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Integrated Assessment of the Vulnerability of the Abidjan Coastline (Ivory Coast) to Marine Oil Pollution

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Abstract

This study proposes an integrated approach to assess the vulnerability of the Abidjan coastline to marine pollution by hydrocarbons. The objective is to identify the most vulnerable coastal sectors through a multicriteria analysis in support of environmental management. The methodology combines morpho-sedimentary, biological, and socio-economic indicators, integrated within a Geographic Information System (GIS). Multicriteria analysis (MCA), coupled with the Jenks classification method, was used to weight and rank the parameters according to four sensitivity levels. The results reveal strong spatial variability in coastal vulnerability. The municipalities of Yopougon and Port-Bouët emerge as the most vulnerable areas due to high population density, the presence of petroleum-related activities, and the richness of coastal ecosystems. Attécoubé, Treichville, and Bingerville display moderate vulnerability, characterized by moderate population density and a mixture of natural and urban environments, serving as transitional zones between ecological areas and industrialized spaces. In contrast, Koumassi, Marcory, and Plateau exhibit low vulnerability, dominated by highly urbanized and artificialized areas, while Cocody shows relatively high vulnerability. The developed approach therefore constitutes a decision-support tool for institutions responsible for managing marine pollution, notably the Ivorian Anti-Pollution Centre (CIAPOL) and the National Office of Civil Protection (ONPC). It can be adapted to other coastal areas of West Africa facing similar challenges.

Keywords

Coastal Vulnerability, Marine Pollution, Hydrocarbons, Abidjan, Multicriteria Mapping, ESI, GIS

1. Introduction

West Africa's coastal areas are under increasing pressure from rapid urbanization, port activities, and oil development, which increase the risk of marine pollution (INS, 2021), as well as the majority of its oil import, storage, transport, and distribution activities. The morphological and sedimentary dynamics of this coastline, which condition its physical response to such pressures, have been characterized in the foundational studies of Abe (2005) regarding the Abidjan sector.

This configuration makes it a metropolis highly exposed to accidental or chronic pollution, which can have a lasting impact on coastal ecosystems, particularly the sensitive Ramsar wetlands (Yao Kokore, & N'douba, 2005; Yao et al., 2010) and the health of coastal populations. Despite the importance of these issues, coastal vulnerability assessments remain limited in West Africa and are virtually non-existent for Abidjan. In this article, vulnerability is understood as the degree of exposure, sensitivity, and resilience of coastal systems, expressing their ability to resist, adapt, or recover after a disturbance (Turner et al., 2023; IPCC, 2014). It depends on the nature of the events, the ecological fragility of the receiving environments, and the adaptive capacity of human and socio-economic infrastructure (Michel & Dahlin et al., 1997). In this context, assessing the vulnerability of the Abidjan coastline to oil spills is a strategic issue for land-use planning and risk prevention. It aims to identify the most exposed areas and populations, shed light on the sensitivity of receiving environments, and prioritize risk levels in order to improve decision-making. The approach adopted is based on the integration and spatialization of physical, biological, and socioeconomic data within a Geographic Information System (GIS), This technical framework for data administration and thematic project development follows the standards established for oil spill response (CEDRE, 2005), thereby contributing to the sustainable strengthening of urban and environmental resilience while supporting the preservation of coastal ecosystems.

2. Materials and Methods

2.1. Presentation of the Study Area

The study area (**Figure 1**) is located in southern Côte d'Ivoire, bordered by the Atlantic Ocean, between 5˚20'11"N latitude and 4˚01'36"W longitude. It corresponds to the coastal strip separating the ocean from the Ebrié lagoon, the largest lagoon in West Africa.

2.2. Tools and Data Used

The assessment is based on the integration of multi-source data processed with QGIS 3.34. The spatial data were derived from Sentinel-2 (MSI) satellite images acquired via the Copernicus Open Access Hub. Two cloud-free scenes were selected to cover the dry and rainy seasons (January 15, 2021, and July 20, 2021). Pre-processing was conducted using SNAP and planimetric accuracy was refined using high-resolution orthophotos (5 cm) and differential GPS surveys. The database environment was organized within PostgreSQL/PostGIS and Excel was used for statistical aggregation and index weighting. All data were georeferenced in the WGS 84/UTM zone 30N coordinate system, then structured into thematic raster and vector layers for mapping vulnerable areas.

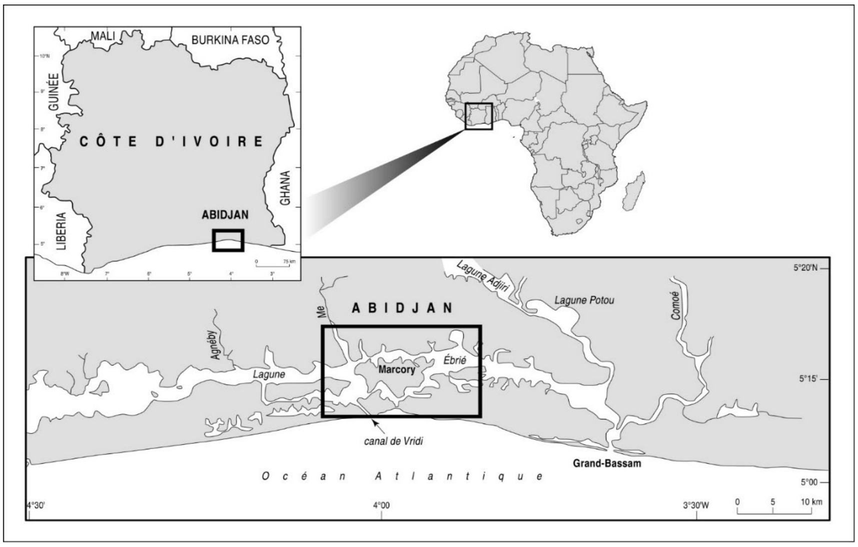

Figure 1. Location of the study area.

Physical and hydrodynamic data

The data taken into account are: the type of coastline (vegetated lagoon banks, mangroves, mudflats; sandy beaches, dune ridges, defense structures, port infrastructure); the nature of the intertidal substrate (sediment grain size); wave exposure (exposed, sheltered); bathymetry; winds; currents; and local tides (intensity, direction, variation).

Biological data

This concerns living resources, sensitive ecosystems, and areas of heritage interest along the coast and lagoon. The parameters considered are:

- Mangroves (extent, density, and conservation status);
- Seagrass beds and lagoon vegetation (distribution and estimated coverage);
- Avifauna (presence, diversity, types, and periods of occurrence);
- Marine mammals (species, types, and periods of occurrence);
- Natural resources (species, production areas, nurseries, and habitats);
- Protected and heritage areas (parks and reserves, wetlands, etc.).

Socioeconomic data

Demographic and socio-economic data were sourced from the 2021 General Population and Housing Census (RGPH), provided by the National Institute of Statistics (INS) of Côte d'Ivoire. These data cover sites, facilities, and activities whose operation may be directly or indirectly compromised by pollution. The parameters selected for the analysis include:

- Population density and distribution;
- Land use and critical infrastructure;
- Economic value of the coastline;
- Dominant economic activities (port, industry, fishing, tourism);
- Institutional and operational response capacity.

2.3. Coastal Vulnerability Assessment Methodology

This was conducted using an integrated approach that combined four complementary methods:

ARVAM/PARETO method

The selection of the variables followed a two step hybrid approach. First the ARVAM/PARETO method (Analysis of Resilience, Vulnerability, and Threats) was applied to identify the most discriminating parameters, retaining only those accounting for 80% of the cumulative risk. Subsequently, to ensure the model reproducibility and minimize subjectivity, equal weight was assigned to all selected indicator during index aggregation (Table 1). This approach ensure a balance between methodological rigor and operational simplicity.

Table 1. Summary of selected vulnerability indicators.

Thematic vulnerability component	Retained parameters (80% of impact)	Justification
Morpho-sedimentary	Substrate type, Slope, Orientation	Determine pollutant persistence and clean-up difficulty
Biological	Mangroves, protected areas, Avifauna	High ecological value areas with low regeneration capacity
Socio-economic	Population density, Port infrastructure, Tourism activities	Major stakes for the national economy and public health

Index method

The selected indicators were standardized in order to assign vulnerability ratings to each coastal area. Four indices were used for the assessment, and each area was ranked on a scale from 1 (low) to 4 (very high).

The Environmental Sensitivity Index (ESI) was established based on the coastal typology developed by NOAA (Jensen et al., 1998) and then adapted to the geomorphological characteristics of the Ivorian coastline. The different types of coastline identified were classified on a sensitivity scale from 1 to 9, in accordance with ESI standards.

The biological sensitivity index (V) was assessed based on fauna and flora inventories, regulated coastal habitats, and the hydrographic network (Jury et al., 1994). The analysis takes into account the presence of sensitive species (manatees, hippopotamuses, sea turtles, coastal birdlife) as well as the main plant habitats (coastal forests, coastal savannas). Ecological diversity, protection status, and the functional roles of species and habitats were used as sensitivity indicators.

The socio-economic sensitivity index (Veco), inspired by the work of Levratto and Clémenceau (2005), classifies activities, infrastructure, and coastal use according to their economic importance and sensitivity to pollution. It is based on vulnerability coefficients established from an inventory of coastal infrastructure, maritime activities, and demographic characteristics of the areas studied.

The overall vulnerability index (Vglo) was obtained by combining morpho-sedimentary (ESI), biological (V), and socioeconomic (Veco), parameters, assessed by coastal units (Dutrieux et al., 2000; Fattal et al., 2010). This approach uses a set of interdependent variables describing coastal morphology, natural habitats, and anthropogenic activities (Brewster, 2002). Using an equal weighting approach to ensure reproducibility. The final score is calculated as the arithmetic mean rounded to the nearest integer. This statistical classification ensures that the global index reflects the most probable vulnerability level based on the distribution of thematic indices. The calculation is denoted by the rond function, as shown in the following formula:

$$\text{Vglo} = \text{Rond}\ (\text{ESI} + \text{V} + \text{Véco})/3)$$

where

- Vglo: global vulnerability index for each unit;
- ESI: Morpho-sedimentary sensitivity index;
- V: biological sensitivity index;
- Veco: socio-economic sensitivity index;
- Rond: nearest integer.

If the decimal is less than 0.5 Ex:1.33 become 1;

If the decimal to or greater 0.5 Ex 2.66 become 3.

Multi-criteria analysis (MCA) method

All the indices derived from the physical, biological, and socio-economic parameters of the coastal units of Abidjan were integrated into the MCA framework. The overall vulnerability index Vglo was calculated using a weighting of criteria defined according to the ARVAM/PARETO method, which identified the most decisive parameters. The combination of these indices, carried out using GIS, led to the production of thematic layers and vulnerability mapping.

Jenks classification method

This method groups values according to homogeneous levels of sensitivity, ensuring statistically optimal classification. Four hierarchical classes have been identified:

- Very low vulnerability (highly urbanized and artificial areas);
- Low vulnerability (Partially artificialized with low ecological activity);
- Medium vulnerability (mixed natural/urban areas);
- High vulnerability (high-risk ecological or socioeconomic areas).

This classification was used to establish the overall vulnerability map of the Abidjan coastline. This entire process is summarized in **Figure 2**.

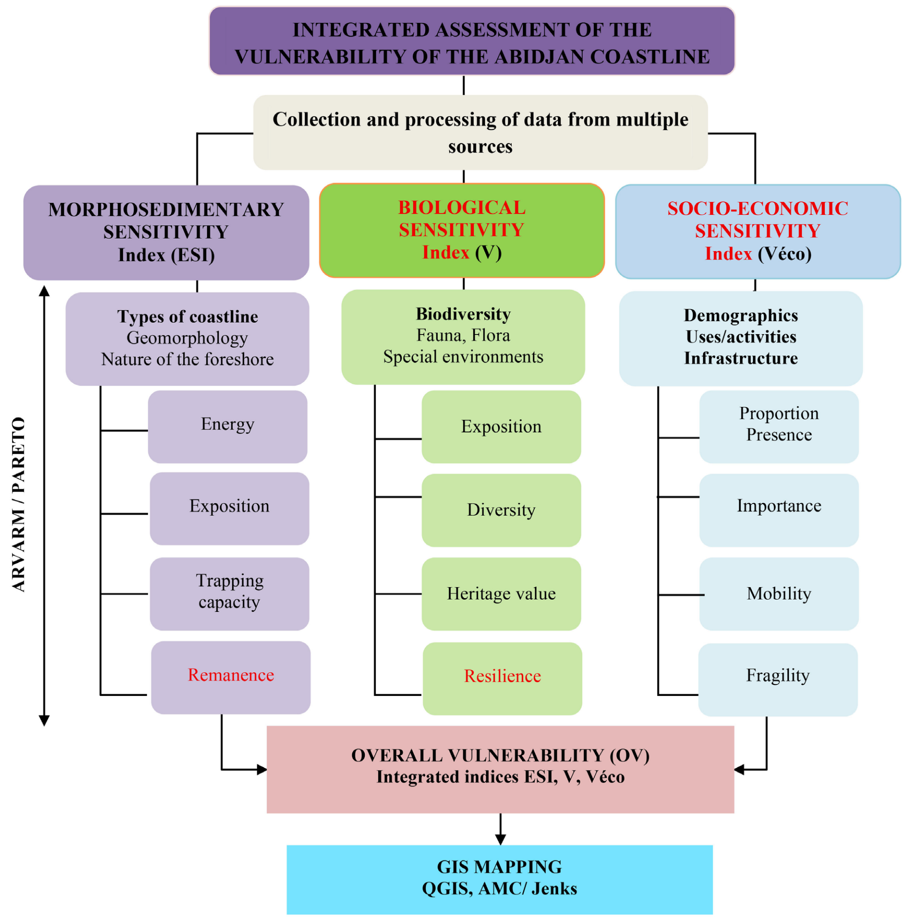

Figure 2. Summary of methodology.

3. Results

Following all treatments and analyses, significant spatial heterogeneity in vulnerability was observed along the Abidjan coastline. The map produced highlights four levels of sensitivity, defined on the basis of the morphological, ecological, and socioeconomic characteristics of the various coastal municipalities.

3.1. Morphological and Sedimentary Characteristics of the Abidjan Coastline

This area has marked sedimentary diversity (Figure 3). Analysis of the coastline and its composition provide an effective means of assessing morphological stability and sensitivity to marine pollution 3: Sedimentary nature of the coastline in the Abidjan area.

The Abidjan coastline is dominated by a heavily artificialized sandy foreshore, composed of sandy sandstone from the Continental Terminal (Plio-Quaternary), fluvial-lagoon clayey sand (Quaternary), marine sandbars (recent Quaternary), and artificialized coastlines (dykes, walls, quays, jetties). Fluvial-lagoon clayey sands, widely present around the Ebrié lagoon, dominate in the municipalities of Yopougon, Plateau, Attécoubé, Cocody, Koumassi, Marcory, Port-Bouët, Treichville, and Bingerville. Sandstone sands appear locally on the shores of Yopougon, Plateau, Attécoubé, Cocody, and Bingerville, while marine sandbars extend along the beaches of Port-Bouët and Yopougon. These loose facies reflect the predominance of the lagoon environment in the sedimentary dynamics of the coastline.

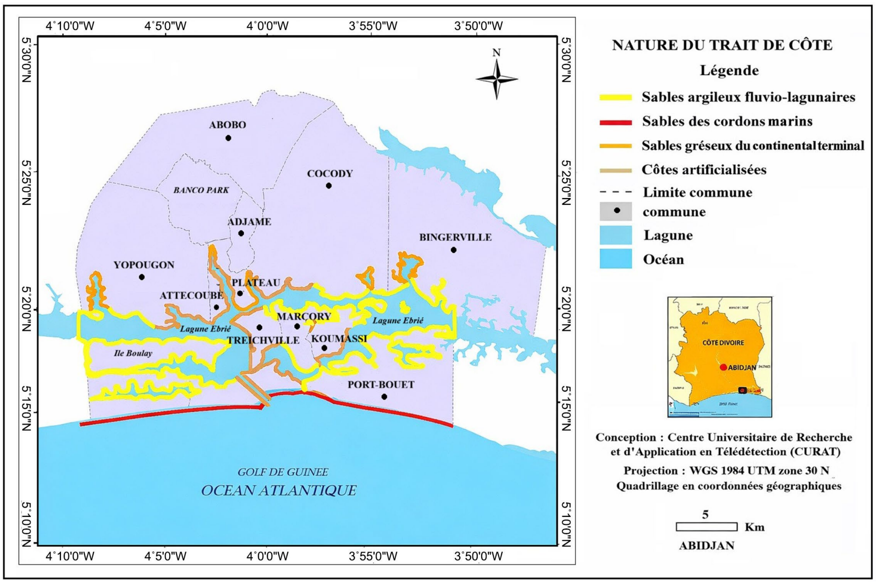

Figure 3. Sedimentary nature of the coastline in the Abidjan area.

3.2. Morpho-Sedimentary Sensitivity of the Abidjan Coast

Assessed using the ESI index, morpho-sedimentary sensitivity takes into account the type of coastline, the nature of the foreshore, and the hydrodynamic energy of the environment. Table 2 below shows the local sensitivity associated with each type of coastline.

Table 2. ESI index adapted to the Abidjan coastal strip.

Energy	Coastal typology	Average duration of pollution	Value ESI	Municipalities
Exposed coasts (high energy)	Sands of marine ridges	1 to 2 years	3	Port-Bouët, Yopougon
	Sandstone sands of the terminal continent	2 to 3 years	4	Port-Bouët, Plateau, Yopougon, Attécoubé, Cocody, Bingerville
Sheltered coasts (low energy)	Fluvial-lagoon clay sands	3 to 5 years	5	Yopougon, Plateau, Attécoubé, Cocody, Koumassi, Marcory, Port-Bouët, Treichville, Bingerville
	Artificial coasts (Dikes, walls, quays, jetties)	>5 years	6	Yopougon, Plateau, Attécoubé, Cocody, Koumassi, Marcory, Port-Bouët, Treichville, Bingerville
	(Estuaries; river mouths)	>10 years	8	Port-Bouët, Yopougon
	Riverbanks and lagoons	>10 years	8	Yopougon, Plateau, Attécoubé, Cocody, Koumassi, Marcory, Port-Bouët, Treichville, Bingerville
	Mangrove forests	>10 years	9	Port-Bouët, Yopougon (Îles Boulay) Cocody (Baie de Cocody)

The morpho-sedimentary sensitivity index of the Abidjan coast (ESI A) ranges from 3 (relatively low sensitivity) to 9 (very high sensitivity). Facies with an index of 1 and 2 (low sensitivity), such as cliffs and rocky reefs, do not exist in the area. The different coastal facies present in the area are illustrated in the following Table 3.

Table 3. Morpho-sedimentary rating (ESI) by coastal municipality.

Coastal typology	Valeur ESI	Yop	Plat	Atté	Coco	Kou	Mar	Port-B	Trei	Bing
Sand dunes	**3**	3	-	-	-	-	-	3	-	
Sandstone sands of the terminal continent	**4**	4	4	4	4	-	-	4	-	4
Clayey sands fluvial lagoons	**5**	5	5	5	5	5	5	5	5	5
Artificial coasts Dikes	**6**	-	-	-	-	-	-	6	6	-
Walls, quays, jetties	**6**	6	6	6	6	6	6	6	6	-
Coastal marshes Estuaries; river mouths	**8**	8	-	-	-	-	-	8	-	-
Riverbanks Rivers and lagoons	**8**	8	8	8	8	8	8	8	8	8
Mangrove forests	**9**	9	-	-	9	-	-	9	-	
Cumulative value of the ESI index (C_{ESI})	**=ΣESI**	**43**	**23**	**23**	**32**	**19**	**19**	**49**	**25**	**17**
Interpolation (Jenks)/ESI index ($I_{ESI\ A}$)		**4**	**2**	**2**	**3**	**1**	**1**	**4**	**2**	**1**

The sum (Σ) of the ESI values for each morphosedimentary entity gives cumulative values ranging from 17 to 49.

By interpolating these cumulative values, four classes of increasing morphosedimentary sensitivity (from 1: low sensitivity to 4: very high sensitivity) were defined using the Jenks method. Thus:

- Values 17 and 19 are reduced to ESI index 1 (low morphosedimentary sensitivity);
- Values 23 and 25 are assimilated into the ESI 2 index (medium sensitivity);
- The value 32 becomes the ESI 3 index (high sensitivity);
- Values 43 and 49 become the ESI 4 index (very high morphosedimentary sensitivity).

The spatial distribution of this sensitivity is illustrated in Figure 4, which presents the mapping of ESI indices calculated for each district.

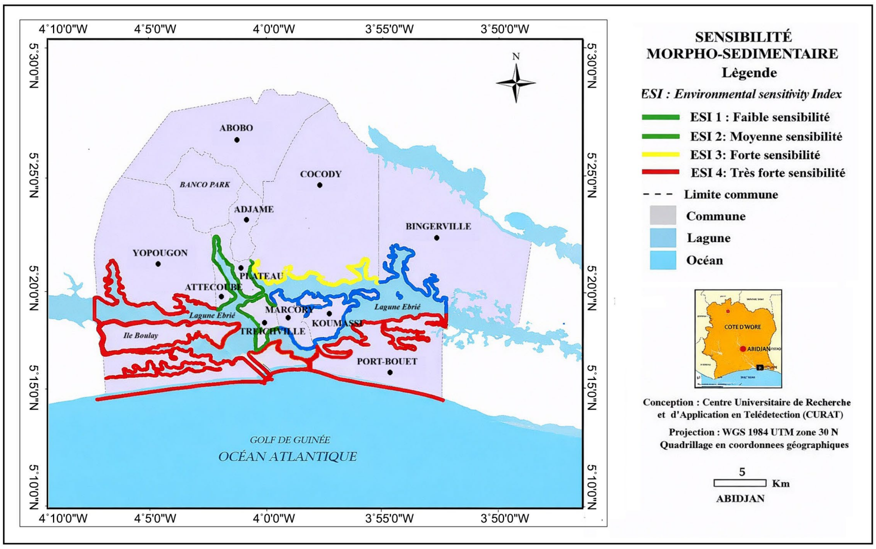

Figure 4. Map of morpho-sedimentary sensitivity in the Abidjan area.

The map of the Abidjan coastline shows morpho-sedimentary sensitivity according to the nature of the coastline. Areas of low sensitivity (blue), located in Koumassi, Marcory, and Bingerville, correspond to easily cleanable sandy foreshores. Plateau, Attécoubé, and Treichville are characterized by medium sensitivity (green), dominated by sandy facies and artificial areas. Cocody has high sensitivity (yellow) due to the presence of mangroves and lagoon banks. Finally, very high sensitivity (red) is observed in Port-Bouët and Yopougon, where the most vulnerable facies are concentrated.

3.3. Biological Sensitivity of the Abidjan Area

This was assessed based on an inventory and ranking of species and natural environments. Three entities were considered: fauna, flora, and hydrography. Each was assigned a rating based on its presence (value = 4) or absence (value = 0) for each coastal unit (Table 4).

Table 4. Biological sensitivity ratings by municipality.

Biological entities	Ressources	Yop	Plat	Atté	Coco	Kou	Mar	Port-B	Trei	Bing
Fauna	Lamantins	0	0	0	0	0	0	4	0	0
	Oiseaux côtiers	4	0	0	4	0	0	4	0	0
	Poissons	4	0	0	0	0	0	4	4	
Flora	Forêts classés	4	0	0	0	0	0	4	0	0
	Forêts de mangroves	4	0	0	4	0	0	4	0	0
	Parcs et Réserves	4	0	4	0	0	0	0	0	4
Hydrography	Lagunes	4	4	4	4	4	4	4	4	4
Cumulative value of ratings (Σ)		24	4	8	12	4	4	24	8	8
Interpolation (Jenks)		**4**	**1**	**2**	**3**	**1**	**1**	**4**	**2**	**2**

The sum of these values gives a biological scale ranging from 4 to 24. This scale is adjusted according to Jenks' classification method. The result is an ascending classification from 1 (low sensitivity) to 4 (very high sensitivity). Thus:

- The value 4 is equivalent to index 1 (low biological sensitivity);
- The value 8 becomes index 2 (medium biological sensitivity);
- The value 12 becomes index 3 (high biological sensitivity);
- The value 24 becomes 4 (very high biological sensitivity).

This assessment enabled the municipalities studied to be ranked according to four levels of biological sensitivity. Based on this identification, a variable color code was assigned to each section of the coastline (Figure 5).

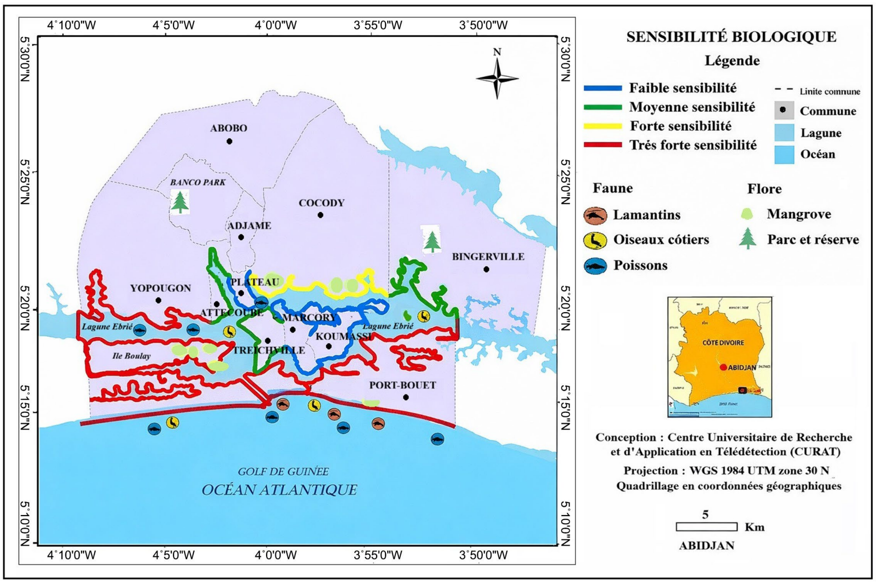

Figure 5. Biological sensitivity map of the Abidjan area.

The map highlights four levels of biological vulnerability along the coastline.

***Low sensitivity* (*blue*):** this category covers the municipalities of Plateau, Koumassi, and Marcory, where biodiversity is limited. Despite the presence of natural bat habitats on the plateau, these elements are not taken into account in our assessment.

***Medium sensitivity* (*green*):** Attécoubé, Treichville, and Bingerville have reduced biological diversity due to heavy anthropization of the riverbanks. Natural habitats there are fragmented or replaced by urban infrastructure.

***High sensitivity* (*Yellow*),** Cocody is distinguished by the presence of remarkable ecological habitats, notably mangroves and areas that host vulnerable coastal birds.

***Very high sensitivity* (*Red*):** Yopougon and Port-Bouët are home to classified forests, mangroves, parks and reserves, coastal marshes, and diverse wildlife. These complex environments are priority areas.

Socio-economic sensitivity of the Abidjan area

The assessment of socio-economic sensitivity also took into account the demographics and socio-economic uses of the various municipalities. Based on population estimates and the presence of well-defined uses/activities by area, ratings ranging from 1 (low sensitivity) to 4 (very high sensitivity) were assigned (Table 5):

Table 5. Ratings of socioeconomic entities by municipality.

N⁰	Designation	Yop	Plat	Atté	Coco	Kou	Mar	Port-B	Trei	Bing
	Demographics									
	Sensitivity index Demographic (D)	4	1	2	3	3	2	3	2	1
	Uses/activities									
1	Ports	1	1	1	1	1	1	1	4	1
2	Oil industries	1	1	1	1	1	1	4	3	1
3	Mining industries/ quarries	4	1	1	1	1	1	1	1	4
4	Industrial zones	4	1	1	2	4	1	4	1	1
5	Fishing villages	4	1	1	1	3	1	4	1	1
6	Aquaculture facilities	4	1	1	1	1	1	4	1	4
7	Tourist sites	4	4	1	3	1	3	4	1	3
8	Beaches	4	1	1	1	1	1	4	1	3
9	Cultural and sports sites	1	4	1	2	1	3	2	4	1
10	Water intakes	4	1	1	3	1	1	2	1	3
11	Lagoon transport terminals	0	4	4	4	1	1	1	4	1
	Cumulative value of land-use ratings (C_U)	**31**	**20**	**11**	**20**	**16**	**15**	**31**	**22**	**23**
	Sum of land-uses (ΣU)	7	3	1	5	2	2	8	4	5
	Sum of land-use ratings (C_U + ΣU)	**38**	**23**	**12**	**25**	**18**	**17**	**39**	**26**	**28**
	Interpolation of the land-use sensitivity index (U)	**4**	**2**	**1**	**3**	**1**	**1**	**4**	**3**	**3**
	Sum of ratings for socio-economic entitie (D + U)	**8**	**3**	**3**	**6**	**4**	**3**	**7**	**5**	**4**
	Interpolation of the socio-economic sensitivity index (Véco)	**4**	**1**	**1**	**3**	**2**	**1**	**4**	**3**	**2**

The demographic sensitivity index was established based on the proportion of inhabitants in each municipality, divided into four categories:

- Index 1: municipalities with fewer than 100,000 inhabitants (Plateau, Bingerville);

- Index 2: 100,000 to 300,000 inhabitants (Attécoubé, Marcory, Treichville);
- Index 3: 300,000 to 500,000 inhabitants (Cocody, Koumassi, Port-Bouët);
- Index 4: more than 500,000 inhabitants (Yopougon).

The sensitivity index for uses/activities was developed based on eleven (11) coastal uses according to four criteria: presence, extent, economic importance, and the total number of uses per municipality.

C_U (Cumulative rating of uses/activities) is the sum of the ratings assigned to each use present in the municipality.

ΣU represents the total number of uses identified in the municipality.

$C_U + \Sigma U$ is the integrated indicator combining the intensity of uses and their diversity.

U is the value of the interpolated index of uses, sensitivity class (1 to 4), obtained after discretization using the Jenks method.

Each use has been rated from 1 to 4, where 1 corresponds to absence, 2 to presence, 3 to a significant dimension, and 4 to high economic importance. At the same time, the cumulative uses have also been classified:

- Index 1 (0 to 1 use),
- Index 2 (2 to 4 uses),
- Index 3 (5 to 7 uses),
- Index 4 (More than 8 uses).

The weighted sum of these ratings made it possible to classify the sensitivity of municipal uses from 1 (low sensitivity) to 4 (very high sensitivity), using the Jenks method. The cumulative values of the uses defined four classes:

- Values 12, 15, and 17 are reduced to index 1 (low sensitivity);
- The value 23 becomes index 2 (medium sensitivity);
- The values 25, 26, and 28 become index 3 (High sensitivity);
- The values 38 and 39 become index 4 (Very high sensitivity).

The final socio-economic sensitivity index (Véco) ratings were obtained by adding together, for each municipality, the ratings related to demographics and particularly sensitive coastal uses. This combination produced a matrix of values that were reclassified into four sensitivity levels, ranging from 1 to 4:

- The value 3 is equivalent to index 1 (Low sensitivity);
- The value 4 becomes index 2 (medium sensitivity);
- The values 5 and 6 become index 3 (High sensitivity);
- The values 7 and 8 become 4 (very high sensitivity).

Figure 6 shows the distribution of the gradual socioeconomic sensitivity of municipalities using a color code.

Of the nine (09) municipalities, four (4) stand out for their very high socioeconomic sensitivity. Yopougon and Port-Bouët are distinguished by very high sensitivity (red), linked to high population density, the presence of numerous strategic uses (industry, tourism, water sports), and direct exposure to the coastline. Treichville and Cocody have high sensitivity (yellow) due to a concentration of major port, tourism, and infrastructure activities. Koumassi has medium socioeconomic sensitivity (green), despite a large population and significant but nonstructural industrial activities. Finally, Plateau, Attécoubé, Marcory, and Bingerville have low socio-economic sensitivity (Blue) because major coastal uses are limited there and their economic dependence on the coastline is low.

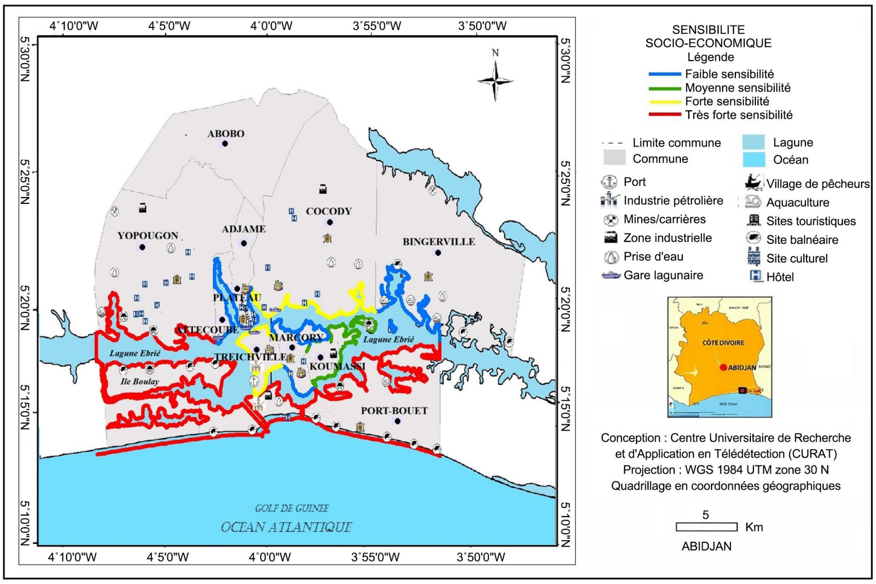

Figure 6. Socio-economic sensitivity map of the Abidjan area.

3.4. Overall Vulnerability of the Abidjan Coast

By applying the same processing and classification procedures as for the partial indices, we obtain an integrated summary of coastal vulnerability. The following Table 6 presents the final indices resulting from the combination of all parameters.

Table 6. Sensitivity ratings by municipality.

Coastal units	Morpho-sédimentaire (ESI)	Biologique (V)	Socio-économique ($V_{éco}$)	Somme	Moyenne	Global V_{glo} (arrondi)	Vulnerability level
Yopougon	4	4	4	12	4.00	4	Very high vulnerability
Plateau	2	1	1	4	1.33	1	Low Vulnerability
Attécoubé	2	2	1	5	1.66	2	Medium vulnerability
Cocody	3	3	3	9	3.00	3	High vulnerability
Koumassi	1	1	2	4	1.33	1	Low vulnerability
Marcory	1	1	1	3	1.00	1	Low Vulnerability
Port-Bouët	4	4	4	12	4.00	4	Very high vulnerability
Treichville	2	2	3	7	2.33	2	Medium vulnerability
Bingerville	1	2	2	4	1.33	1	Low Vulnerability

The three dimensions analyzed (morpho-sedimentary (ESI), biological (V), socio-economic (Véco)) each generate a specific level of sensitivity, which combine to define the overall vulnerability of the Abidjan coastline. The overall vulnerability index is produced by superimposing the ratings of all the thematic sensitivities addressed. It ranges from a vulnerability scale of 1 (low vulnerability) to 4 (very high vulnerability).

Based on all the analyses, the map (Figure 7) illustrates the spatial distribution of the level of risk along the coastline. This summary document is designed for operational use and represents the areas at risk using a color code applied to the coastline.

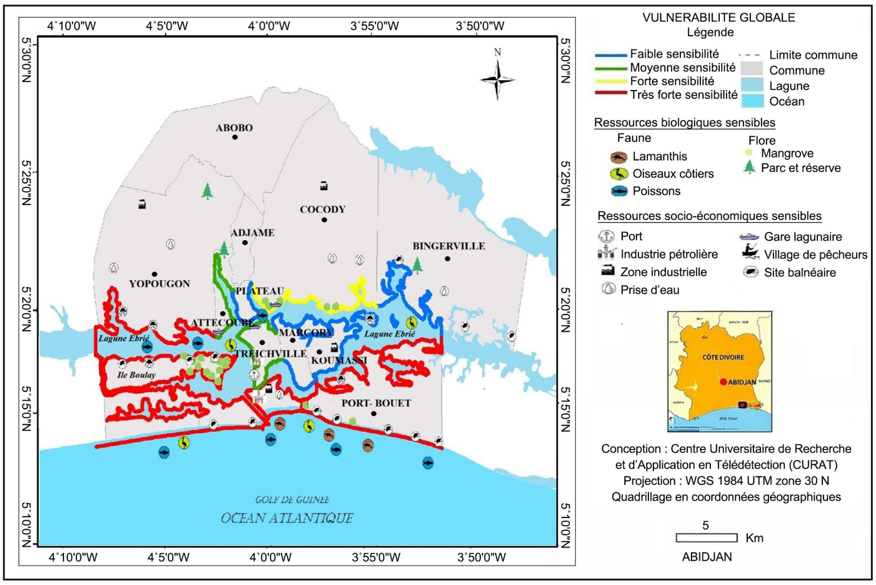

Figure 7. Overall vulnerability map of the Abidjan area.

The overall vulnerability of each municipality is the result of a combination of thematic vulnerability levels.

Port-Bouët and Yopougon have the highest overall vulnerability (red). In Port-Bouët, the presence of the oil terminal, the port of Abidjan, and hydrocarbon depots greatly increases the risk of pollution. In Yopougon, heavy urbanization, industrial activities, and domestic waste exert significant pressure on the Ebrié lagoon. The combination of these factors, coupled with the presence of sensitive ecosystems, explains their higher level of vulnerability.

In Cocody, the high vulnerability (yellow) is explained by the coexistence of fragile ecosystems (mangroves, lagoon habitats, protected birdlife areas) and sustained urbanization along the Ebrié lagoon. These biologically rich environments react strongly to disturbances.

Attécoubé and Treichville, have medium vulnerability (green), linked to the coexistence of sensitive natural environments and expanding urbanized areas. Attécoubé retains functional lagoon banks despite increasing urbanization. Treichville remains exposed due to the proximity of port activities.

Plateau, Koumassi, Marcory and Bingerville are characterized by low vulnerability (blue). Plateau, Abidjan's administrative district and business center, is characterized by dense urbanization, little direct coastal use, and limited biodiversity. Koumassi, which is highly urbanized and industrialized, has no major ecosystems. Marcory, a residential, commercial, and artificialized area, has few strategic coastal activities. Bingerville, with its strong development and tourism activities, still has residual wetlands that provide a transition zone. These areas have virtually no natural environments and are mainly engaged in tertiary economic activity. Their direct exposure is limited.

4. Discussions

The division of the coastline into coherent geomorphological units, in accordance with ICZM recommendations (UNESCO, 1997), has enabled the consistent and operational application of thematic indices, as also highlighted by Robinson et al., 2002, and Ngongang Meppa, 2012.

The ESI index, which is widely used and adapted to different environmental contexts (Michel & Dahlin, 1997; NOAA, 2002; Fattal & Fichaut, 2002; Le Berre et al., 2005; OMI/IPIECA, 2007), has proven relevant for identifying sensitive morphological areas, particularly mangrove areas, tidal marshes, and lagoon banks. These results are consistent with work carried out in Côte d'Ivoire and the sub-region (Tastet, 1985; Hauhouot, 2008; Konan, 2011).

The biological sensitivity index (V = FA + FL + ES + HY) highlights the high sensitivity of coastal areas with remarkable ecosystems, particularly in Yopougon, Cocody, and Port-Bouët. This approach is consistent with methodologies developed for coastal sensitivity mapping (Kerambrun et al., 1996; Lagabrielle, 2001; Thomas, 2007; Fattal, 2008; Castanedo et al., 2009). Furthermore, in line with the findings of Kuznetsov and Fattal, 2024, environments with low self-purification capacity, such as mangroves and lagoon areas, show increased persistence of pollutants, which increases their ecological vulnerability.

The socio-economic sensitivity index (Véco = P + M + I + (Σ)A) + O + D), although based on the structure proposed by Lagabrielle (2001), is distinguished by the economic entities included. It highlights the major role of uses, infrastructure, activities, and exposed populations, confirming the high sensitivity of densely populated areas, particularly in Yopougon and Port-Bouët. Similar work has been carried out by Levratto and Clémenceau, 2005, and Bokor L. et al, 2005.

The aggregation of the three thematic indices via round function produces a consistent and easy to interpret overall vulnerability index, in line with the approaches of Fattal et al. (2007) and Villain-Gandossi (1999). Although effective, this weighting system remains sensitive to expert subjectivity and data availability. Moreover, it is important to note that these maps are static, whereas oil spills are dynamic events governed by shifting winds and currents. Similarly, biological sensitivity is subject to seasonal fluctuations that a static index cannot fully capture. Nevertheless, the maps produced, validated by field observations, serve a strong operational purpose. They allow for the identification critical areas, guide territorial planning, and support the creation of a sensitivity atlas of Abidjan, in line with the recommendations of Lascoumes P., 2007; Lardon S. and Roche S., 2008, and Joliveau T. et al., 2013. While, there is room for improvement through the integration of real time data, these results provide a solid methodological basis for future national and regional assessments.

5. Conclusion and Prospects

The integrated assessment of the Abidjan coastline reveals a highly contrasting overall vulnerability, decreasing from west to east. Port areas, industrialized areas, and ecologically sensitive areas have the highest levels of vulnerability, while urbanized and stabilized areas appear to be less exposed. This spatial distribution highlights a direct correlation between the density of human activities and the fragility of ecosystems. This confirms the relevance of an approach combining morpho-sedimentary, biological, and socio-economic parameters. This spatial analysis highlights priority areas for protection. The results clearly identify priority areas for protection and provide a decision-making tool to guide integrated coastal management strategies. They also provide operational support for national institutions responsible for preventing and combating marine pollution, in particular CIAPOL and ONPC, by strengthening the planning and effectiveness of interventions.

Several areas for improvement can strengthen this approach:

1) Enriching and regularly updating more detailed ecological databases;

2) Deepening socio-economic analysis by estimating the value of activities, infrastructure, and community resilience;

3) Combining mapping and hydrodynamic modeling approaches for a more predictive assessment of impacts;

4) Developing real-time decision support tools, such as interactive platforms or early warning systems, to strengthen the operational capacities of CIAPOL and ONPC.

This study thus provides a solid scientific basis for more proactive, integrated, and sustainable management of marine pollution risks along the Ivorian coastline.

Conflicts of Interest

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

References

Abe J. (2005). *Contribution à la connaissance de la morphologie et de la dynamique sédimen taire du littoral ivoirien (cas du littoral d'Abidjan), essais de modélisation en vue d'une gestion rationnelle*. Thèse de doctorat d'état ès sciences naturelles, spécialité océanologie, Université de Cocody, 353p.

Bokor, L., Clemenceau, I., & Palvadeau, E. (2005). *Plan POLMAR: Mise en place de l'atlas hiérarchisé des zones sensibles à protéger en priorité en région Corse, Rapport final, BRGM/RP-53869-FR, 40p*. BRGM.

Brewster (2002). The Development of a Comprehensive Littoral Vulnerability Assessment. Approach for a Small Island Developing State: A Case of Study for BARBADOS. *Littoral, The Changing Coast, Eurocoast/EUCC/Portugal*. Ed Eurocoast, 189-198. https://www.eucc.net/

Castanedo, S., Juanes, J. A., Medina, R., Puente, A., Fernandez, F., Olabarrieta, M. et al. (2009). Oil Spill Vulnerability Assessment Integrating Physical, Biological and Socio-Economical Aspects: Application to the Cantabrian Coast (Bay of Biscay, Spain). *Journal of Environmental Management, 91,* 149-159. https://doi.org/10.1016/j.jenvman.2009.07.013

CEDRE (2005). *Administration de données géographiques relatives à la lutte antipollution: Élaboration de projets thématiques*. ENSG.

Dutrieux, E., Canovas, S., Denis, J., Henocque, Y., Quod, J. P., & Bigot, L. (2000). *Guide méthodologique pour l'élaboration de cartes de vulnérabilité des zones côtières de l'Océan Indien. Manuels et guides No. 38.* 44p. https://unesdoc.unesco.org/ark:/48223/pf0000121250

Fattal P., Maanan M., Tillier I., Rollo N., Robin M., & Pottier P., (2010). Coastal Vunerability to Oil Spill Pollution: the Case of Noirmoutier Island (France). *Journal of Coastal Research, 26,* 879-887. https://doi.org/10.2112/08-1159.1

Fattal, P. (2008). *Le littoral de la Loire-Atlantique: Etude de la sensibilité de l'environnement aux pollutions par hydrocarbures. Mémoire d'Habilitation à Diriger des Recherches (HDR).* Université de Nantes.

Fattal, P. (2008). *Le littoral de la Loire-Atlantique: Etude de la sensibilité de l'environnement aux pollutions par hydrocarbures. Mémoire d'Habilitation à Diriger des Recherches (HDR).* Université de Nantes.

Fattal, P., & Fichaut, B. (2002). Les premiers bilans des impacts morphologiques dus aux techniques de nettoyage. *Annales de Géographie, 111,* 3-24. https://doi.org/10.3406/geo.2002.2083

Fattal, P., Robin, M., & Pottier, P. (2007). Évaluation de la vulnérabilité côtière face aux pollutions par hydrocarbures: Application à l'île de Noirmoutier. *Territoire en mouvement, 1,* 54-69. https://doi.org/10.4000/tem.551

Hauhouot, C. (2008). *Morphologie et dynamique du trait de côte en Côte d'Ivoire in Géographie du littoral de Côte d'Ivoire. Eléments de réflexion pour une politique de gestion intégrée*. CNRS-LETG UMR 6554, Géolittomer (France) et IGT-Université de Cocody, Abidjan (Côte d'Ivoire).

INS (2021). *Recensement Général de la Population et de l'Habitat 2021. Résultats globaux* (*RGPH*) 2021. Résultats globaux définitifs. Institut National de la Statistique, Côte d'Ivoire. https://www.anstat.ci/

IPCC (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jensen, J. R., Halls, J. N., & Michel, J. (1998). A Systems Approach to Environmental Sensitivity Index (ESI) Mapping for oil Spill Contingency Planning and Response. *Photogrammetric Engineering & Remote Sensing, 64,* 1003-1014.

Joliveau, T., Noucher, M., & Roche, S. (2013). La cartographie 2.0, vers une approche critique d'un nouveau régime cartographique. *L'Information géographique, 77,* 29-46. https://doi.org/10.3917/lig.774.0029

Jury, S. H., Howell, W. H., O'grady, D. F., & Watson, W. H. (1994). *A Field Guide to Coastal Marine Sensitivity and Biological Resources. NOAA Technical Report NMFS-117.*

Kerambrun, L., David, L., Pages-Jones, L., & Rebout, C. (1996). *Atlas Polmar-Terre du département de la Manche.* Brest, CEDRE. 70p.

Konan, K. E. (2011). *Impacts des vagues géantes d'aout 2007 sur le cordon littoral ivoirien: Cas du littoral d'Abidjan à Grand-Bassam* (*Côte d'Ivoire*). Mémoire de Master, Université Liège (Belgique).

Kuznetsov, A. N., & Fattal, P. (2024). Modelling Fuel Oil Transformation on Geographically Different Seacoasts and Assessing Their Self-Cleansing Capacity. *Environmental Science and Pollution Research, 31,* 28178-28197. https://doi.org/10.1007/s11356-024-32902-0

Lagabrielle, E. (2001). *Méthodologie d'élaboration d'un atlas de sensibilité aux pollutions accidentelles par hydrocarbures: Application à la Réunion*. Thèse de doctorat, Université de La Réunion.

Lardon, S., & Roche, S. (2008). Représentations spatiales dans les démarches participatives. *Revue Internationale de Géomatique, 18,* 471-492.

Lascoumes, P. (2007). Gouverner par les cartes. *Genèses, 68,* 2-3. https://doi.org/10.3917/gen.068.0002

Le Berre, I., Gouriou, V., Nedelec, M., & Albrecht, M. (2005). SIG et lutte antipollution marine par les hydrocarbures. In F. Gourmelon, & M, Robin (Eds.), *Information Géographique et Aménagement du Territoire* (pp. 237-256). Springer.

Levratto, N., & Clemenceau, I. (2005). Élaboration d'un indice de vulnérabilité socio-économique d'un littoral: Une application au cas de la région Corse. *VertigO, 6,* 16. https://doi.org/10.4000/vertigo.2470

Michel, J., & Dahlin, J. (1997). *Guidelines for Developing Digital Environmental Sensibility Index Atlases and Databases.* Seattle, NOAA, 43p. https://response.restoration.noaa.gov/sites/default/files/digital_ESI_guidelines.pdf

Ngongang Meppa, J. (2012). *Contribution à l'étude de la dynamique et de la gestion de l'environnement littoral de la baie d'Ambas (Cameroun): Approche par télédétection et systèmes d'information géographique*. Thèse de doctorat, Université de Nantes.

NOAA (2002). *Environmental Sensitivity Index* (*ESI*) *Guidelines.* NOAA Technical Memorandum NOS OR&R 11. https://response.restoration.noaa.gov/sites/default/files/ESI_Guidelines.pdf

OMI/IPIECA (2007). *Sensitivity Mapping for Oil Spill Response.* International Maritime Organization (IMO) & IPIECA.

Robinson, J., Greenaway, A., & Smith, R. (2002). Coastal Zone Monitoring and Management: Integrating Geomorphological and Environmental Indicators. *Journal of Coastal Research, 18,* 803-812.

Tastet, J. P. (1985). Le littoral ivoirien: Géologie, morphologie, dynamique. *Annuaire des Universités privées de Côte d'Ivoire, 21,* 189-218.

Thomas, T. (2007). *Cartographie de la vulnérabilité du littoral aux pollutions par hydrocarbures: De l'évaluation des enjeux à l'aide à la décision*. Thèse de doctorat, Université de Nantes.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L. et al. (2003). A Framework for Vulnerability Analysis in Sustainability Science. *Proceedings of the National Academy of Sciences, 100,* 8074-8079. https://doi.org/10.1073/pnas.1231335100

UNESCO (1997). *Guide méthodologique d'aide à la gestion intégrée des zones côtières. IOC, Manuals and Guides No. 36,* 49p. https://unesdoc.unesco.org/ark:/48223/pf0000121249_fre/PDF/121249freo.pdf.multi

Villain-Gandossi, C. (1999). Une analyse de l'approche globale des risques. In *Risques naturels* (pp. 11-21). CTHS.

Yao Kokore, B., & N'douba, V. (2005). *Fiche descriptive sur les zones humides Ramsar. Comité Ramsar, Côte d'Ivoire*. https://rsis.ramsar.org/ris/1583

Yao, K. S., Abe, J., Bamba, S. B., Konan, K. E., & Aka, K. (2010). Dynamique d'un périmètre littoral portuaire: La côte de San-Pédro, Sud-Ouest de la Côte d'Ivoire. *Revue Paralia, 3,* 2.1-2.12. https://doi.org/10.5150/revue-paralia.2010.002