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Evaluation of the Impacts of Sea Level Rise Hazards in Douala-Cameroon

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Abstract

Global warming and its associated impacts of Sea Level Rise hazards of flooding by storm surge, inundation, salt water intrusion to ground water, salt water incursion to rivers/estuaries affects low lying coastal Countries and small islands. Douala, with ecological and socio-economic vital values for the country is exposed to and should be prepared for the impacts of Sea Level Rise hazards while partaking in mitigation schemes. Consequently, vulnerability of fresh water resources of Sea Level Rise (SLR) hazards was assessed and projected areas at risk mapped. These were estimated using the coastal vulnerability index matrix. Projected areas at risk were obtained using the geographical information system geo-processing query. The calculated coastal vulnerability index (CVI)-SLR was 3.6 for the Douala low lying region indicating that it is high. Inundation (4) followed by SWI into ground water aquifers (3.86) was the dominant Sea Level Rise hazard impacts for the study area. Bareground (132.21 and 446.82 km^2) and settlement (152. And 476.5 km^2) classes of land cover will be more affected by 5 and 10 m projected flood levels. This study therefore suggests that major investments should be made to improve the data base of climate change variables of the coastlines of Douala and the entire nation since information from these databases will form the basis for the development of adaptation strategies to any future SLR hazards.

Subject Areas

Environmental Sciences, Hydrology

Keywords

Evaluation, Sea Level Rise, Vulnerability, Geographical Information System, Remote Sensing, Hazards, Douala-Cameroon

1. Introduction

Coastal zones are vital and important places for communities the world over due to its fertile soils, marine resources, water transportation, intrinsic values, tourism, aesthetic scenic splendour for survival and development as in [1] [2] [3]. Coastal areas are a critical part of the economies of virtually all nations bordering the sea, particularly subsistence economies. Coastal habitats provide important areas for fish and wildlife, including many endangered species. As posited in [4] and the Inter-governmental panel on climate change (IPCC) [5], they filter and process agricultural and industrial wastes and buffer inland areas against storm and wave damage as in [6] and [7].

It is estimated that more than 60% of world's population currently live within 100 km of the coasts and these figures will increase in the near future as in [8]. [9] further indicated that population densities in coastal cities are three times the global mean. Projected impacts of global warming will alter many ecosystems including coastal ecosystem and populations will be affected by Sea Level Rise (SLR). According to [5] the impacts of SLR will be most profound in small islands and low lying coastal areas in many Countries.

A number of approaches have been adopted to assess vulnerability of different coasts as in [2]. Identifying sections of shoreline susceptible to sea-level rise is necessary for more effective coastal zone management. This could increase resilience and help reduce the impacts of climate change on both infrastructure and human beings. One of such resources which require efficient management is fresh water resources of coastal area (surface and ground water). The efficient management of this resource requires a state-of-the art evaluation of its quality with respect to influences from other natural agencies.

Therefore, a vulnerability assessment of fresh water resource quality in Douala to the hazards of SLR is needed to support policy formulation for sustainable management. The assessment is also important as it will serve as a guideline for resource allocation, and for the preparation of adaptation options for salt water intrusion (SWI) into fresh water resources.

The low lying coastline of Douala-Cameroon is also at risk to SLR. However, the risks could be minimal, but impacts enormous, because Cameroon experiences subsidence at its coasts as in [10] [11]. Consequently, impacts on its low lying area of Douala could be immense. Douala is the seat of many industries, urban centers and tourism zones. As such, a vulnerability assessment of fresh water resource quality to the hazards of SLR in Douala is needed to reinforce policies for sustainable coastal zones development and as a guideline for resource allocation and for the preparation of adaptation options for salt water intrusion (SWI) into fresh water.

[12] [13] indicate that levels of vulnerability assessments are varied and can be classified as science-driven to policy driven, strictly quantitative to semi-quantitative, non-adaptive to perfectly adaptive, simplistic to sophisticated. Each evaluation needs data with different levels of detail and accuracy. There have been

several approaches to vulnerability analysis that have used physical characteristics of the coastal system to classify the coast, producing a ranking of sections of shoreline in terms of its sensitivity to a rise in relative sea level as in [14] [15]. An index, based on physical variables such as coastal landforms, relief, geology, relative SLR, shoreline displacement, tide range and wave height, has been used to assess the vulnerability of coasts in the USA, Europe, Canada, Brazil, India and Argentina as in [14] [16]-[23].

Vulnerability indices of this type which can be transfer to other regions have not been carried out in Cameroon, though their major disadvantage is the subjectivity in assigning numerical values to the descriptive entities and relative weights of different attributes as in [24]. The purpose of this paper is to evaluate the degree of vulnerability to SLR hazards of the low-lying metropolitan town of Douala to its fresh water resources. It is also meant to determine the land classes most at risk to SLR hazards which are to be considered when planning for adaptation to SLR.

A major limitation of the vulnerability evaluation in Douala is the lack of data. This study makes use of developed coastal vulnerability matrix and a corresponding coastal vulnerability index – CVI (SLR) of Douala to SLR using pointers of effects of SLR with commonly determined and available data.

2. Materials and Methods

2.1. Determination of Physical Parameters of Sea Level Rise Hazards on Water Resource Quality in Metropolitan Douala

The SLR hazards pollution potential of fresh water resources for Douala was assessed using the coastal vulnerability index (CVI) model for SLR; CVI (SLR) developed by [25]. The impacts induced by SLR were evaluated for the Douala low lying region. CVI provides numerical basis for ranking sections of the coastline in terms of potential for change that can be used to identify regions where risks could be relatively high. **Table 1** shows the physical and human influenced parameter that is used for the evaluation of impacts of SLR hazards on water resource quality in Douala.

The CVI to SLR was calculated based on the ratio of the total value of the parameter value ranks to the sum of the least vulnerable value ranks; weighting factors were considered. The CVI approach applied [26] was based on the concept as in [18] to assess the vulnerability of the US coasts to rising sea levels at a national scale.

The CVI (SLR) for Douala to SLR hazards was determined through the integration of 4 sub-indices, each one corresponding to a specific impact of SLR (flooding due to storm surges, permanent inundation, saltwater intrusion to groundwater resources and salt water incursion to rivers/estuaries) as shown on **Table 1**.

Each sub-index was determined by semi-quantitative assessment of physical and human influenced parameter (10 physical and 6 human influenced parameter as seen on Table 1. These variables are appropriate without reducing the quality of the assessment as in [26] and each parameter can contribute to the definition of more than one sub index. Several methods were used to determine the indicators governing parameters of physical and human influenced processes of the impact of SLR hazard (Table 2 and Table 3).

Table 1. SLR hazards and corresponding physical and human influenced parameters

Hazards of Sea Level Rise	Physical parameters	Human parameters
Coastal flooding due to storm surge	1. Rate of Sea Level Rise 2. Coastal slope 3. Significant wave height 4. Tidal range	1. Engineered frontage 2. Natural protection degradation 3. Coastal protection structures
Inundation	1. Rate of Sea Level Rise 2. Coastal slope 3. Tidal range	1. Natural protection degradation 2. Coastal protection structures
Salt water intrusion to ground water resources	1. Rate of Sea Level Rise 2. Proximity to coast 3. Type of aquifer 4. Hydraulic conductivity 5. Depth to ground water level above sea	1. Ground water consumption 2. Land use pattern
Salt water intrusion to rivers/estuaries	1. Rate of Sea Level Rise 2. Tidal range 3. Water depth at down stream 4. Discharge	4. River flow regulation 2. Engineered frontage 3. Land use pattern

Table 2. Method of generation of physical parameters of vulnerability to Sea Level Rise for Douala coast.

Parameter	*Method of generation of data
Rate of SLR	Satellite image reading and GIAA data
Coastal slope (%)	3 D Analyst tool in ArcGIS 10.3
Significant wave height	[27] Calculated from Port Sonara data Hydrographer of the navy [28]
Tidal range	[29]
Proximity to the coasts	ArcGIS 10.3
Type of aquifer	Geologic log data and map from GEOFOR
Hydraulic conductivity	[30]
Depth to ground water level above sea	[30]
Water depth at down stream	
Discharge	[31] [32], IRGM, Yaounde

*Values from previous work and calculated data of some variables were used to assign rankings; GIA: Glacial Isostatic Adjustments.

Table 3. Method of generation of human influenced parameters of vulnerability to sea level rise for Douala coast.

Parameter	Method
Flow reduction	
Engineered frontage	Based on the 0.7 km^2 area indicated for harbor in Cameroon by IPCC as in [33]
Ground water consumption	[34]
Land use pattern	Calculated change detection analysis for 2014 and 1986 Landsat imagery
Natural protection degradation	Calculated change detection analysis for 2014 and 1986 Landsat imagery
Coastal protection structures	

2.2. Coastal Vulnerability Index for Sea Level Rise

The use of vulnerability ranks of regional data produces a vulnerability matrix which calculates the impact of sub-indices and the overall vulnerability index using weights assigned for the corresponding group of parameters which is 0.5 as in [25]. The modified calculation formula of the sub-indice is shown in Equation (1).

$$CVI_{Hazard} = \frac{0.5 * \left(\sum_1^n (PPn * Rn) + \sum_1^n (HPm * Rn) \right)}{CVI_{least\ vulnerable}} \tag{1}$$

where:

CVI_{Hazard} = physical hazard sub-index

PP = physical parameter

HP = Human Influence parameter

R = Corresponding vulnerability range of the parameter

n and m = the number of physical and human influenced parameters respectively considered for a particular hazard

$CVI_{least\ vulnerable}$ = results of ratio of the sum of weighted parameters to the least vulnerable case result for the hazard studied.

The calculated indices range between 1 and 5 indicating the level of vulnerability accordingly. The vulnerability ranges to determine the ranks of each parameter according to the regional data are based on distribution of available data related to each parameter at locations around the world. Each parameter is assigned a vulnerability rank of very low to very high vulnerability (1 - 5).

2.3. Indicators for an Evaluation of Projected Areas at Risk of Sea Level Rise Hazards

Geographical information system (GIS) tools were applied to indicate areas of water resources at risk from SLR hazard and to quantify the potential impacts of flooding levels on the coastal water resources. Shape files of land use land cover (LULC) classes were clipped with extracted flooding levels from digital elevation model (DEM). These indicated the areas and extent of flooding/inundation scenarios and SWIs at risk as a result of SLR.

The capability of Landsat enhanced thematic mapper (TM), Sentinel-1 C band synthetic aperture radar (SAR) and the integration of radar and Landsat imagery for extracting land use land cover (LULC) information in the coastal low lying strip of Douala-Cameroon using various image processing techniques and the support vector machine (SVM) algorithm as in [35] was made used of. Conventional methods of pre-processing and training data sets for the classification of Landsat imagery were used.

Different layers of the optical images were assigned appropriate band names and wavelengths and stacked together. The respective regions of interests (ROIs) training sites for calibration and data for validation were obtained from a high resolution Google earth map. These were imported to ArcGIS 10.3. With the help of Arc toolbox, in the GIS environment, the Keyhole Markup language Zipped (KMZ) data were converted to layers, saved as shape files and exported to the Environment for Visualisation (ENVI 4.8) software for processing.

The layers were overlaid on the image of the study area into ENVI as vector files. These were further converted to separate region of interest (ROI)s by name. The necessary growing of different ROIs was done, editing of colours of ROIs to separate them and consequently merging of the same ROIs. ROIs were then saved to appropriate folders, and they were reconciled via map to enable the classification of the study area.

For the study, the DEM was obtained from https://www.earthexplorer.usgs.gov/ website. The DEM was necessary because Douala is a low lying area. DEM outlines the elevations and enables the visualisation of low elevation areas and potential areas at risk of flooding.

The obtained LULC of the study area which represent an initial requirement for the analysis of hazards of SLR were used for assessment of critical land areas at risk (settlement, bare-ground, mangroves and swampy vegetation). The land use classes were converted to shape files (a simple, non-topological format for storing geometric locations and attribute information of geographic features) of each land use, with the help of the ENVI software. This format of keeping GIS data permitted the LULC of the areas that are prone to flooding hazards to be overlaid on the DEM of the study area to appreciate the areas at risk of flooding and hence SWI into fresh water aquifers.

2.4. Projected flooding scenarios and areas at risk of flooding

The empirical equation as in [36], was used to assess flooding levels.

$$\mathrm{Dft} = \mathrm{MHW} + \mathrm{St} + \mathrm{Wf} + \mathrm{Pf} \tag{2}$$

where: Dft = flooding levels (m), St = relative SLR (mm/year), Wf = Height of storm waves (m), Pf = SLR due to lowering of atmospheric pressure (mm/yr).

For the tide height which is a critical component of any coastal flooding event, an upper limit tide level is needed for risk assessment and one such upper level

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that is widely available is mean the high water springs (MHWS). This is traditionally computed as the long term average. Data from the Port Sonara tide gauge was used to obtain the MHWS and MLWS. This was supported by secondary literature data obtained from the Admiralty tide data by the UK meteorological office. Flooding values obtained were used to estimate the potential land lost which is caused by flooding.

The application of ArcGIS spatial analyst tool was used on maps of DEM to assess the land cover land area resources which are potentially at risk of SLR hazards as a result of global warming on the coastal environment of Douala. A SLR toolbox was created for the assessment of projected critical elements at risk of inundation for the study area. It contains geoprocessing tools for analysis and models to run a process. The extract by mask tool was used to extract cells of the inundation zones that corresponded to the areas defined by the mask (mask stands for critical elements at risk like mangroves, settlement, water). The extract by attributes which is based on a logical query builder was used to create an SQL expression as shown on Figure 1. It aids in the selection of a subset of raster cells based on different flooding and or inundation levels.

3. Results

3.1. Coastal Vulnerability Index for Sea Level Rise Hazards – CVI (SLR) of Douala

3.1.1. Sub-Indices of Physical Vulnerability of the Hazards of Sea Level Rise

The range of physical parameters is shown on Table 4. Data from Topex/ Poseidon as in [37] and now Jason satellite on the rate of SLR (±5 cm sensitivity) indicated relative rates of SLR of between 3 - 4 mm/yr. These results were confirmed by SLR experts from the joint Archive for SLR from the University of Hawaii.

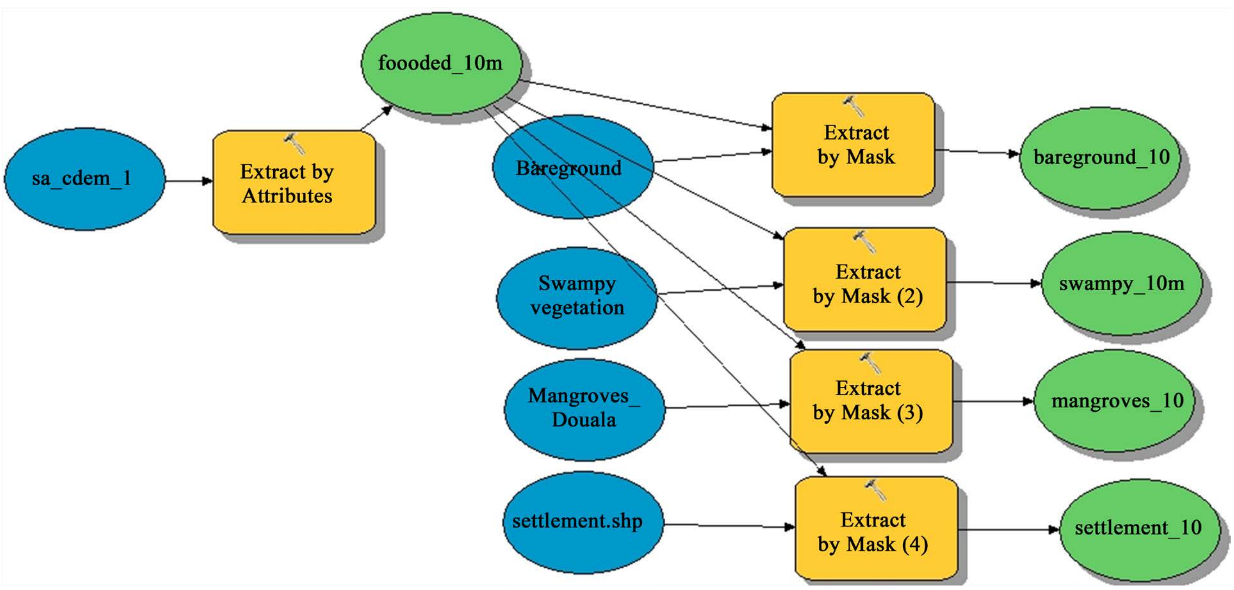

Figure 1. Flow chart used in obtaining areas at risk of inundation in ArcGIS.

Table 4. Ranking of physical parameter of vulnerability to SLR for Douala coast using coastal vulnerability indices.

Parameter	Range	Ranking
Rate of SLR	2.85 - 3.85	Moderate
Coastal slope (%)	0 - 49.2	Very high
Significant wave height	0.5 - 0.85 0.89 - 1.01 0.60 - 0.80 0.5, 0.6	Low Low Low Low
Tidal range	2 - 4	Moderate
Proximity to the coasts	100 - 400	High
Type of aquifer	Unconfined	High
Hydraulic conductivity	0.29 - 99.4 m/day	High
Depth to ground water level above sea	0.5 - 22.88 m	Moderate
Water depth at down stream	>3 m	Moderate
Discharge	49 - 1424 m^3/s	High for dry season

This data did not take into consideration the rates of vertical land movements at the coasts. The vertical adjustments in land movements at the coasts for this study were done using Peltier Glacial Isostatic Adjustments (GIA) data. This is the only geological process which is capable of being modelled on a global basis of correcting for land movements in tide gauge records. Results of GIA from Port Sonara have been highlighted to be (−0.15) as in [38] [39]. Therefore −0.15 was subtracted from the Cameroon's estimated SLR figures from satellites to give a corrected rate of change of sea-level of between 2.85 - 3.85 mm/year. Thus, based on this estimation, the SLR for this area is ranked as moderate.

For the coastal slope of the area, the calculated range in percentage was between 0 to 49.2 and was ranked as very high. Values of significant wave height ranged from 0.5 to 1.01 and corresponded to a low ranking. For the aquifer type of the area, it was assessed as being unconfined and thus ranked as high. The hydraulic conductivity was ranked as high and had as corresponding values of 0.29 to 94.4 m/day. The depth to the ground water table (0.5 to 22.88) and the downstream water depth (>3 m) were ranked as moderate.

The discharge of River Wouri for the different seasons ranged from a minimum value of 48 (dry) to a maximum value of 1424 (wet) m^3/s. based on these ranges, the dry season value was ranked as high while the wet season value was low. Data from global tidal ranges indicated that, the Cameroon coasts falls within the meso-tidal classification (2 - 4). The tidal range for the study area was thus classified as moderate. The developed index for classification and ranking of these ranges are as in [26].

3.1.2. Sub-Indices of human vulnerability of the Hazards of Sea Level Rise

The range/value of human parameters and ranking are shown on **Table 5**. The river Wouri has not been regulated in terms of dam construction or regulative structures, thus this parameter was ranked as low. The value for engineered frontage was 0.33% and based on the assigned ranges ranking as in [26], this parameter was ranked as low. The ranges for ground water consumption (40% to 50%), natural protection degradation (40% to 20%) and coastal protection structures (<5%) in the area (Table 5) are ranked high.

A change detection analysis for selected land use classes of the study area was obtained as shown on Table 6. Negative values for mangrove image difference (−1.38) highlight the degradation of mangroves. Douala is an industrial area with dense settlement and was thus ranked as high in terms of its land use pattern. This corroborates with the positive image difference of 16.53 for settlement class observed in this study.

3.2. Coastal Vulnerability Index—CVI (SLR) Matrix

The sub-indices for each impact have to be computed in order to calculate the coastal vulnerability index-CVI (SLR). The end results of the impact vulnerability

Table 5. Human parameters of vulnerability to Sea Level Rise for Douala coast using coastal vulnerability indices.

Parameter	Range/value	Ranking
Flow reduction	Not affected	low
Engineered frontage	0.33%	Very low
Ground water consumption	40% - 50%	high
Land use pattern	Settlement and industries	High
Natural protection degradation	40% - 20%	High
Coastal protection structures	<5%	High

Table 6. Change detection for the 2018 and 2000 Landsat imagery.

	Water	Mangroves	Settlement	Row total	Class total
Unclassified	0.046	0.592	0.354	3.326	100
Mangroves	0.936	50.428	2.65	58.387	100
Palms	0.936	5.11	0.694	49.859	100
Settlement	1.595	11.355	60.463	72.376	100
Water	66.119	4.947	1.072	55.329	100
Bare ground	3.613	11.269	27.116	80.512	100
Swampy vegetation	4.145	4.432	1.516	67.798	100
Vegetation forest	2.092	9.572	5.876	56.207	100
Rubber	0.271	2.295	0.643	49.07	100
Class total	100	100	100	0	0
Cass changes	33.881	49.572	39.537	0	0
Images difference	54.263	−1.38	16.527	0	0

sub-indices for flooding due to storm surge, inundation, SWI into ground water and SWI into rivers/estuary are 3.4, 4, 3.8 and 3.3 respectively for the Douala low lying region as presented on **Table 7**.

Human or physically influenced parameters would impact SLR hazards differently, especially when general consensus from climate change scientists advocates that humans are the cause of global warming as in [40]. The influence of groups of parameters and the level of influence are shown on **Figure 2** for each SLR hazard. The levels of influence were obtained by dividing the total value of parameters of each group by the least vulnerable case result of the group. The

Table 7. Coastal vulnerability index-CVI (SLR) matrix for Douala-Cameroon.

Impact	Physical Influenced Parameter							Human Influenced Parameter							Impact total	CVI impact
	Parameter	1	2	3	4	5	**Total**	**Parameter**	1	2	3	4	5	**Total**		
1.Flooding due to storm surge	Rate of sea level rise			1			**3**	Engineered frontage		1				**2**		
	coastal slope					1	**5**	Natural protection degradation				1		**4**		
	Significant wave height		1				**2**	coastal protection structures					1	**5**		
	Tidal range			1			**3**									
	Total	**0**	**1**	**2**	**0**	**1**	**13**	**Total**	**1**	**1**	**0**	**1**	**1**	**11**	**12**	**3.43**
2.Inundation	Rate of sea level rise			1			**3**	Natural protection degradation				1		**4**		
	coastal slope					1	**5**	coastal protection structures					1	**5**		
	Tidal range			1			**3**									
	Total	**0**	**0**	**2**	**0**	**1**	**11**	**Total**	**0**	**0**	**0**	**1**	**1**	**9**	**10**	**4**
Salt water instusion to ground water resource	Rate of sea level rise			1			**3**	Gound water consumption				1		**4**		
	Proximity to the coasts				1		**4**	Land use pattern				1		**4**		
	Type of aquifer					1	**5**									
	Hydraullic conductivity				1		**4**									
	Depth to ground water level above sea			1			**3**									
	Total	**0**	**0**	**2**	**2**	**1**	**19**	**Total**	**0**	**0**	**0**	**2**	**0**	**8**	**13.5**	**3.8**
Salt water instusion to river and estuarise	Rate of sea level rise			1			**3**	River flow regulation	1					**1**		
	Tidal range			1			**3**	Engineered frontage		1				**2**		
	Water depth at down stream					1	**5**	Land use pattern				1		**4**		
	Discharge					1	**5**									
	Total	**0**	**0**	**2**	**0**	**2**	**16**	**Total**	**1**	**1**	**0**	**1**	**0**	**7**	**11.5**	**3.3**
														CVI (SLR)	**47**	**3.6**

computation matrix for flooding due to storm surge which is governed by SLR as an example includes, the usage of 4 physical parameters and 3 humanly-influenced parameters.

The total value of the vulnerability of the parameters is summed accordingly;

Physical parameters: 1 * 3 + 1 * 5 + 1 * 2 + 1 * 3 = 13

Humanly influenced parameter: 1 * 2 + 1 * 4 + 1 * 5 = 11

Weights of each group of parameters are assigned a value of 0.5 as in [26]. Consequently, the total value of the vulnerability parameters for flooding due to storm surge was calculated as;

Total value impact: 0.5 * 13 + 0.5 * 11 = 12

The final computation of the sub-index of SLR hazard requires the total value to be divided by the least vulnerable case value which is presented on **Table 8** for the different SLR hazards.

The least vulnerable case of flooding due to storm surge were as follows 0.5 * (4 * 1) + 0.5 * (3 * 1) = 3.5.

Consequently, the sub-index of vulnerability of Douala to flooding due to storm surge as a result of SLR was;

$$\text{CVI (flooding due to storm surge)} = 12/3.5 = 3.428$$

Thus, the study area is moderately vulnerable when flooding due to storm surge occurs as a result of SLR (**Table 9**). This is so because 3.43 is between 2.5≤CVI (SLR) <3.5 (falls in the range of moderate vulnerability) as in [25].

From **Figure 2**, it was observed that inundation (4.5 versus 3.66), flooding due to storm surge (3.5 versus 3.25) and SWI into ground water (4 versus 3.8) were affected more by humanly influenced parameters than physical parameters. However, for SWI to rivers and estuaries, physical parameters had a greater

Table 8. Most vulnerable and least vulnerable case results of the impacts of Sea Level Rise into fresh water resources.

Hazard	Number of physical parameters	Number of human influenced parameters	Least vulnerable case of hazard
Flooding due to storm surge	4	3	3.5
Inundation	3	2	2.5
SWI to ground water	5	2	3.5
SWI to rivers/estuary	4	3	3.5

Table 9. Ranking of computed CVI (SLR) value for Douala-cameroon.

Impact	Computed CVI (SLR)	Range	Degree of vulnerability
Flooding due to storm surge	3.43	2.5 ≤ CVI (SLR) < 3.5	moderate
Inundation	4	3.5 ≤ CVI(SLR) < 4.5	High
SWI to ground water	3.86	3.5 ≤ CVI(SLR) < 4.5	High
SWI to rivers/estuary	3.3	2.5 ≤ CVI (SLR) < 3.5	moderate

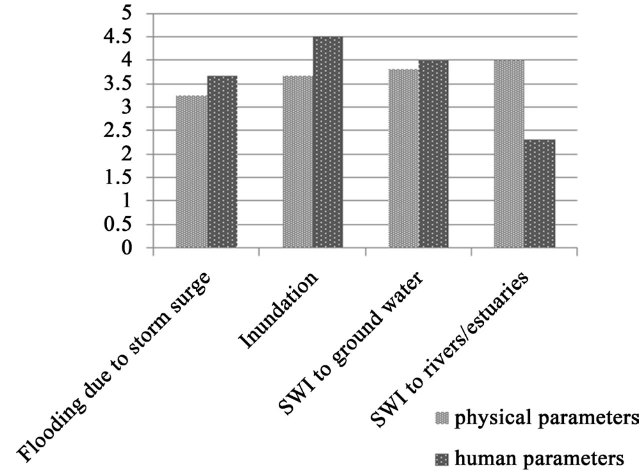

Figure 2. Physical and human influenced parameters due to Sea Level Rise hazards for Douala.

influence of 4 as opposed to 2.3. Therefore, the results show that physical parameters have a greater influence only on surface water.

The flooding levels of the study area were calculated using equation 2. Results show a value of minimum high water of 2.7 m, the mean wave height of storm waves (1.6 m) and the low estimate value of SLR (0.39 m by 2050 and 0.86 m by 2100) indicated the flooding levels of 4.69 that was rounded up to 5 m.

When the maximum flooding scenario was calculated using the maximum high water value of 2.7 m with a return period of 1/100 years, it gave a storm wave height of 6.20 m as in [41]. From the SLR estimate of (0.39 m and 0.86 m by the year 2050 and 2100 respectively), it was observed that flooding levels of up to 10 m could be experienced.

3.3. Projected Critical Elements at Risk of Inundation

Nine classes of land cover types were identified for the Landsat and the fused Landsat and SAR imagery for the study area namely: water, settlement, bare ground, dark mangroves, green mangroves, swampy vegetation, forest vegetation/others, and palms as in [35].

The shape files obtained from the LULC classes were overlaid on the DEM of the study area, the results showed that a 5 m inundation scenario was associated with a risk of inundation of settlement (132.21 km^2), bare-ground (152.6 km^2), mangroves (64.5 km^2) and swampy vegetation (34.6 km^2) as shown on Table 10.

For the 10 m inundation scenarios, critical elements at risk of inundation for the same LULC classes were: settlement (446.82 km^2), bare-ground (476.5 km^2), mangroves (542.4 km^2) and swampy vegetation (125.3 km^2) as shown on Table 10 and Figure 3 and Figure 4 respectively for settlement and bare-ground land use classes.

From the 5 and 10 m inundation scenarios for this study area, it is clear that the greatest threat to the assessed LULC classes will be incurred by bare-ground followed by settlement. These are followed by mangroves and swampy vegetation.

Table 10. Potential areas at risk of 5 and 10 m inundation scenario in Douala.

Critical elements	5 m flooded area km²	10 m flooded area km²
Settlement	132.21	446.82
Bare-ground	152.6	476.5
Mangroves	64.5	542.4
Swampy vegetation	34.6	125.3

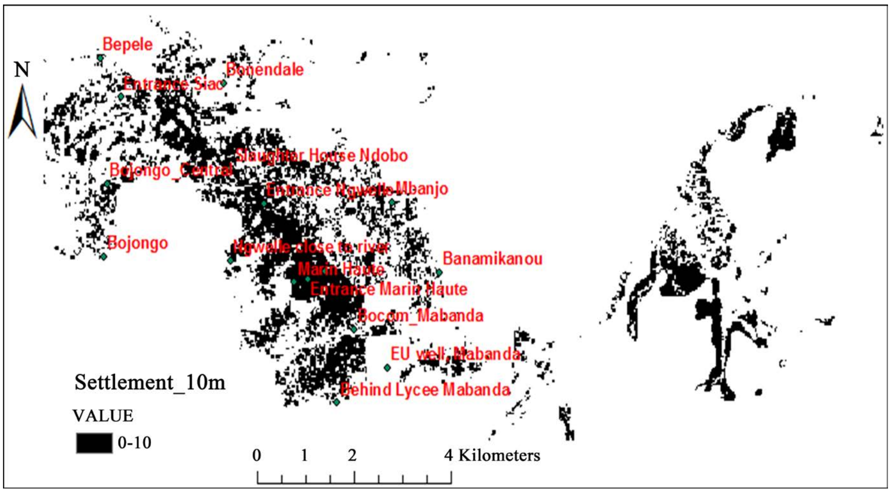

Figure 3. Settlement areas at risk of a 10 m inundation in Douala.

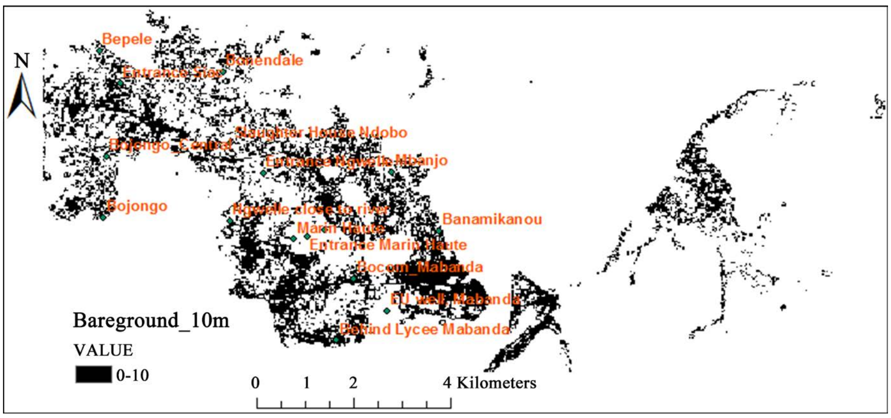

Figure 4. Bare-ground areas at risk of a 10 m inundation in Douala.

Hence, a significant damage could be incurred on the water resources in this area. Other activities could be directly or indirectly affected as a result of these inundated areas for the study area.

4. Discussion

4.1. Coastal Vulnerability

The computed CVI (SLR) for the Cameroon estuary was observed to be 3.60 (**Table 7**) according to the developed vulnerability assessment model as in [25]. This value 3.60 indicates that the overall vulnerability of low lying areas, deltaic regions to impacts of hazards of SLR are high. This result fell in line with opinions of climate change scientists that coastal low-lying areas, especially deltaic regions are vulnerable to hazards of SLR as in [2] [40] [42] [43] [44] [45]. Similar studies as in [46] [47] in their separate studies on predicted impacts of SLR in India, indicated that low lying and deltaic areas are susceptible to impacts of SLR hazard impacts due to global warming.

From the results, when individual impacts are considered, vulnerability rankings is in the order of inundation, SWI into ground water, flooding due to storm surge and SWI into rivers/estuaries with CVI-(SLR) values of 4, 3.86, 3.43 and 3.3 respectively in order of highest ranked to lowest rank hazard impact.

The (CVI = 4) for inundation indicates that the vulnerability of this area to inundation is high and worrisome as many vital resources could be permanently submerged. Several studies as in [2] [44] [48] [49] have highlighted the fact that estuaries, deltaic regions will be more vulnerable to land loss due to inundation in the 21st Century. The situation of inundation is exacerbated by the level of human influenced parameter (4.5). The absence of coastal protection structures and the fact that mangrove forest areas being felled for farming and settlement (**Table 5**) will further aggravate the situation. From **Table 6**, mangroves status show a decline (−1.38), while settlements are increasing (16.527) and water as a class of land cover shows a marked increase (54.3). The marked increase in water as a class could further serve as a pointer to increase in SLR in the study area. Another study as in [50] on the vulnerability of mangroves of Cameroon to climate change highlighted a spatial change of mangroves between 1975 ± 2007. They indicated an overall decline of 5% in mangrove area since 1975, increase in settlement and decrease in mudflat/sand that could serve like a soft structural measure for inundation. Inundation could also have an influence on SWI.

SWI into ground water resources with a CVI = 3.86 is the second important SLR hazard that could impact on the coastal community of Douala. With increasing use of the ground water resource by big industries in the area who also supply public standpipe perhaps for philanthropic reasons from the same resource, there is need for continuous monitoring for ground water quality in the area.

Douala is the "break basket" of Cameroon, with more than 70% of the industries of the Country located here, this implies that the land use pattern is basically settlement and for industrial activities, consequently, based on the index ranking for land use pattern, this parameter will facilitate SWI into fresh water aquifers. These results are in agreement with interviews of respondents of the area, who indicated that wells are salty and not good for consumption. Most of the companies use boreholes for production. Additionally, the supply of portable water by conventional means to the inhabitants by the government is not met as in [34]. Most inhabitants, resort to alternative sources of water for domestic chores as in [34] whose study indicated that about 76.4% and 49.6% of the inhabitants of Douala IV use well and other sources of water for cooking and drinking respectively. Hence ground water consumption is high and is influencing SWI into ground water aquifers.

Flooding due to storm surge (CVI = 3.43) is the third important vulnerability hazard of SLR in the region. In terms of ranking, it is moderately vulnerable to the hazards of SLR. These results are consistent with the respondents of Douala IV who perceived flooding as the most devastating hazard in the area as in [51]. The same reasons indicated as potential factors that could aggravate inundation are also tenable for flooding due to storm surge (the absence of coastal protection structures and the degradation of natural protection structures like the cutting down of mangroves). These increases the vulnerability to SLR hazard of flooding relative to inundation.

As opposed to ground waters, SWI into surface water resources (River Wouri) of the region had a lower CVI 3.3. The impact of this SLR hazard is ranked to be moderately vulnerable. It is the only hazard where the level of physical influence is more than human level influence. This is a result of the water depth at downstream and the river's discharge. The water depth downstream is not shallow and so it influences the velocity of the river. This is because increasing water depth decreases fresh water velocity thus SWI increases with increasing depth. The minimum discharge of river Wouri is only 49 m^3/s, consequently, low river discharge decreases the amount of turbulent energy since fresh water velocity decreases, and thus SWI increases. The level of human influenced parameter of flow regulation pattern (2.3) affected the hazard ranking and it was moderate.

4.2. Evaluation of Projected Areas at Risk of Flooding

DEM combine with relative sea level change for this study indicates that mangrove forest of 64.5 and 542.4 km^2 will be lost to a 5 and 10 m inundation scenario due to SLR in Douala. Mangrove systems play an integral role at the interface between terrestrial, freshwater and marine systems, providing protection to both terrestrial and estuarine systems from high-energy marine processes. They have an important role in protecting coasts during storm events, both by frictional reduction of wave energy and by promoting sedimentary resilience to erosion through the root mat as in [52] [53]. Their studies following the 2004 tsunami found that, in some places, human deaths and loss of property were reduced by the presence of coastal vegetation shielding coastal villages. Likewise, the loss of mangrove forest for the study area will allow salty water from the ocean to easily penetrate inland and alter the characteristics of ground water. Similar studies as in [54] using the IPCC simple inundation model indicated that land lost as a result of SLR in the Cameroon estuary mangroves stood at 49.5 km^2 for a SLR of 20 cm and 330 km^2 for a maximum SLR of 90 cm by the year 2050 and 2100.

Coastal zones are an integral part of the economies of most nations. This is because they contribute more than half of the GDP of coastal Countries as in [8]. GDP are effectively generated with the use of good water quality. Consequently, water needed for any service must be of good quality. Water resources in Douala are already stressed from pollution as a result of population increase, urbanisation, and industrialisation. Unfortunately, these activities are creating problems of global warming. The risk of inundation of low lying coastal areas due to SLR worldwide has been highlighted as in [2]. The needs for site specific assessment of coastal areas are necessary based on the inherent variations in coastal systems and also for an understanding of the influence and response of coastal areas towards SLR as in [55] [56] [45]. Impacts of global warming like SLR with its associated hazards (flooding due to storm surge, inundation, SWI into aquifers and estuaries) could put more pressure on the water resources of the area.

Apart from mangrove areas at risk of inundation, bare-ground areas will be compromised as a result of inundation caused by SLR. Bare-ground (152.6 and 476.5 km^2) will be lost due to 5 and 10 m inundation as a result of SLR. Inundation implies salinity intrusion into rivers, estuaries and coastal aquifers, which could further decrease the quality of water for the inhabitants in the region by the unavailability of fresh water and soil degradation (bare-ground) areas. Results from questionnaire administration indicate that the organoleptic quality of water in some parts of the study area is salty. Additionally, SWI might affect industrial production and consequently reduce the GDP contribution to the economy of the Country as in [49].

The inundation scenario of 5 and 10 m indicated settlement areas of 132.21, 446.82 km^2 will be at risk. This implies that those who reside in these areas might have to relocate as a result of inundation related to the heights of this scenarios. The dangers of living within these coastal low-lying regions which are vulnerable to natural and anthropogenic SLR hazards have been extensively highlighted as in [2] [43] [44] [49] [57] [58] [59] [60]. For instance a DEM assessment of land lost within a 1 m high water mark has resulted in 18,600 km^2 loss in Nigeria as in [61]. In Poland it was1700 km^2 as in [62] and 2165 km^2 in the Netherlands as in [63]. Spatial temporal analysis in Turkey revealed inundation of 545, 1286 and 2125 km^2 of coastal areas for average sea-level rates of change of 5, 10 and 15 mm/yr. for 200 years respectively. Ground water quality could be more vulnerable to saline water intrusion and compromise the livelihoods of the inhabitants in the study area directly and indirectly. The foregoing results is a clear indication that impacts of global warming like SLR with its associated hazards (flooding due to storm surge, inundation, SWI into aquifers and estuaries) could degrade the quality of water resources of the coasts of Douala.

5. Conclusions

The magnitude of sea level change impacts will vary from place to place depending on the topography, geology, natural land movements and human activities. Potential impacts are uneven and likely to affect the most vulnerable due to multiple stresses and their lower ability to prepare, adapt and respond.

The low lying coastal area of Douala was evaluated by using coastal vulnerability assessment model to SLR using site specific data and the assessment matrix indicating sub-indices and CVI (SLR) was realized. The extend of inundation on certain critical elements was assessed by overlaying the mapped LULC classes shape files onto a 30 m DEM of the region of interest

The CVI (SLR) for Douala was calculated as 3.6 with hazard indices of 4, 3.86, 3.43 and 3 for inundation, SWI into ground water aquifers, flooding due to storm surge and SWI into rivers/estuaries respectively.

Based on the observed results from the CVI (SLR) calculated for this study, it can be concluded that:

- The study area indicates that vulnerability to impacts of SLR hazard is high;
- The dominant SLR hazard was inundation followed by SWI into aquifers;
- Bare-ground and settlement classes will be more impacted due to inundation.

Applying CVI-(SLR) model to assess SLR hazards impact for the study area has enabled an appreciation of the hazard which should be prioritized for adaptation measures. The use of remote sensing, GIS tools and DEM tools has enabled the quantification of risky areas to the impacts of SLR. The high population density of this and its vital economic sectors make the potential impacts of SLR hazards impact on its water resources of particular concern especially ground water resource quality.

Conflicts of Interest

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

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