

Case Study

Hydrogeomorphological dynamics and erosion of the soft coasts in tropical Africa, the case study of the Wouri estuary, Cameroon

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Abstract

Coastal erosion poses a significant challenge along Africa's Atlantic coast, with flooding ranking as the second most pressing threat after erosion. This issue is particularly acute in Cameroon, especially along the Kribian coast and the Wouri estuary, where Cape Cameroon is undergoing severe erosional processes. The central research question of this study examines whether the erosion in the Wouri estuary is due to local factors or part of a broader dynamic affecting the entire Atlantic African shoreline. The study aims to achieve three main objectives: (i) to map shoreline dynamics in the Wouri estuary from 1975 to 2019, identifying and quantifying eroding segments; (ii) to analyze factors contributing to erosion in the Wouri estuary and those common to other Atlantic African coasts; and (iii) to contextualize these findings within current scientific literature. Utilizing Hilhorst's theory of "reciprocity" or "complexity", the study recognizes that coastal areas are shaped by both physical and human factors influencing natural hazards like erosion and flooding. To investigate the causes of coastal erosion, a smaller-scale map (1:5000) derived from Landsat images (30-m resolution) and a larger-scale map (1:1500) based on Pleiades and Google Earth images (0.5-m resolution) were employed, focusing on Cape Cameroon. The imagery covers various years: Landsat (1975, 1986, 2000, 2016, 2024), Pleiades (2013, 2018), and Google Earth (2000, 2016). Shoreline extraction utilized both automatic (unsupervised classification) and semi-automatic (digitization) methods, especially in cloud-obscured areas. The Digital Shoreline Analysis System (DSAS) within ArcGIS 10.7.1 quantified shoreline retreat rates using the End Point Rate (EPR) method while meticulously calculating sources of error and uncertainty. Analysis of Landsat imagery revealed that over 75% of the Wouri estuary's shoreline is eroding, with average retreat rates ranging from -3 m/year to -11 m/year between 1975 and 2020. Hotspots for erosion include Cape Cameroon, the coastal spit around Manoka Island, and the vicinity of the APD. The northern tip of Cape Cameroon retreats at an estimated rate of -15 m/year, with a maximum retreat at 53 m. Conversely, an annual accretion rate of $+5$ m/year was noted at Toubé from 1975 to 2024. These findings highlight the dynamic nature of the coastal region, which may reflect broader trends across West African coasts experiencing intense erosion. This study lays a foundation for comprehensive coastal research and management, providing insights applicable to other African coastlines to mitigate the impacts of coastal erosion.

Keywords Hydrogeomorphological dynamic · Coastal erosion · Soft coasts · Tropical Africa · Wouri estuary · Cameroon · Gulf of Guinea

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1 Introduction and background of study

Land-sea interface zones, characterized by complex ecology, are dynamic areas influenced by numerous factors [1]. Since the expansion of the seas approximately 6000 years ago, coastal erosion has become a notable phenomenon. According to the International Geographic Union [2], 70% of the world's coasts are experiencing erosion, 20% remain stable, and only 10% exhibit accretion. Determining the causes of coastal erosion is challenging due to the multiplicity of environmental factors involved.

Coastal retreat is influenced by both natural and anthropogenic factors. Among the natural factors, global warming and rising sea levels are predominant [3], potentially leading to flooding [4–8]. Additionally, the construction of dams upstream impedes sediment transport downstream [9], impacting sediment availability at the coast and potentially degrading natural ecosystems [10, 11]. Ref. [12] emphasize the exacerbating effects of climate change, particularly rising sea levels and intensified storm activity, on coastal erosion, advocating for adaptation measures. Ref. [13] delves into the actions of waves and currents, detailing their interaction with coastal infrastructure, while [14] highlights the role of storms and hurricanes. Ref. [15] explores the sediment transport by longshore currents, which alters coastal morphology over time. Ref. [16] examines wind erosion, particularly in regions where wind is a significant agent of sediment movement. Ref. [17, 18] provide insights into the environmental impacts of natural events like cyclones on coastal ecosystems, assessing changes in shoreline erosion and sedimentation processes.

About Human Activities and Coastal Erosion [19], explores how human activities, such as urbanization and sand extraction, contribute to coastal erosion, proposing ecosystem restoration as a mitigation strategy. Ref. [15] discusses the reduction in sediment supply due to dam construction, advocating for integrated catchment management. Ref. [20] addresses the adverse effects of sand extraction on beach stability, calling for stricter regulations. Ref. [21] examines the impact of intensive agriculture near the coast, which can exacerbate erosion through land modification. Ref. [25] analyzes how port infrastructure and dykes alter natural currents, leading to beach erosion in adjacent areas.

Central and West Africa are regions where human influence significantly impacts coastal processes. Mangroves, which serve as natural barriers against erosion, are particularly at risk [22–24].

While these authors have contributed significantly to understanding coastal erosion, there are notable gaps. For instance, Ref. [13] analysis of waves and currents could benefit from integrating recent climate change impacts. Ref. [15] work on storms lacks a discussion on regional variability and protective infrastructure. Ref. [15] study could expand to include the combined effects of currents and tides. Ref. [16] analysis on wind erosion would be more robust with additional empirical data. Ref. [19] solutions for urbanization impacts could be further detailed. Ref. [20] focus on sand extraction could delve into sustainable alternatives. Ref. [21] Examining agriculture could incorporate policy implications, while [25] analysis could benefit from case studies on mitigation measures.

Regarding quantitative Analysis of Coastal Retreat, several studies have quantified coastal retreat, with Ref. [26] reporting a retreat of over 5 m/year around the Mediterranean. Similar erosion rates are observed in the soft coasts of northern Morocco [27], Algeria [28], and France [29]. Ref. [30] analyzed the response of the Puri shoreline to natural and anthropogenic factors.

Cameroon's coastal dynamics are no exception, with [31] reporting that of the 134,849 m of shoreline in southern Cameroon, 118,020 m (87.52%) are eroding, 16,620 m (21.33%) are accreting, and 320 m (0.24%) are stable. Ref. [32] found a retreat rate exceeding +0.54 m/year between 1986 and 2015. The Wouri estuary, a hotspot for shoreline retreat [33, 34], also hosts one of Africa's largest mangrove forests [35] and is Central Africa's largest port [36]. This estuary is heavily impacted by human activities [37, 38], with intertidal mangroves affected by rising sea levels.

Several studies on the Cameroonian coast have limitations. Ref. [39] focused on geophysical approaches, potentially overlooking human and geomorphological factors. Ref. [40] merely superimposed shoreline without quantifying erosion. Ref. [32] used a model ('SYMPHONIE') to explain coastal changes but lacked justification for their recession values. Ref. [31] utilized DSAS but did not address uncertainties in results. Ref. [41] examined tidal impacts but overlooked catchment configuration and topography.

The Digital Shoreline Analysis System (DSAS) is instrumental in mapping coastal erosion, quantifying shoreline dynamics, and estimating uncertainties [38, 42, 43]. Comparative analyses with new tools for QGIS [44] and the application of DSAS in complex coastal contexts [45] have advanced its utility.

This study aims to assess the rate of coastal erosion from 1975 to 2024 in the Wouri estuary, identify contributing factors, and compare findings with other Atlantic African coasts. Specifically, it seeks to analyze (i) coastal morphology, (ii) shoreline dynamics to identify and quantify eroding and/or accreting sections, and (iii) erosion factors within the

Wouri estuary. The methodological approach integrates remote sensing (using Landsat, Pleiades, and Google Earth imagery), GIS, and field observations, employing DSAS V5 with ArcMap 10.5® for mapping, supported by theoretical frameworks from [46] among others.

This comprehensive approach allows for a discussion on the specific erosion factors in the Wouri estuary and their comparison with other Atlantic African coasts.

2 The geographical and hydro-geomorphological setting

2.1 Geographical and administrative situation of the Wouri Estuary

The Wouri estuary is largely located in the Wouri department, whose capital is Douala, and the Sanaga Maritime department, whose capital is Edéa. The location is between 9° 20' 00" and 9° 40' 30" E, then 3° 40' 20" and 4° 10' 0" N (Fig. 1). The estuary covers an area of approximately 1200 km² and open to the Atlantic Ocean [41]; he is divided into the communes of Douala 1, 2, 3, 4, 5, 6, Mouanko, Tiko and Dizangué.

The main city of the Wouri estuary is Douala. It occupies the highest elevation on either side of the Wouri. The city is experiencing rapid growth. In 1916, there were approximately 15,255 inhabitants [47] In 1976, the population of Douala had reached 400,000, making it a true metropolis [48] According to [49] statistics, the estuary currently has over 5 million inhabitants, a large proportion of whom live in the economic city of Douala. Douala is also home to 60% of Cameroon's industries, as well as the largest port in Central Africa in terms of maritime traffic. Douala is also the home to 60% of Cameroon's industries.

2.2 Land use in the Wouri estuary

The Wouri estuary, a significant coastal area in Cameroon, encompasses approximately 24% of the nation's mangrove forests, which include ecologically vital regions such as the Douala-Edéa National Park and the Mabé Nature Reserve. These mangroves are dominated by species like *Rhizophora spp.*, with *Avicennia germinans* and *Nypa fruticans* also present [50]. In the mangrove ecosystem, these species fulfill complementary ecological roles that enhance environmental stability, conserve biodiversity, and bolster resilience against climate change. Their interactions with other species and their capacity to adapt to harsh environmental conditions make them integral to these ecosystems.

Despite the ecological significance of *Rhizophora spp.* and *Nypa fruticans*, their presence can have adverse effects, such as competition with native species, accumulation of waste, and increased sensitivity to climate change, which can be amplified by human activities and environmental alterations [50]. Therefore, sustainable management of these species and the mangrove ecosystems they inhabit is essential to mitigate these impacts and to preserve the biodiversity and ecosystem services they provide.

An Atlantic forest on the southeastern shore of the estuary plays a crucial role in the protection and conservation of biodiversity. Subsistence farming occurs on Manoka Island and within portions of the Douala-Edéa reserve [37, 51], although these activities have visible environmental impacts in this anthropogenically influenced region [37].

2.3 Climatic characteristics

The Wouri estuary area is located in the equatorial climatic band, with extremely abundant rainfall (Douala: 4025 mm/year) and widely distributed throughout the year, creating very characteristic conditions for weathering by leaching [52]. Locally, it lies in the coastal agroecological zone with monomodal rainfall, which is characterized by higher rainfall than anywhere else, according to the National Climate Change Adaptation Plan [53].

This coastal equatorial climate has a short dry season (November to March), and a long rainy season (April to October). The region receives 3500 to 4500 mm of rainfall per year, with peaks in July and August, with an average temperature of 26.4 °C [54]. This temperature value is not identical throughout the estuary. It is 26.5 °C on the island of Manoka, 28.5 °C around the town of Douala, 26.2 °C at Tiko, etc.

The solar radiation intensity ranged from 3.04 kWh/m²/dr to 5.41 kWh/m²/dr in the city of Douala, with an average value of 4.31 kWh/m²/dr. Minimum and maximum values are recorded in the rainy season (July to September) and maximum values in the dry season (December to February) [55].

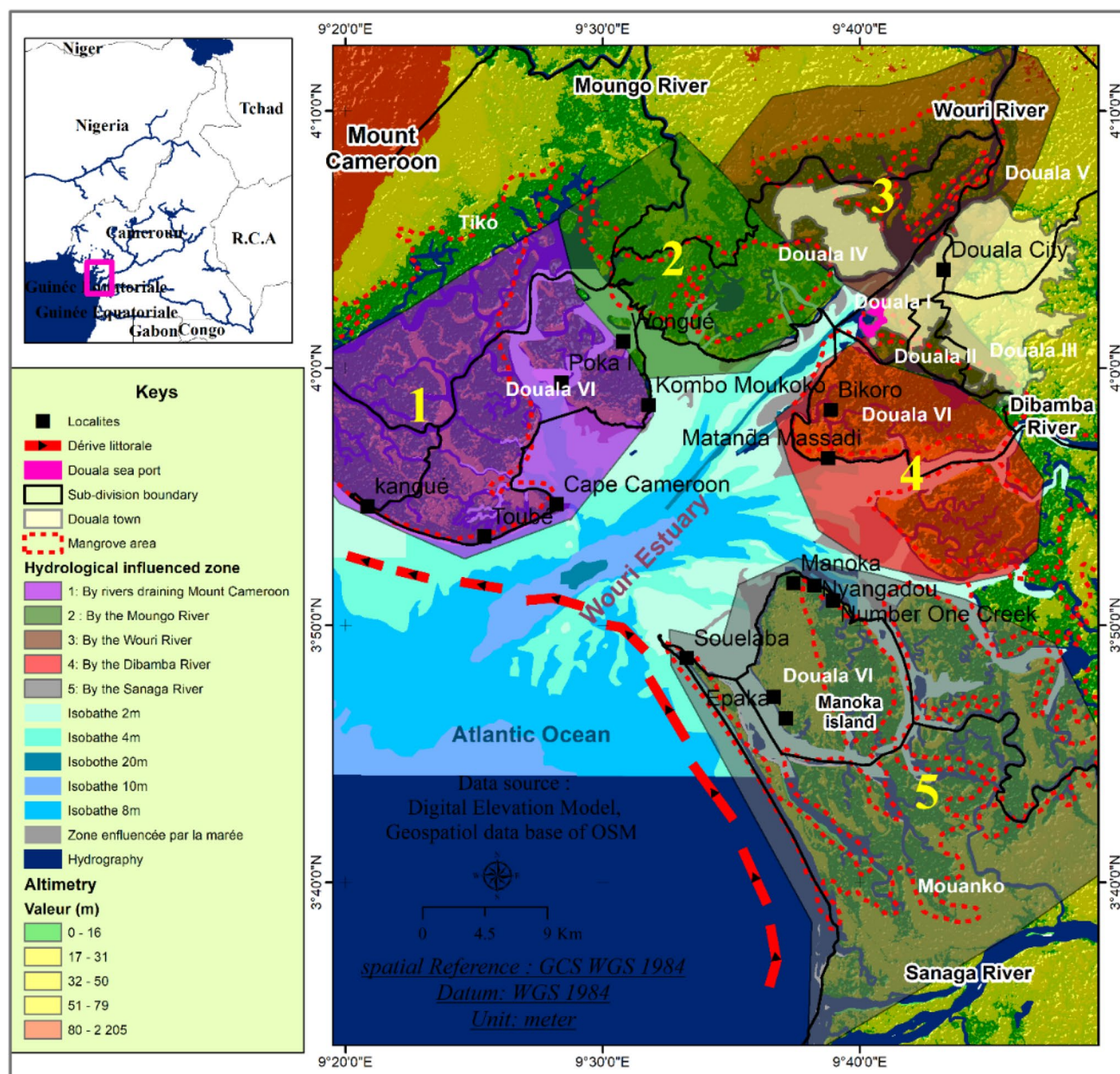


Fig. 1 Location of the Wouri estuary

2.4 The hydrogeomorphological context of the Wouri estuary

The information on hydrogeomorphological dynamics used in this section comes mainly from the literature review. In general, four major rivers supply water to the estuary. These are the Sanaga, the Dikamba, the Wouri, and the Mounjo, from east to west. According to a report by the Netherland Economic Institute [56], fluvial inputs of sediment into the estuary are estimated at 1 million tonnes per year, 70% of which occurs during the rainy season. The main contributing rivers are the Sanaga, Wouri, Dikamba and Mounjo. It should be noted that the Sanaga no longer flows directly into the Wouri estuary, which means that its high sediment load only reaches part of the estuary. The same applies to the Mounjo River, where most of the sediment load is trapped in the mangroves as soon as it reaches the estuary.

2.4.1 The Sanaga river

Until 1896, the Sanaga merged with the Wouri estuary [57]. Now, it only flows into the estuary during exceptional periods of intense flooding, as it now discharges to the south-east of the Wouri estuary. In the Adamaoua region, this river is considered to be Cameroon's water reservoir. A vast sedimentary basin is formed by a succession of plateau, bounded to the west by the Cameroon Volcanic Line (CVL), a succession of volcanic ranges, and to the north by the Adamaoua plateau. The climate here is subtropical, with annual rainfall ranging from 900 to 1500 mm. The length is 918 km and the average flow rate is 2072 m³/s, six times the rate of the Wouri. The flow was put at 520 m³/s at low water and 6000 m³/s at high water by [58]. More than a quarter of Cameroon is covered by its catchment area [59]. The Precambrian basement or "base formation" dominates the geology of the Sanaga basin. Clay and clayey-sandy sediments cover almost the entire surface catchment area. The Sanaga flows through a highly anthropogenic catchment with high rainfall, particularly in its western part. Its catchment area is subject to a high level of agricultural activity and an increase in the number of hydroelectric dams on its main channel and on its tributaries. Also More than 2.5 million cubic meters of silt and clay transported annually by the Sanaga come from the west (Fig. 3). The Bamiléké and Bamoun tributaries (location/catchment area) have a turbidity of over 950 g/m³ [60]. Human activities and the changing seasons affect the mobility of these sediments [61]. There is a high sediment load at the Sanaga's mouth, which shows its high sediment load. The Souelaba headland, which can be up to 200 m wide, is reworked by marine currents once at the mouth. The island of Manoka is protected by this low ridge, with a forest covering, that's between 5 and 6 m high.

2.4.2 The Dibamba river

To the south of the Wouri river lies the Dibamba basin. It rises in the western highlands and drains a series of small hills along the lower Sanaga watershed (maximum altitude 1053 m, with Mount Moukak). The terrain drained is exclusively weathered crystalline basement, which is weathered. The Dibamba River is 150 km long and has a catchment area of 2400 km². The estimated flood flow at its entrance ranges from 480 m³/s [62] to 1000 m³/s [58]. The flow drops to 70 m³/s at low water during the dry season. The average annual rainfall in the region amounts to 2660 mm per year. The average annual run-off is around 1600 mm/year, giving an average of 125 m³/s [63]. In the section closest to the city of Douala, the river is heavily used for sand extraction. The river joins a tidal arm in the south-eastern part of the estuary and flows into the Wouri estuary, passing through the mangroves to the south of Douala.

2.5 The Wouri river

The Wouri is the second-largest river in the region, supplying water to the Wouri estuary. The basin covers 21,600 km² [64] and the area surrounding Douala covers 11,700 km². Two main tributaries feed it. The first is the Nkam, which comes from the mountains in the north-western part of the basin. There are sharp topographical contrasts in the Makombé, which drains a terrain of sharp topographical contrasts. Most of the Wouri basin has a geological cover consisting of basement formations represented mainly by biotite gneiss and secondarily by anatexites and syntectonic granites. It is surrounded to the north and west by volcanic chains formed by a thick cover of Pliocene and Quaternary sediments [65]. The sedimentary load is made up of unconsolidated volcanic material.

The Wouri's average flow at its mouth is 140 m³/s at low water and 2000 m³/s at high water, according to [58]. It has an average gradient of 5.7 m at the outlet.

2.5.1 The Moungo river

Mountain massifs around the Monts Rumpi, which reaches 1768 m, are the source of the Moungo River, which is 150 km long and rises from the slopes of the mountain massifs around the Monts Rumpi [66]. The Moungo has a surface area of 4200 km². According to [67], it has an average cumulative flow of 10 m³/s at low water and 1300 m³/s at high water. It flows into the Bay of Moundou through a delta [68].

For around 100 km, the river is navigable in its southern part, then flows through the coastal plain before entering the mangroves, where it divides into numerous small channels that empty into the Wouri estuary. The geography of the catchment is diverse. A portion of Cameroon's volcanic line and Mt Cameroun are drains in the upstream part of the

Moungo, which flows over bedrock. Conglomerate, sandstone (Basic Sandstone), dark grey shaly clay, marl rich in organic matter and thin limestone beds [69, 70] mark its catchment [71, 72]. Continental and fluvial-deltaic deposits dominate at its mouth, with some intercalations of marine facies covered by mangroves.

There are several other major rivers that contribute sediment to the Wouri estuary, in addition to these major rivers. These are the Benoe, Ombe, Tole, and Mokota (Fig. 1), which rise on the slopes of Mount Cameroon and drain a number of mountains, including Bokesi Mount (495 m), Ebongo Mount (588 m), Engel Mount (581 m) Mount Cameroon is the main summit and is a Quaternary volcano made up of basalts (oceanite), trachy-basalts (hawaiiite), trachyte, tephrite and phonate [73]. It peaks at over 4040 m. The northern edge of the estuary is marked by it.

2.6 Intrinsic description of the Wouri estuary

There are multiple straight channels separated by sufficiently vegetated banks with large accumulations of sediment at the outlet of the Wouri river, well before the installation of the port. The accumulation of sediment in the form of banks leads to the division of the initial channel, causing the divergence of flows and, consequently, a local reduction in flow velocity [74]. The Wouri forms a sufficiently calibrated straight channel, with tidal channels on either side, before entering the ocean to the south of the autonomous port of Douala (APD) (Fig. 2).

The soil in the estuary is ferrallitic in the landward parts and hydromorphic sandy loam on the coastal fringes [75]. The original forest vegetation has been degraded by human activity and consists mainly of grasses, shrubs, fruit trees, arable species, and mangroves around the Wouri.

2.6.1 Geomorphological configuration around the estuary itself

Mt Cameroun, an active volcano rising to 4095 m, dominates the geomorphological context of the estuary. The Wouri estuary is crowned by a series of volcanic mountains, all belonging to the Cameroonian volcanic arc [76].

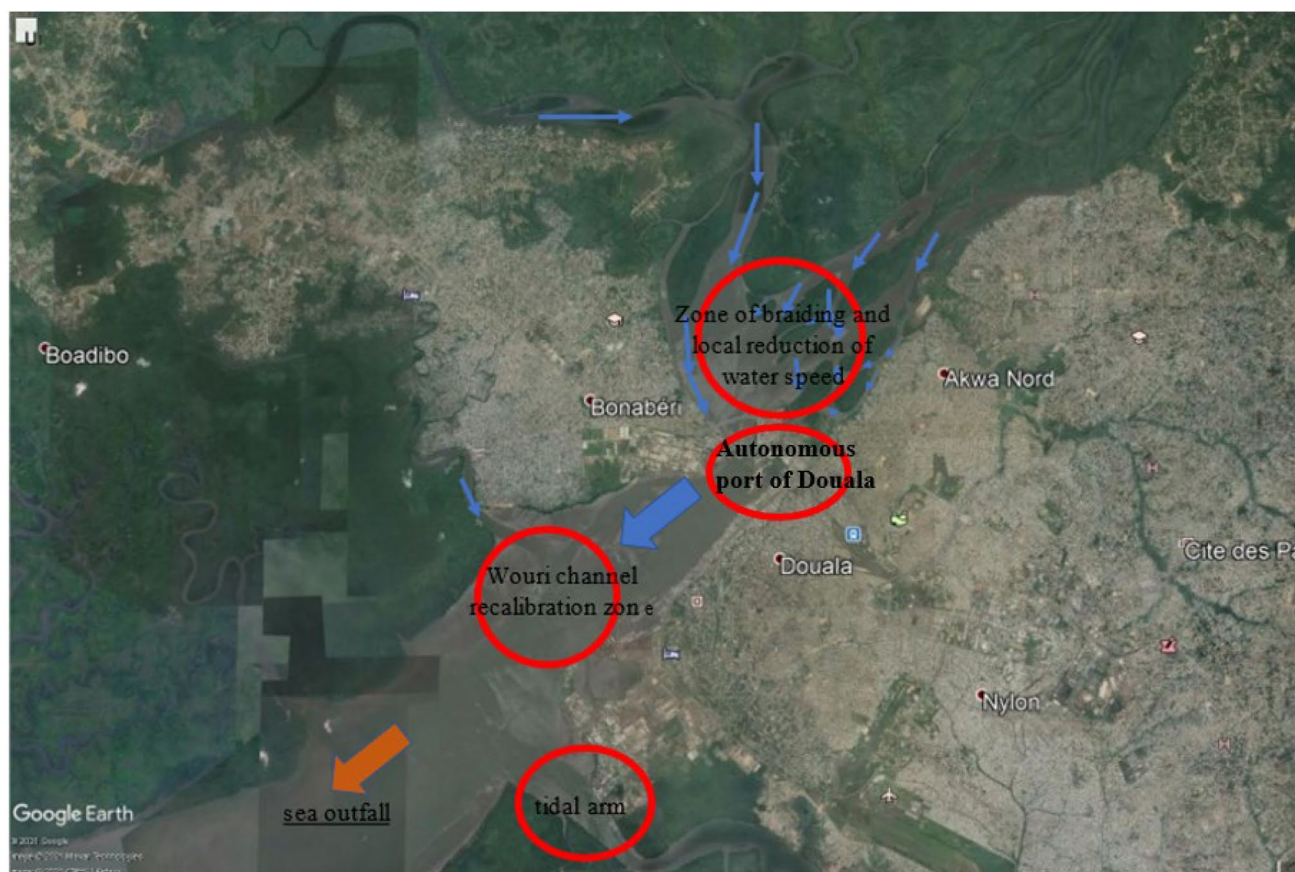


Fig. 2 View of the Wouri estuary (Source: Google Earth image, 2020)

The Moungo catchment area contains four mountain ranges: Mount Bahosi (1487 m), Ngongonja (609 m), Mount Mumdemé (461 m), and Mount Ngamokoli (322 m). There are 12 mountain ranges in the Wouri catchment area, the most important of which are Mount Manengouba [77]. (2411 m), Mount Lahke (1407 m), Mount Nlonako (1653 m), and Mount Moulak. Lastly, the largest number of ranges are located in the Sanaga catchment area (more than 26) Mount Toukwet (1130 m), Mount Lekete (1086 m), Mount Nolanga (813 m), etc. are some of the most important ones (Fig. 3).

2.7 The geological context of the Wouri estuary

There are three prominent geological entities at the level of the Wouri estuary: (1) a crystalline zone, formed of migmatites and granites [78], developed towards the NE dating from the Palaeozoic; (2) the Quaternary volcanic zone of Mt Cameroon, corresponding to the highest peaks and essentially basaltic to the NW. The basin is composed of loose, low-lying coasts stretching for at least 220 km from the mouth of the Sanaga River to the Wouri estuary. Mt Cameroon is the most active volcano in the Cameroon volcanic line, an active tectonic–magmatic alignment oriented N30°E, comprising 6 major volcanoes in the oceanic domain and more than 7 in the continental domain [79]. The Mt Cameroon morphology of these cinder cones plays a significant role in shaping the shoreline [80].

Sand and clay make up the soil in the Wouri estuary. It's a fragile substrate, but it's also protected and compensated for by nature. There is a natural barrier against coastal erosion provided by a thick layer of mangroves and coastal forest. Four major rivers, the Sanaga, Dibamba, Wouri and Moungo, with significant sediment loads, supply the estuary with sediment (Fig. 4).

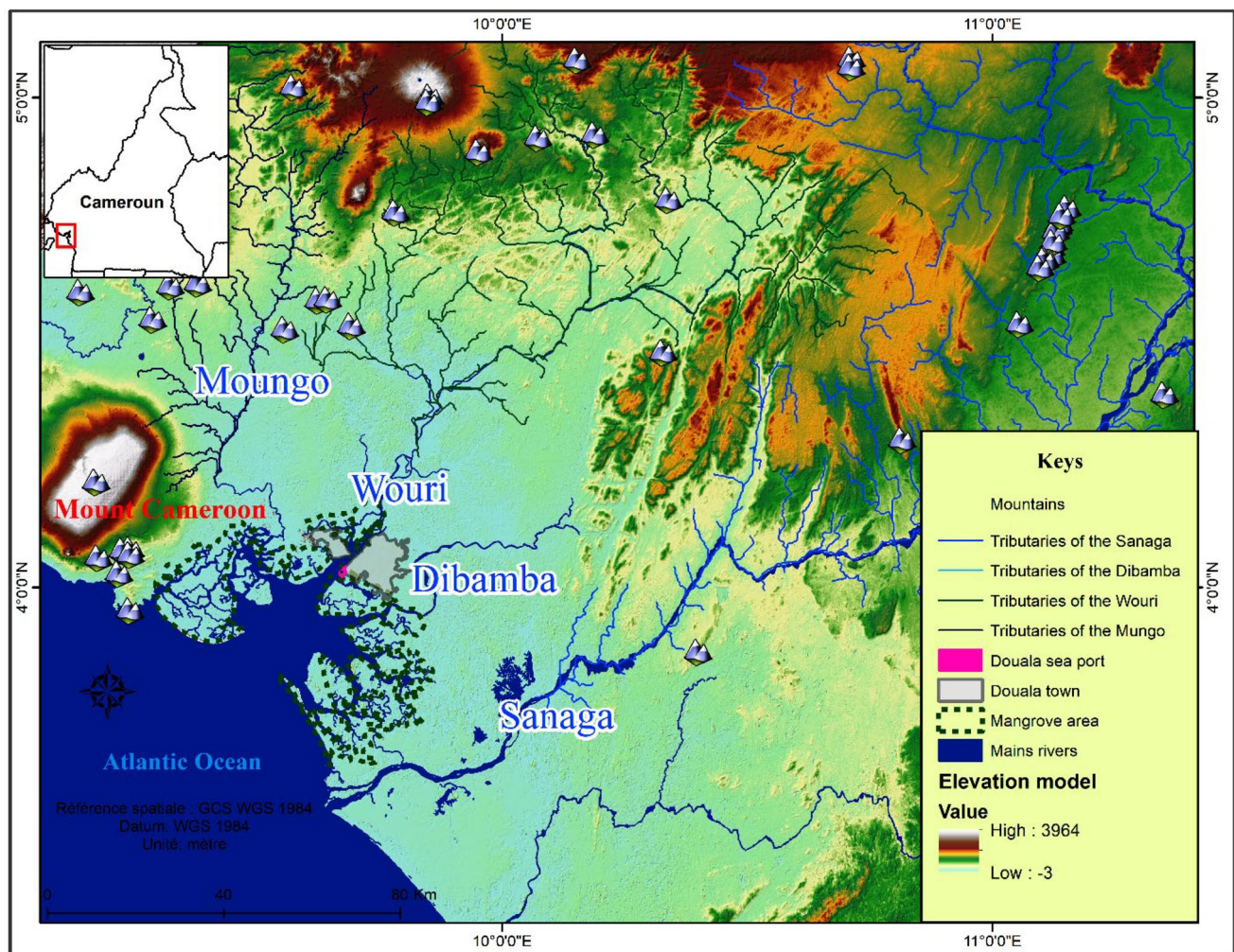


Fig. 3 Morphological configuration of the Wouri estuary and its immediate environment

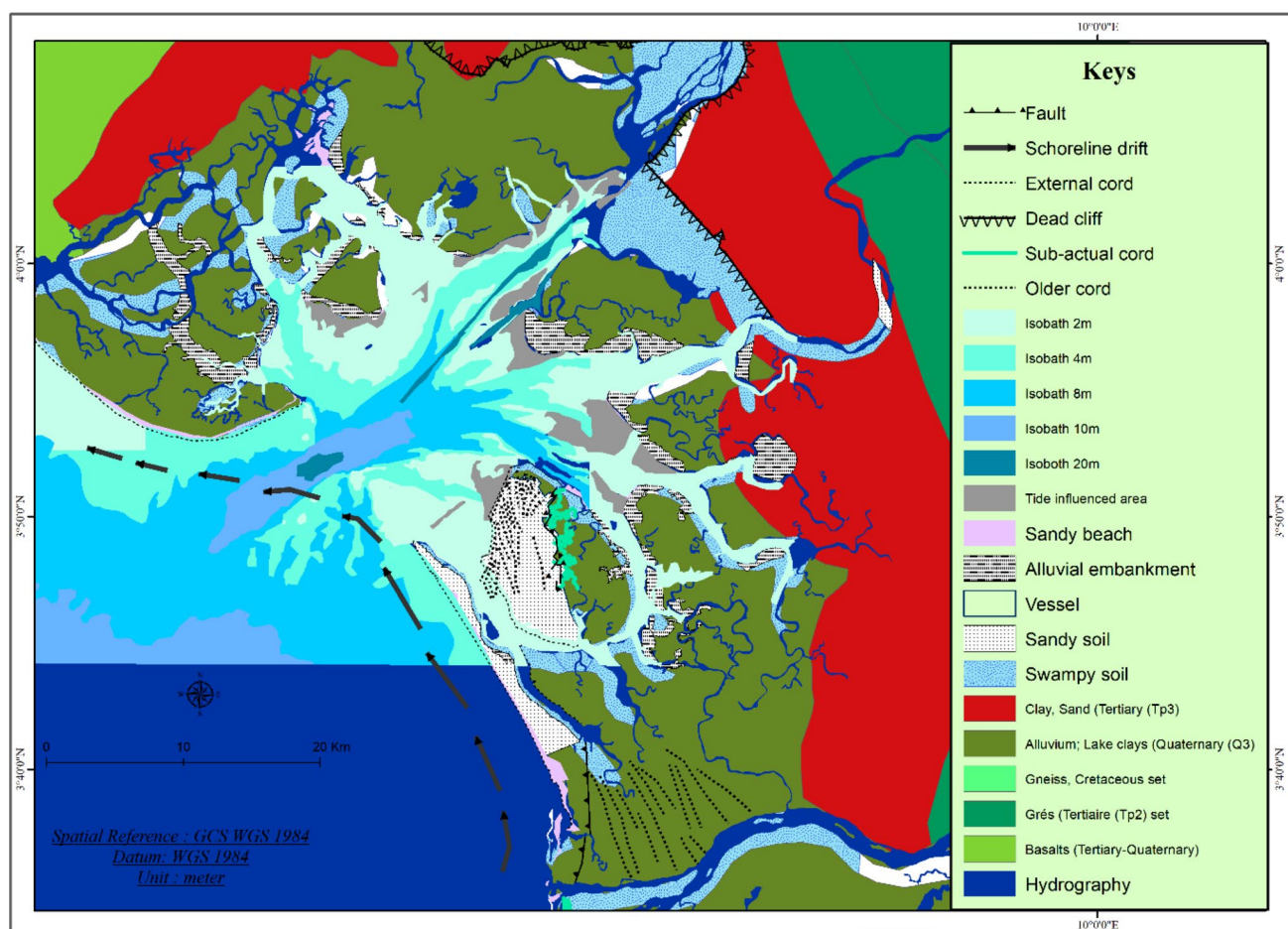


Fig. 4 Geological configuration of the Wouri estuary

The Douala sedimentary basin, composed of low-lying unconsolidated coasts stretching for at least 220 km from the mouth of the Sanaga River to the Wouri estuary, is where the Wouri estuary emerges from.

Inside the estuary, altitudes vary from 0 to 16 m (Fig. 1), with relatively flat relief made up mainly of loose rock that is highly vulnerable to erosion.

The Wouri estuary lies at the heart of the Douala sedimentary basin, centered on an old Pan-African mylonite syncline, along the axis of which flows the Wouri River [57]. In this environment, differences in altitude are small and are essentially made up of the remains of sandy strips and small islands of Mio-Pliocene sands and gravels, sometimes bearing a ferruginous armourstone, as in the middle of the Docteur [81].

Sand and Paleogene-Neogene alluvium cover the eastern shoreline of the Wouri estuary, from the mouth of the River Nyong [82], recent volcanic formations of the Mount Cameroon region are extended to the west by the islands of Bioko and Soto. The sedimentary deposits are coherent, resulting in a degree of heterogeneity in the shape of the shoreline. The morphology of these structures plays an important role in the appearance of the shoreline [79].

Two authors have divided the Wouri estuary into three distinct geological entities. A crystalline zone composed of migmatites and granites [77] developed towards the northeast; a volcanic zone corresponding to the highest peaks and primarily basaltic [65, 83].

2.7.1 Marine context in the Wouri estuary

2.7.1.1 The tide in the Wouri estuary The Wouri estuary is where the strongest tides in Cameroon are found [32] Tide heights in the estuary vary greatly; they are semi-diurnal and asymmetrical [84] There is an average amplitude of 2.5 m towards the port However, surges are frequent during windstorms and are highly variable in the estuary (on average

2.8 m towards the Port and 1.7 m towards Cape Cameroon) The tides are amplified in the shallow parts of the estuary at the level of the Wouri and Dibanda rivers [83].

2.7.1.2 Prevailing winds in the Wouri estuary From 1960 to 2001, we have been able to understand the wind directions and speeds in the Wouri estuary by analyzing the annual and seasonal boreal wind rose for the Cameroon coast.

The seasons affect the winds in the Wouri estuary. In the winter, the prevailing winds are SW, S, and SSW. The same trend will continue in the spring, with the only difference being that W winds (16 km/h) will make their appearance and S winds will decrease in intensity. In the summer, the SW and SSW winds dominate, followed by the SWS and S winds. In autumn, the SW winds take over again, with more than 24 km/h, followed by the WSW and SSW (16 km/h) winds [85]. An annual report shows that SW winds dominate (Fig. 5). The predominance of SW winds on the Cameroon coast, coming from the Atlantic Ocean, was supported by [57].

The overcoast [32] varies from near the Port Autonome de Douala to Cap Cameroun.

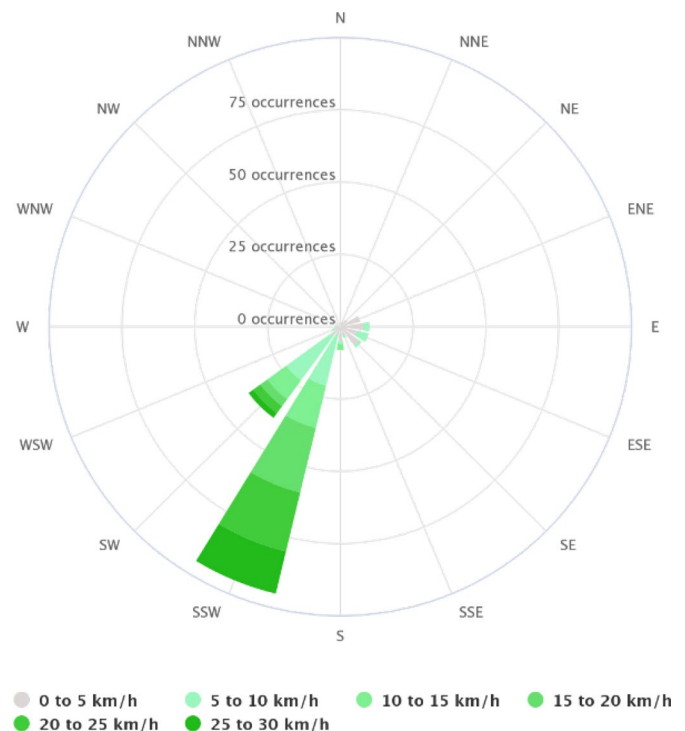
The trade winds (regular intertropical wind between 23°27 north and 23°27 south) are very active in the Gulf of Guinea, blowing regularly from east to west from subtropical high pressure (subtropical ridge) They occur mainly between December and March, during the dry season.

2.7.1.3 Currents at work in the Wouri estuary In the estuary, the main current is longshore drift. Sediment transport and accumulation in the outer estuary are influenced by it. The waves generated by the local SW wind and long-period swells that affect the entire West African coast make it essentially conditioned. Two types of swell have been identified [32] The NNW swell is caused by easterly winds in the region west of Namibia, while the other is caused by westerly winds in the southern Atlantic Ocean around 50°S [32] Swell height varies significantly with a maximum occurring in June–July–August and a minimum occurring in December–January–February [32].

In the Wouri estuary, a counter-current situation occurs. It brings together river currents related to the Wouri, Moungo, Dibamba, and Sanaga rivers (Fig. 6), as well as ocean currents (mainly longshore drift and large SW swells) The considerable quantities of clay, sand, and silt carried by the latter tend to accumulate in the estuary because of this convergence of several currents, which limits the speed of the coastal currents and influences the fluvial hydro-sedimentary dynamics. Fluvial currents are weak at Douala at less than 0.70 m/s [56].

All things considered, large waves influence this shoreline, and the materials brought in by the rivers (sand and kaolin clays, etc.) are absorbed by the south-east longshore drift and a west–east coastal current [57] Longshore drift and coastal currents play an important role in the remobilization of sediment, in the form of longitudinal sediment transport [86].

Fig. 5 Wind direction and speed in the Wouri estuary (Source: meteoblue web site, 2021)



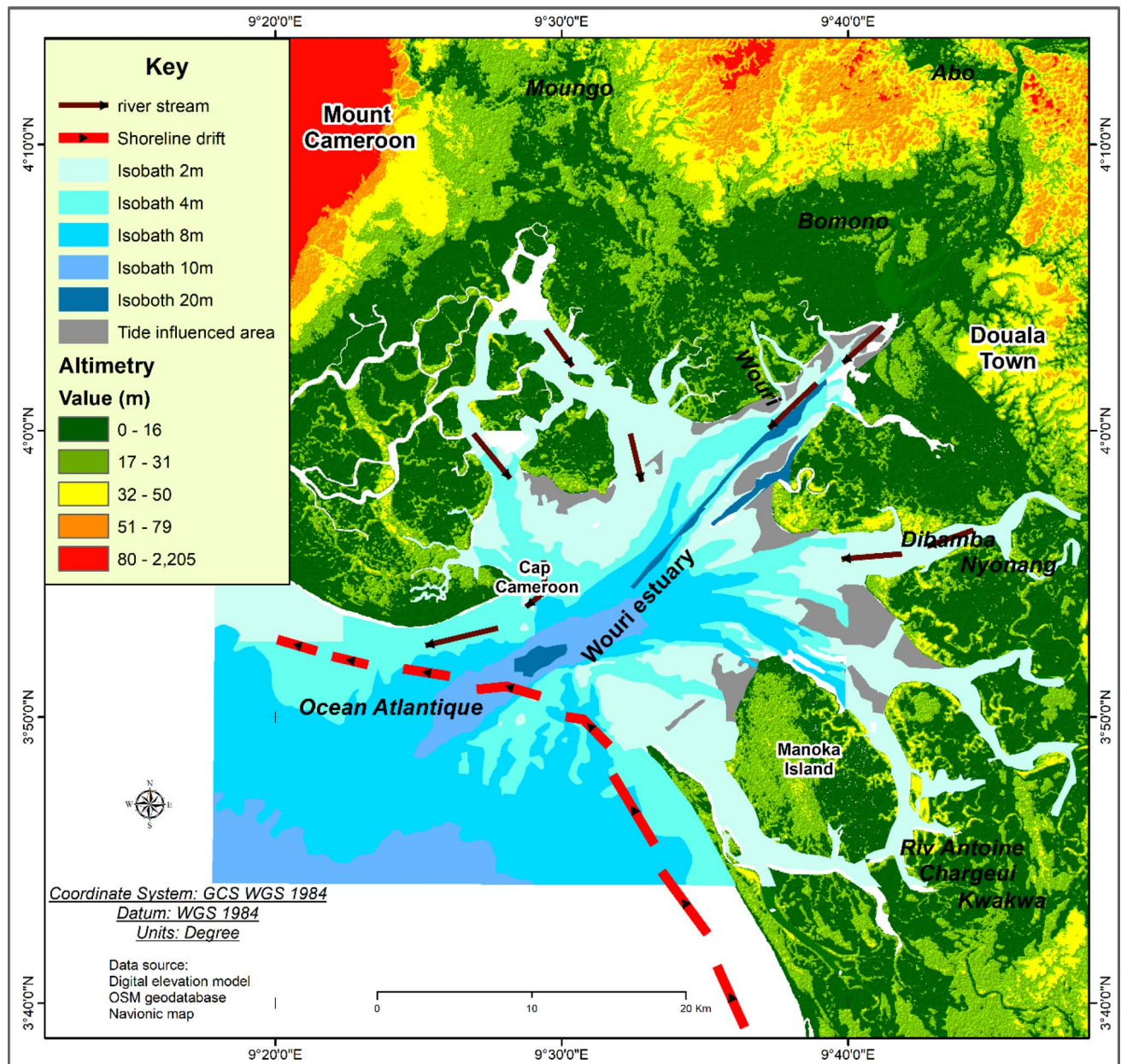


Fig. 6 Counter-current situation in the Wouri eqtuary. On the one hand, there is the current from the various rivers flowing into the estuary, and on the other, the oceanic drift current

2.7.1.4 Variation in bathymetry in the Wouri estuary The presence of channels causes significant variations in the depth of the Wouri estuary. The analyzed area has a total surface area of around 117.2 ha (source: Navionic data processing). The water levels downstream of the estuary are lower than those at its entrance (Fig. 9). A 200-m-wide and 650-m-long channel reaches depths of over 20 m in places in the most downstream part of the estuary, to the southwest of Cape Cameroon. There is a wider and deeper channel in the southwest part of the estuary, which gradually narrows to the level of the autonomous port of Douala (APD). There are two arms to this main channel, one of which borders the island of Manoka to the north, and the other is 25 m deep, reaching the city of Douala. The access channel to the port is permanently dredged.

Close to farmland surrounded by mangrove forests, the lowest bathymetric values range from 2 to 8 m (Fig. 6). The speed of waves and their height at shore are affected by this reduction in depth. Tidal currents have little or no effect on the outermost parts of the estuary, where longshore drift is greatest, as a result. They are only allowed on the barrier beaches.

3 Tools and methods

At Cap Cameroun, coastal erosion was mapped, as well as throughout the Wouri estuary. A spatial resolution of 0.5 m was used in the first case. Landsat images were used in the second case.

3.1 Pleiades and Google Earth images processing

A series of high-resolution images from multiple sources were utilized to assess coastal erosion along the Cape Cameroon shoreline. Specifically, Pleiades satellite imagery from 2013 and 2018, as well as Google Earth aerial photographs from 2000 and 2016, were employed, all possessing identical spatial resolutions of 0.5 m (Table 1). The Cape Cameroon region, characterized by intense erosion, was the primary focus of this study. Figure 7 illustrates the various processing stages applied to both Google Earth aerial images and Pleiades imagery.

To determine the spatial resolution of images in Google Earth, a systematic four-step process was followed: (1) Launch Google Earth Pro; (2) Click on the "Show information" icon located in the top right corner of the interface; (3) In the "Information" panel, select either "Image" or "Image data"; (4) The spatial resolution is displayed in meters or feet per pixel (m/p or p/p) [87, 88].

3.2 Landsat images process

There were two main problems with the Landsat images collected. (i) There was cloud cover on some images. However, very little of this cloud cover was found along the shoreline. To solve this problem, we digitized these sections rather than extracting them automatically; (ii) Seasonality. To solve this problem, we opted for images taken during the dry season. This is also a period when the tides are at their lowest, as are the monsoons. Table 2 below summarizes the characteristics of the Landsat images.

Some images had a cloud rate greater than 10% which is the recognized rate (images from 2000, 2016 and 2024). However, these clouds were mostly outside the Wouri estuary (Fig. 9). In the areas where there was cloud on the shoreline, we proceeded by manual digitization of the shoreline. In the literature, there are authors who have used images with cloud rates greater than 10% and who have arrived at reliable results. These are the cases of [89], who analyzed the vegetation cover in a large city using satellite images. Despite cloud cover reaching up to 25%, the researchers used image processing techniques to extract relevant data on the health of the vegetation. Also, in a lake monitoring study in Africa, [90] used Landsat images with 30% cloud cover. The researchers focused on the analysis of water levels and seasonal changes. They incorporated atmospheric correction models to compensate for the effect of clouds, which allowed them to obtain reliable results on water resource dynamics. Finally, a study by [91] examined flood risks in a coastal region using satellite images with 15–20% cloud cover. The authors used classification algorithms to identify risk areas, taking into account areas covered by clouds. Their work highlighted the importance of using satellite data, even with cloud cover, for environmental risk planning and management.

Table 1 Characteristics of Pleiades (2013 and 2018) and Google Earth (2000 and 2016) images used in small-scale coastal erosion mapping of Cape Cameroon, Wouri estuary

Cape Cameroon	Images Pléiades 1
Date	16 December 2018
Spatial resolution	0.5 m
Sensor	Pléiade
Identifier	DS_PHR1A_201812160944155_FR1_PX_E009N03_0622_03147
Cape Cameroon	Pleiades 2 images
Date taken	19 April 2013
Spatial resolution	0.5 m
Sensor	Pléiade
Identifier	DS_PHR1B_201304190944536_FR1_PX_E009N03_0721_01956-1
Cape Cameroon	Google Earth 1 and 2 images
Date taken	23/11/2000 & 3/05/2016
Spatial Resolution	0.5 m

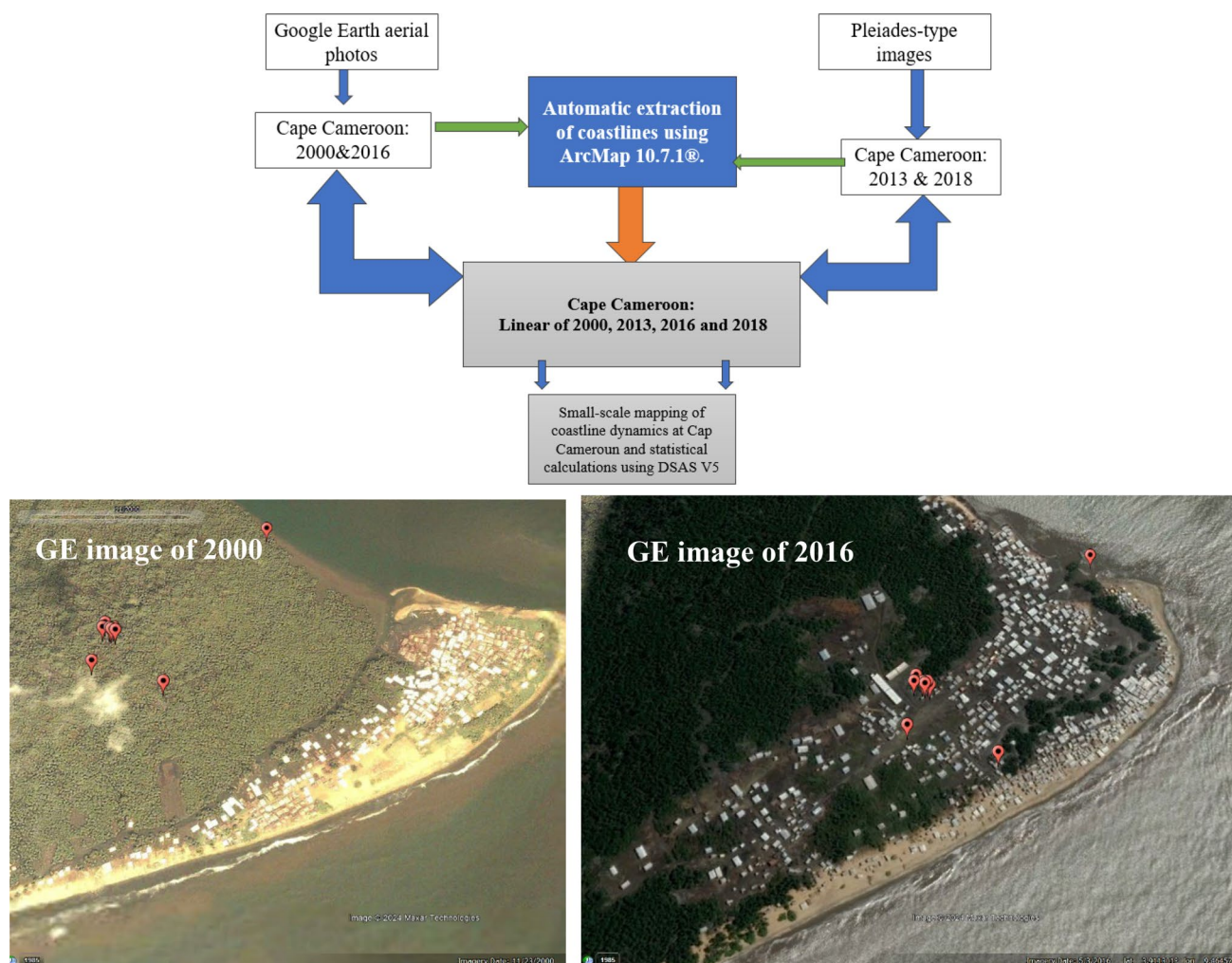


Fig. 7 Steps for processing Pleiades images and Google Earth aerial photos

Table 2 Characteristics of Landsat images used for coastal erosion mapping in the Wouri estuary and Kribi area

Date	Path and row	Spatial resolution	Code	Sensor	Seasons	Zones	Clouds rate
1975/06/06	LM02_L1TP_200 057	60 m	8 bits	Mss	Dryer	Shoreline extraction	
1986/12/12	LT05_L1TP_187 057	30 m	8 bits	TM	Dryer	Shoreline extraction	6%
1986/02/9	LT5 186 057	30 m	8 bits	TM	Dryer	Shoreline extraction	5%
2000/11/6	LE7 186 057	30 m	8 bits	ETM	Dryer	Shoreline extraction	15%
2000/3/5	LE7 187 057	30 m	8 bits	ETM	Dryer	Shoreline extraction	50%
2016/02/21	LC08 187 057	30/15 m	16 bits	L8	Dryer	Shoreline extraction	21.05
2016/03/31	LC08 186 057	30/15 m	16 bits	L8	Dryer	Shoreline extraction	5.23%
2024/12/20	LC08 187 057	30/15 m	16 bits	L8	Dryer	Shoreline extraction	16.75%
2024/12/27	LC08 186 057	30/15 m	16 bits	L8	Dryer	Shoreline extraction	5.69%

Landsat images are used on a small-scale to analyze shoreline dynamics between 1975 and 2024 (49 years) and to classify land use. The 1975 (60 m spatial resolution) image has been merged (Pan sharpen) to reduce its spatial resolution to 30 m, which is compatible with the other images. Figure 8 below summarizes the steps involved in processing Landsat images using Erdas Imagine and ArcGIS 10.5 software. This processing mainly aims to extract the shoreline features to facilitate coastal erosion mapping.

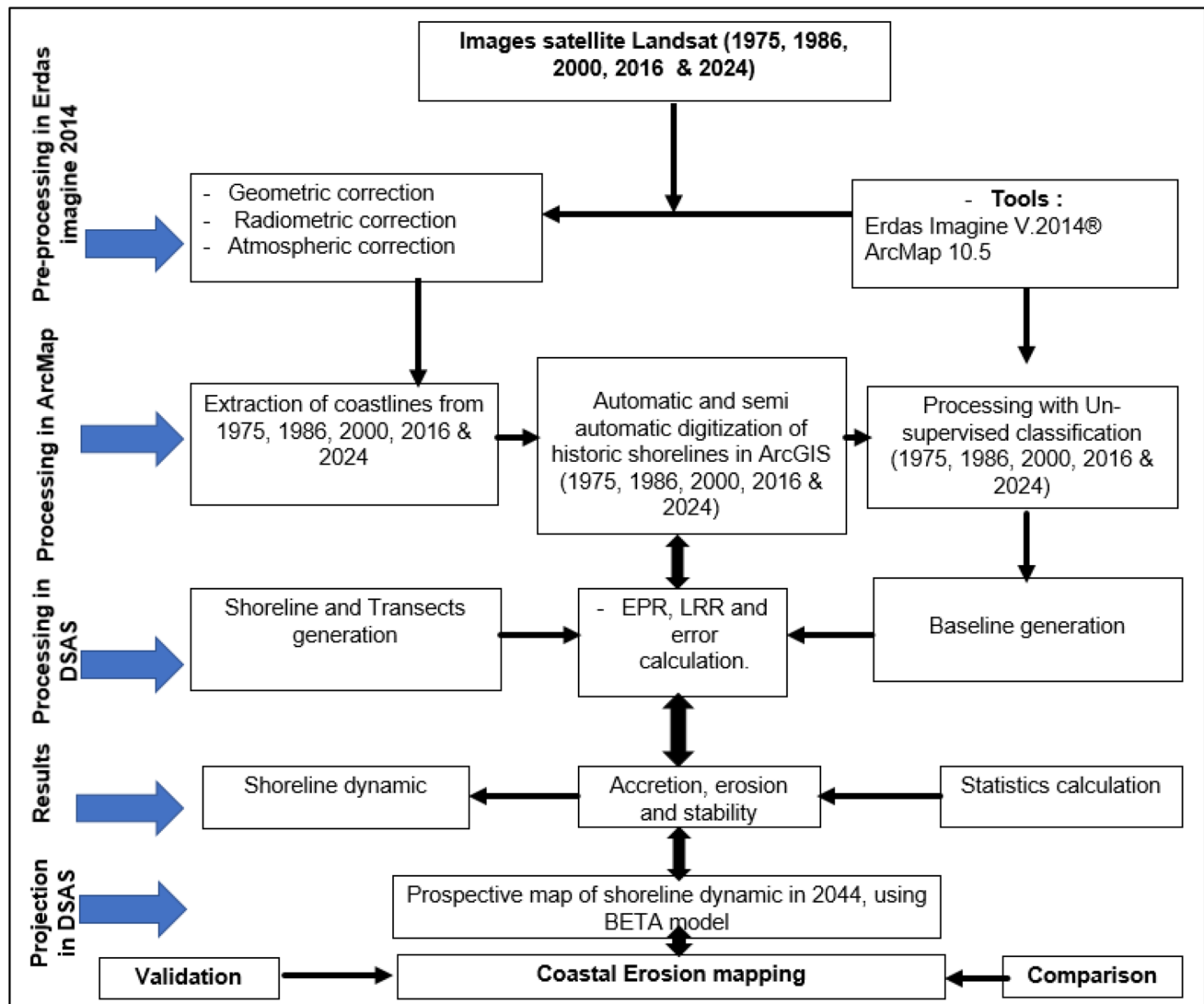


Fig. 8 Landsat image processing using Erdas Imagine and ArcGIS 10.5 software

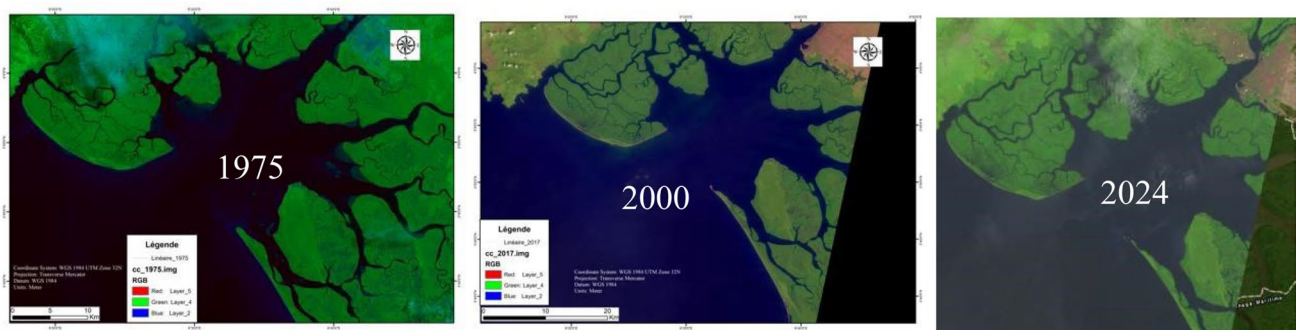


Fig. 9 Images with automatic linear extraction

To enhance the analytical framework, the estuary has been divided into six distinct zones (Fig. 1). This segmentation is informed by the areas of influence exerted by the major rivers that contribute to the Wouri Estuary.

- Zone One: Influenced by the rivers originating from the slopes of Mount Cameroon.

- Zone Two: Influenced by the Mounjo River.
- Zone Three: Influenced by the Wouri River.
- Zone Four: Influenced by the Dibamba River.
- Zone Five: Influenced by the Kwakwa River.
- Zone Six: Influenced by the Atlantic Ocean and its associated marine currents.

This zonal approach allows for a more precise understanding of the hydrodynamic and ecological interactions within the estuary.

3.3 Coastal erosion mapping method

It uses the DSAS tool, which is grafted onto ArcGIS software. Parameterization at several stages is required for the production of erosion models.

3.3.1 Extraction of coastal lines

According to the French national network of shoreline observatories, the shoreline can be defined as the demarcation line between the sea and the land. However, the characterization of this boundary becomes more complex depending on the type of coast and the methods employed to delineate it. Various markers can be utilized based on the available data:

- “The limit of vegetation;
- The foot or summit of a cliff (rocky or sandy);
- The line where the topographic surface intersects the highest astronomical sea level (Shom definition);
- A protective structure built along the shoreline”.

In this study, the sand-vegetation boundary has been selected for analysis, given the relatively low spatial resolution of the imagery utilized. This approach is subject to changes in vegetation cover. In the Wouri estuary, there have certainly been changes in mangrove ecosystems during this study period [11], but there is still a presence of vegetation in contact with the ocean.

The processing of images with minimal cloud cover from the Wouri Estuary (1975, 2017, and 2018) was automated (Fig. 9). No manual corrections were applied to the sections of the shoreline represented by cloud-free images. Conversely, a semi-automatic approach was adopted for images affected by significant cloud cover, which obscured portions of the shoreline. Consequently, digitization errors were assessed in Sect. III-2-4.

Unsupervised classification was executed using ArcGIS 10.7.1^{*}. The resultant data were then converted into vector format and represented as polylines, with undesirable segments trimmed for clarity.

3.3.2 Treatment of different coastal lines in Arcmap 10.5^{*}

The shoreline is established by integrating various linear features. For this project, a buffer zone of 100 m was created surrounding the merged shoreline file. The terrestrial portion of this buffer (onshore) is automatically digitized to define the baseline, which serves as the reference point for calculations of shoreline dynamics.

The parameters considered when establishing the baseline include the Group field, ID field, and search distance field [41]. For the shoreline, the primary parameters are the Shoreline date field, Shoreline uncertainty field, data uncertainty (m), and landward intersection [41]. All calculations are grounded in historical shorelines, ensuring a robust analysis of shoreline changes over time.

3.3.3 Treatment under DSAS

The values that give an idea of the dynamics of the shoreline are the transects. A transect spacing of 50 m is used for this study. The transects are each 500 m long. They are straight lines of 50 m, perpendicular to the shoreline. A pixel error of 30 m per pixel was used for Landsat images and 0.5 for GE and Pleiades images. The orientation of the transects was defined by the ‘Offshore’ option. The Offshore option means that the transects generated will be oriented toward the ocean and that the End Point Rate (EPR) calculations will be based on the oldest shoreline (1975).

3.3.4 Calculation of statistics and quantification of shoreline dynamic (EPR and LRR)

DSAS performs several calculations on global changes in shoreline positions [92]. The annual rate of shoreline change is calculated for each period. In this research, we used the End Point Rate (EPR) method. The end point rate (EPR) is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline. The major advantages of the EPR are the ease of computation and minimal requirement of only two shoreline dates. The disadvantage is that in cases where more data are available, the additional information is ignored [41] and [93] based on the formula:

$$R = D/T_e \quad (1)$$

R is the speed in meters per year (m/year), D is the distance in meters, and T_e is the time elapsed between the oldest and the most recent shoreline (years).

The uncertainties of the annual rate of change (in meters per year) are defined, together with the 95% confidence intervals LCI95 or WCI95 (According to [41], LCI95 is the Confidence Interval of Linear Regression–LCI%, where % is the CI value entered in the Calculate Rates window; WCI Confidence Interval of Weighted Linear Regression–WCI%, where % is the CI value entered in the Calculate Rates window). The uncertainty value considers both positional uncertainties associated with natural influences on the position of the shoreline (wind, waves, and tides) and measurement uncertainties (e.g. digitization or global positioning system errors) [94]. We based our work on the USGS report of 2006, which expresses the error mages from the equations:

$$ECI = \frac{\sqrt{(uncyA)^2 + (uncyB)^2}}{date A + date B} \quad (2)$$

The rate of shoreline changes for a single transect is calculated as the quadrature sum of the uncertainties for each year of shoreline position divided by the number of years between shoreline surveys:

$$U_{R_i} = \frac{\sqrt{Up1_i^2 + Up2_i^2}}{year_2 - year_1} \quad (3)$$

U_{p1i} and U_{p2i} are the uncertainties of the position of the first and second shoreline (year 1), respectively, at transect i , calculated by Eq. (2 or 3). For the linear regression method (long term), the uncertainty of the shoreline change rate of a single transect U_{Ri} is found here as a percentage at 90% on the linear [94]. Table 3 summarizes the different margins of error calculated.

The error types calculated for this work include pixel errors (E_p), RMS orthorectification (ERM), digitization error (E_d), planimetric error (PE), measured errors (E_m), uncertainties in calculations (ECI) (m/year), and annual error (E_a) (m/44 years) [93] and [95].

Table 3 Errors linked to the model

Date	1975–2000	2000–2016	2016–2024
Pixel error (E_p)	2	5	/
RMS ortho-rectification (ERMs)	15	22	12
Digitisation error (E_d)	7	15	/
Planimetric error (PE)	/	23	23
Total error (E_t)	15	38	10
Measured errors (E_m) (m)	42	56	30
Annual error (E_a) (m/44 years)	/	0.65	
Uncertainties in calculations (ECI) (m/year)	2	7.2	0.52

3.4 Prospective analysis of coastline dynamics up to 2044, with DSAS

DSAS (Digital Shoreline Analysis System) is a spatial analysis tool developed by the USGS (United States Geological Survey) to study coastal changes, such as shoreline erosion or accretion, using geospatial data over time. The BETA model that is integrated into it is used to make projections of coastal kinematics [43]. It is a statistical approach to predict future scenarios by analyzing historical data. In the case of DSAS, it is used to project the future position of a shoreline by analyzing past rates of change (erosion or accretion). The BETA model has an advantage in enabling (i) proactive and more effective management of coastal zones and better anticipation of risks. (ii) Long-term planning by helping to define adaptation strategies to protect coastal infrastructures. (iii) Enables clear visualization, with future projections that can be used to raise awareness among stakeholders.

However, the BETA prediction model has some caveats to consider: (i) sensitivity to Input Data; here, the BETA model is very sensitive to the quality of the input data. Errors in the input data can lead to inaccurate forecasts [96]. (ii) There are generalization limitations; the results obtained may not be generalizable to other coastal areas with different geomorphological characteristics, thus limiting the applicability of the forecasts [97]; (iii) The difficulty of integrating human factors into the model. It often focuses on physical factors and may neglect the impact of human activities on coastal erosion, which may give an incomplete picture of coastal dynamics [98]; (iv) Finally, the margin of error can be problematic. Indeed, the model may present a significant margin of error, especially over extended periods, which may affect the reliability of long-term forecasts [99].

To overcome these errors, we have paid particular attention to the quality of the input data, by ensuring that the coastline extraction process is correct and by adding additional validation methods, such as field observations.

4 Results

4.1 Mapping coastal erosion in the Wouri estuary using Landsat images

Large-scale cartographic processing of coastal erosion was conducted using Landsat imagery. For a comprehensive representation, the analysis was segmented into four periods: 1975–1986, 1986–2000, 2000–2016, and 2016–2024, across six designated zones. The criteria for zone division are detailed in Sect. III-2. The observation periods were chosen based on the availability of high-quality images with low cloud cover, which complicates inter-period comparisons due to disparities in data quality.

The maps generated are characterized by erosion rates expressed in meters per year (m/year) or as the final shoreline retreat rate (EPR). Dynamic shoreline values ranging from + 10 to – 10 indicate stability in the shoreline during the observed period. A negative value signifies erosion, while a positive value indicates accretion.

For each period, both qualitative analyses (focused on identifying areas of accretion, erosion, and stability) and quantitative analyses (based on statistics related to shoreline retreat, accretion, and stability) were conducted. This dual approach allows for a thorough understanding of the coastal dynamics over time.

4.1.1 Large-scale shoreline dynamics between 1975 and 1986 in EPR (11 years)

The Wouri estuary began to show signs of eroding between 1975 and 1986, but they remained uneven. Over a distance of around 1.5 km, zone 1 is the most striking point. Then there's zone 3 between Pointe Olga and Malanda Massadi (Fig. 10) and the Dongo zone at Pointe Malimba. The area around Manoka shows erosion, though it's scattered. On the west coast of the island, it can be seen near the Number Two Creek area, and in the south-western part, near the Epaka I area. Zone 6 (the coastal spit around Manoka Island) is experiencing erosion between Souélaba Point and the village of Youmé.

During these 11 years, statistical values for shoreline dynamics are relatively low in some areas of the estuary. The average End Point Rate (EPR) reveals a retreat of – 13 m in Zone 1, while Zone 2 remains completely stable. Zone 3 exhibits a retreat of – 40 m, and Zone 4 shows a retreat of – 2 m. Zone 5 experiences a retreat of – 25 m and an average annual erosion rate of – 11 m/year. In contrast, accretion is observed in several zones: Zone 1 (+ 21 m), Zone 2 (+ 17 m/year), Zone 3 (+ 42 m), Zone 4 (+ 3 m), Zone 5 (+ 2 m), and Zone 6 (+ 2 m). Notably, Zone 3, corresponding to the area on either side of the Douala Autonomous Port, is the most eroded zone during this period (– 40 m). This timeframe coincides with major works to widen the banks of the Wouri, aimed at increasing the storage capacity of the Douala Autonomous Port.

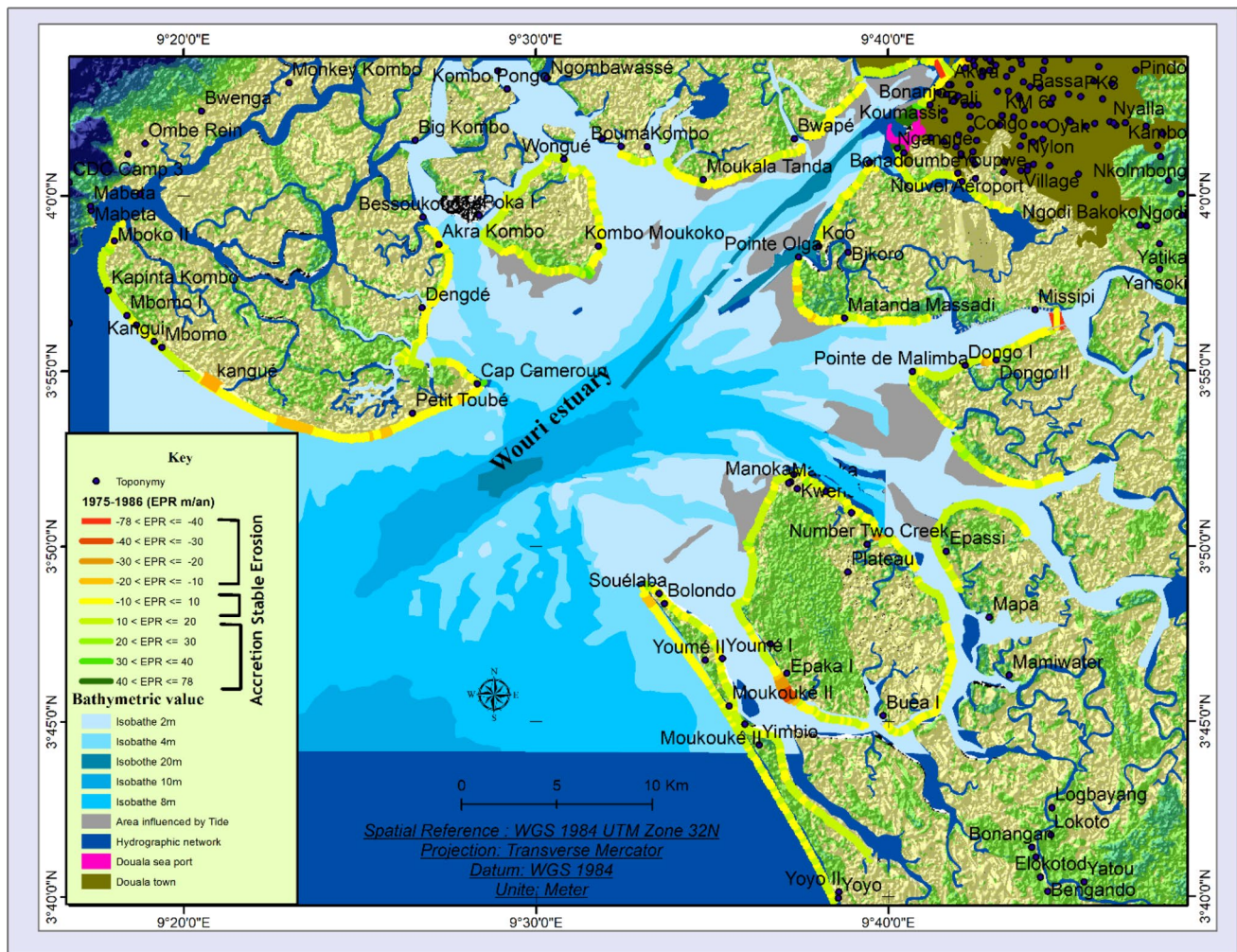
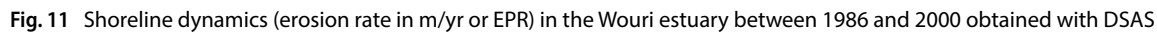


Fig. 10 Shoreline dynamics (erosion rate in m/year or EPR) in the Wouri estuary, 1975–1986 obtained with DSAS. Topography is extracted from the digital terrain model downloaded from the USGS website: <https://earthexplorer.usgs.gov/>. Bathymetry is obtained from the Navi-onic website: <https://www.navionics.com/fr/charts>. Transect 1 is located at Yoyo and the last transect is above Mboko II. The same applies to the fig. that follow

4.1.2 Shoreline dynamics between 1986 and 2000 (14 years)

Between 1986 and 2000, widespread erosion occurred throughout the Wouri estuary, with varying degrees of severity (Fig. 11). A maximum erosion zone is observed between Cape Cameroon and Kangué in Zone 1. In contrast, the western part (Mboko) exhibits minimal accretion. Notably, the eastern portion of Zone 2, previously experiencing accretion, is now undergoing erosion. The Kombo Moukoko region is shifting from stability to increased instability. In Zone 3, substantial accretion is observed, particularly around the APD channel. The tidal arm southwest of Douala shows minimal erosion. However, erosion has intensified south of Olga Point, especially north of Malanda Massadi. Zone 4 is also experiencing erosion, while the town of Epassi is undergoing accretion. Zone 5, encompassing Manoka Island, exhibits some variability, with the sector towards Epaka remaining eroded. The northern part of the island, towards Dahomey, shows signs of erosion. At the base of the spit, Zone 6 is expanding southward but eroding towards Souélabá.

Over the 14 years, statistical analysis of the Fig. 11 above reveals the following average values for shoreline dynamics: Zone 1 exhibits a shoreline retreat of -25 m and accretion of +8 m/year. Zone 2 shows a shoreline retreat of -11 m and accretion of +21 m. In Zone 3, the shoreline retreated by an estimated -13 m and accreted by +35 m/year. Zone 5 recorded a shoreline retreat of -16 m, compared to 15 m of accretion. Finally, Zone 6 shows a shoreline retreat of -21 m/year and accretion of -23 m/year. Notably, Zone 1, home to Cape Cameroon, the estuary's main economic hub with a population



4.1.3 IV-1-3 Shoreline dynamics between 2000 and 2016 (16 years)

Over these 16 years, zone 1 remains the most eroded, with an average retreat of -17 m, compared with an average accretion of $+21$ m. Zone 2 has once again remained stable. This zone is sufficiently protected to the north by the Moukalan Tanda point and to the south by the Cap Cameroun point; in addition, the bathymetry is sufficiently low (2 m), which seriously slows the speed of the marine currents that reach it. Zone 3 shows an average retreat of

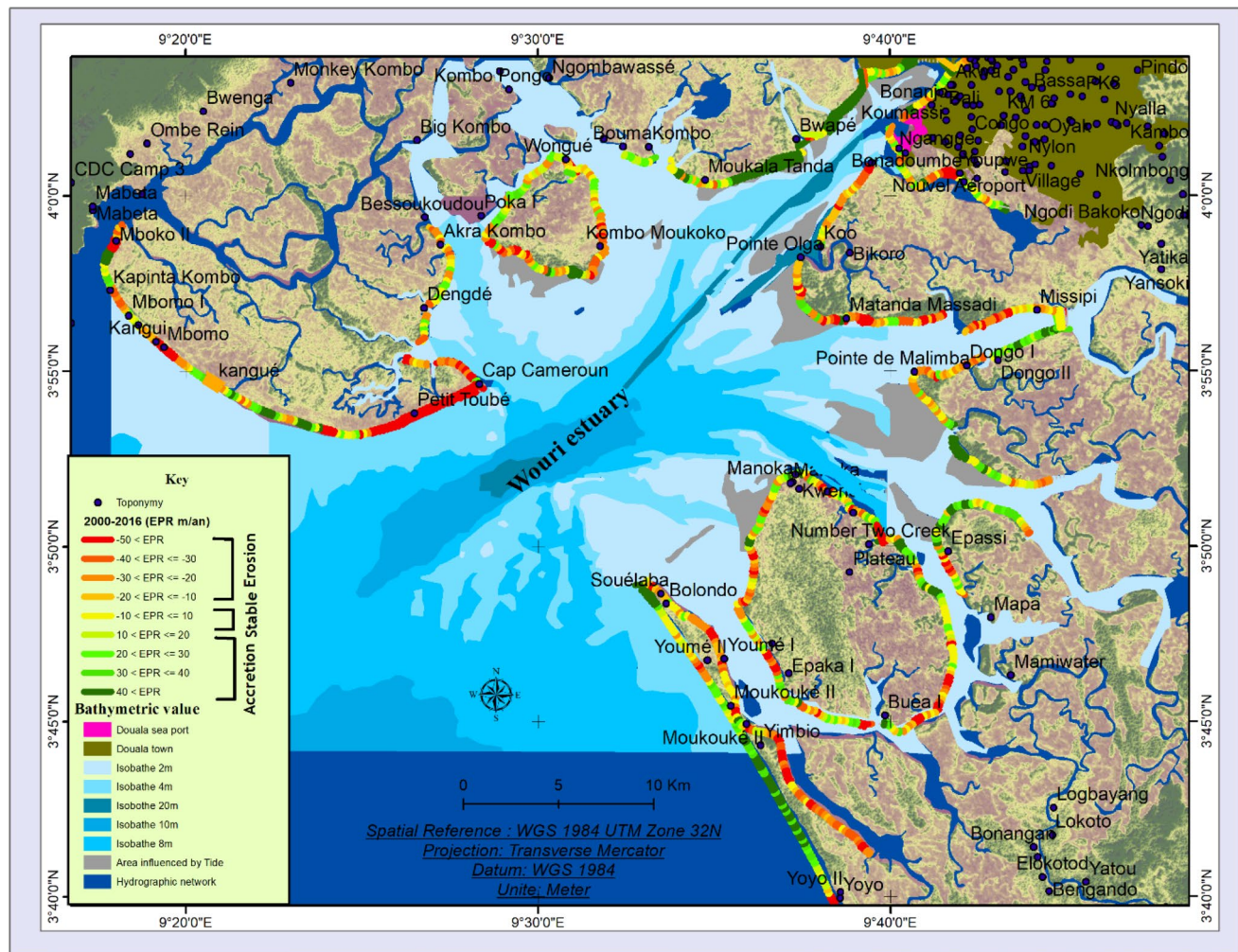


Fig. 12 Shoreline dynamics in EPR (m/yr) in the Wouri estuary between 2000 and 2016 obtained with DSAS

– 14 m/year compared with an accretion of + 28 m/year. Zone 4 has remained stable. This zone has almost the same characteristics as zone 2. Zone 5 shows an average shoreline retreat of -11 m/year and an accretion of + 10 m/year. Zone 6 does not show any shoreline retreat, but is rather accreting (+ 32 m/year).

4.1.4 Shoreline dynamics between 2016 and 2024 (08 years)

Over the past four (04) years, there has been an increase in the number of eroding sectors in the Wouri estuary (Fig. 13) zone 1 was eroded overall. Along with Cape Cameroon and *Petit Toubé*, *Kangué* and *Mboko* are also deteriorating. The decline in Zone 2 contrasts with the previous period. The same holds true for zone 3, which has undergone remarkable transformations, with the appearance of numerous zones of extreme erosion. There is little accretion at its tip towards the ocean and on its northern side, even though Zone 4 is eroding at its right and left ends. The same thing happens to the island of Manoka (zone 5) which experiences erosion, albeit with a few pockets of moderate accretion and stability. On the other hand, Zone 6 is more likely to become fatter, especially at its base, facing the ocean, and at its tip, near the locality of *Souélaba*.

In this recent 08-year period, zone 1 shows an average retreat of – 16 m/year, compared with an accretion of + 11 m/year. Zone 2 is experiencing erosion, with an average retreat of – 19 m/year and an average accretion of + 10 m/year. This zone, whose main locality is Kombo Moukoko, has seen recent demographic growth. The population has risen from around 1210 in 2010 to over 3000 in 2024. Most of the population are fishermen. Zone 3 still holds the record for retreats, with – 39 m/year compared with + 14 m/year of accretion. This period coincides with the major works to widen the site of the autonomous port of Douala. Zone 4 shows little erosion, with a rate of – 8 m/year and + 9 m/year of accretion. Zone

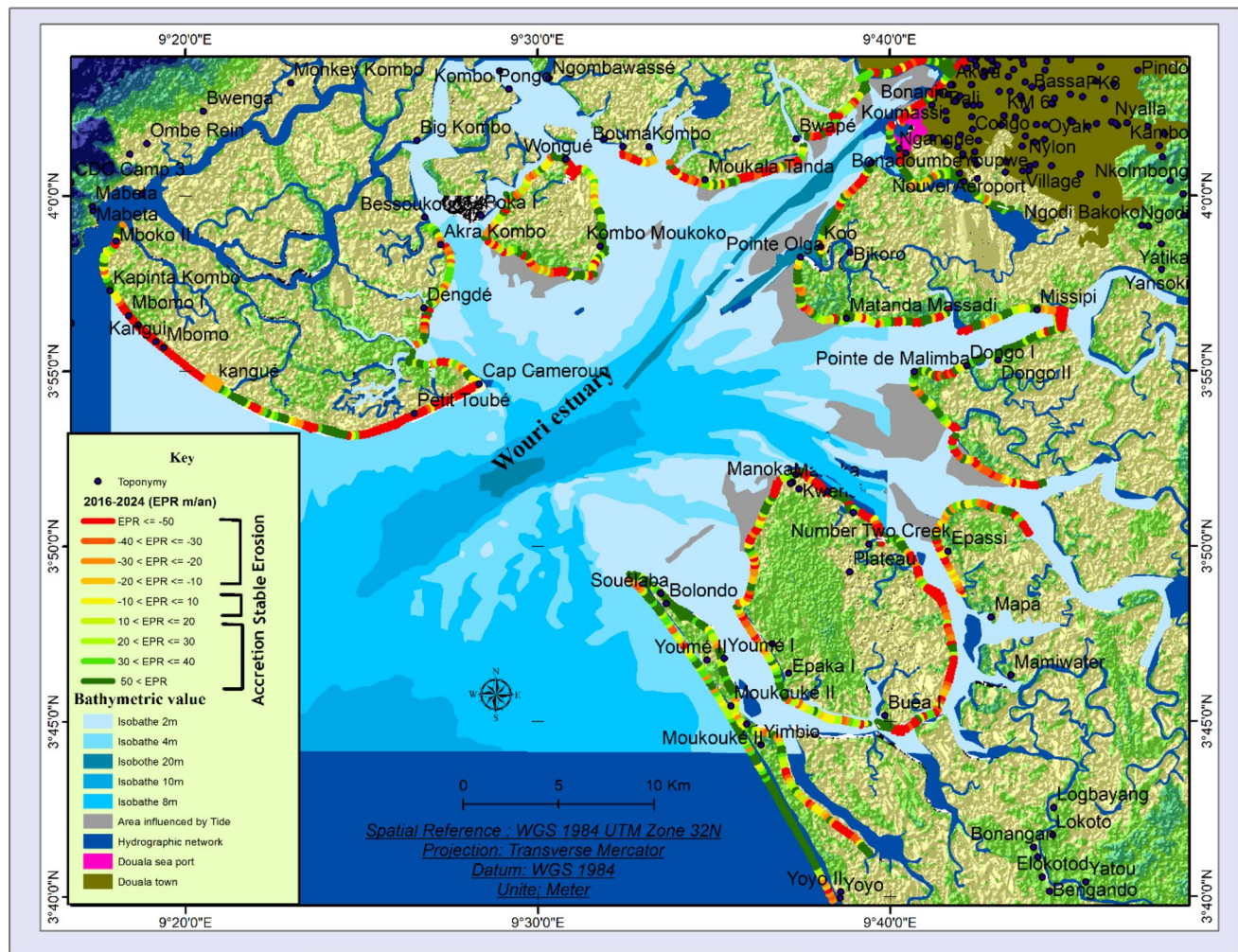


Fig. 13 Shoreline dynamics in EPR (m/year) in the Wouri estuary between 2016 and 2024 obtained with DSAS

5 shows – 21 m/year of shoreline retreat compared with + 22 m of accretion. Finally, zone 6 shows an average shoreline retreat of – 9 m and accretion of more than 40 m.

This analysis, based on low spatial resolution Landsat images, provided a general trend in coastal erosion in the Wouri estuary. The Cap Cameroun area, which is currently a hot spot for coastal erosion in the estuary, needs to be analyzed using high spatial-resolution images. The following session will therefore zoom in on this area using Pleiades and Google Earth images.

4.1.5 Comparative analysis of coastal kinematic in the Wouri estuary in LRR and EPR between 1975 and 2024

In the context of the Digital Shoreline Analysis System (DSAS), the End Point Rate (EPR) and the Linear Reduction Rate (LRR) are two distinct methods of assessing coastal change. The EPR measures the rate of change between two shoreline positions at different times, calculated by taking the difference in position and dividing by the elapsed time, providing a direct estimate of the rate of erosion or accretion. The LRR, on the other hand, represents a linear rate of reduction in change over a wider period, incorporating local variations to provide a smoothed view of long-term coastal trends. In this way, the EPR provides an instantaneous measure of change, while the LRR allows general trends in erosion or accretion to be observed over an extended period.

A comparative analysis of the coastline dynamics values shows a slight but significant difference, which makes it easier to judge which of the approaches gives a more accurate and consistent picture (Table 4).

The End Point Rate (EPR) reveals an average accretion rate of + 3.10 for the entire Wouri estuary, indicating the environment's potential to yield significant gains under favorable conditions. However, the average retreat rate of -1.25

Table 4 Comparison of coastline dynamics rates in EPR and LRR

	Average accretion rate	Average erosion rate	Median	Standard deviation	Max.	Min.
EPR	3.10 m/year	– 1.25 m/an	2.50	0.63	10.79	– 2.91
LRR	2.90 m/year	– 0.8 m/year	2.60	0.72	8.03	– 2.74

underscores a vulnerability to sudden declines. This suggests that while the EPR can demonstrate impressive performance, the variability in results across different sites points to notable instances of retreat.

In comparison, the Long-Term Rate of Retreat (LRR) exhibits an average accretion rate of +2.90, which is slightly lower than that of the EPR. Nevertheless, its average retreat rate of -0.80 is less pronounced, suggesting that although the positive outcomes are somewhat diminished, the LRR demonstrates greater resilience to retreat, thereby offering a more stable and predictable framework. The EPR may be favored for rapid gains, whereas the LRR is better suited for contexts that prioritize stability and controlled retreat.

It is important to note that the LRR's standard deviation is higher, indicating greater variability in its performance. Extreme values show that the EPR can reach significant peaks, with a maximum of 8.03, while the LRR achieves a maximum of 10.79. This suggests that while the LRR may occasionally outperform the EPR, such instances are less frequent.

Furthermore, the median EPR value stands at 2.50, compared to a slightly higher median of 2.60 for the LRR. This indicates that the majority of LRR values are concentrated within a higher range, despite a lower mean. The stability of the LRR is evident, presenting consistent performance with a minimum of –2.74 and a maximum of 10.79. Thus, while the EPR can provide remarkable individual performances, the LRR appears to offer a more sustainable and predictable approach, which may be preferable in contexts requiring long-term reliability.

Examining Zone 1, where Cap Cameroon and Toubé are located, the average retreat/erosion value for the EPR is approximately –18 m/year, translating to a total retreat of –882 m over the 49 years from 1975 to 2024. In contrast, the LRR indicates an average retreat of –15 m/year, corresponding to a total average retreat of –735 m. The difference between the two methodologies is –147 m, highlighting the significant shoreline retreat at Cap Cameroon. A quantitative analysis of vulnerability to erosion and submersion conducted by a team of Cameroonian-Quebec researchers estimated a retreat of 25 m/year for Cap Cameroon (Marie, personal communication). Figures 14 and 15 illustrate the shoreline dynamics for the EPR and LRR from 1975 to 2024 in the Wouri estuary.

4.1.6 Projection of shoreline dynamics in 2044 in the Wouri estuary using BETA prediction model

Compared with current trends, the BETA prediction model showed that coastal erosion will intensify in the Wouri estuary between now and 2044. Zone 1, for example, which is the hot spot for coastal erosion, will continue to erode most intensively. Taking 2024 as the reference year, a retreat of 21 m/year, or 420 m, is expected by 2044. In zone 5, the spit of coastline around the island of Manoka is also likely to undergo severe erosion. This would undermine its protective function for this island, which is rich in biodiversity. Figure 16 below shows an overlay of the different shoreline (1975, 2034, and 2044) and a specialization of erosion, accretion and stability of the shoreline.

Several authors have used this model for prospective studies. Such is the case of [102]. In a very thorough study, these authors presented a generic index based on BETA regression to assess the exposure of buildings to coastal retreat, focusing on the coast of the Pays de la Loire region in France.

The same applies to [103] who, in a scientific article, developed a synthetic index to quantify the vulnerability of road infrastructures to coastal hazards, integrating BETA regression models to assess the potential impacts of erosion on roads in the future.

Finally [104] assessed the vulnerability of sandy coasts to erosion using predictive models, including BETA regression, for coastal hazard mapping in the Vendée region of France.

4.2 Mapping coastal erosion at Cape Cameroon using Pleiades and Google Earth images

The shoreline in the Wouri estuary recedes the most in Cape Cameroon. Mapping large areas has shown this so well. This approach, based on very high-resolution Pleiades images and Google Earth aerial photos, aims to produce more refined statistics, in order to quantify the retreat of the shoreline with as little error as possible.

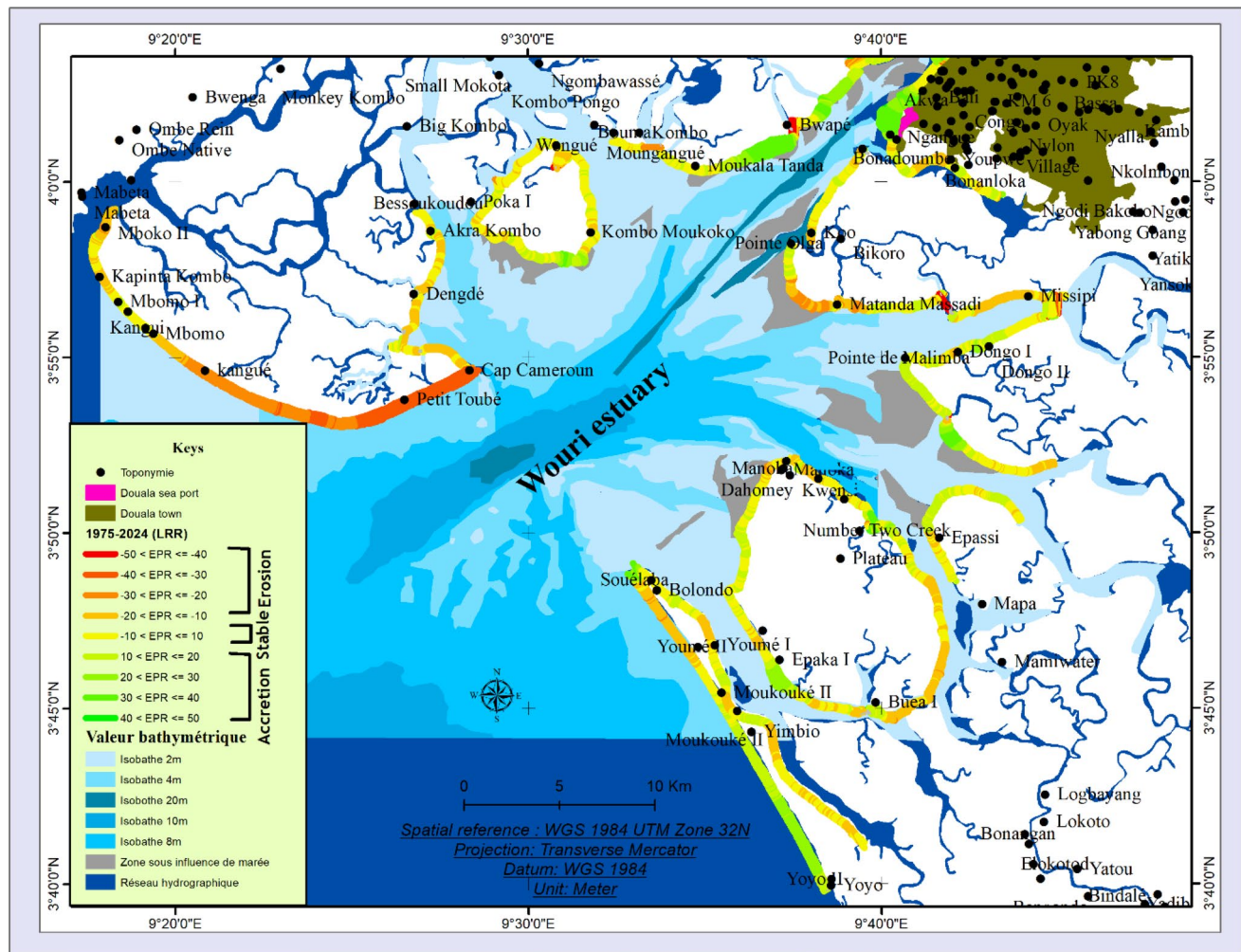


Fig. 14 Dynamics of the coastline in the Wouri estuary between 1975 and 2024 in LRR (m/year), based on Landsat satellite images

4.2.1 Evolution of the shoreline between 2000 and 2016 (16 years), using Pleiades images from 2013 and Google Earth aerial photographs from 2000 and 2016

The tip of Cape Cameroon has suffered severe erosion over the last 16 years. As far south as the town of Toubé, it has spread. Cape Cameroon remains the center of erosion. The shoreline became appreciably firmer after the town of Toubé (Fig. 17).

Quantitatively, the magnitude of the shoreline retreat is -5 m to the north of Cape Cameroon and -32 m to the south of the said locale. The shoreline retreat at Petit Toubé was -8 m/year. The linear length to the north of Cape Cameroon shows a slight increase in accretion. An elevation of $+2$ m/year was observed only at the southern end. The Cape Cameroon area shows a record shoreline retreat of -33 m/year (Fig. 18).

4.2.2 From 2016 to 2018 (2 years)

The coastal strip remains eroded in this period. The northern end of Cape Cameroon has a shoreline retreat estimated at $+15$ m/year. There were two accretions to the north of Cape Cameroon. The most shoreline retreat rate is measured at Cape Cameroon and is estimated to be 53 m. At Toubé, a small accretion of $+5$ m/year is visible over a distance of no more than 100 m. The shoreline retreat of $+4$ m/year was reached to the south of Toubé, where erosion increased over a distance of more than 2 km. Figures 19 and 20 show the behavior of the shoreline during this analysis period.

If we look at the results obtained with Landsat and those obtained with Pleiades, we can see that there is consistency between the two. In the period 2000–2016, both image sources showed erosion at Cape Cameroon. The tip of

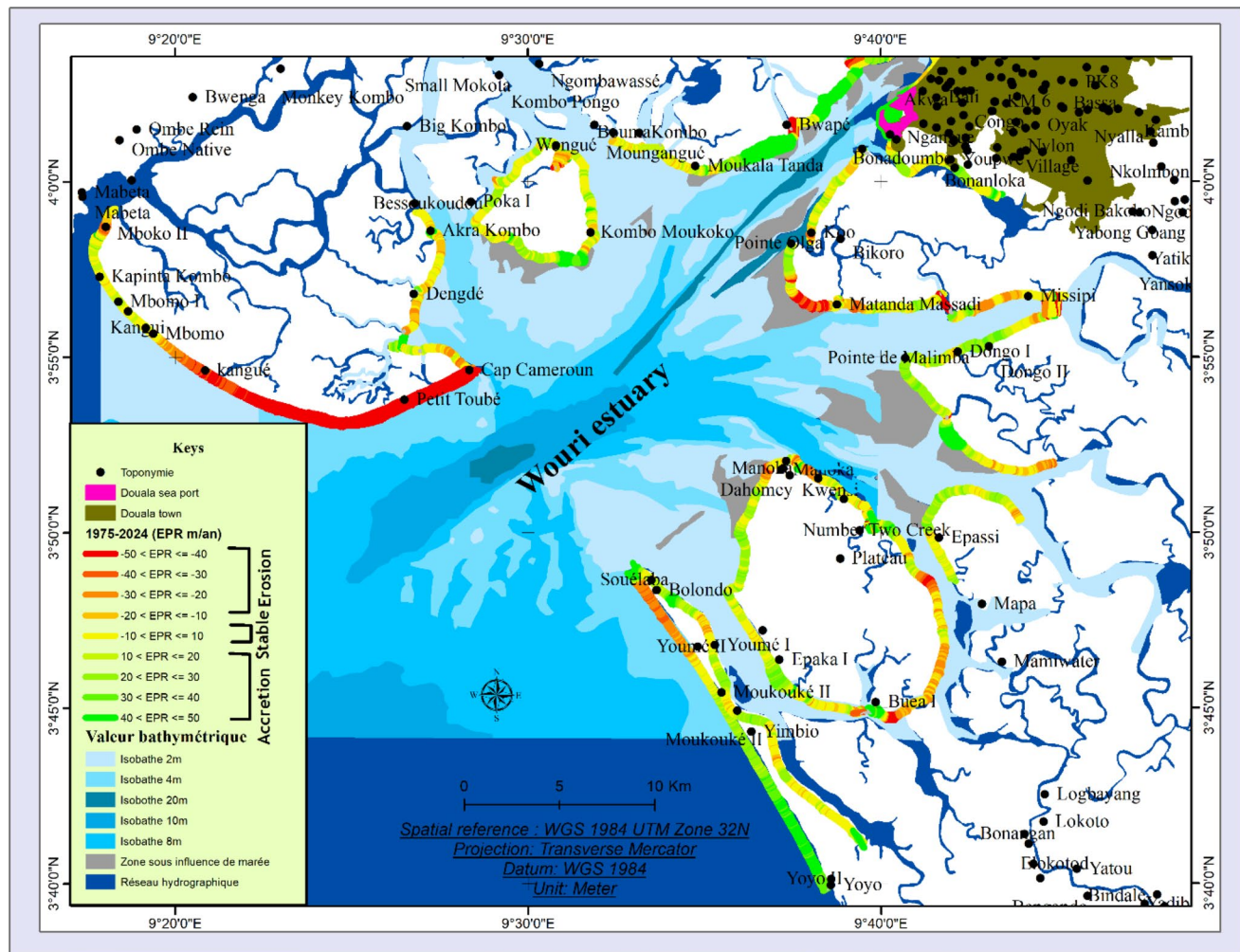
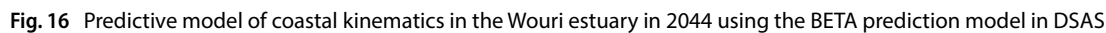


Fig. 15 Coastline dynamics in the Wouri estuary between 1975 and 2024 in EPR (m/year), based on Landsat satellite images

Cape Cameroun and the town of Toubé were the main points of control. As a result, Cape Cameroon continues to exhibit the highest rate of shoreline retreat within the Wouri estuary. The remains of houses destroyed by coastal erosion in the intertidal zone were seen on an on-site visit in March 2024 (Fig. 21).

4.3 IV-3 Comparison of mapping results with field observations in the Wouri estuary

The previous analyses have been complemented and refined by field observations, testimonies from long-time residents of the intertidal zone, and Google Earth aerial photos from 2000 and 2016. Field observations along the Cameroonian shoreline have enabled us to identify remnants (such as house foundations, tree trunks, etc.) that attest to the existence of coastal erosion at Cap Cameroun. A total of five field visits were conducted: two in 2014, one in 2015, one in July–August 2018, and one in May 2019. The most striking spatial evidence in the Wouri estuary is the presence of the FM radio antenna at Cap Cameroun, built in 1992 in the middle of the territory, now located over 300 m offshore. Similarly, colonial remnants, such as the prison where Cameroonian resistance fighter Douala Manga Bell was held, provide tangible evidence. Built by the Germans around 1910, this reinforced concrete structure still stands on the eastern shores of Manoka Island, bordering the coastal spit (Souélaba Point). This prison, a veritable indestructible fortress, is now situated almost 40 m into the ocean (Fig. 21).



Given the extent of erosion at Cape Cameroon and other locations, the situation in the Wouri estuary is even more concerning. A correlation seems to be established when comparing this erosion phenomenon with the explanatory factors discussed above. Existing literature supports this idea.

Long before this work, several authors had already mentioned coastal erosion in the Wouri estuary. [105] used Landsat images from 1984 and 2017, Google Earth aerial photographs from 2000 and 2016, and GPS surveys to analyze the dynamics of the shoreline between Cap Cameroun and Toubé in the Wouri estuary. Between 2016 and 2017, Cap Cameroun showed an average retreat of 1.4 m. The study also revealed an average rate of change in the shoreline of Cap Cameroun of 452.4 m, between 1984 and 2017, with an annual average of 13.70 m. This shows that Cap Cameroun has experienced a higher rate of shoreline retreat than any other in the coastal region. The annual shoreline retreat for the zone as a whole would be 9.56/year, while that of Cap is 13.70 m/year, with a difference of 10%, i.e. a difference of 4.14 m/year. At Toubé, between 1984 and 2017, changes in the shoreline were measured at different rates, with an average shoreline retreat rate of 13.75 m/year. The main factors identified were the strong presence of fishermen, who weaken the environment by cutting mangroves, and the action of longshore drift.

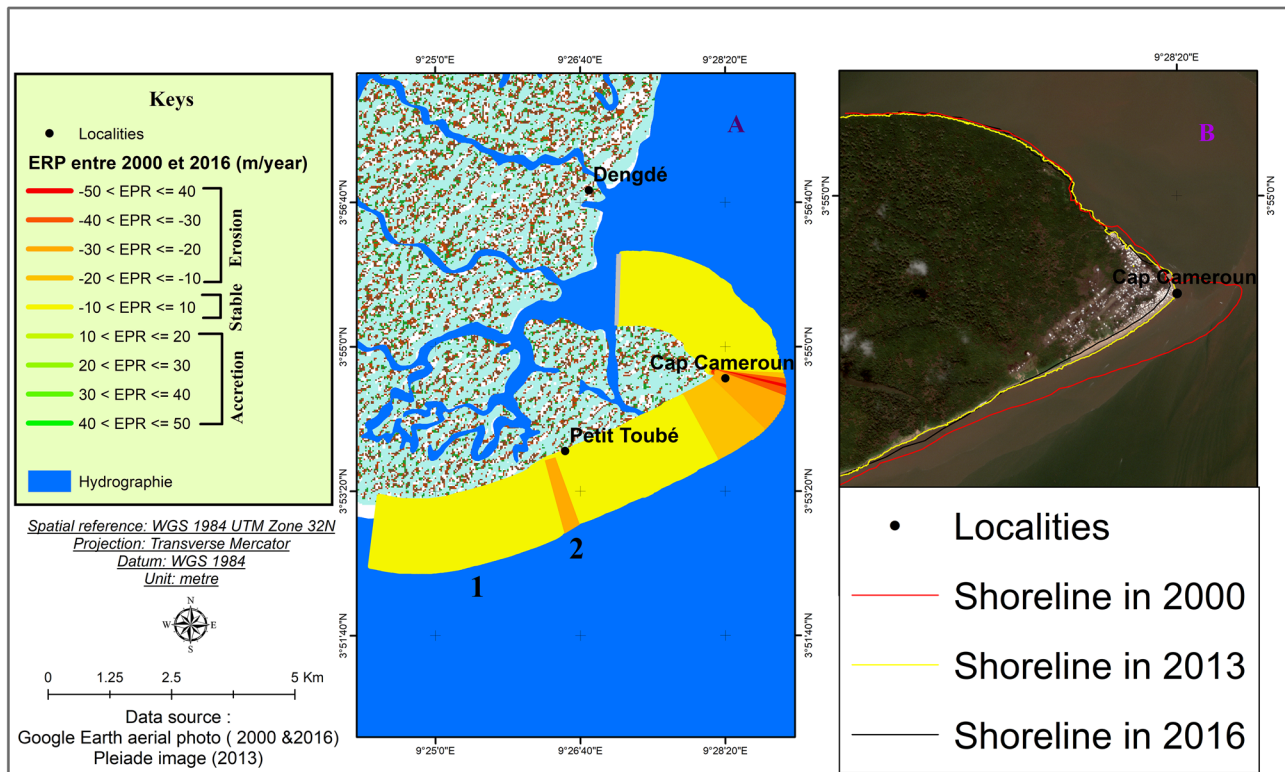
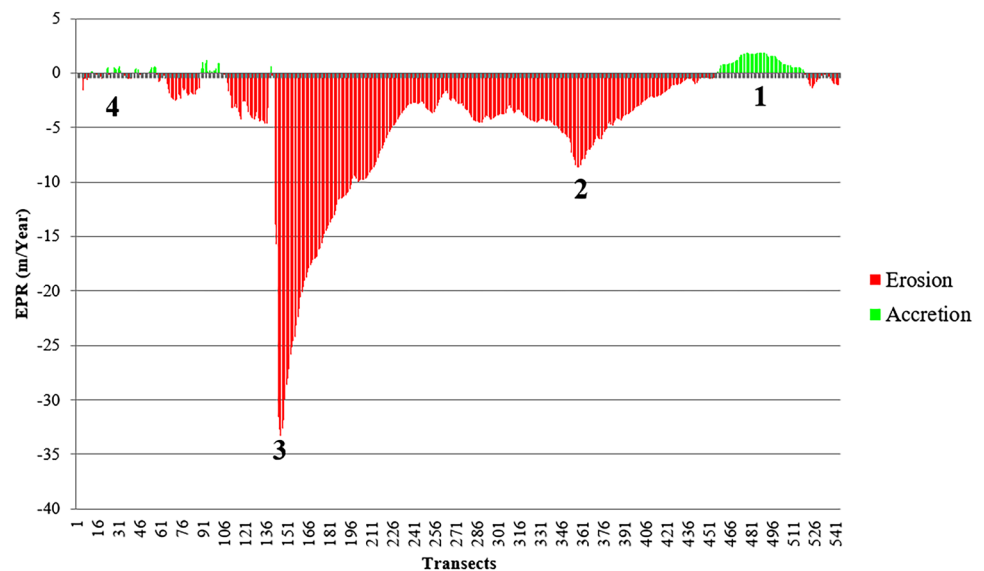


Fig. 17 Left **A** shoreline dynamics in m/year calculated with DSAS, extracted from aerial photos posted on Google Earth (years 2000 & 2016), and the 2013 Pleiades image (obtained from the PERSONAZ project). Line in **B** this is the superposition of the 2013 Pleiades' image and the shoreline of 2000, 2013 and 2016

Fig. 18 Shoreline dynamics in EPR (m/year) between 2000 and 2016 using Pleiades images and Google Earth aerial photos with DSAS, with shorelines divided into 533 transects 50 m apart



The work by [33], in the Wouri estuary covers the period 1948–2012. They used topographic surveys from the archives of the French Naval Hydrographic and Oceanographic Service (SHOM) on the Wouri estuary from 1948 to the present day to analyze the retreat of the shoreline in the Wouri estuary as a whole. In zone 1, which corresponds to Cap Cameroun, an average shoreline retreat of 3.2 m/year was estimated between 1948 and 1996, i.e. 48 years. For the same zone, we obtained an average shoreline retreat of 3.10 m/year between 1975 and 1986 (11 years). On either side of the PAD port facilities, these authors mention a shoreline retreat of – 0.6 m/year on the east bank of the port and – 5.8 m around

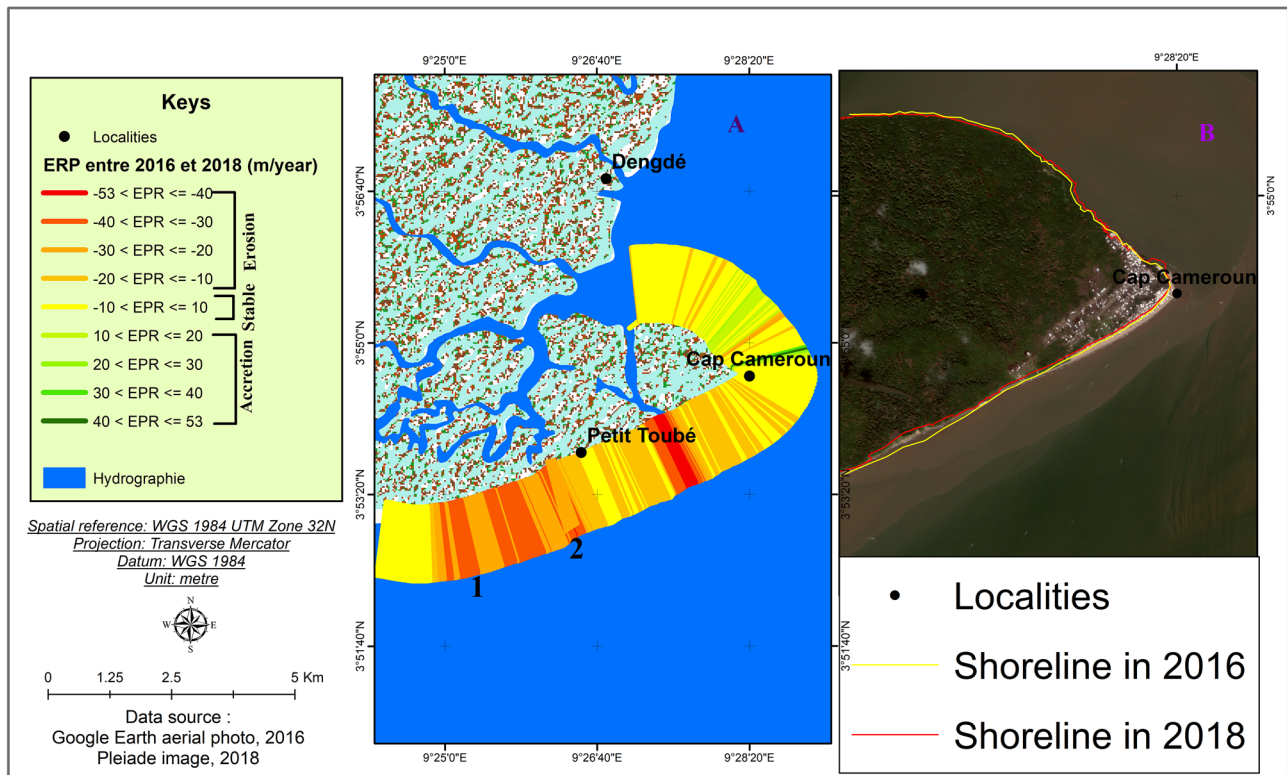
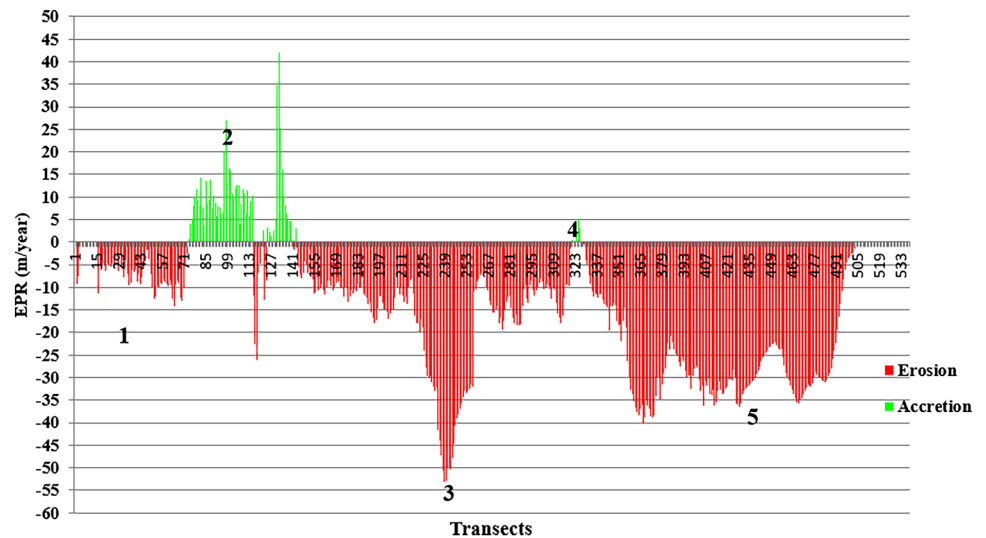


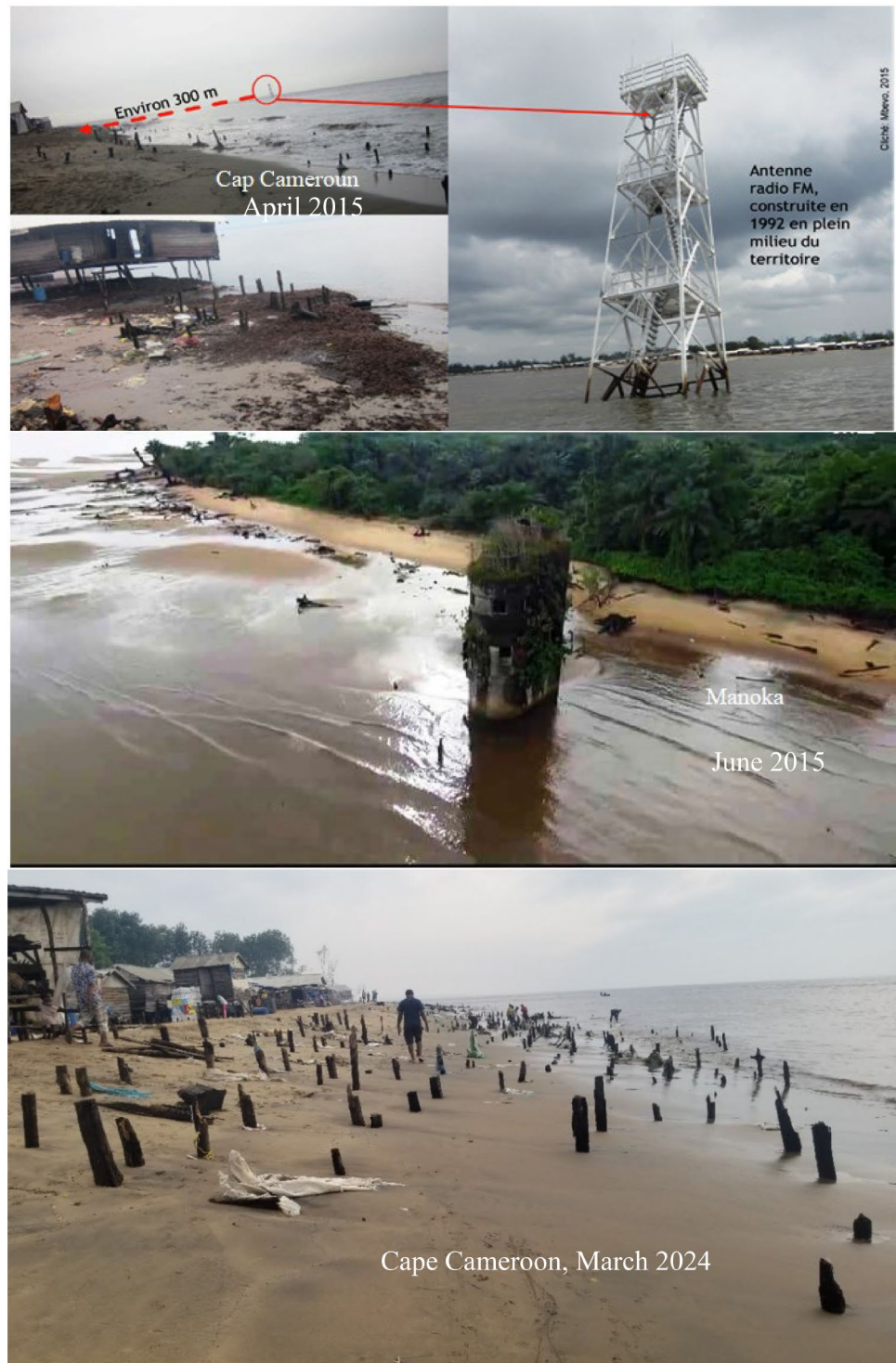
Fig. 19 **A** Shoreline dynamics in m/year between 2016 and 2018 calculated with DSAS, extracted from aerial photos posted on Google Earth (the year 2016), and the 2018 Pleiades image (obtained from the PERSONAZ project). Line in **B**: this is the superposition of the 2018 Pleiades image and the 2016 and 2018 shorelines

Fig. 20 Shoreline dynamics in EPR (m/year) between 2000 and 2016 calculated with DSAS, obtained from linear extract of Pleiades (2018) and Google Earth (2016) images, with shorelines divided into 523 transects 50 m apart



the port site. For zone 2 (taken as a whole), we found an average shoreline retreat of 3.69 m/year. For zone 5 around Manoka Island, the same authors conclude that erosion is low, with an annual shoreline retreat of $-0.4/\text{year}$. On the coastal spit (zone 6), towards Souélaba Point, they obtain a shoreline retreat of 1.4 m/year. In contrast, we calculated a higher average shoreline retreat of 3.3 m/year around Manoka Island and 2.28 m/year on the spit. Between 1996 and 2012, according to these authors, the Wouri estuary was fairly stable, except for the areas around Cap Cameroun and a thin section of Pointe Olga. Erosion is said to have increased at Cap Cameroun, with an average retreat of 5.8 m/year, 3.2 m/year around the PAD, 2 m/year on Manoka Island, and 2 m/year on the coastal spit. Between 2000 and 2016 (the

Fig. 21 Evidence of severe erosion in the Wouri estuary. Cap Cameroon (April 2015 and March 2024); Manoka (June 2015); Photo credit: Mbevo



period closest to theirs), we quantified a shoreline retreat of 4 m/year at Cap Cameroun, 4.53 m/year around the PAD, 1.74 m/year around Manoka Island, and 1.8 m/year on the spit. These results are similar, although we did not use the same sources of input data. Similarly, the boundaries of the zones are not the same, as we extended the analyses to the tidal inlets and the entire coastal strip around the Mabé mangrove reserve. In any case, the Wouri estuary is undergoing permanent and disproportionate erosion. The main factors cited by the authors are natural processes such as tidal action, climate change, and human activity.

Ref. [32] also assessed changes in the shoreline along the entire Cameroonian shoreline. After identifying eroded areas, they quantified an average retreat of more than 0.54 m/year over the entire shoreline between 1986 and 2015. The main factors they identified were the predominance of socio-economic activities on the Cameroonian coast, as well as tidal action, which often reaches more than 2 m in the Wouri estuary. In the Douala area, which is made up of sedimentary rocks, [106] quantified a shoreline retreat of around 4.78 m, or a linear shoreline retreat rate of 31.86 cm/year, based on Landsat images from 1978, 2000 and 2015.

Ref. [34] worked on the Manoka Island area, which corresponds to zone 5 delimited as part of this work. As base data, they used Landsat images from 1975, 1986, 2000, 2007 and 2010. These dates are similar to those used in this study, with the exception of 2007 and 2010. The results show that the shoreline in this zone has retreated by an estimated ± 30 m over the last 35 years. Occasionally, average retreats of -0.79 m/year to -3.4 m/year were recorded. This regression of the linear area rhymes with the destruction of the mangrove, which is estimated to have shrunk by 11% compared with the area it covered in 1975. Climate change is also cited as one of the main causes.

Over Cameroon [107] and [106] cite a similar connection between the hydrodynamics of the adjacent beaches in Anglet and Southern Italy. The predominant action of the tides on sediment dynamics is highlighted. Ref. [107] examined the shorelines of Benin, Côte d'Ivoire, and Ghana to discover a strong correlation between tides and ocean currents in the destruction of shorelines. During high tide, the most destruction is observed. Cape Cameroon is currently experiencing the same situation that this is the same situation that Cape Cameroon is in. The temporal variations over several years of cumulative erosion are not explained by the fact that erosion over a year corresponds to the occurrence of high tides. Over time, the extent of eroding areas varies greatly both on the Atlantic coast, as at Cape Cameroon, and in the interior of the estuary, even though the tides have not changed. For example, in the Wouri estuary, the extension of period.

5.2 Mains factors of coastal erosion

5.2.1 Development, urbanization, dredging and coastal erosion on Cameroon's shoreline

Cameroon's shoreline is well-developed when it comes to coastal development. The construction of the APD in early 1881 marked the starting point in the Wouri estuary [33]. The width of the Wouri channel was narrowed by the port extension out to sea. This will lead to erosion on the other side of the channel.

The expansion and extension of the city of Douala over the existing mangrove zones will reduce the area occupied by the tide in this part of the estuary (Fig. 22). The urban fabric is estimated to have grown from 2478 hectares in 1975 to 18,614 hectares in 2018 [108]. Significant sediment removal and the resuspension of previously deposited sediments are caused by regular dredging operations in the APD boat channel ship channel [39]. The void created by this removal increases the depth of the channel, which could lead to a narrowing of the unquantified tidal wave in the Wouri estuary [109]. The speed of tidal propagation is dependent on the configuration of the seabed. The thicker the sand on the bottom, the slower the waves and tides get.

Wouldn't it be a good idea to deposit dredged sediments in areas with a sediment deficit, such as Cape Cameroon, instead of selling them or dumping them out to sea? These sediments could be reclaimed and then pumped back to eroded sites [110].

5.3 Sinking of the coastal spit at Souélaba headland

The strong erosion at Cape Cameroon is explained in this paragraph. The results of the shoreline dynamics study and observations made in situ indicate that the deepening of the spit around Manoka Island could partly explain the coastal erosion at Cape Cameroon.

The estuary closes off when this spit of shoreline deepens, encouraging erosion towards Cape Cameroon on the opposite side of the estuary. The dynamic nature of this spit, whose width ranges from 60 to 80 m, has already been highlighted by [57]. The drift currents at work in this estuary are diverted towards Cape Cameroon by this narrowing (Figs. 15, 16, 17 and 18) show that the maximum erosion at Cape Cameroon occurred between 2000 and 2017, corresponding to the most spectacular escalation of the spit at Souélaba headland.

The strong erosion at Cape Cameroon could also be favored by the deep bathymetry in this area. The Navionic bathymetric map shows a depth of -4 m around Cape Cameroon, and a channel with a depth of more than 20 m is located just offshore. In this zone, the waves will be less attenuated than in others. Actually, the Kombo Mokoko point (to the

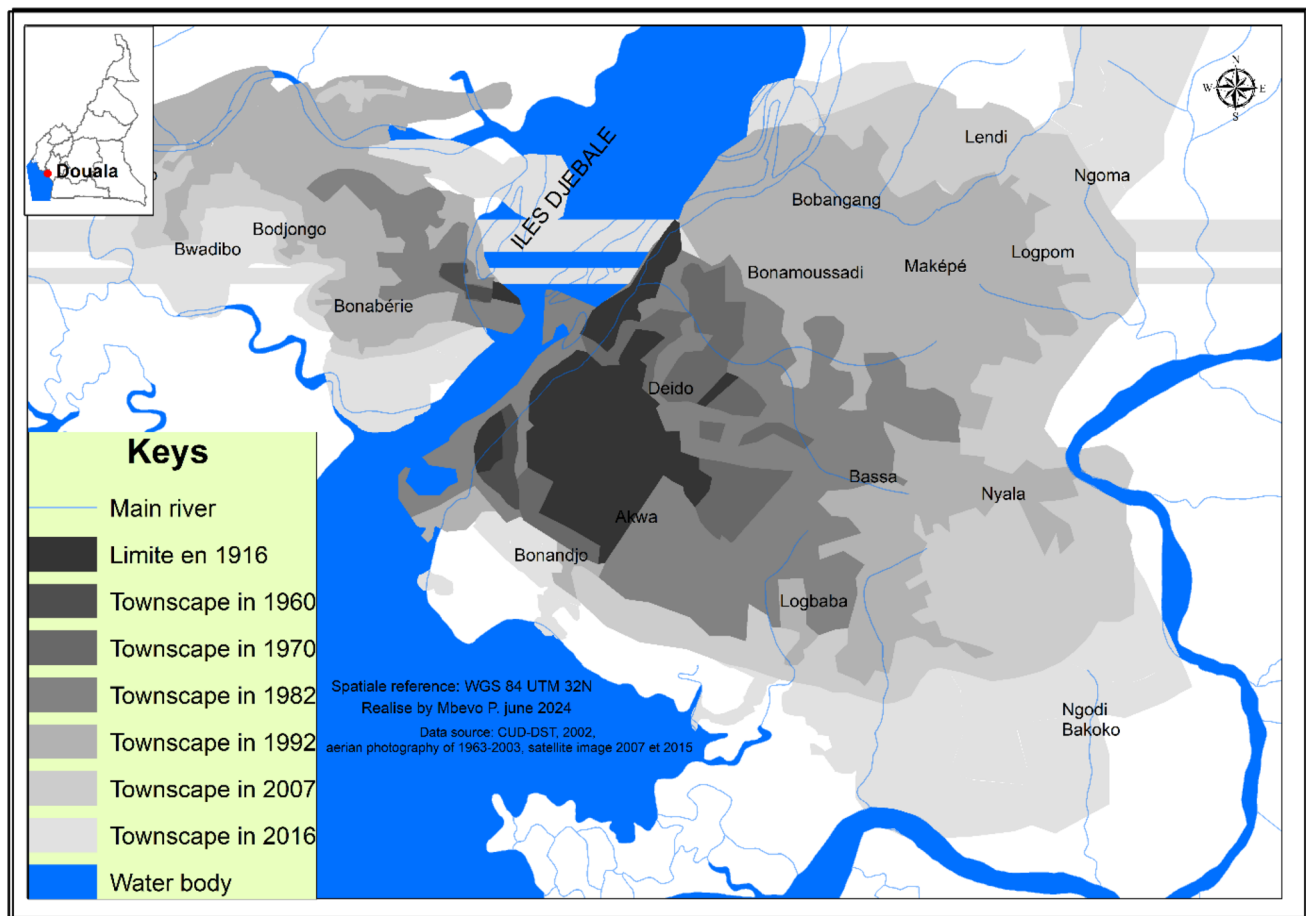


Fig.22 Dynamic of the urbanized area in Douala town, between 1916 and 2016, using aerial image

north of Cape Cameroon), which is = 2 m deep, has a more stable line. The amplitude of the waves is lower in the interior of the estuary because this point is set back. This explains why the shoreline is stable at this point.

5.4 Marine dynamics and its influence on the morpho-dynamics of the shoreline

Most of the other estuaries worldwide see their balance disturbed by human activities, such as dredging and enlarging the channel leading to the port of Douala, and the extraction of sands, which alters the morphology of the estuary and consequently its hydrodynamics. The action of ocean and river currents that meet in the estuary is one of the natural factors that make up the whole picture. The hydrodynamics of the mouths of Cameroon are affected by these factors, but the most likely consequences are an amplification of the tides and an increase in sediment transport along the channel [111]. Rising sea levels will further accentuate this trend. The quantity of sediments transported to the mouths of Cameroon is affected by the changes in land use in the various BVs and the construction of a dam on the Sanaga [112]. The development of agro-industrial activities will increase the sediment flow towards the estuary, while the dams retaining sediments upstream will decrease it [113, 114]. No quantitative assessment of the processes involved is prevented by the lack of regular measurements of the sediment load of rivers.

Changes in turbidity, nutrients, and their dispersion can be caused by all of these processes [61]. As a result, the marine resources of the estuary are impacted, as evidenced by the interviews conducted with this community by [115]. The reduction in biodiversity and the decrease in fish populations are caused by the reduction in biodiversity. Thus, the evolution of fishing in the Wouri estuary is marked by significant environmental difficulties, necessitating responsible handling of this vital resource for local populations [116]. Thus, the evolution of fishing in the Wouri estuary is marked by major environmental challenges, which require sustainable management of this essential resource for local communities.



Fig. 23 Mangrove wood piled up behind houses in Petit Toubé for smoking fish and cooking food. Photo credit: Mbevo, March 2024

5.5 Degradation/deforestation of plant cover/and increased coastal erosion in the Wouri estuary

Stabilizing coastal areas is dependent on mangroves. It favors accretion through its root system, which fixes the soil; it slows down the tide and ipso facto constitutes a natural barrier against coastal erosion; it intercepts water from rainfall and considerably reduces its flow [34]. The degradation or deforestation of it appears to be a factor in the vulnerability and amplification of coastal erosion [107].

The mangroves of the Wouri estuary are in danger [37]. The agro-industrial activity on its edges and the growth of fishing populations have made this anthropized area fragile. In Cape Cameroon, Manoka, in short, the estuary, the destruction of the mangrove is a reality [34]. There is a connection between coastal erosion and destruction [33]. The 2018 land use map shows that areas of stagnant water outside of the usual channel are where the mangrove has disappeared. In 1985, such a correlation had already been established by [117], who raised the issue of man's responsibility for increasing erosion in Senegal through land clearance for energy needs, land cultivation, etc. [118] emphasize the crucial role of vegetation cover in stabilizing the Sine-Saloum delta in the same country.

The FAO has raised the alarm about the degradation/degradation of the mangrove in Cameroon, estimating the annual loss of over 300 ha [119] The Mabé Mangrove Reserve, where Cape Cameroon is located, has lost an area of more than 1,162.25 ha over the past 30 years, representing a loss rate of 13.68% of its total area [120] As shown in Fig. 23, these mangroves are used for smoking fish, building housing and many other purposes.

5.6 Population growth and coastal erosion in the Wouri estuary

The steady population growth in the Wouri estuary is having a significant impact on the natural environment. This demographic dynamic appears to be driven by Douala, the main economic city. The population is growing, needs are increasing, and pressure on natural resources is increasing. This is what's happening in Cape Cameroon, as the number of fishermen grows. Cape Cameroon accounts for more than half of the fish supplies for the city of Douala. In situ fish smoking techniques are environmentally destructive. The mangrove wood is used abusively. Ref. [37] has already highlighted the high level of human activity in the Wouri estuary and the resulting environmental impacts. Marine

intrusion, flooding, soil pollution, and coastal erosion are some of the impacts. Population growth and coastal erosion are not unique to the Cameroonian coast, however. It's a global one. Looking at the islands of the Indian Ocean.

Ref. [121] notes that coastal erosion is worsening as a result of population growth and that population growth is aggravating coastal erosion and accelerating the degradation of coral reefs. There are coral reefs.

The authors of the Ivory Coast, [122] highlight the impact of human activities on the evolution of coastal areas in Port-Bout Bay. Natural hazards, including coastal erosion, are thought to be caused by demographic growth, which is the main factor in coastal dynamics.

5.7 Dynamics related to the Sanaga and its repercussions on morpho-dynamics in the Wouri estuary

The Sanaga River is the largest in Cameroon, covering over 140,000 km² with a length of 918 km. Until the eighteenth century, it flowed directly into the Wouri estuary, but has since shifted 11 km south, only feeding the estuary during exceptional floods. This impacts the dynamics of the Wouri, as the sediment supply from the Sanaga during these over-flow events greatly influences the estuary [32, 57].

The Sanaga's hydro-sedimentary kinetics have also been significantly altered by the construction of several dams, including the Mbakaou reservoir dam (6°18'16" N, 12°48'30" E), the Bamendjing reservoir dam (5°41'55" N, 10°30'03" E), and the Songloulou hydroelectric dam (4°04'41" N, 10°27'54" E) [61]. These dams have modified the river's flow and sediment transport.

The complex interplay between the Sanaga River and the Wouri estuary is not yet fully understood. The Sanaga plays a dual role, both supplying sediment during floods and being impacted by human developments along its length. Further research is needed to elucidate these dynamics and their implications for the broader regional ecosystem. Understanding the Sanaga's evolving relationship with the Wouri is crucial for effective management and conservation of this vital waterway.

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The Mapé reservoir dam (6°01'56" N, 11°18'18" E), built in 1988, is an impoundment dam located in the Bankim district, 11 km north-east of Magba. It is located on the Mapé River. The purpose of this regulation is to regulate the level of the Sanaga River to increase hydroelectricity production from downstream dams.

The construction of the Lom Pangar dam took place between 2012 and 2016 (5°22'17" N, 13°30'45" E). This is an embankment dam with a section containing a gravity dam on the Lom, located about 88 km north of Bertoua in the East Region of Cameroon. A major tributary of the middle course of the Sanaga is located on the Nachtigal dam, which is currently under construction. In September 2020, construction began.

The most downstream part also features the Édéa dam. It was constructed in 1950 and completed in 1954. Between 1966 and 1976, the power station was extended and rehabilitated in 2008. The capacity of the plant was increased from 4 to 265 MW. The sediment that no longer reaches the shoreline and feeds the spit is trapped by these dams. The development of this zone and the erosion observed between 1975 and 1986 may be due to this factor.

When it comes to dams on the African continent, we're thinking about the Akossombo dam, constructed in 1963 on the Volta in Ghana, which is said to capture more than 90% of the sediment on its way to the Togolese coast. Major erosion and scouring of the piers of the Accra-Lomé international road bridge were caused by it [123].

The dams on the Sanaga aim to regulate the flow and therefore flooding by regulating the flow. If there is a significant reduction in flooding, there should be less overflow from the Sanaga into the Wouri Estuary, which would encourage coastal erosion. The study by [124] shows, however, that the development of reservoirs and their operation up to 2004 did not significantly affect downstream peak flows. The construction of new dams may have changed this.

The reduction in sediment input from dams on the Sanaga could be offset by increased sediment input from deforestation, slash-and-burn farming, and the expansion of agroindustries in the Sanaga watershed. The Sanaga watershed has been heavily deforested for over 30 years. This is likely to increase the load of suspended and bottom sediments. This has been indicated by several authors [122, 125].

Finally, there is another factor affecting the sediment load transported by the Sanaga: climate change. Climatic variability strongly affects the suspended load, even in humid tropical regions. The most important factor here is the amount of rainfall during the dry season. The decrease in rainfall leads to a significant water deficit in the soils and a drop in river flow [122]. In the early 1970s, there was a major and widespread water deficit in the Sahel. This deficit had a major

impact on hydrology and solid transport in Cameroon [102]. Climate change is affecting not only the Sanaga River, but all other West African rivers [67].

5.8 Dynamics of other rivers: Mungo, Wouri, Dibamba, and others

These three rivers have catchment areas of an order of magnitude smaller than the Sanaga, and therefore their sediment inputs are smaller. However, there are no dams located along these rivers. There are varying geographical influences on accretion in the Wouri estuary. Zone 1 is directly influenced by the rivers that drain Mount Cameroon. These young terrains are much less altered and consolidated than the rest of the African craton, and they incise a formidable relief. Even if it hasn't been quantified, the associated sediment movement must be significant. The Mungo is influencing Zone 2 and the western part of Zone 3, draining the young volcanic terrain. This is the only river in the estuary for which there is an estimate of suspended solids transported: 46.5 mg/l [114]. An erosion rate of 17t/km²/year is calculated by these authors. There is a catchment that is also occupied by a preserved forest, but whose land is much older than the Ntem further south. The central part of zone 3 is influenced by the Wouri, while the western part is influenced by the Dibamba. Finally, zones 4, 5, and 6 are affected by the Sanaga.

At the end, climate change and land use are some of the factors that affect the sedimentary flows of these rivers. These rivers were affected by the drought of the 1970s, which affected the Sanaga. This sediment supply could be linked to the reduction in coastal erosion documented between 1975 and 1986. Changes in land use have had a major impact on the Dibamba with the development of the city of Douala and agro-industries. The foot of Mount Cameroon is where these changes in land use are significant.

5.9 Dynamics linked to bathymetry and its impact on morpho-dynamics

The Wouri estuary has different bathymetric levels. They diminish from the open sea to the banks. The areas where the depths are greatest experience major tidal movements that attack the land and subject it to coastal erosion. There is ample evidence of this provided by Navionics bathymetric maps. There is a bathymetric value of +4 m in the Cape Cameroon region, where the estuary experiences the greatest erosion [124]. The area of deposition of cream of mud along the channel migrates seasonally between periods of high and low water, which shows that bathymetric levels vary with the seasons. The estuary's immediate environment is fed by three main rivers, which provide an average annual inflow of 28.109 m³/year. We get a lot of sediment in the estuary during the rainy season, which affects the bathymetry [122].

5.10 Influences of seasonality on coastal erosion and management initiatives

Seasonality significantly influences coastal erosion through various mechanisms. Firstly, winter swells and storms result in higher and more frequent waves, thereby exacerbating coastal erosion [126]. In particular, storms and intense swells during the rainy season on African coasts (from May to October) accelerate the rate of coastal erosion [127]. Additionally, spring tides, especially during equinoxes, contribute to increased coastal erosion [128]. Heavy rainfall during this period can lead to surface runoff and coastal landslides [129].

In Cameroon, the Littoral region (encompassing Douala and Limbe) experiences heightened vulnerability to coastal erosion during the rainy season (Cameroon Ministry of the Environment and Forestry, 2018). This season coincides with the monsoon, which sweeps along the Cameroonian shoreline. The presence of these monsoons can distort the perception of shorelines in satellite imagery. The storms and swells prevalent during this season have already inflicted considerable damage to coastal infrastructure in areas such as Kribi, Ebodje, and Douala [128]. Additionally, weak coastal infrastructure and deforestation are accelerating the process of coastal erosion in Cameroon [127].

In response to the increasing incidence of erosion in Africa, including Cameroon, several environmental research and action programs have been initiated. Notably, the United Nations Environment Programme (UNEP) has supported an extensive Integrated Coastal Zone Management Programme (2019). Similarly, the United Nations Industrial Development Organization (UNIDO) has backed a successful project aimed at the sustainable development of coastal zones (2020). Furthermore, the Government of Cameroon has established a National Coastal Zone Management Strategy (2020), a comprehensive initiative that extensively addresses issues related to coastal erosion.

5.11 Comparative use of high spatial resolution and medium spatial resolution satellite images in coastal erosion mapping

Conducting comparative work on coastal erosion using high spatial resolution (HR) and medium spatial resolution (MR) satellite images separately presents unique opportunities and challenges. Each of these image categories offers distinct perspectives on the phenomenon of coastal erosion, and their targeted use can enrich the understanding of coastal dynamics.

HR images, with their ability to capture fine details, are particularly useful for the analysis of specific coastal features, such as topography, littoral structures, and sensitive habitats such as mangroves and dunes. For example, they allow to assess the immediate impacts of erosion on coastal infrastructure, to monitor changes in vegetation, or to observe variations in beach grain sizes. The use of HR images can therefore provide valuable data for detailed studies and targeted interventions [130].

In contrast, MR images are essential for an overview of erosion trends at larger scales. They allow the analysis of phenomena such as shoreline regression or sediment accumulation over large sections of the coast. Due to their ability to provide broader coverage, MR images are particularly suited to observe coastal dynamics that occur over large areas, often masked in HR analyses due to local variability [131].

For the comparison to be effective, we have defined a robust methodology that exploits the strengths of each image type. For example, results obtained from HR images are used to calibrate and validate erosion models derived from MR images. By integrating data from both resolutions, it is possible to create a more comprehensive predictive model of coastal erosion, which accounts for observed local variations and global trends [132].

However, using HR and MR images separately also presents challenges. Differences in resolution can make it difficult to interpret the results, as the scales of observation are not directly comparable. Additionally, HR images can be expensive and sometimes less accessible, which may limit their use in some studies. It is therefore essential to consider these limitations when designing the study [133, 134], especially when it comes to changing the plant cover [135].

6 Conclusion

Finally, this work on coastal erosion in the Wouri estuary has led us to analyse the phenomenon and quantify the dynamics and morpho-dynamics of the shoreline between 1975 and 2024. The factors amplifying these dynamics are also addressed and discussed in the light of field knowledge and existing literature. It appears that the hot-spot of coastal erosion in the estuary is the Cape Cameroon locality, with retreats of more than 15 m/year in places. The main factors are demographic growth in the estuary, destruction of the mangrove swamps, the action of the tide and marine currents, and human development in the estuary, reflected in the spatial expansion of the city of Douala and port development. Far from being a case typical of the Cameroonian shoreline, the issues addressed in this study are of universal concern to all the countries that share the ocean shoreline. From the Senegalese coast to the Nigerian coast, coastal erosion is present everywhere. It is even more active on the coasts of West Africa, particularly in Benin and Togo. This is why the World Bank has financed a vast project (the WACA project) to curb erosion in this area. The need to coordinate solution initiatives is proving decisive, in order to avoid spreading the phenomenon to other areas.

Finally, managing coastal erosion in the Wouri Estuary in Cameroon requires an integrated and sustainable approach, combining nature-based interventions with adapted engineering strategies. Sustainable solutions include the restoration of mangroves, which play a crucial role in coastal protection by absorbing wave energy and stabilizing sediments. These natural ecosystems also promote biodiversity and support local livelihoods. In addition, the development of surrounding wetlands can help absorb excess water during floods, while improving water quality. The use of protective structures, such as vegetated seawalls or breakwaters made of natural materials, can also reduce the impact of erosion without harming local ecosystems. At the same time, it is essential to involve local communities in the planning and implementation of these projects, thus ensuring that solutions meet socio-economic needs while preserving the environment. Raising awareness and educating people about the challenges of coastal erosion and the importance of natural ecosystems will also strengthen community engagement. By integrating these different approaches, it is possible to create a coherent and effective management framework to combat coastal erosion,

thus ensuring the sustainability of natural resources and the resilience of coastal communities in the face of climate change. This model could also serve as an example for other coastal regions facing similar challenges.

Author contributions Philippes Mbevo Fendoung contributed to the conceptualization, methodology, mapping, analysis, and writing of the article following his fieldwork. Aurélia Hubert-Ferrari's role consisted of constructing the methodology, revision, editing, and analysis. All the authors read and approved the version. Aurélia Hubert-Ferrari's role involved constructing the methodology, review, editing, and analysis. All authors have read and agreed to the published version of the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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