degradation on loam soils (B.Humberto and L.Rattan, 2008).
4. Peat soils: also known as organic soils or peat lands, are formed from partially decomposed plant material in waterlogged conditions. They are rich in organic matter and can hold large amounts of water. However, peat soils are highly vulnerable to degradation due to drainage, deforestation, and conversion for agriculture or peat extraction (Catherine Bowyer, Sirini Withana, Ian Fenn, Samuela Bassi, Megan Lewis, Tamsin Cooper (IEEP) Patricia Benito, 2008; Lead et al., 2019; Stocking & Murnaghan, 2020; Wu et al., 2020). Concentration of peat may lead to land degradation (URT, 2022) contributing to significant amount of carbon dioxide emissions and daggering the environment (URT, 2017).
5. Volcanic soils: also known as *andisols*, formed from volcanic activity (Mohamed et al., 2020). They are generally fertile due to their high mineral content and good water retention capacity. However, volcanic soils can be susceptible to erosion when exposed to heavy rainfall or improper land management practices (B.Humberto and L.Rattan, 2008). Proper erosion control measures, such as contour plowing and terracing, are crucial to prevent land degradation on volcanic soils (Srinivasa Raju & Nagesh Kumar, 2018).
6. Saline and Alkaline soils are characterized by high salt content and high pH levels(B.Humberto and L.Rattan, 2008). These soils can result from natural processes or be worsened by poor irrigation practices, excessive fertilization, and waterlogging (Kumsa & Assen, 2022). Saline-Alkaline soils are often infertile for most crops due to

limited water and nutrient availability. Land degradation in these soils can lead to soil salinization, reduced agricultural productivity, and loss of biodiversity (Zorn & Komac, 2013).

2.11.2 Soil erodibility

Soil erodibility is the susceptibility of soil to agent of erosion, its estimate the ability of soils to resist erosion, based on the physical characteristics of each soil (Singh & Khera, 2010). This is determined by inherent soil properties such as soil texture, structure, soil organic matter content, clay minerals and transmission properties (Cassol et al., 2018). Ground cover exerts a strong moderating impact on dissipating the energy supplied by agents of soil erosion. The soil erodibility factor (K), represents both susceptibility of soil to erosion and the amount and rate of runoff, as measured under standard plot conditions (Parveen & Kumar, 2012). The soil erodibility factor K measures the susceptibility of soil particles to detachments and transport by rainfall and runoff (Renard, 1997).

2.11.3 Soil pH

Soil pH, is the measure acidity or alkalinity of the soil (B.Humberto and L.Rattan, 2008). It is a significant implications for nutrient availability, microbial activity, and plant growth. Soil pH can provide valuable insights into the condition of the land and its potential degradation (Stocking & Murnaghan, 2020). While the specific pH criteria for land degradation can vary depending on the context, extreme pH values in some cases, acidic or alkaline pH values can be indicative of land degradation (Zorn & Komac, 2013). For instance, severely acidic soils with a pH below 4 or highly alkaline soils with a pH above 10 are likely to indicate significant degradation, rendering the land unsuitable for most vegetation and agricultural activities (Singh & Khera, 2010).

1. Acidic soils: Land degradation due to soil acidity is typically indicated by excessively low pH values. Acidic soils often have a pH below 6.5, but the severity of degradation can vary based on the intended land use (Singh & Khera, 2010). For example, agricultural land may be considered degraded if the pH falls below the optimum range for specific crops or if it is significantly lower than the natural pH of the region (Tolche et al., 2021).
2. Alkaline soils: usually they have a pH above 8.5, but the specific threshold for degradation depends on the intended land use and the tolerance of plants to alkaline conditions (Zorn & Komac, 2013). Land degradation related to soil alkalinity is

characterized by excessively high pH values. If the pH exceeds the suitable range for desired crops or if it deviates significantly from the natural pH of the region, it can indicate land degradation (Kumsa & Assen, 2022).

2.11.4 Slope

A slope is a measure of the steepness surface. It is calculated as the ratio of the vertical (Z) change to the horizontal (X) change between two points (Chauhan, 2021). Slopes can be positive, negative, zero or undefined. In geography and geology, slope is used to describe terrain or surface of the Earth and may be expressed as degree, percentage or other metric units (Parveen & Kumar, 2012).

2.11.5 Topographic Witness Index (TWI)

Topographic Witness Index (TWI) is based on the topographic characteristics of an area and provides an indication of land-form vulnerability to erosion and degradation processes (Tolche et al., 2021). The TWI takes into account the slope and contributing area of a location to estimate the potential for erosion and sediment transport. While it is not a direct measure of land degradation, the TWI can provide valuable information about areas at risk of degradation (Parveen & Kumar, 2012).

2.11.6 Vegetation Condition Index (VCI)

The Vegetation Condition Index (VCI) is an index derived from remotely sensed information, it compares the current NDVI to the range of values observed in the same period in previous years (Kloos et al., 2021). The VCI is expressed in % and gives an idea where the observed value is situated between the extreme values (minimum and maximum) in the previous years. Lower and higher values indicate bad and good vegetation state conditions, respectively (Sholihah et al., 2016).

2.11.7 Soil Moisture Index (SMI)

The Soil Moisture Index (SMI) quantifies the moisture condition at various depths in the soil(Das et al., 2021). It is mainly driven by precipitation via the process of infiltration (Mohamed et al., 2020). Soil moisture varies on small scales with soil properties and drainage patterns. It may be estimated from thermal bands in satellite images such as Landsat images through radiance convention models such as those used by (Mohamed et al., 2020; Parveen & Kumar, 2012; Tolche et al., 2021).

2.11.8 Land-use land-cover (LULC)

Land use and land cover are maps representing spatial information on different classes of physical coverage of the Earth's surface such as vegetation, built-up, bare-land and water covers, residential, industrial, waste, recreational and commercial uses. Since these aspects are spatially and temporal variable (Chen et al., 2020). LULC are appropriate for capturing land cover or use changes (Lamichhane & Shakya, 2019). Land use maps contain spatial information on the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it (Duan et al., 2022).

2.11.9 Rainfall erosivity

Rainfall erosivity contributes to large amount of soil loss and has significant impacts on land degradation through soil erosion due to the impact of rain in the soil. It is also known as the R-factor represents and measures the erosive force of a specific amount of rainfall which is determined by the intensity, distribution, duration and pattern of rainfall whether for single storms or a series of storms, and by the amount and rate of the resulting runoff (Tadesse, 2014). The intensity of a specific rainfall is the highest determinant factor of the extent of water erosion. The R-factor was developed based on the alternative empirical equation in area with less moist climatic zone due to the lack of rain-fall (Hurni, 1985).

2.12 Population density

Population density is the measure of the number of people per unit area, commonly represented as people per square mile (or square kilometer). It implies an estimated number of people residing a specific unit of land (Sileshi, 2016). The population density may influence the use and pressure on wetlands resources and may likely result to degradation of the environment (Ortega-gaucin et al., 2021).

CHAPTER THREE

METHODOLOGY

3.0 Overview

This chapter provides an overall description of data acquisition, data preprocessing and data analysis methods that were used in in this study to arrival at the results. This study adapts the GIS based multi-criteria decision support process model, Analytical Hierarchy process on data processing towards achieving the main objective. The step-by-step process performance in this study is summarized in Figure 3.1

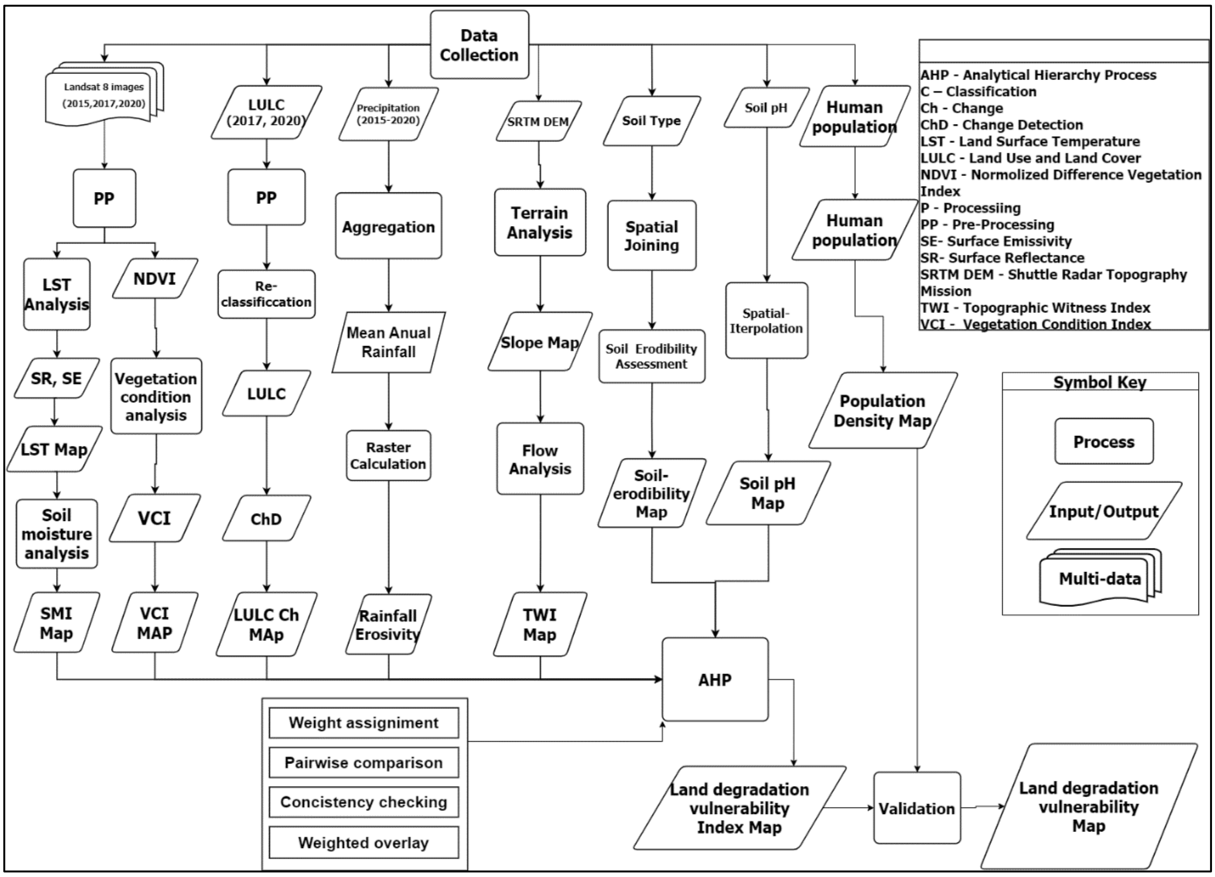


Figure 3. 1: A work-flow for the study.

3.1 Data collection

Various GIS and Remote Sensing sets of data will be utilized in this assessment. Their acquisition will be based on the purpose and characteristics of the data such as summarized in the Table 3.1. The datasets were quantified to determine factors that influence land degradation. In this context, various mathematical models, classification and reclassification procedures will be carried so as to identify land degradation vulnerability zones in the wetlands.

Table 3. 1: The datasets for the study, their sources and characteristics.

S/ No	Dataset	Source	Variable	Temporal resolution	Spatial resolution	Temporal coverage
1	Classified Land Use/Land Cover	Esri https://www.esri.com/land-use-land-cover	Land Use/Land Cover		10m	2015,2017 and 2020
2	Landsat 8	United State Geological Survey https://earthexplorer.usgss.gov	Vegetation Condition Index, Soil Moisture Index		30m	2015,2017 and 2020
3	Climate Hazards Infrared Precipitation with Station data.	Climate Hazard Centre https://www.chc.ucsb.edu/data/chirps	Rainfall	10 days	4km	2015-2020
4	Shuttle Radar Topographic Mission	United State Geological Survey https://www.usgss.gov/centre/eros/science/srtm	Digital Elevation Model		30m	2014
5	Soil	Open science framework TanzaniaSoil Information Services https://osf.io/4ngau/#!	Soil biophysical properties		250m	2018

3.2 Data pre-processing

3.2.1 Coordinate projection from global to local coordinate system

The data from various sources were in a different coordinate systems from the study area, therefore, the data were re-projected from global coordinate systems to local coordinate system so as maintain correspondence between datasets and the area of study to easier the further steps of the processing. After re-projection, the datasets were in uniform coordinate system which is a Projected Universal Transverse Mercator (UTM) Coordinate reference system (CRS) Arc1960 zone 36S

3.2.2 Rainfall data Aggregation for combining the annual datasets

1. For rainfall data the sum function was used to determine the total rainfall for the whole year which results into one aggregated layer with rainfall data.
2. For NDVI and VCI data the mean function was used to determine the mean vegetation cover for the whole year which results into one aggregated layer with NDVI data.

3.2.3 Spatial extraction of the data for the study area

Since datasets had different coverage extents as they were sourced, they had to be extracted using the study area boundary shape file by using clipping or and masking functions so as to obtain the dataset layers with the same coverage as the area of study, this was done using the spatial analysis tools in ArcGIS 10.8.

3.3.5 Gap filling of the missing data/sinks

This is called void filling or fill sinks, it was done on the downloaded Digital Elevation Model (DEM) as to remove small imperfections in the data, the process which increases the accuracy of the DEM.

3.3 Surface analysis of the terrain and soil properties.

3.3.1 Estimation of Slope Gradient from SRTM-DEM

The filled Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of 30 m spatial resolution for the study are was processed to obtain slope gradient (in percentage) using a spatial analysis tool in ArcGIS 10.8 based on the equation (3.1) (Parveen & Kumar, 2012; Tolche et al., 2021).

$$Slope = ((Z_i - Z_j) / (X_i - X_j)) * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3.1)$$

3.3.2 Topographic witness index (TWI) estimation from SRTM-DEM

This was evaluated from the corrected DEM raster, it involved a series of spatial based mathematical models to obtain TWI values based on equations (3.3.2 - 3.3.9) according to (Parveen & Kumar, 2012)using raster tool and spatial analysis tools of flow direction and flow accumulation. The flow direction tool of spatial analysis was used to obtain the flow direction for the wetlands terrain using equation (3.3.2), then flow accumulation was evaluated using flow accumulation conditional operation as in equation (3.3.3) which resulted to a network of flowing streams on the area which after they were scaled using equation (3.3.4). The slope in degrees values were converted into radiance values and then tangent slope using

$$TWI = (FA_{scaled} / Tan_{slope}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3.2)$$

$$Z_{max} = ((Z_i - Z_j) / D) * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3.3)$$

$$FA = Cond\ (Value > 100, 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3.4)$$

$$FA_{\ scaled} = (sca+1)*cell\ size \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3.5)$$

$$Slope_{rad} = (Slope_d * 1.570796) / 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3.6)$$

$$Tan_{slope} = Cond\ (Slope_{rad} > 0, \tan (Slope_{rad}), 0.001) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3.7)$$

Where, Z_{max} –Maximum drop, Z_i –Z_j –Change in Z-value, and D- Distance, FA – flow accumulation, FA_{scaled} – scaled flow accumulation, $Slope_r$ -slope in radiance, Tanslope – slope tangent.

3.3 Pedological analysis.

This involved analysis of soil factors that contribute to the soil degradation which are soil types, soil erodibility, and soil ph.

3.3.1 Estimation of soil erodibility (K) from soil types data

Using the shape file for soil types from Tanzania Soil Information Services (TanSIS) which are of 1km of spatial resolution, the types of soil that are in Mara wetlands were clipped and resampled to 30m of spatial resolution, and projected into CRS Arc1960 UTM Zone 36S the layer was used to obtain the content of each soil texture in each type of soil type as the percentage content of top soil for clay soil, sandy soil, silt soil, and organic-carbon soil. Soil erodibility (K) values were obtained using field calculator tool using equations, in the attribute table and the soil polygon data was reclassified as, and converted into raster layer using polygon to raster tool. The mathematical models in equation (3.3.1-3.3.5) were used as according to (Cassol et al., 2018; Parveen & Kumar, 2012; Singh & Khera, 2010).

$K = F_{sa} * F_{cl-si} * F_{orgc} * F_{hisa}$ …………………………………………………… (3.3.1)

F_{sa} = (0.2 ∗ exp [-0.25 ∗ Msa ∗ (1 – Msi/100)]) ……………………......…………… (3.3.2)

F_{cl-si} = ($M_{si}/M_{cl}-M_{si}$) ^0.3 ……………………………………………….……….. (3.3.3)

F_{orgc} = (1 − 0.25∗orgc/ (orgc+exp [3.72−2.95∗$Orgc$])) …………………..………. (3.3.4)

F_{hisa} = [1 − 0.7∗ (1− M_{cl} 100) (1− M_c 100) +exp [−5.551+2.29(1− M_{cl} 100)] …… (3.3.5)

Where: M_{sa}- The sand fraction content (%), M_{si} - the silt fraction content (%), M_{cl} - the clay fraction content (%), *orgc*-organic matter content (%), F_{sa}- values for soil with higher coarse sand content and higher for soil with little sand, $F_{cl\text{-}si}$-values for soils with high clay-silt ratios, *Forgc*-values in soil with high organic content, F_{hisa}-values in soil with extremely high sand content, *K*-soil erodibility values

3.3.2 Estimation of soil pH using Inverse Distance Weighting IDW

The measured soil acidity (pH) values obtained from Tanzania soil information services (TanSIS) as measured from soil samples from various geographical areas in Tanzania were clipped and projected into CRS Arc1960 UTM Zone 36S for Mara Region and were interpolated in ArcGIS 10.8 using Inverse Distance Weighting (IDW) method in spatial analysis tool to obtain the general soil acidity for the region and clipped for Mara wetlands. The Inverse Distance Weighting creates a GRID raster surface with equally spaced cells from irregularly paced points (Verma et al., 2013).

3.4 Estimation of rainfall erosivity (R) from Terra-climate rainfall data.

Using the rainfall data downloaded from Terra-Climate with a monthly temporal resolution and approximately 4km spatial resolution to calculate the rainfall erosivity factor. The data where clipped and projected into CRS Arc1960 UTM Zone 36S for Mara Region and averaged to get the annually average precipitation (rainfall) for Mara region. The average annual rainfall of Mara wetlands is approximately between 827-1034 mm/yr. The equation (3.4) was used in calculating the rainfall erosive intensity as according to (Cassol et al., 2018; Parveen & Kumar, 2012).

R = -8.12+ (0.562∗P) ………………………………………………….…… (3.4)

Where; R is the rainfall erosivity factor (MJ mm ha-1 h -1 yr-1) and P is the mean annual rainfall (mm)

3.5 Estimation of Vegetation condition index (VCI) from Landsat 8

This was obtained after delineating and analyzing the study area of Mara wetlands and projecting from the Landsat 8 image of 30m spatial resolution by using raster calculator tool in ArcGIS 10.8, first, NDVI values for each year was calculated using equation (3.5.1), then the $NDVI_{min}$ and $NDVI_{max}$ values were calculated using cell statistic operator. Thereafter, the VCI for each year was calculated using raster calculator tool using equation (3.5.2) and the average VCI (VCI_{mean}) was calculated using cell statistic operator.

$NDVI= (NIR-RED)/ (NIR+RED)$ ……………………………………………..…. (3.5.1)

$VCI= (NVDI_j -NDVI_{min})/ (NDVI_{max} -NDVI_{min})$ ………………………………….. (3.5.2)

NDVI- normalized difference vegetation index, $NDVI_{min}$ – minimum normalized difference vegetation index between 2015 and 2020, $NDVI_{max}$ - maximum normalized difference vegetation index between 2015 and 2020 and *VCI* - vegetation condition index

3.6 Estimation of Soil Moisture Index (SMI) from Landsat 8

Soil moisture index was estimated from the land surface temperature measured from respective surface reflectance band 10 of Landsat 8 images with the use of mathematical models as in equations (3.6.1 - 3.6.6) after estimating the amount of land surface temperature for the period of study

Calculation of TOA (Top of Atmospheric) spectral radiance.

$TOA (L) = M_L * Q_{cal} + A_L$ ………………………………………………….……….. (3.6.2)

Where; SMI= soil moisture index, M_L = band 10 multiplicative radiance, Q_{cal} = corresponds to band 10, A_L = Band 10 additive radiance

TOA to Brightness Temperature conversion

$BT = (K_2 / (Ln (K_1 / L) + 1)) - 273.15$ ……………………………………..…. (3.6.3)

Where: K_1 and K_2 = Band 10 thermal conversion constants. Absolute zero (approx. -273.15°C) was added to the radiant temperature is adjusted to obtain the results in Celsius

To calculate the proportion of vegetation (P_v) the NDVI layers were already estimated in previous steps, therefore,

P_v = Square ((NDVI – $NDVI_{min}$) / ($NDVI_{max}$ – $NDVI_{min}$)) ……………………………. (3.6.4)
Calculate Emissivity ε

ε = 0.004 * P_v + 0.986 ……………………………………………………………… (3.6.5)

By applying the formula in the raster calculator, the value of 0.986 corresponds to a correction value of the equation.

Then the surface brightness and surface emissivity were to compute the land surface temperature,

LST = (BT / (1 + (0.00115 * BT / 1.4388) * Ln (ε))) ………………………………… (3.6.6)

Lastly, the soil moisture index was calculated and the mean soil moisture index was developed using cell statistic operator.

SMI = (LST_{max} – LST) / (LST_{max} - LST_{min}) …………………………………….…….. (3.6.1)

3.7 Land-use land cover change detection

The LULC imageries were acquired from Esri with general 11 cover classes. Then they were cleared by removing unwanted class layers and clipped to fit an area of study. The remained classes were reclassified into five influential classes with relation to land degradation as water, built-up, crop land, bare land, and dense vegetation. Then the LULC change was evaluated to understand how LULC have changed and how the change affects the wetlands.

3.8 Comparative matrix analysis of the criteria for land degradation

A GIS based multi-criteria analysis and AHP method was used for land degradation vulnerability assessment to test the relative importance of the factors of land degradation. As proposed by (Tolche et al., 2021), in the firstly, criteria, sub-criteria, and decision alternatives were created following the objective of the study. Secondly, using the fundamental 9-point scale of measurements, Table (3.2), pairwise comparison matrix was generated for criteria and sub-criteria Tables (3.3 and 3.4). The relative weight of each variable was determined by a knowledge-based spatial decision support system and referring to literature. Then consistency among criteria was assessed to determine the consistency index (CI) of pairwise comparisons, and a consistency ratio (CR) using equations (3.8.1 and 3.8.2).

Table 3. 2: Pair-wise comparison matrix of the criteria for land degradation.

CRITERIA	VCI	TWI	Rainfall erosivity	Soil erodibility	LULC	SMI	Soil pH	TOTAL
VCI	1.00	2.60	3.60	4.70	4.80	3.40	2.80	**22.90**
TWI	0.38	1.00	2.80	1.70	4.60	2.80	2.64	**15.92**
Rainfall erosivity	0.28	0.36	1.00	2.80	3.60	3.68	3.72	**15.43**
Soil erodibility	0.21	0.59	0.36	1.00	1.70	3.60	1.90	**9.36**
LULC	1.70	0.22	0.28	0.59	1.00	3.50	3.40	**10.68**
SMI	0.29	0.36	0.27	0.29	0.29	1.00	3.70	**6.19**
Soil pH	0.36	0.38	0.27	0.53	0.29	0.27	1.00	**3.10**
TOTAL								**83.59**

CI= (K_{max} -n)/ (n-1) ……………………………………………………….. (3.8.1)

CR= (CI/RI) ……………………………………………………………………….. (3.8.2)

Where, CI- consistency index, *CR*- consistency ratio, *RI*- random index, K_{max} – principle Eugene value of the matrix,

3.9 Estimation of LDVI and weighted overlay analysis for mapping land degradation vulnerability

Land Degradation Vulnerability Index was calculated using weighted overlay models in equation (3.9) and the thematic maps of each criteria were overlaid basing on the weights of their criteria and sub-criteria as (Tolche et al., 2021).

LDV= $\sum_{i=1}^{n}\sum_{j=1}^{m}(\propto i(\beta ij))$ …………………………………………………….…….. (3.9)

Where, LDVI- land degradation vulnerability index, $\propto i$- criteria weight obtained from AHP, βij- the weight of sub-criteria j^{th} for criteria i^{th} obtained from AHP, *n* is total numbers of criteria, and *m* is the entire number of sub-criteria in i^{th} criteria.

3.10 Estimating human population density in the Mara wetlands for validation

The population data were obtained from the National Bureau of Statistics which are the primary results of the 2022 national census in CSV format. Then they were joined with the wetland wards administrative boundaries where the area of each ward was calculated in a new field, then the population density was calculated using a formula as in equation (3.10) as per (Sileshi, 2016)

$$Population\ density = \left(\frac{Population\ size}{Unit\ Area}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

Where, Unit Area= Km^2 of individual ward.

3.11 Validation of land degradation vulnerability with human population density in the Mara wetlands

The land degradation vulnerability index obtained in the process described on section 3.9 provides the description for vulnerability status of the Mara wetlands. Therefore, to verify, the population density map is overlaid with the land degradation vulnerability index map and the In-Situ images showing the human activities that makes the wetlands vulnerable to land degradation (Mbaga, 2022).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Overview

In this chapter the results obtained through the implementation research methodology and discussion are presented according to the intended objectives of this research which was to analyze soil degradation vulnerability in Mara Wetlands. These results include maps showing the factors that contribute to soil degradation, also the model results are presented after integrating the factors and the land degradation map of Mara Wetlands. The discussion section shows how the results have correlated with other studies done on similar geographic environment.

4.1 Factors for land degradation

4.1.1 Soil types

In Mara wetlands, soil type map results in figure (4.1.1) show that major components of soil characterized by varying soil profiles of the 'A' horizon (mineral, mixed with humus, dark colored) being Eutric Fluvisols, Eutric Vertisols, Eutric Leptosols, Luvic Phaeozems, Eutric Planosol and Umbric Nitosols (Hasab et al., 2020) where, the type of a soil can be subjected to land degradation depending on its characteristics. Soil types that are generally shallow, have low organic matters, friable, coarse and permeable makes their erodibility potential very high hence highly vulnerable to land degradation and vice versa (Zorn & Komac, 2013).

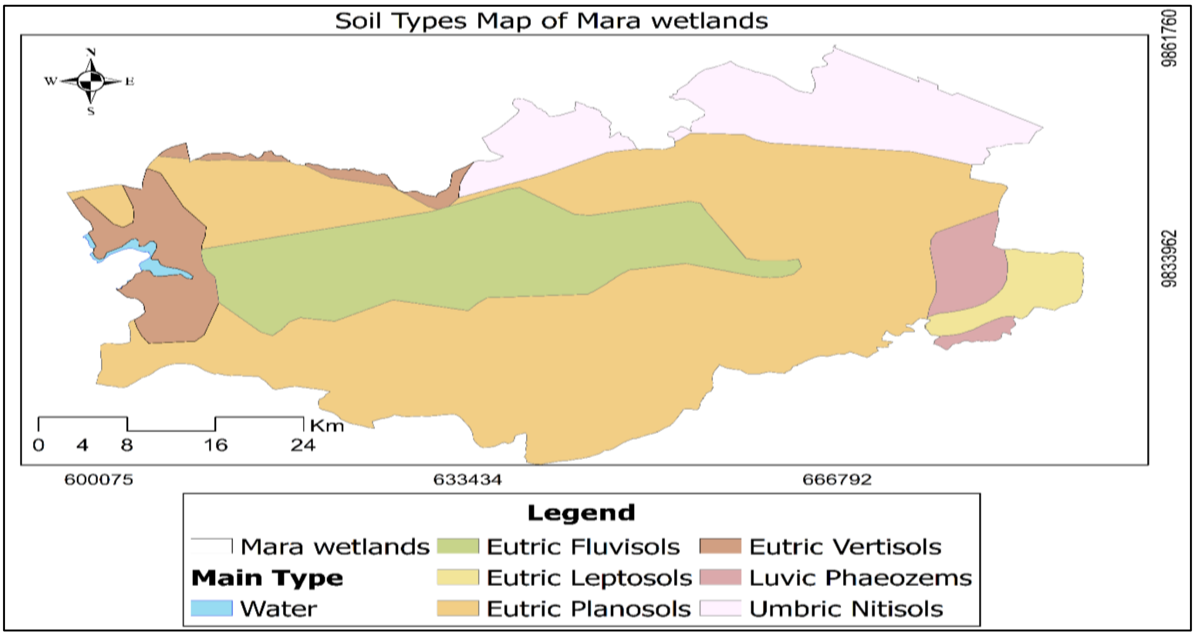


Figure 4.1. 1: Soil Types map of Mara wetlands

4.1.2 Elevation

The slope map in figure (4.1.2) show that, most of parts in Mara wetlands have slope gradients are highly distributed, making the area to have likelihood occurrences of soil erosion which contributes to greater rates of land degradation in some parts (Chauhan, 2021). Generally, the steeper the slope, the greater is surface runoff velocity and volume and so the higher the land degradation vulnerability, provided that other factors remain constant. Slopes were classified into, very gentle slopes (0–2%), gentle slopes (2–6%), moderately slopes (6–11%), moderately steep slopes (11–20%), and steep slopes (20-58%) (Tolche et al., 2021).

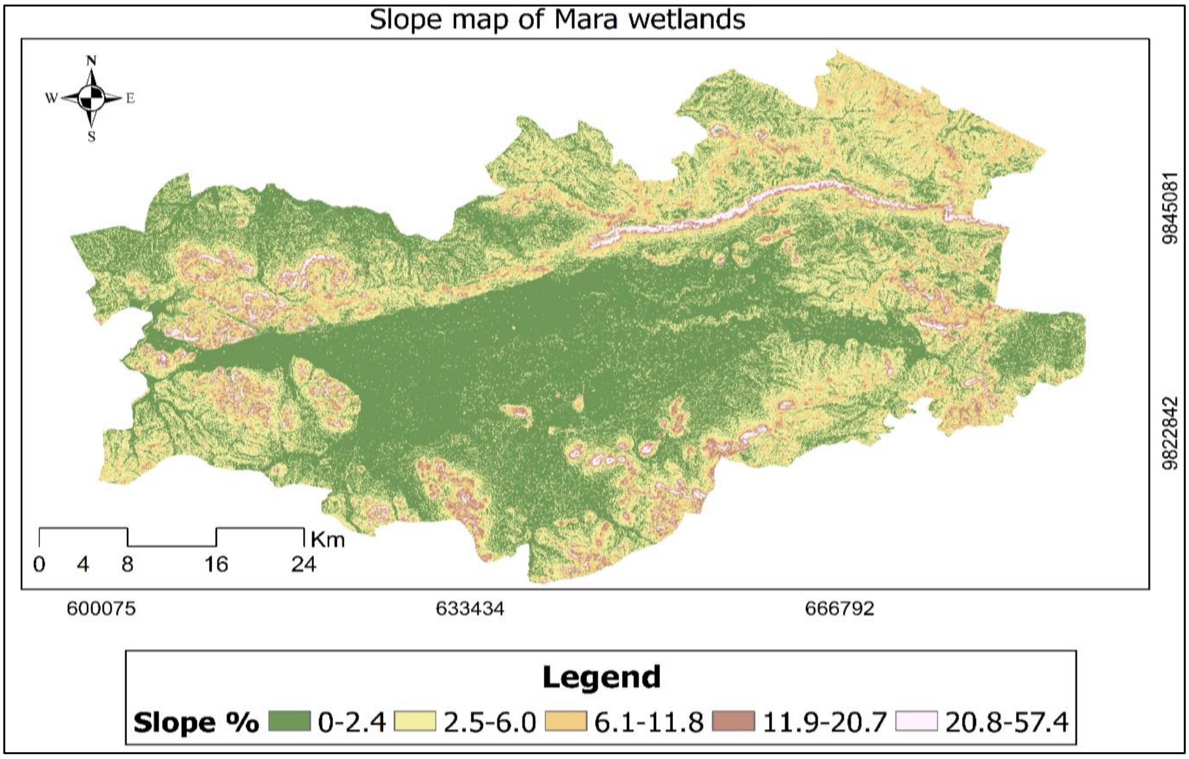


Figure 4.1. 2: Slope map of Mara wetlands

4.1.3 Human population density

The human population size of Mara wetlands is estimated to be 1,662,991 people (NBS, 2022) which in relation with the area it is estimated to fall in the range of (0-653.82) of people per Km^2 as observed in figure (4.1.3). Where by the higher population density is associated with higher pressure on the environment and resources (Ortega-gaucin et al., 2021). High population density is evaluated to be on the eastern parts of the wetland area which possess high pressure on the wetlands resources (NBS, 2022). Other areas with low population density are subjected to various agricultural, fishing, livestock keeping and fishing (Mutie et al., 2005). Therefore the higher the population density the higher the land degradation vulnerability index.

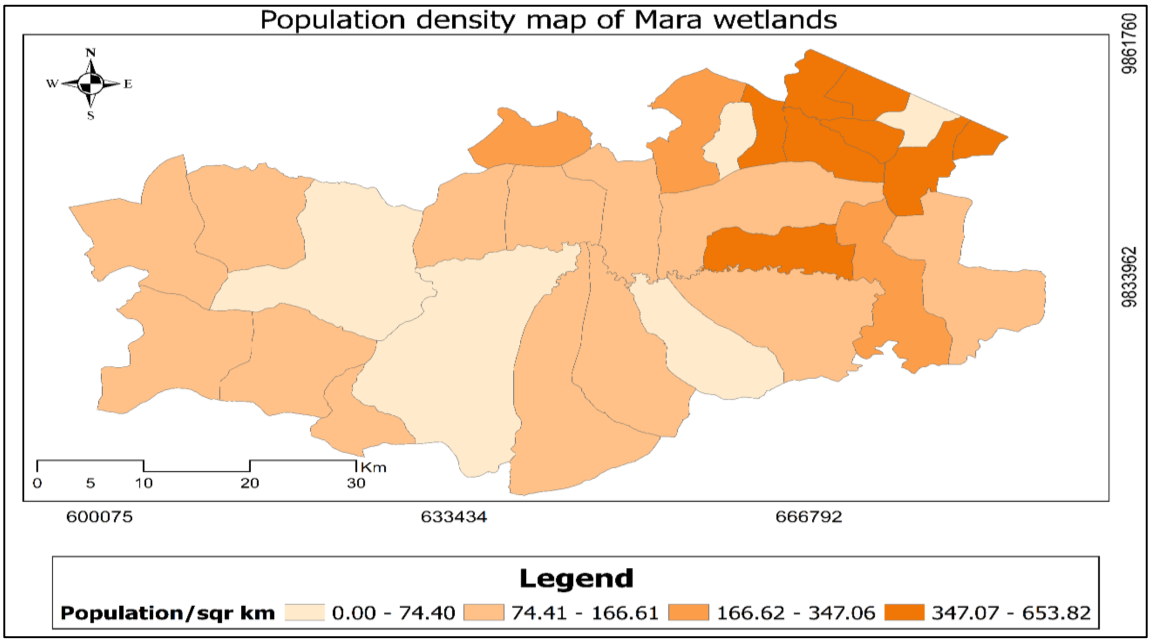


Figure 4.1. 3: The population density map of Mara wetlands

4.1.4 Land surface temperature of Mara wetlands

The area have surface land surface temperature in the range of (27-34) degree Celsius as in figure (4.1.4). The higher the LST the greater the risk of the land to be degraded (Tolche et al., 2021). Higher LST measure endangers existence of micro-organisms in the soil important for maintaining soil surface exchange (Kloos et al., 2021). For this study, areas with LST value (31.66-34.80) degree Celsius are prone to land degradation because of being subjected to higher rate of evapotranspiration and soil dryness which makes the soil to erosion.

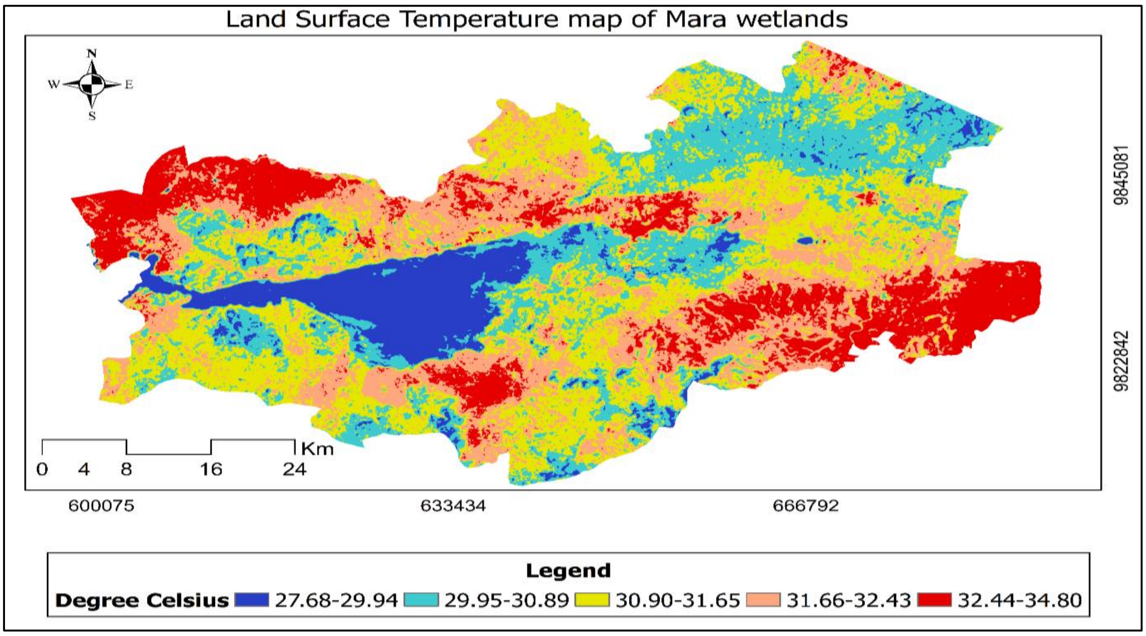


Figure 4.1. 4: Land surface temperature map of Mara wetlands

4.1.5 Mara wetlands annual rainfall

Mara wetlands is tropical-wet with a mean annual rainfall ranging between 827-1034 mm/yr., as seen in figure (4.1.5). Rainfall in Mara wetlands is distributed between March to May and September to January but the most frequent rainfall events occur in April and are of high intensity causing rapid runoff capable of creating flashy floods in streams and rivers (Semester et al., 2010). The higher the rainfall the more the likely of erosion, landslides, and floods which directly contributes on degradation (Parveen & Kumar, 2012). In April the rainfall has the most erosive potential. At this time of the year much of the agricultural land area has been prepared and is ready for planting. The soils are therefore loose and erodible easily.

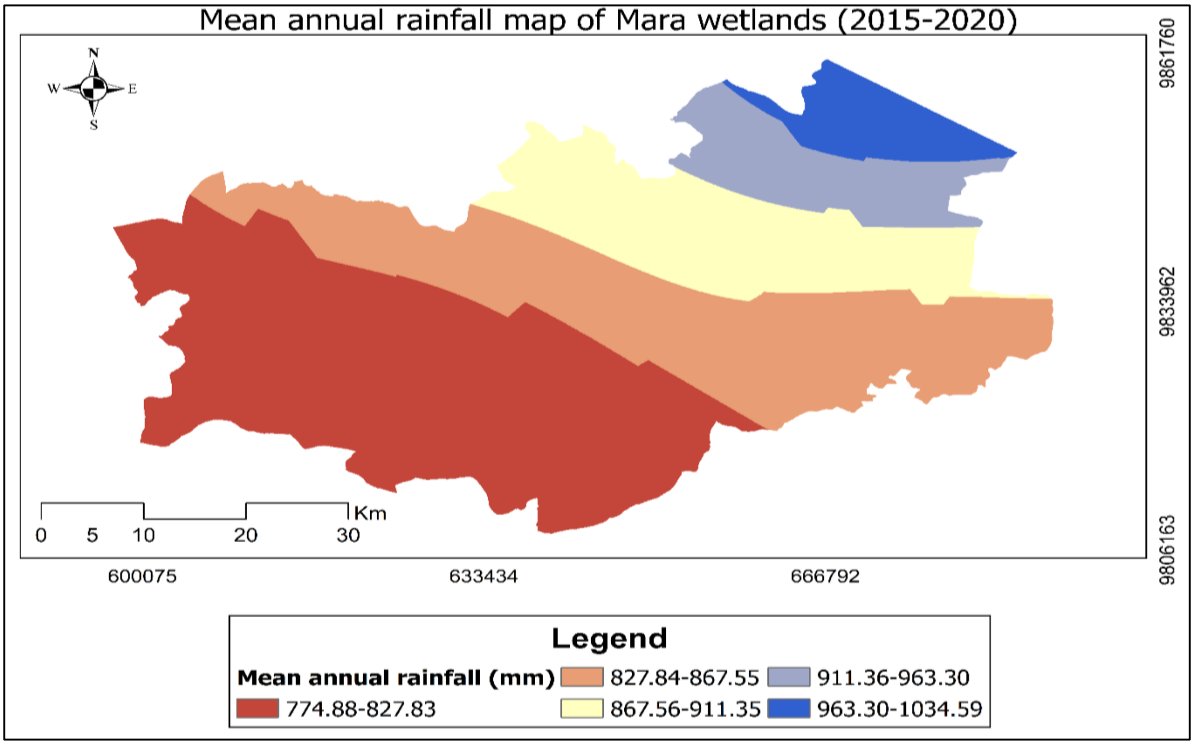


Figure 4.1. 5: Mean annual rainfall map of Mara wetlands for years (2015-2020)

4.2 Criteria-factors for land degradation

4.2.1 Soil erodibility (*K*) factor

The K value were calculated basing on the mathematical equations as in chapter three, and for the case study of Mara wetlands, the soil erodibility values ranges from 0.012 to 0.052 which were further classified into, basing on the vulnerability criteria for land degradation, whereby the lower value of K factor is associated with the soils having low permeability and low antecedent soil moisture and the higher the value of K factor the higher the associated vulnerability of the soil to land degradation, because these are soils with low organic contents.

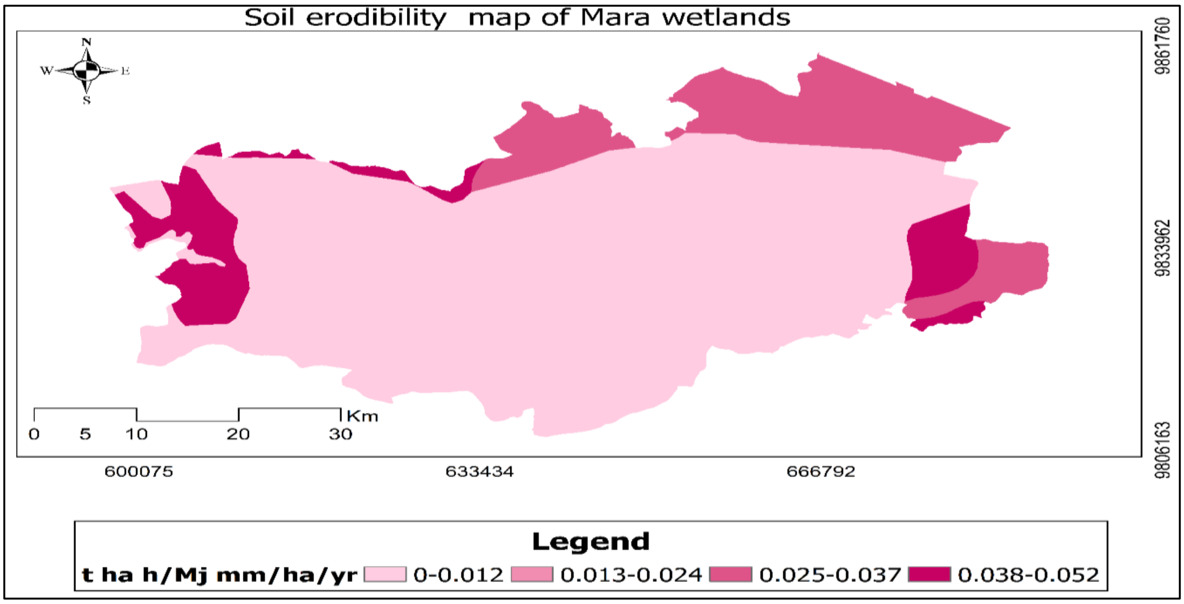


Figure 4.2. 1: Soil erodibility map of Mara wetlands showing the rate of soil erosion in tons/acre/year (t ha h/MJ mm/ha/yr).

4.2.2 Rainfall erosivity (R) factor

Rainfall erosivity was prepared based on the method described in equation (3.4). The low values of R factor represent low rainfall intensity and vice versa is true (Institute of Water Research, 2002). R factor map shows that rainfall Intensity is high in the northern part of the district and lower part of the wetlands. An average R factor values in Mara wetlands ranges from (422.37 to 529.87) MJ.mm/ ha/h/yr., as in figure. (4.2.2).

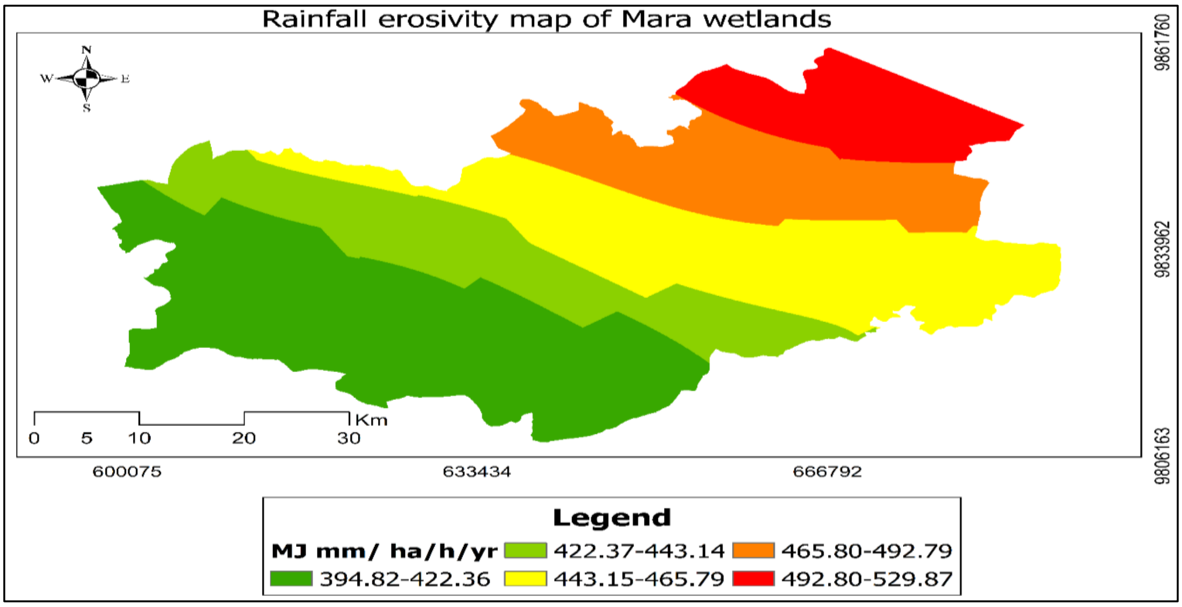


Figure 4.2. 2: Rainfall erosivity map of Mara wetlands showing the rate of soil erosion in mega joules/acre/year (MJ mm/ha/h/yr).

4.2.3 Soil acidity (pH) factor

The areas have varying soil pH contents of the range (4.7-7.7) pH value. Areas with 5.6< pH are having acidic conditions and those with >6.5 pH are said to have alkaline soil. Soil alkalinity or acidity may results to land degradation such as areas with 4.8 pH< and 7.6 pH> are highly vulnerable (Tolche et al., 2021).

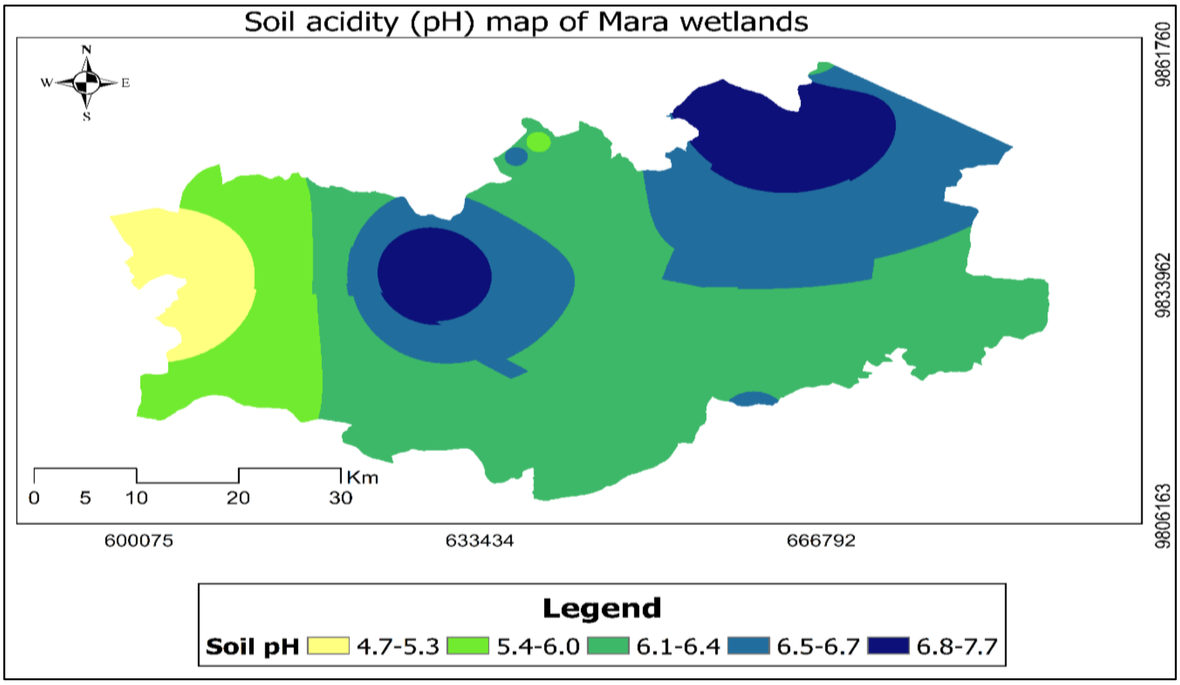


Figure 4.2. 3: Soil pH map of Mara Wetlands

4.2.4 Topographic witness index (TWI) factor

The wetlands have topographic witness index ranging from (3.09 to 14.33) which is within the average range for the terrain as in figure (4.2.4). The areas with TWI (7>TWI>11) index value are very vulnerable to soil erosion and water logging events making some areas to be vulnerable to land degradation (Tolche et al., 2021). The Mara wetlands is characterized with areas varying in the water flow and accumulation behavior such as in the northern parts with very high TWI.

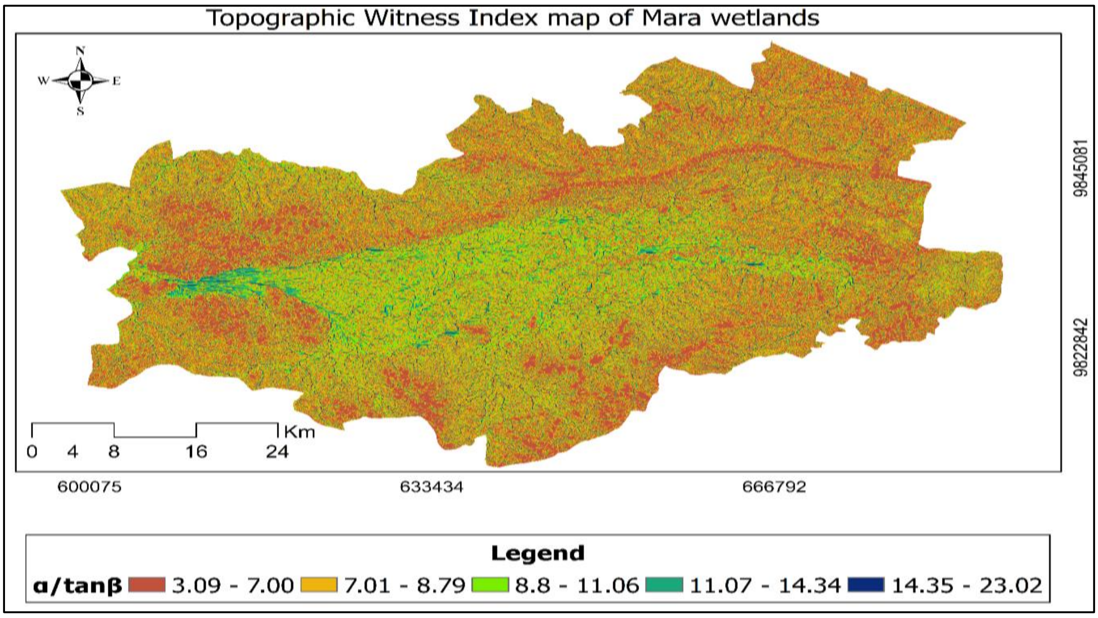


Figure 4.2. 4: Topographic witness index (TWI) map of Mara wetlands showing the rate of flow accumulation of surface water per gradient slope.

4.2.5 Vegetation Condition Index (VCI) factor

The VCI map as in figure (4.2.5) is expressed in % and gives an idea where the observed value is situated between the extreme values (minimum and maximum) as an average for the three years. Lower and higher percentage values indicate good and bad vegetation state conditions, respectively which were categorized from very dry to less dry. Approximately an area about 12 km^2 have poor vegetation condition.

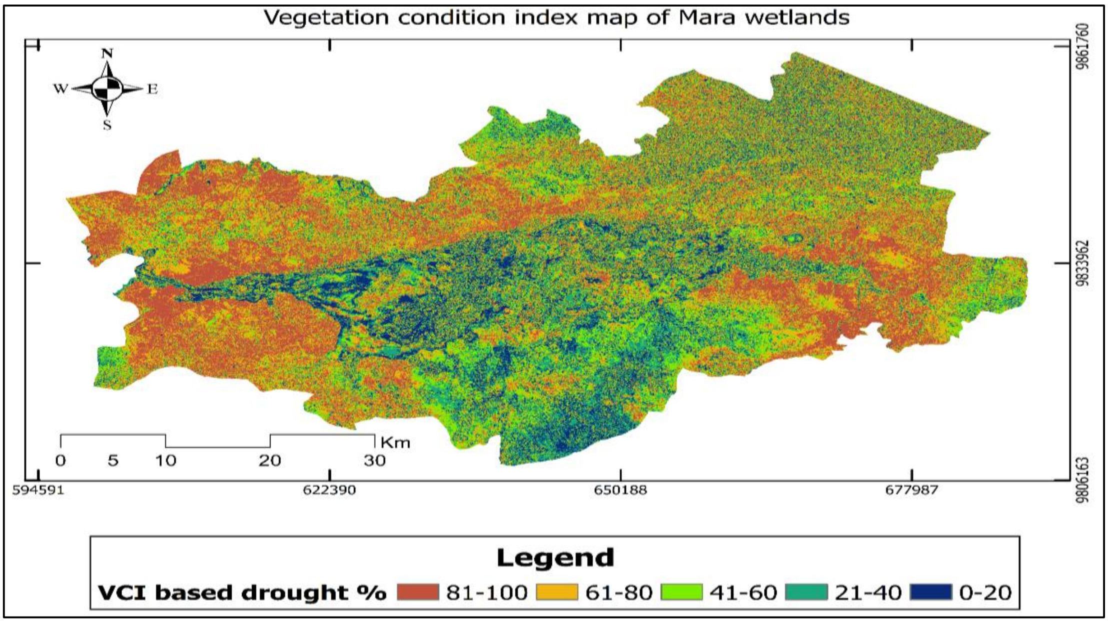


Figure 4.2. 5: Vegetation condition index map of Mara wetlands.

4.2.6 Soil Moisture Index (SMI) factor

The SMI in area ranges between (0.1 and 0.2) as in figure (4.2.6). The areas with smaller value of SMI are subjected to soil erosion and degradation due to lack of conducive conditions for existence of the microorganisms and extreme pH conditions for most of savanna vegetation (USAID, 2019). The western and some parts in southern-east of the wetlands are soil dry and subjected to be very risky to erosion and degradation.

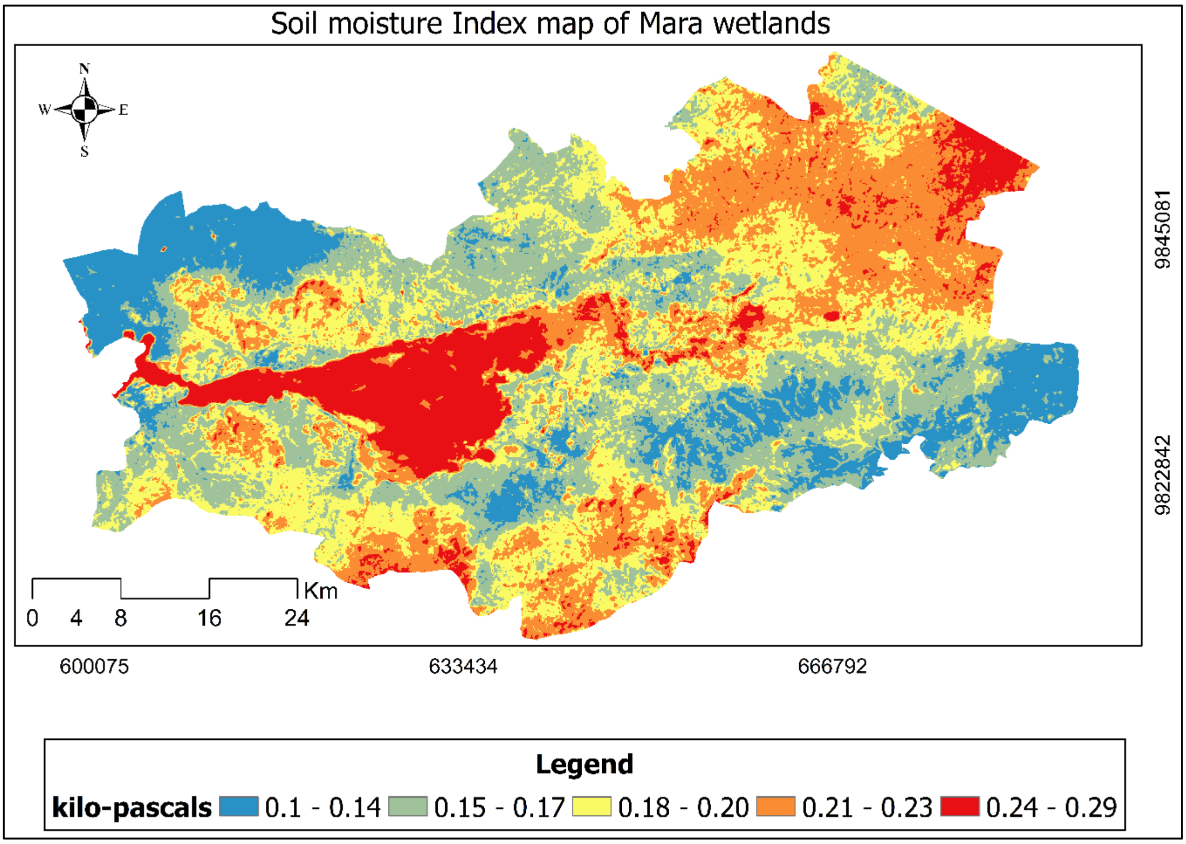
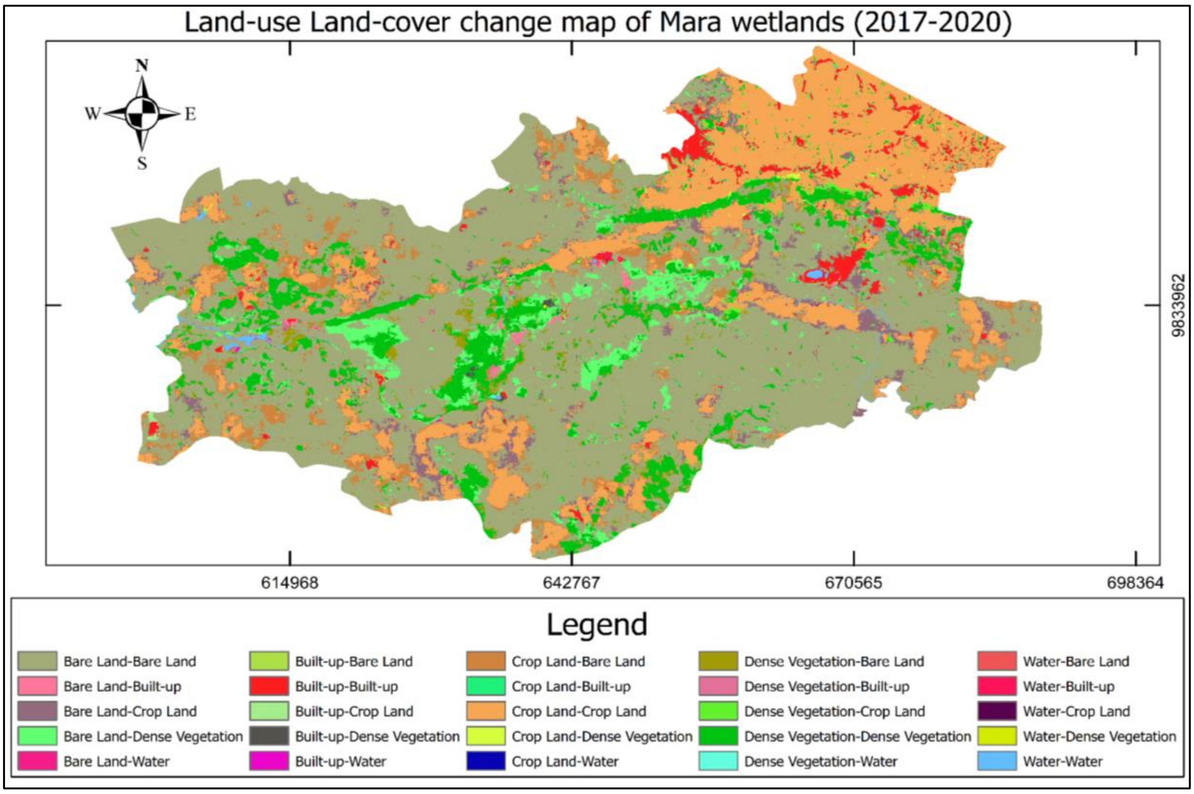


Figure 4.2. 6: Soil moisture index map of Mara wetlands

4.2.7 Land-use land-cover change factor

Mara wetlands is covered with water, dense vegetation, crop lands, built-up and bare lands and mostly used for agriculture, livestock grazing, fishing, mining and resident. Some uses and cover variability subjects the wetlands to degradation as in figure (4.2.7). Changes in LULC over water, dense vegetation and croplands indicate proneness to land degradation (Ngie et al., 2017). The changes may posse threats on wetlands resources if they involves convention of the primary wetlands such as a change from dense vegetation to built-up, vegetation to bare-land and water to crop land (Lamichhane & Shakya, 2019). Where in Mara wetlands mostly changes are observed from dense vegetation and water to built-up and cropland respectively.



4.2. 7: Land use land cover change map of Mara wetlands

4.3 Comparative matrix analysis of the criteria for land degradation vulnerability

The weight and correlation ratio (CR) values for each criteria and sub-criteria were evaluated to fit the maximum recommended value by (Saaty, 1980) as in table (4.3), the general CI, RI and CR for the criteria being: 0.1046, 1.32 and 0.08 respectively for seven used criteria (Sileshi, 2016). The results were used in weighted overlay for all the 8-criteria which were evaluated based on a measurement scale of 5, where 1- low influence, 2- moderate influence, 3- equally influence, 4- likely high influence, and 5- high influence (Konkey et al., 2014)

Table 4. 1: Weights and Consistency Ratio (CR) for criteria and sub-criteria for land degradation vulnerability of Mara wetlands.

Main Criteria	***Weight (%)***	***CR***	***Sub-criteria***	***Weight***	***CR***
VCI (%)	30.11		0-20	0.25	*0.016*
			21-40	0.19	
			41-60	0.18	
			61-80	0.18	
			81-100	0.20	

Main Criteria	***Weight (%)***	***CR***	***Sub-criteria***	***Weight***	***CR***
Rainfall erosivity (MJ mm/ha/hr/yr)	16.44	0.08	394.82-422.36	0.12	*0.013*
			422.37-443.14	0.18	
			443.15-465.79	0.31	
			465.80-492.79	0.32	
			492.80-529.87	0.32	
SMI	5.5		0.10-0.14	0.26	*0.010*
			0.15-0.17	0.23	
			0.18-0.20	0.23	
			0.21-0.23	0.02	
			0.24-0.29	0.13	
LULC	12.34		Water	0.30	*0.014*
			Built-up	0.22	
			Bare-land	0.23	
			Swampy	0.02	
			Agricultural	0.13	
Soil erodibility (t ha hr/MJ/ha/mm)	7.56		0-0.00012	0.10	*0.012*
			0.00013-0.00098	0.17	
			0.00099-0.00298	0.21	
			0.00299-0.064	0.02	
Soil pH	3.70		4.70-5.43	0.13	*0.010*
			5.44-6.06	0.19	
			6.07-6.47	0.28	
			6.48-6.76	0.02	
			6.76-7.67	0.21	
TWI	19.50		3.09-6.95	0.14	*0.012*
			6.96-8.75	0.21	
			8.76-11.06	0.20	
			11.07-14.34	0.02	
			14.35-23.02	0.27	
TOTAL	***100***				

4.4 Land degradation vulnerability index of the wetlands

The land degradation vulnerability is influenced mainly from surface runoff erosion, vegetation type and topographic factor (Mwalyosi, 2002). Figure (4.4) depicts the land degradation vulnerability in Mara wetlands and the distribution of the land degradation vulnerability index was classified into four categories according to their proportion of distribution as extreme vulnerable (2.15%), slight vulnerable (4.37%), moderate vulnerable (51.88%) and less vulnerable (41.60%). The land degradation vulnerability in Mara wetlands was found to be more pronounced on the north-western parts of an area and eastern-central parts (USAID, 2019).

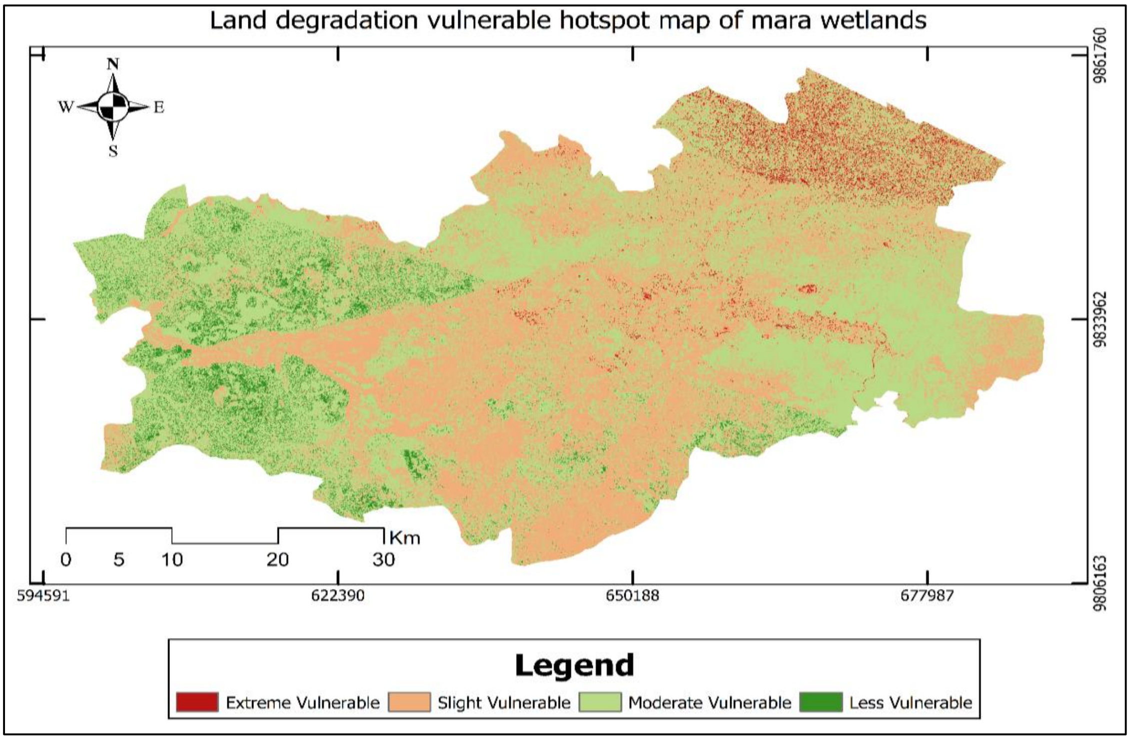


Figure 4.4: Land degradation vulnerability index map of Mara wetlands

4.5 Validation land degradation vulnerability with human population and associated activities

The vulnerability of the Mara wetlands to land degradation may be validated with ongoing pressure on the wetland's resources by overlying the land vulnerability index map with human population density map of Mara wetlands as (Mwansasu, 2016). Figure (4.5) shows that; the high land degradation vulnerability is associated with high human population density in the wetlands. The increasing human population in the wetlands triggers unsustainable human activities as in the images (A, B, C and D) from (URT, 2022) resulting to pressure on resources and subsequent negative impacts on the environment. Activities which results on polluting water resources, deforestation for timber and firewood as well as charcoal production which leaves the topsoil unprotected and vulnerable to being eroded, cultivating crops such as maize, millets, rice and grazing of animals along the water resources polluting and destroying water resources which in the results destroy the ecosystem of the wetlands (NELSACCU, 2015).

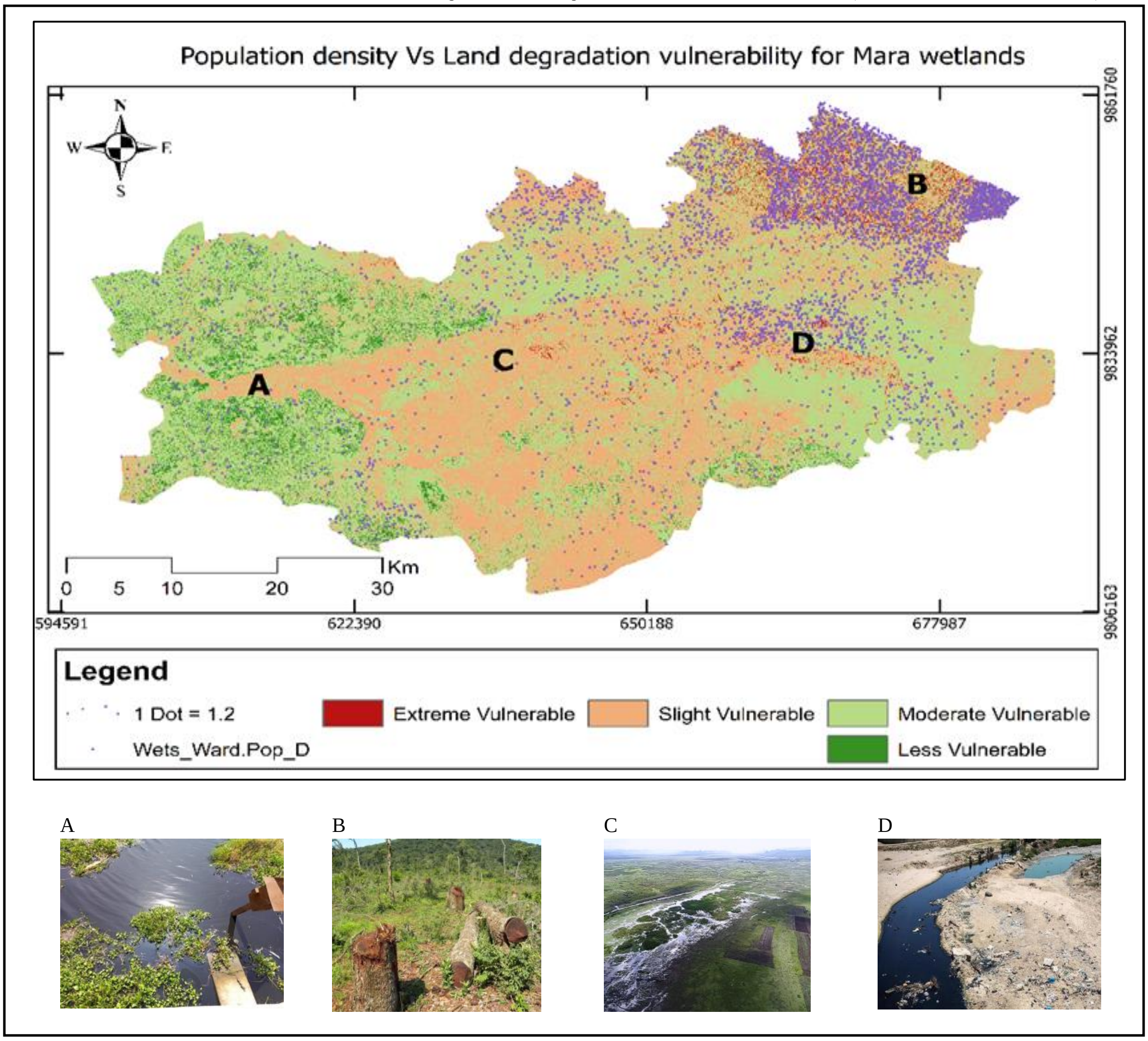


Figure 4. 4. 1: The population density vs. land degradation in Mara wetlands evidenced with varieties human activities described with images (A,B,C and D) improper waste management, polluting water resources resulting into darkening and odor smell water (A &D), unsustainable harvest of forest resources (B) and cultivating crops, and grazing animals along the river channel and banks (C)

CHAPTER FIVE

CONCLUSION, CHALLENGES AND RECOMMENDATION

5.0 Conclusion

The study has been able to assess the vulnerability of the Mara wetlands by using GIS and remote sensing based multi criteria analysis method. The criteria for land degradation vulnerability were established on the identified land use and land cover change, soil erodibility, rainfall erosivity, soil pH, vegetation condition index, soil moisture index and topographic witness index criteria factors.

The factor criteria for land degradation vulnerability were measured basing on their relative influence on the vulnerability of the wetlands to land degradation and overlaid using weighed overlay model. The study shows that the areas in the northern part about 2.15% of the wetlands are highly vulnerable, 41.60% are slightly vulnerable, 51.88% are moderately vulnerable, 4.37% are less vulnerable, based on the criteria established and analytical hierarchy process and proven that the method is significant and effective. The study also reveals that having uncontrolled environmental practices, climate changes and unstable terrain characteristics may be dangerous to environment and people's livelihood.

Most of the factors used for land degradation vulnerability assessment for this study were very generic and continuous, however the analysis was possible it was challenging to obtain some data and information which could have narrowed the scope of study, since there is inadequate spatial data and information in the region.

5.1 Recommendation

Researches needs to be conducted on the influence of wetlands on ongoing socio-economic and climatic changes in-order to aid the war towards harsh or risks of environmental aspects and achieving environmental sustainability. The studies should focus on how and what extent social economic changes such as the levels of income and employment of the people, poverty and environmental disaster awareness and climatic changes such as drought severity viability pose threats on wetlands in Tanzania.

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