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Simulation of the impacts of Sea Level Rise on coastal ecosystems in Benin using a combined approach of machine learning and the Sea Level Affecting Marshes Model

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Abstract: Sea Level Rise in the coastal zone of Benin leads to risks of erosion and flooding, which have significant consequences on the socio-economic life of the local population. This study utilized the Sea Level Affecting Marshes Model (SLAMM) model inputting the Digital Elevation Map (DEM), the National Wetlands Inventory (NWI) categories and the slope of each cell using the ArcGIS Pro toolbox to assess erosion, inundation risks, and Greenhouse Gas Sequestration resulting from sea level rise in the coastal zone of the Benin Coast. In order to create the National Wetlands Inventory (NWI) categories, Support Vector Machines (SVM) in the Machine Learning tool were used as a classifier in supervised classification. The research simulated the effects of a 1.468 m sea level rise in the study area from 2021 to 2090, considering wetland types, marsh accretion, wave erosion, and surface elevation change. The largest land cover increases were observed in Estuarine Open Water and Open Ocean, expanding by approximately 106.2 hectares across different sea level rise scenarios (RCP 8.5_Upper Limit). These gains were counterbalanced by losses of approximately 106.2 hectares in Inland Open Water, Ocean Beaches, Mangroves, Regularly Flooded Marsh, Swamp, Undeveloped, and Developed Dryland. Notably, Estuarine Open Water (97.7 hectares) and Open Ocean (8.5 hectares) experienced the most significant expansion, indicating submergence and saltwater intrusion by 2090 due to sea level rise. The largest reductions occurred in less tidal-influenced categories like Inland Open Water (-81.4 hectares), Ocean Beach (-7.9 hectares), Swamp (-5.1 hectares), Regularly Flooded Marsh (-4.6 hectares), and Undeveloped Dryland (-2.9 hectares). As the sea level rises by 1.468m, these categories are expected to be notably diminished, with Estuarine Open Water and Open Ocean becoming dominant. Erosion and flooding in the coastal zone are projected to have severe adverse impacts, including a gradual decline in greenhouse gas sequestration capacity. The outputs of this research will aid coastal management organizations in evaluating the consequences of sea level rise and identifying areas with high mitigation requirements.

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Keywords: Sea Level Rise; Machine Learning; SLAMM model; coastal ecosystems; Benin

1. Introduction

One of the projected effects of global warming is an increase in sea level. In that sequence, melting continental glaciers, the Greenland ice sheet, the Antarctic ice sheet, and ocean expansion (thermal expansion) brought on by rising ocean temperatures are the sources of sea level rise (IPCC, 2019). With 40% of the global population residing within 60 kilometers of coastal areas and expectations of further growth in the coming decades, the resulting effects on the coastline include the disturbance of ecosystems and the increased risks of erosion and flooding (Acclimaterra, 2018). The expectation is that a larger number of people will face increased exposure to threats from sea-level rise (SLR) in the future due to the high population density and substantial population growth rates in coastal areas (Neumann et al., 2015). According to (Anderson et al., 2018), the rise in mean water levels leads to various consequences such as marine flooding. Additionally, as highlighted by Vitousek et al. (2017), an increase in the groundwater table can result in drainage issues. Furthermore, the rising water levels also contribute to the blockage of drains and other conduits connected to the ocean by saltwater, as indicated by (Acclimaterra, 2018). As water depths increase over reefs and other coastal structures, there are changes in wave dynamics (Intergovernmental Oceanographic Commission, 2023). These changes can lead to amplified wave power reaching the shore (Konko et al., 2018), heightened beach erosion (Hiripong et al, 2019), and the intrusion of saltwater, which can bring about modifications in coastal ecosystems and aquifers (Obama, 2017). These effects are made worse when climate change-related increases in mean sea level are combined with sporadic sea level rises brought on by processes including storm surges, tides, eddies, wave events, and regional climatic indices (Dahl, Fitzpatrick, et al., 2017; Dewi et al., 2020; Habel et al., 2017). The extensive impacts of sea-level rise and the need to anticipate and implement adaptation measures have led to the widespread utilization of numerical models such as the Sea Level Affecting Marshes Model (SLAMM). These models are employed to facilitate the ability to anticipate and proactively establish adaptation measures (Payo et al., 2016; Stamp et al., 2019).

Various ML techniques have been used in recent years to include Artificial Intelligence (AI) into these models in order tote natural disasters in general and flood hazards in particular. These techniques include Logistic Regression (LR) (Callo-Concha, 2018; Ndour et al., 2018), Support Vector Machines (SVM) (Rawson et al., 2021; Rimala et al., 2019), Random Forest (RF) (Sahour et al., 2020), and Artificial Neural Networks (ANN) (Pham et al., 2020). The loss of coastal wetlands owing to more frequent flooding demonstrates how susceptible they are to SLR (Deguenon et al., 2022). Due to modeling uncertainty for the different contributing processes, such as increases in land water storage, land ice loss, and ocean thermal expansion, projecting future SLR is difficult (Tragaki et al., 2018). Although historical sea level patterns are useful for planning for changes in the future, they are insufficient for determining risk in the face of future uncertainties (Dahl, et al., 2017).

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global mean SLR by the year 2100 will range between 52 and 98 cm under the scenario with the highest emissions and 28-61 cm under the scenario with the lowest emissions (IPCC, 2019). In contrast, given the breadth of uncertainty, future global mean SLR scenarios are a typical technique to take into account various future circumstances and design response choices (Passeri et al., 2015). It is required to have local forecasts of SLR, land cover that accommodates different risk tolerances, and span a variety of timelines useful for planning to prepare for changes brought on by rising sea levels at a local level (Deguenon et al., 2022). To manage both natural and human communities

effectively, coastal managers need scientific evidence about the possible effects of SLR. Thus, it should be given top importance to conduct integrated, interdisciplinary studies that take into account the different elements that have an impact on coastal systems at local scales because they will assist coastal scientists and stakeholders (Almar et al., 2020). Determining the long-term effects of SLR is challenging because of the complexity of coastal systems.

In this study, spatially explicit estimates for sea level rise (SLR) impacts on the acreage of the Benin coastal zone were generated using SLAMM v. 6.7 and artificial intelligence techniques. These estimates have been utilized for modeling Greenhouse Gas Sequestration. The present paper showcases the findings of this study. These projections, based on three different SLR scenarios, serve as inputs for a broader research endeavor aimed at comprehensively analyzing and designing effective adaptation practices. The objective is to safeguard, restore, and/or facilitate the migration of invaluable coastal zone ecosystems. The paper offers valuable insights on how to interpret and utilize vulnerability information to inform such analyses and design processes.

2. Methodology

2.1. Study area

The coastal area of Benin, specifically located between latitudes 6°10' and 6°40' and longitudes 1°40' and 2°45' (Figure 1), is the focus of the research. Approximately 12,000 km2 of land, accounting for 10.5% of Benin's national area, is covered by this region. The presence of ancient and recent lagoons spanning over 30 km2 gives it the characterization of a lagoon coast. It is composed of depressions and blind drainage areas. The climate exhibits a daily thermal amplitude of around 33°C, with annual rainfall ranging from 820 mm to 1300 mm (CEDEO, 2013). In Troll's classification (1965), the Beninese coast is classified within the humid tropical summer climate zone (V2). Two rainy seasons, from April to July and September to November, are experienced in the study area, with two dry seasons, from August to September and December to March, interspersed (Adam & Boko, 1993). The coastal landscape is dominated by agriculture, particularly palm tree vegetation (*Elaeis guineensis*), with sandy, ferritic, and hydromorphic soils being prevalent (Adam & Boko, 1993). Various ecosystems, including dry forests, gallery forests, boundary rainforests, marshes, wetlands (listed in Ramsar sites No. 1017 and No. 1018), and riverbanks (Mono, Ouémé, Couffo), thrive in the region. The economic hub of the country, comprising major cities, ports, airports, and industrial facilities, is situated along the Beninese coastline. The total area covered by the six departments bordering the coastline is 11,720 km², and it is inhabited by a population of 2.7 million people, resulting in an average density of 230 inhabitants per km², higher than the rest of the country. While the majority of the population resides in rural areas, there is a significant urban population growth rate of approximately 7.4% per year, exerting increased pressure on infrastructure and the labor market in cities. The local population engages in diverse activities, including agriculture, fishing, salt farming, tourism, trade, quarrying, livestock breeding, and agricultural product processing (Environnement & Climat, 2019). Migration to this coastal strip contributes to high population density, rapid growth rates, and demand for land for construction.

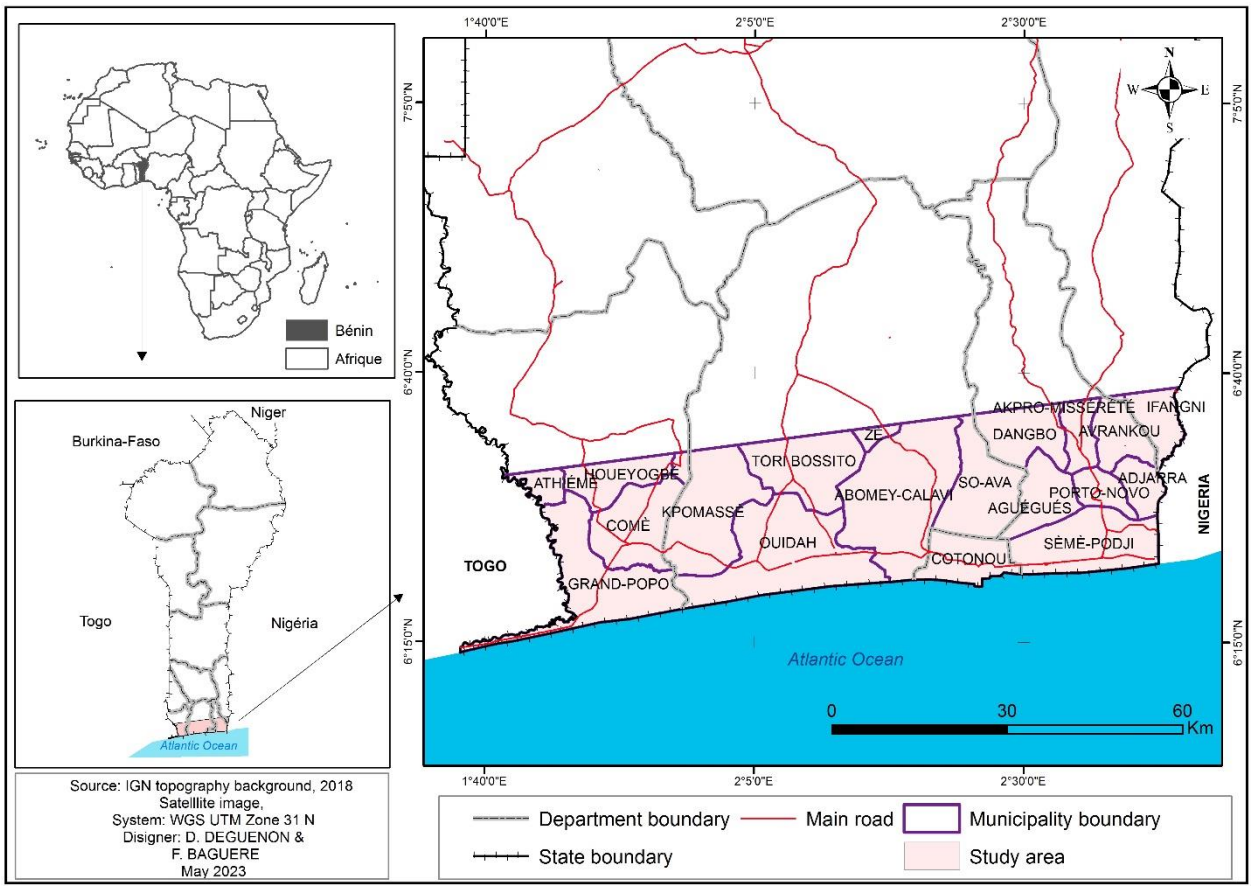

Figure 1. The map illustrates the geographic extent of the area under investigation.

2.2. Sea Level Affecting Marshes Model (SLAMM)

The Sea Level Affecting Marshes Model (SLAMM) is a simulation model that replicates the key processes involved in wetland conversions and shoreline modifications during long-term sea-level rise. In this study, the SLAMM 6.7 beta-64bit model (available at http://warrenpinnacle.com/prof/SLAMM6/) was utilized. The model calculates the relative sea-level change for each cell at every time step. The fractional conversion from one class to another within a cell is determined based on the relative elevation change divided by the elevation range of that class. Additionally, if a cell is protected by a dike or levee, it is not permitted to undergo changes.

SLAMM simulations are performed on a cell-by-cell basis, utilizing the slope of each cell to determine its maximum elevation relative to a user-defined sea-level reference point. Sediment accretion is incorporated by adding it to the cell's new elevation for the current time step, based on the wetland class of the cell. The lower boundary of each cell defines a threshold, and when the sea level rises beyond this threshold, the wetland class of the cell converts to the classification class below it. If the cell is now in a saline environment, it may convert to a wetland class associated with regularly-flooded marshes or transitional salt marshes. The erosion process is determined by the proximity of the cell to water and incorporates a wave erosion model integrated into the larger SLAMM model (Elliott et al., 2019).

SLAMM 6.7 encompasses five primary processes: inundation, erosion, saturation, accretion, and salinity. Inundation tracks the rise of water levels and the salt boundary by adjusting cell elevations while maintaining a constant Mean Tide Level (MTL) at zero. Erosion occurs when specific conditions, such as maximum fetch threshold and proximity to estuarine water or open ocean, are met. Saturation allows coastal swamps and fresh marshes to expand onto adjacent uplands as the water table rises due to sea-level rise.

Accretion refers to the upward movement of marshes through sediment accumulation and biogenic production. Salinity, an optional process, allows for migration of land categories based on changes in salinity using a salt wedge model or linked data from existing salinity models.

Each cell in SLAMM can consist of up to three SLAMM categories, but for the purposes of this study, each cell was initially assigned to a single category. However, the model allows for incremental changes within smaller horizontal steps than the cell width. SLAMM assumes quasi-equilibrium between wetland categories and sea-level rise, permitting only one category change per time step. A time step of 20 years was used in this study to simulate the period from 2021 to 2090, aligning with the time scales used in IPCC sea-level rise scenarios. However, alternative time steps and specific time series can be employed. The full list of inputs and parameters used for the simulation of coastal area changes under the three sea-level scenarios is provided in Table 1. Key input data utilized in SLAMM include the Digital Elevation Model (DEM), the National Wetland Inventory (NWI), and slope information. Table 1 further describes the purpose of each input file. In the study area, 10 wetland categories were considered, although SLAMM has a database with definitions of 23 categories.

Table 1. Input files used in SLAMM modeling.

Input file	Purpose
DEM	Contains initial elevation data for individual cells and is utilized for generating a raster file representing slope information..
NWI	Is created through the classification of satellite images using an Artificial Intelligence Tool called Support Vector Machine in ArcGIS Pro. The NWI file includes 25 wetland categories obtained from analyzing aerial imagery and considers the elevations of both saltwater and freshwater wetland classes.
SLOPE	Obtained through the utilization of ArcGIS Pro's Slope Tool on the DEM, this particular file presents information regarding the highest and lowest elevations associated with individual cells measuring 10x10 meters.

The digital elevation map (DEM) data used in this study, measured in meters, was obtained from the website https://www.earthdata.nasa.gov/. The downloaded DEM ranges from a minimum of -4 meters to a maximum of 127 meters, with a mean elevation of 18.56 meters.

To assess changes in cell composition, the slope of each cell is calculated using the ArcGIS Pro toolbox. The slope data is measured in degrees, with an average slope of 0.28° and the steepest slopes ranging from 2 to 5°.

The National Wetlands Inventory (NWI) categories, based on data from the year 2021, were used to determine the dominant wetland category for each cell. These NWI categories are then converted into SLAMM categories, aiding in refining the elevation estimates for each cell.

2.3. *Machine Learning Approach*

In order to create the National Wetlands Inventory (NWI) categories, we obtained 2021 Landsat images that covered our study area from the USGS website (https://earthexplorer.usgs.gov/). These images were acquired at no cost. We then processed and classified the images using ArGis Pro software. During the classification process, we employed a supervised approach. This involved dividing the image into smaller sections known as training fields. Within these training fields, we identified predictor variables that were

recorded in the sampling units. Based on these variables, we assigned prior classes to the sampling units, allowing us to allocate the appropriate wetland categories. Minimum distance, maximum likelihood, and Support Vector Machines (SVM) are among the most widely used classifiers in supervised classification. A minimum of 30 training examples were picked for each class. ArcGIS Pro was used to choose training samples, compare sample properties, and refine training samples. The performance of Support Vector Machines (SVM) is built upon the principle of Structural Risk Minimization. This principle is an approach to inductive model selection that aims to strike a balance between the complexity of the hypothesis space and the accuracy of fitting the training data. It forms the underlying basis for SVM's effectiveness. SVM has demonstrated useful applications that are highly accurate. To display changes over time, the geospatial analyst tool in ArcGIS Pro was loaded with coastal maps. SLAMM land-cover maps were examined and site-specific considerations were. The examination of elevation was very helpful.

Table 2. Input parameters in the SLAMM model.

Parameter	**Global**
Description	Flooding
NWI Photo Date (YYYY)	2021
Marsh Erosion (horz. m/yr)	0
DEM Date (YYYY)	2010
Historic Eustatic Trend (mm/yr)	1
Historic Trend (mm/yr)	2
Direction Offshore [n,s,e,w]	South
Salt Elev. (m above MTL)	0
GT Great Diurnal Tide Range (m)	0
MTL-NAVD88 (m)	1

2.4. Greenhouse Gas Sequestration

The rate at which greenhouse gases are being captured and stored for different land cover types during each time step, denoted as t, can be represented as:

$$\frac{dM_{GHG}}{dt} = \frac{dM_{CO_2}}{dt} - 21\frac{dM_{CH_4}}{dt}$$

where:

M_{GHG} = Mass of greenhouse gases sequestered at a specific time, measured in terms of carbon dioxide (CO2) mass,

M_{CO_2} (t) = Mass of carbon dioxide sequestered at the given time (CO2 mass),

M_{CH_4}(t) = Amount of methane emitted at the specified time, measured in terms of methane mass (CH4 mass),

21 = Historically assumed 100-year global warming potential (GWP) for methane, as established by Forster et al. (2007). However, recent studies indicate that methane may have a considerably higher GWP of 34, as reported by Change in 2013.

3. Results

3.1. Impact of Sea Level Rise

Both human systems and environmental systems are impacted by rising sea levels in a variety of ways. These associated phenomena, among others, reflect climatic pressures including flooding, coastal erosion, accretion, and salinization of lagoon waters. The effects of a sea level rise on the coast of Benin are depicted in Figure 2.

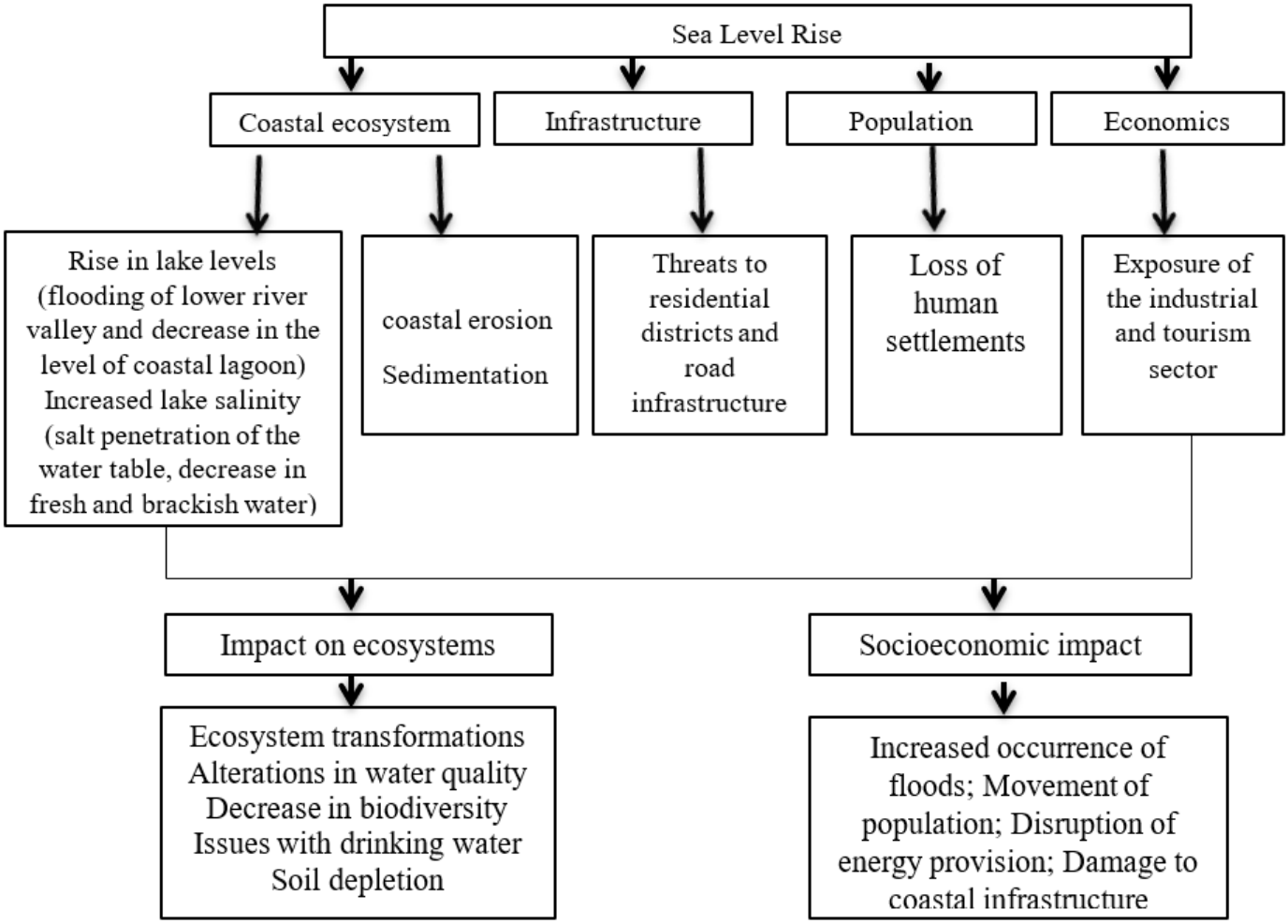

Figure 2. Summary of the impact of sea-level rise on the coastal zone.

- Grand Popo and Ouidah, located on the western part of the Benin coastline, are susceptible to climate change risks such as sea-level rise (SLR) and erosion caused by flooding. These areas have a predominantly agricultural and peri-urban character. Notably, they encompass various conservation areas and possess a significant tourism potential. Within this region, the Mono estuary is situated, with its estuarine system interconnected with the sea through a narrow mouth.

Unfortunately, these areas have been experiencing a heightened frequency of storm surges, leading to the submersion of substantial portions of the beaches, numerous fishing shelters, and the houses of local communities. This poses a significant threat to public infrastructure, fishing activities, coastal ecosystems, and the overall economic well-being of the region. The anticipated effects of SLR and extreme weather events will further exacerbate the incidence and severity of coastal flooding, magnifying its impacts.

To address these challenges, adaptation measures could involve implementing a comprehensive range of interventions. These may include sediment management, dredging, and the stabilization or construction of the estuary. Furthermore, targeted improvements in select public urban infrastructure could be pursued, guided by further analysis to enhance the resilience of the affected areas.

- The eastern coast, characterized by climate change risks such as sea-level rise (SLR) and erosion caused by flooding, is primarily an industrial region. It features multiple groins aimed at mitigating erosion, although erosion remains a prevalent issue, with

a few areas experiencing accretion. This coastal area is particularly susceptible to intense storm surges and frequent coastal floods, resulting in the destruction of residences, roads, ship groundings, and other infrastructure.

To adapt to these challenges, potential measures could involve the management and establishment of natural protected areas. These protected areas would serve as buffers to safeguard critical road infrastructures located in the eastern part of the national coastline. By preserving and utilizing these natural spaces strategically, the impacts of coastal hazards could be mitigated and the resilience of the region's transport and natural resources sector could be enhanced.

- Cotonou, situated in a coastal region, faces climate change risks such as erosion and flooding, particularly in the urban sector. This bustling city serves as a significant hub for port infrastructure but is also highly vulnerable to erosion. To address this issue, several groins have been constructed to mitigate the erosion challenges in the area.

Furthermore, Cotonou is prone to high storm surges and faces a constant risk of coastal flooding. To adapt to these risks, potential options include retrofitting or upgrading critical urban infrastructures. By enhancing the resilience of key urban elements, Cotonou can better manage the anticipated increase in both the frequency and volume of flooding events.

Table 3. Projected changes in the acreage of SLAMM land use categories from 2021 to 2090 at Benin coastal area under the RCP 8.5_Upper Limit scenario.

RCP 8.5_Upper Limit				0.240m			0.514m			0.918m			1.468m		
				Area						Area			Area		Area
SLAMM code	Land cover category	Initial coverage	%	2021	2030	Change	2021	2050	Change	2021	2070	Change	2021	2090	Change
1	Developed Dry Land	590.8	20.1	589.0	589.0	-1.8	589.0	589.0	-1.8	589.0	589.0	-1.8	589.0	588.5	-2.2
2	Undeveloped Dryland	1306.5	44.5	1305.6	1305.6	-0.9	1305.6	1305.6	-0.9	1305.6	1305.6	-0.9	1305.6	1303.6	-2.9
3	Swamp	262.0	8.9	258.3	258.3	-3.7	258.3	258.3	-3.7	258.3	258.3	-3.7	258.3	256.9	-5.1
8	Regularly Flooded Marsh	283.6	9.7	280.6	280.6	-3.0	280.6	280.6	-3.0	280.6	280.6	-3.0	280.6	279.0	-4.6
9	Mangrove	104.8	3.6	106.2	101.3	-3.5	106.2	101.3	-3.5	106.2	101.3	-3.5	106.2	102.5	-2.3
12	Ocean Beach	44.5	1.5	37.2	36.7	-7.8	37.2	36.7	-7.8	37.2	36.7	-7.8	37.2	36.7	-7.9
15	Inland Open Water	105.9	3.6	24.5	24.5	-81.3	24.5	24.5	-81.3	24.5	24.5	-81.3	24.5	24.5	-81.4
17	Estuarine Open Water	209.8	7.1	298.5	303.4	93.6	298.5	303.4	93.6	298.5	303.4	93.6	298.5	307.5	97.7
19	Open Ocean	26.5	0.9	34.5	34.9	8.4	34.5	34.9	8.4	34.5	34.9	8.4	34.5	35.0	8.5
		2934.4		2934.3	2934.4			2934.4				2934.4		2934.3	

The effect of sea level rise has a more pronounced trend at an elevation of 1.468 m, according to Table 3 and Figure 3. From initial coverage to an elevation of 0.240m, a variation in areas in the various class groups can be seen. However, both at SLR 0.514m and 0.918m, the observed impact will stay constant.

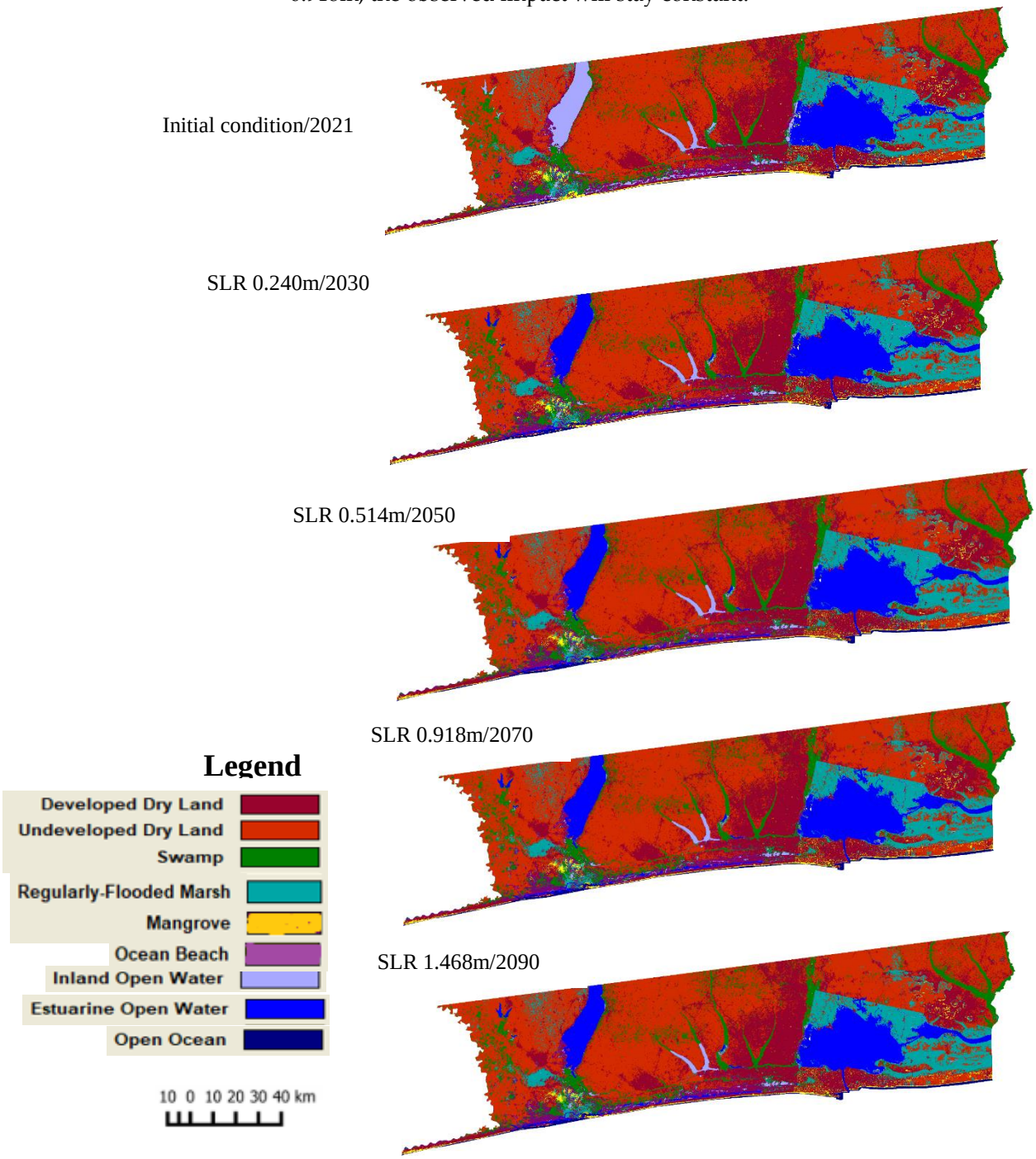

Figure 3. SLAMM land use categories from 2021 to 2090 for Benin coast under RCP 8.5_Upper Limit scenarios.

4. Expected change on the coast

- Coastal erosion will get a lot worse as a result of sea level rise brought on by global warming. Benin's coastline has a delicate ecology that is vulnerable to the harmful effects of climate change, including:
- Rising sea and ocean levels (as depicted in Figure 4)

- Apparent retreat of the coastline east of Cotonou
- Alterations in average rainfall patterns
- Heightened atmospheric temperature negatively impacting natural ecosystems, human communities, water resources, and coastal infrastructure

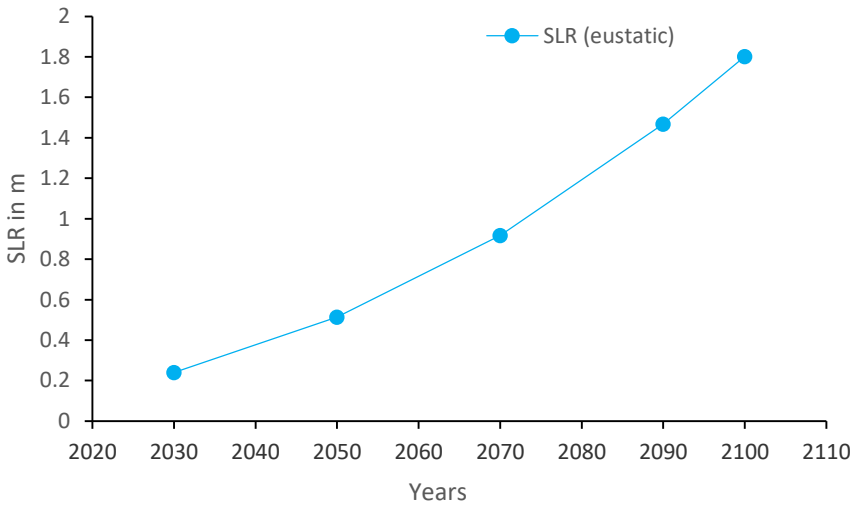

Figure 4. Sea level trends over the years on Benin coast.

The coastal erosion affecting Cotonou, Grand-Popo, and other areas is a dynamic phenomenon specific to the sub-region. It is primarily caused by disruptions in coastal currents responsible for transporting sand, resulting from the construction of upstream dams or coastline developments such as ports. Additionally, the coast experiences the impact of distant ocean swells, characterized by waves arriving at intervals of 10 to 16 seconds, spanning 160 to 220 meters in length.

Coastal drift, also referred to as coastal transport, occurs when the angle of the waves hitting the beach changes between 4° and 9°, leading to the movement of material from west to east. This process causes an annual transport of 1,500,000 cubic meters of sand from Lomé to Cotonou. However, the development of ports in both cities has restricted the accumulation of sand deposits that should have naturally enriched the shorelines, redirecting sediment upstream (towards the west of the Cotonou port).

- Referring to the methodology developed by Vandebroek and Crooks at ESA PWA (2014) (Fox, 2011), SLAMM employs a calculation process to estimate carbon sequestration based on land cover. This approach considers the amount of carbon stored within wetlands as well as the carbon emissions resulting from methane loss in freshwater ecosystems. Within our study area, there is a noticeable annual decrease in the capacity to sequester greenhouse gases, particularly carbon (as depicted in Figure 5).

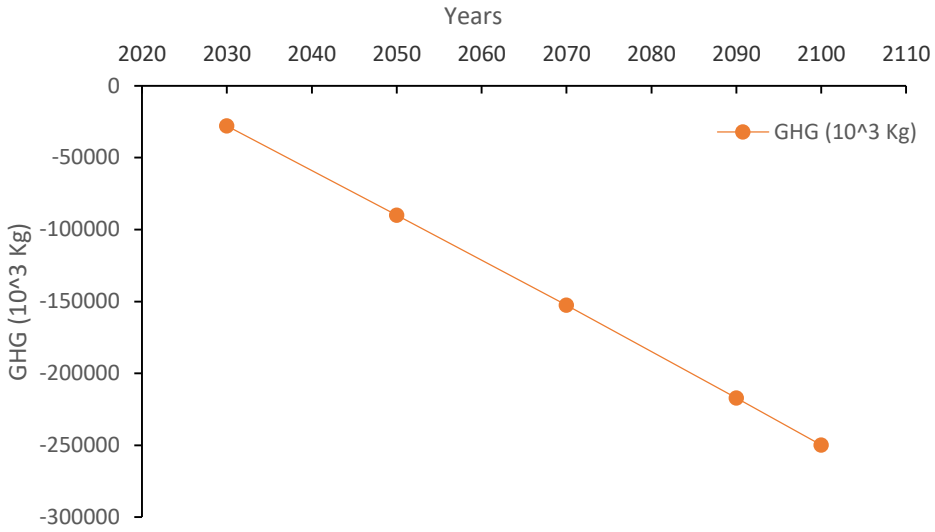

Figure 5. SLAMM estimates Carbon Sequestration in Benin coast.

4. Discussion

4.1. Land cover changes

For coastal wetlands and populations facing the challenges of rising sea levels, inland relocation can be a viable option if sufficient space is available (Kirwan et al., 2016; Schuerch et al., 2018). This is what the SLAMM modeling predicts for the wetlands, roads, towns, and ecosystems along the coast of Benin. The coastal slopes in Benin gradually become flatter as they move inland from the sea. The modeling suggests that while more freshwater wetlands may disappear and be replaced by saline wetlands and open ocean, the availability of existing housing is in favor of this shift (Figure 2).

The largest increases in land cover categories are observed in Estuarine Open Water and Open Ocean. These two categories together gain approximately 106.2 hectares in the area, considering different levels of sea level rise using RCP 8.5_Upper Limit. However, these gains are offset by losses of approximately 106.2 hectares in Inland Open Water, Ocean Beaches, Mangroves, Regularly Flooded Marsh, Swamps, Undeveloped, and Developed Dryland. The significant gains in Estuarine Open Water (97.7 hectares) and Open Ocean (8.5 hectares) indicate the submergence of these areas by 2090 and subsequent saltwater intrusion into coastal ecosystems due to sea level rise (Table 3).

The largest losses are observed in less tidal-influenced categories such as Inland Open Water (-81.4 hectares), Ocean Beach (-7.9 hectares), Swamp (-5.1 hectares), Regularly Flooded Marsh (-4.6 hectares), and Undeveloped Dryland (-2.9 hectares). These categories are projected to significantly decrease as the sea level rises by 1.468m, and they will mainly be replaced by Estuarine Open Water and Open Ocean (Figure 2). The category least affected throughout the simulation is Undeveloped Dryland, as it generally has higher elevation and is located further away from the shore, which delays the impacts of sea level rise.

4.2. Erosion

Based on SLAMM modeling, with a sea level rise of 1.468m, approximately 22.28% of the coastal area in Benin will be susceptible to active erosion. This is the result of projected inland migration of shorelines. The expansion of Ocean Beach and Open Ocean areas, as well as developed coastal regions, indicate this trend. The urban population, primarily concentrated in these areas and growing at a rate of 4% annually, which is nearly twice the global average, is being adversely affected and devastated by erosion (Saghir et al, 2018). The scenario in Benin reveals an increasing demand for land, water, and other

natural resources due to rapid urbanization and net migration to the coast. The construction of man-made structures such as river dams, seawalls, and breakwaters, as well as the extraction of sand from beaches and dunes, have contributed to substantial coastal erosion in Benin. The areas experiencing the most significant rates of retreat, surpassing 10 meters per year, are primarily located near river mouths and harbor jetties, which are indicative of the heavily urbanized regions.(Giardino et al., 2018). The losses and gains observed in the different land cover categories identified in this study reflect the adverse impacts experienced by coastal communities, including significant asset losses (homes, infrastructure, wetlands) on the Cotonou side, as well as the degradation of critical ecosystems like beaches, wetlands, and mangroves.

Furthermore, coastal communities, particularly those who heavily rely on natural resources and are among the poorest, are increasingly vulnerable to the effects of climate change. The erosion process leads to the emission of carbon into the atmosphere, generated by human activities and other sources. Annually, approximately 500,000 individuals in West Africa face the peril of flooding and escalating coastal erosion, leading to substantial economic losses. In 2013, these losses were estimated to account for 2.3% of Togo's GDP, while in 2014, they amounted to 3.2% of Mauritania's GDP.

4.3. Inundation

SLAMM modeling provides significant insights into the anticipated changes in coastal inundation in Benin. For instance, with a sea level rise of 1.468m, approximately 76.58% of the study area is projected to be flooded. This inundation poses a major challenge for rural communities located in low-lying coastal areas, as their economies heavily rely on local natural resources, which are at risk of depletion due to rising sea levels. Comparable circumstances are evident in Senegal, where annual floods impact approximately 200,000 individuals and generate an estimated average cost of $89 million per year. Particularly noteworthy are the exceptional floods experienced in 2009, which resulted in significantly higher damages totaling $104 million in Dakar. Looking ahead to the end of the century, the region is expected to witness coastal retreat due to rising sea levels and related extreme events, such as storm surges. The 5th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2019) identifies West Africa as a climate change hotspot, where unprecedented climatic conditions are projected to manifest earlier than the global average by a margin of one or two decades. Ongoing climate change and variability are poised to exacerbate these challenges.

One notable impact of sea level rise and droughts is the intrusion of saltwater, which can lead to reduced crop yields, land degradation, and even the abandonment of agricultural areas (He et al, 2019). As more coastal regions become submerged due to rising sea levels, the available land for agriculture will decrease. However, from a different perspective, if environmental factors stabilize over time, this saline intrusion may facilitate the transformation of certain wetlands into mangroves.

5. Conclusion

This study demonstrates the suitability of SLAMM modeling as a method to assess the impacts of future sea-level rise (SLR) on coastal resources. Based on the research findings, it is evident that the Beninese coast will primarily experience two significant consequences in response to SLR: flooding and erosion. Among these, the most significant adverse effect of flooding is the potential depletion of local natural resources, which are vital for the economies of rural, low-lying coastal communities. Furthermore, saltwater intrusion poses additional risks such as reduced crop yields, land degradation, and the abandonment of agricultural areas. The importance of this research lies in its initial steps toward evaluating the social and economic vulnerability associated with SLR, providing a valuable framework for guiding political actions and achieving meaningful outcomes.

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