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Coastal landscape dynamics in the Mouths of Cameroon and adjacent watersheds: morphological, environmental, and socio-ecological challenges

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Abstract

The Mouths of Cameroon form a low-lying estuarine system of major ecological, geomorphological, and socio-economic importance along the Cameroonian coast. This study characterizes the geomorphological landscapes of the estuary and its adjacent watersheds using a watershed-based approach and assesses recent shoreline morphodynamics and associated environmental risks. The analysis combines multi-temporal Landsat imagery, field observations, bathymetric and geomorphological interpretation, and comparative assessment of the Sanaga, Wouri, Dibamba, and Mounjo watersheds. The results show that the inner estuary is strongly affected by urban and port expansion around Douala, degradation of mangrove and coastal forest landscapes, subsistence farming in rural sectors, and localized agro-industrial plantation dynamics along the estuarine margins. Marked geological and topographic contrasts, Holocene sandy and clayey deposits, and a complex hydro-sedimentary network of channels, creeks, levees, shallow coastal forms, and barrier features further structure the estuarine landscape. Shoreline analysis between 2016 and 2020 reveals a heterogeneous pattern coexist over short distances. Beyond the estuary, the watershed-based analysis highlights strong contrasts among all the watershed basins in terms of relief, geology, land use, anthropogenic pressure, and degree of connection to the estuarine system. These results indicate that the present dynamics of the Mouths of Cameroon are controlled by interactions between natural coastal and fluvial processes and increasing human pressures, including urbanization, sand extraction, and agro-industrial expansion... The estuary, therefore, appears as a vulnerable socio-ecological system in which geomorphological change, ecological degradation, and shoreline instability are closely interconnected. A watershed-to-estuary perspective is essential for understanding these dynamics and supporting long-term coastal.

Keywords

Mouths of Cameroon; estuarine geomorphology; watershed-based approach; coastal morphodynamics; mangrove degradation; shoreline change; hydro-sedimentary processes; environmental change.

1. Introduction

The coastal zone of southern Cameroon is largely shaped by the Cameroonian coastal sedimentary basin along the Gulf of Guinea. This long-term subsiding margin has accumulated thick sedimentary sequences since the Cretaceous, giving rise to broad lowlands and low-gradient coastal environments favorable to estuarine and deltaic landforms (Sighomnou et al., 2007; Morin and Kuété, 1988; Tchindjang, 2021). In contrast, the inland and northwestern parts of the region are strongly influenced by the Cameroon Volcanic Line, including Mount Cameroon and other prominent reliefs (Zogning, 1989; Tchindjang, 2021). This contrast between low-lying sedimentary plains and higher volcanic topography exerts a major control on regional landscape organization and geomorphological processes.

Within this regional framework, the Mouths of Cameroon constitute one of the most distinctive low-lying estuarine systems on the Cameroonian coast. Located in the northern Gulf of Guinea, the estuary is directly structured by the Wouri, Dibamba, and Mounjo rivers, while the Sanaga exerts a secondary influence through indirect connections and exceptional flood-related inputs (Morin, 1981; Olivry, 1986). The resulting estuarine environment supports extensive wetlands and biologically rich coastal habitats, including large mangrove formations. Its functioning is further shaped by a humid equatorial climate, which enhances hydrological activity and sediment transfers across the estuarine system (MINEPDED, 2015). These mangrove and coastal forest formations are now largely degraded under long-term human pressure (Din, 1991, 2008; Nfotabong Atheull, 2011).

At the same time, the Mouths of Cameroon are among the most intensely transformed coastal environments in the country. The northern estuarine sector includes Douala, Cameroon's main economic city, together with the country's principal port and a major industrial center, making this part of the estuary subject to strong anthropogenic pressure (Didier et al., 2016; Mbongalle, 2019). Rapid urban growth, port activity, deforestation, resource extraction, and agro-industrial plantation development have increased pressure on estuarine and coastal environments. These pressures are reflected in

pollution, wetland degradation, biodiversity loss, and growing exposure to flooding and erosion linked to uncontrolled urban expansion and land-use change (Ngoran et al., 2015; Din et al., 2017; Ngongang et al., 2021; Clarisse et al., 2023). In adjacent watersheds, agro-industrial plantations also contribute to deforestation, soil and water degradation, and biodiversity loss (Ajonina et al., 2013, 2014).

In this context, the Mouths of Cameroon cannot be understood solely as an estuarine space disconnected from its surrounding drainage basins. Their present-day landscapes and morphodynamics result from interactions between local estuarine processes, watershed-scale controls, and increasing anthropogenic pressures. The main objective of this study is therefore to characterize the geomorphological landscapes of the Mouths of Cameroon within the estuary and across adjacent watersheds using a watershed-based approach. A second objective is to assess the morphodynamic implications for the shoreline and the associated risks affecting local populations.

2. Study area

The Mouths of Cameroon form a low-lying estuarine system where the Mounjo, Wouri, and Dibamba rivers (Fig. 1) converge, while the Sanaga River exerts a secondary influence through the Kwakwa channel and during major floods (Morin and Kuété, 1988; Olivry, 1986). The estuary extends over approximately 1,200 km² in the coastal zone of southern Cameroon and forms a key interface between fluvial, estuarine, coastal, and deltaic processes.

Douala, the main urban and economic center of Cameroon, is located upstream along the Wouri River. The city has experienced rapid population growth over the last decades (Dongmo, 1980; Mainet, 1985; Hatcheu, 2003; Nganmo and Priso, 2022). It hosts a large share of the country's industrial activity and its principal port, making the northern estuary particularly exposed to urban, industrial, and port-related pressures (Indjieley, 2007; Tchakonté et al., 2014).

The estuary also includes extensive mangrove ecosystems, including protected sectors such as the Douala-Edéa National Park and the Mabé Reserve. These mangroves represent a significant share of Cameroon's coastal wetlands and are dominated by *Rhizophora* spp., with *Avicennia germinans* and *Nypa fruticans* also present (Din, 2008; Nfotabong Atheull et al., 2009; MINEPDED-RCM, 2017). Their distribution along channels, tidal flats, and low estuarine margins makes them central to both biodiversity conservation and sediment trapping within the system.

The physical functioning of the estuary is also closely linked to seasonal sediment inputs. According to the Netherlands Economic Institute, the system receives about one million tons of sediment per year, around 70% of which is delivered during the rainy season, and a substantial proportion of this load is trapped within the extensive mangrove swamps of the estuary (NEI, 1993).

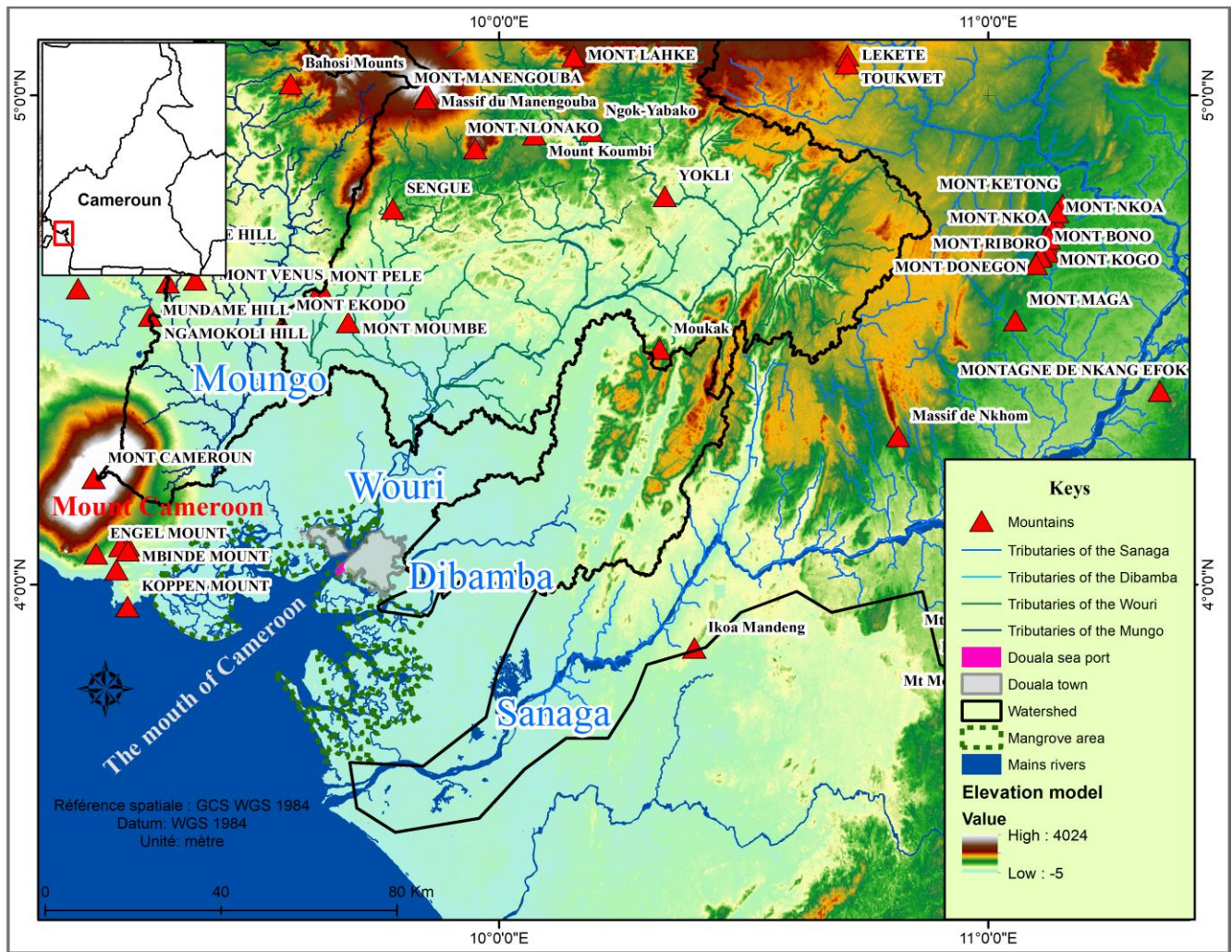


Figure 1: Location of the Mouths of Cameroon, adjacent watersheds, and external morphological configuration marked by the Cameroon Volcanic Line (CVL).

3. Materials and methods

3.1. Data sources and analytical framework

This study combines satellite image analysis, field observations, bathymetric and geological information, and a watershed-based comparison to characterize the geomorphological landscapes of the Mouths of Cameroon and recent coastline morphodynamics. Landsat images acquired between 1975 and 2020 were used to analyze land-use changes within the inner estuary and adjacent watersheds, while images from 2016 and 2020 were used for shoreline extraction and coastline change analysis (Table 1). Field observations in Manoka, Toubé, Cap Cameroun, and Apouh provided ground control and photographic support for interpreting landscape units and local environmental conditions.

Table 1: Landsat data source.

Date	Sensor	Path/row	Resolution (m)
1975/06/06	MSS	200/057	60
1986/12/12	TM	187/057	30
1986/02/09	TM	186/057	30
2000/11/06	ETM	186/057	30
2000/03/05	ETM	187/057	30

2015/02/16	Landsat 8	187/057	30/15
2015/03/16	Landsat 8	186/057	30/15
2016/02/21	Landsat 8	187/057	30/15
2016/03/31	Landsat 8	186/057	30/15
2020/12/20	Landsat 8	187/057	30/15
2020/12/27	Landsat 8	186/057	30/15

3.2. Land-use, geomorphological, and shoreline analyses

Land-use patterns were mapped from Landsat imagery using supervised classification in a GIS environment. The analysis focused on the main landscape classes within the estuary and adjacent watersheds, including urban areas, relict and degraded forests, mangroves and coastal forests, savannah, mixed vegetation, agricultural land, and agro-industrial plantations.

The geomorphological organization of the estuary and surrounding watersheds was interpreted from satellite imagery, Navionics bathymetric information, geological documentation, and field observations. Main landforms, including channels, creeks, levees, abandoned channels, sandy barriers, dune ridges, and low estuarine plains, were identified from their morphology, spatial arrangement, and relationship with fluvial, coastal, and estuarine environments.

Shoreline change was assessed from shoreline positions extracted from Landsat images acquired in 2016 and 2020, following the standard DSAS workflow for baseline definition, transect generation, and shoreline-change rate calculation (Himmelstoss et al., 2021). These shorelines were digitized in a GIS database and analyzed with the Digital Shoreline Analysis System (DSAS) to calculate rates of retreat, stability, and accretion along the coastline. The estuary is divided into five zones to better explain the processes at work there (Fig. 2).

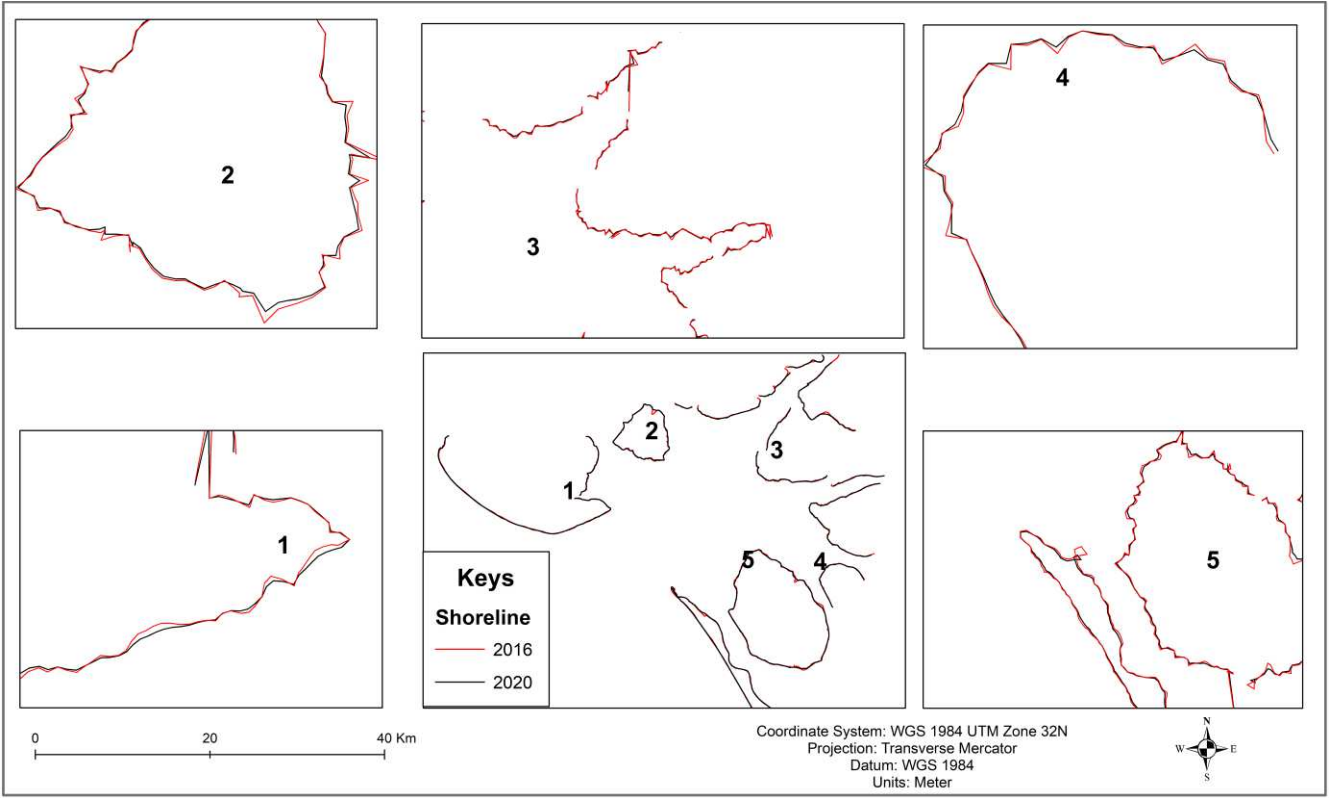


Figure 2: Division of the estuary into five erosion zones

111 **3.3. Watershed-based comparison and limitations**

112 The Sanaga, Wouri, Dibamba, and Moungo watersheds were compared in terms of land use, topography, geology, degree of
113 anthropization, and connection to the estuarine system. This comparison was used to place the Mouths of Cameroon within
114 a broader regional framework and to identify external controls on estuarine functioning. The approach is limited by the
115 spatial resolution and temporal availability of Landsat imagery, the partly indirect nature of bathymetric and
116 geomorphological interpretation, and the short time interval covered by the shoreline analysis. Nevertheless, combining
117 satellite imagery, field observations, bathymetric data, and watershed-scale comparison provides a coherent basis for
118 analyzing the spatial organization and recent evolution of the Mouths of Cameroon.

119

120 **4. Results**

121 The results are organized at two complementary scales. First, the inner estuary is analyzed through its urban, agricultural,
122 forest, plantation, geological, and shoreline dynamics. Second, the adjacent watersheds are compared to assess how external
123 land-use, topographic, and geological controls contribute to the broader functioning of the Mouths of Cameroon.

124 **4.1. Landscapes and morphodynamics in the interior of the Mouths of Cameroon**

125 **4.1.1. A very active urban and port landscape in Douala**

126 One of the most prominent landscape features in the inner Mouths of Cameroon is the rapidly expanding urban environment
127 centered on Douala. Land-use classifications for 1975, 1986, 2015, and 2020 show a marked transformation of the northern
128 estuarine sector, where urban expansion occurred together with the degradation of forest landscapes (Fig. 3).

129 In 1975, relict forest was the dominant class, covering 67,950 ha, whereas degraded forest covered 10,700 ha and
130 urban areas 3,480 ha. By 1986, relict forest had decreased to 52,250 ha, corresponding to a loss of 1,430 ha/year. Over the
131 same period, degraded forest more than doubled to 24,750 ha, while urban areas expanded to 5,130 ha. Between 1986 and
132 2015, relict forest declined more slowly to 49,400 ha, degraded forest increased to 27,400 ha, and urban areas reached 5,300
133 ha. A stronger acceleration occurred between 2015 and 2020, when relict forest decreased to 35,100 ha, while degraded
134 forest increased to 40,310 ha and urban land continued to expand.

135 Port activity reinforces this urban landscape. The Autonomous Port of Douala extends along the Wouri River in a
136 sheltered estuarine setting about 50 km from the open sea (Soullillou, 1993). Its specialized terminals and recent
137 development plans, including possible expansion toward Manoka, make the port a major structuring element of the northern
138 estuary (MINEPAT, 2019).

139 This concentration is also economic: Douala hosts about 60% of Cameroon's industrial activity and the country's
140 principal port, which explains the intensity of urban, industrial, and port-related pressures in the northern estuary (Indjieley,
141 2007; Tchakonté et al., 2014).

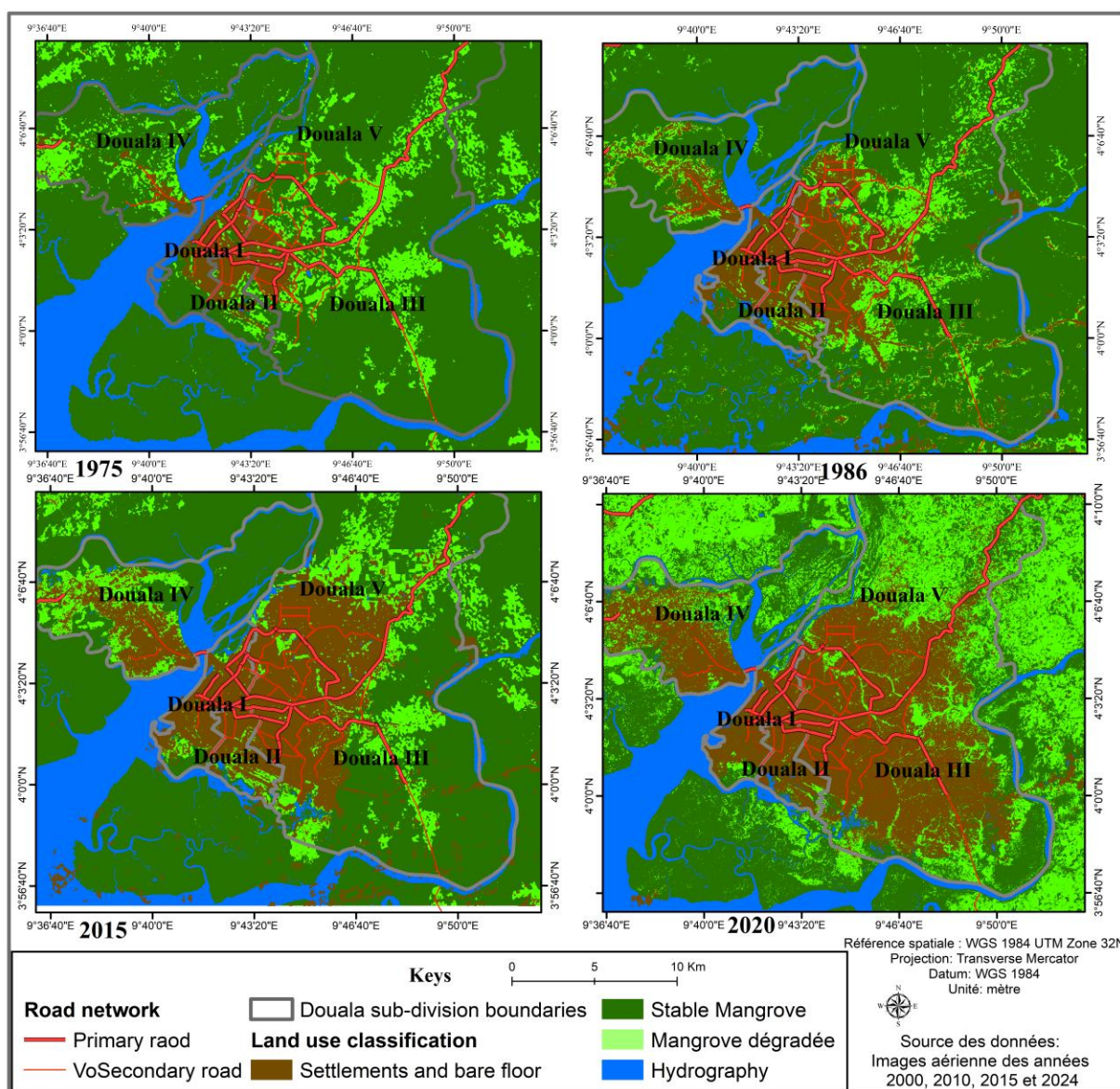


Figure 3: Landscape dynamics orchestrated by the spatial extension of the cit of Douala, between 1975 and 2020.

4.1.2. A landscape marked by subsistence farming

Subsistence farming is another characteristic component of the inner estuarine landscape (Fig. 4). Field observations in Manoka, Toubé, and Cap Cameroun show small cultivated plots embedded within predominantly rural coastal environments. These plots include banana, cassava, yam, pineapple, and sugar cane, and contribute to local food supply in relatively isolated communities.

Although this agriculture remains small-scale, it is associated with progressive land-use change in rural coastal sectors. In several localities, cultivated plots occur alongside degraded vegetation and contribute to the reduction of forest cover already identified from satellite image interpretation. Subsistence farming therefore represents both a livelihood activity and a local factor of landscape transformation within the estuary.



Figure 4: Current agriculture in Manoka, Toubé, and Cap Cameroun. These photos illustrate the diversified nature of subsistence agriculture in rural coastal areas.

4.1.3. Mangrove and coastal forest landscape

Mangroves and coastal forests are key components of Cameroon's inner estuary, but they are now widely degraded. Studies in the Wouri estuary and along the coast have documented strong anthropogenic pressure on mangroves (Din, 2008; Din et al., 2017). Around Douala, mangrove clearing may reach 1,000 ha/year, though this is hard to verify due to informal or illegal cutting.

Degradation is closely tied to wood exploitation by fishing communities, which rely on mangroves (such as *Rhizophora racemosa*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erectus*) for fish smoking, furniture, and heating. Similar uses have been observed in the Wouri estuary (Nfotabong Atheull et al., 2009). Mangrove extraction is both a visible landscape feature and a driver of ecological degradation.

This pressure extends beyond subsistence: wood harvesting also supplies urban and peri-urban demand from Douala, linking local livelihoods to the metropolitan economy. Thus, mangrove degradation reflects both local dependence and broader resource-demand networks.

4.1.4. A landscape of agro-industrial plantations

Agro-industrial plantations are scarce in the inner Mouths of Cameroon due to unfavorable hydromorphic soils, with only a few sectors near Tiko and south of the Dibamba. They are more prevalent on the outer margins, particularly near Mount Cameroon, Moungo, and Mouanko, primarily as SOCAPALM oil palm and rubber plantations (~3,000 ha each). In Apouh (2015), SOCAPALM occupied 7,507 ha of the village's 13,736 ha, with 3,000 ha mature and 2,430 ha young plantations. This expansion reduces land for local communities, as much of the remaining 6,229 ha is unsuitable for cultivation. Plantations also limit access to arable land, non-timber forest products, and increase water pollution from pesticides, restructuring rural landscapes and intensifying environmental pressures.

4.1.5. Morphological landscapes and geological configuration

The Mouths of Cameroon are structured by four geological entities (Fig. 5): a crystalline zone of migmatites and granites (northeast), the Quaternary volcanic zone of Mount Cameroon (northwest), the Meso-Cenozoic Douala sedimentary basin, and Holocene estuarine deposits forming the low-lying plain (Weecksteen, 1957; Gèze, 1943; Morin, 1981). The volcanic zone dominates the relief, while the estuarine plain features low topography and a dead cliff at the Meso-Cenozoic-Holocene contact.

Holocene deposits (sands and clays) form a fragile, hydromorphic substrate fed by the Sanaga, Dibamba, Wouri, and Moungo rivers. Inside the estuary, this system creates channels, creeks, alluvial levees, and low plains, while oceanic sandy barriers and dune ridges result from longshore drift redistributing Sanaga-derived sands, with the newest ridge migrating northwest near Souélaba Point.

The estuary acts as both a sediment receiver and redistributor: barriers reflect drift-driven remobilization, while channels and levees record tidal and flood deposition. This duality explains the landscape's heterogeneity muddy mangroves, sandy ridges, and deep navigation channels coexist closely.

Bathymetry mirrors this complexity: inner estuary channels exceed 20 m depth, contrasting with shallow (2–8 m) mangrove margins. These contrasts highlight the estuary's sensitivity to sediment dynamics. The Port of Douala's access channel requires regular dredging, with 3.7 million m³ of sediment removed in 2018 (Komba et al., 2019), illustrating human-natural sedimentation interactions.

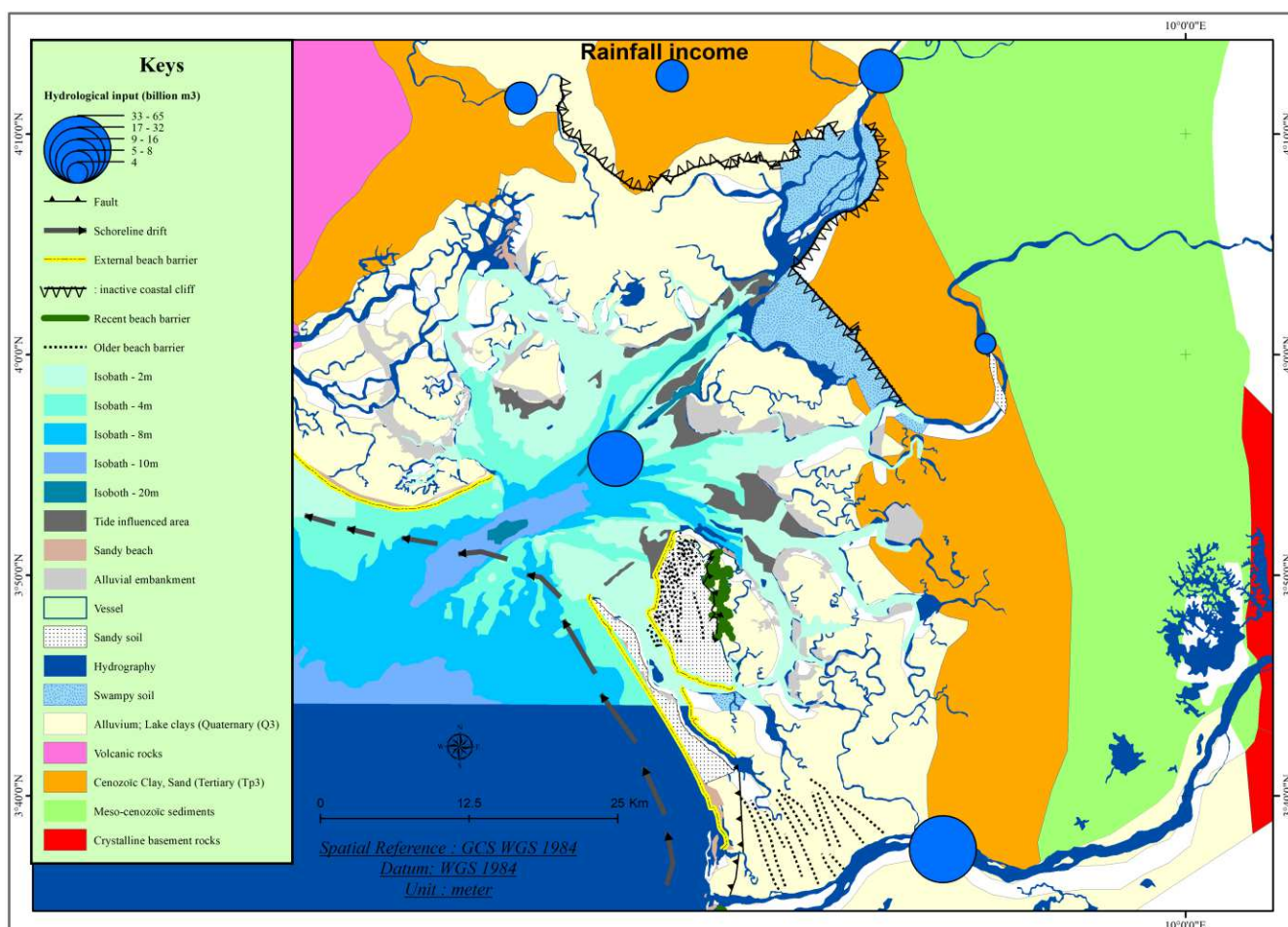


Figure 5: Geological composition of the Mouths of Cameroon, with geomorphological and hydrological components according to Morin (1981) and Olivry (1986), and bathymetric values according to the Navionics map.

4.1.6. Morphodynamics of the coastline in the Mouths of Cameroon

The Mouths of Cameroon's coastline are shaped by fluvial inputs (Wouri: 140–2,000 m³/s; Mounjo: 5 billion m³/year; Dibamba: ~2 billion m³), marine processes (swells, longshore drift, coastal currents), and human interventions (dredging, sand extraction) (Kouandji Bekoumb, 2016; Morin and Kuété, 1988; Ondoa et al., 2018). The Wouri, dominant in the north, forms a braided upstream pattern and a straighter downstream channel, delivering sediment to the port, requiring frequent dredging (Fig. 6).

The Mounjo flows through mangroves, while the Dibamba is heavily impacted by urban demand. In the outer estuary, fluvial inputs interact with marine processes, reducing current velocity and favoring sediment accumulation. Human activities like dredging for the Port of Douala and sand extraction (Fig. 7) along the Dibamba further alter sediment balance (Abaté, 2020; Fossi Fotsi, 2022; Mbevo, 2019).

Shoreline analysis (2016–2020 Landsat images, DSAS) reveals three behaviors (Fig. 8): erosion (e.g., Cap Cameroun, Petit Toubé), stability (e.g., Port of Douala, Manoka Island's west), and accretion (e.g., south of Toubé, Olga Point). Erosion rates range from -8 m/year (Zone 4) to -25 m/year (Zone 3), while accretion rates range from 9 m/year (Zone 4) to 42 m/year (Zone 6). The coastline is heterogeneous, with retreating, stable, and advancing sectors coexisting closely (Table 2). On the ground, in the intertidal zone, one can see the remains of houses destroyed by coastal erosion (Fig. 9).

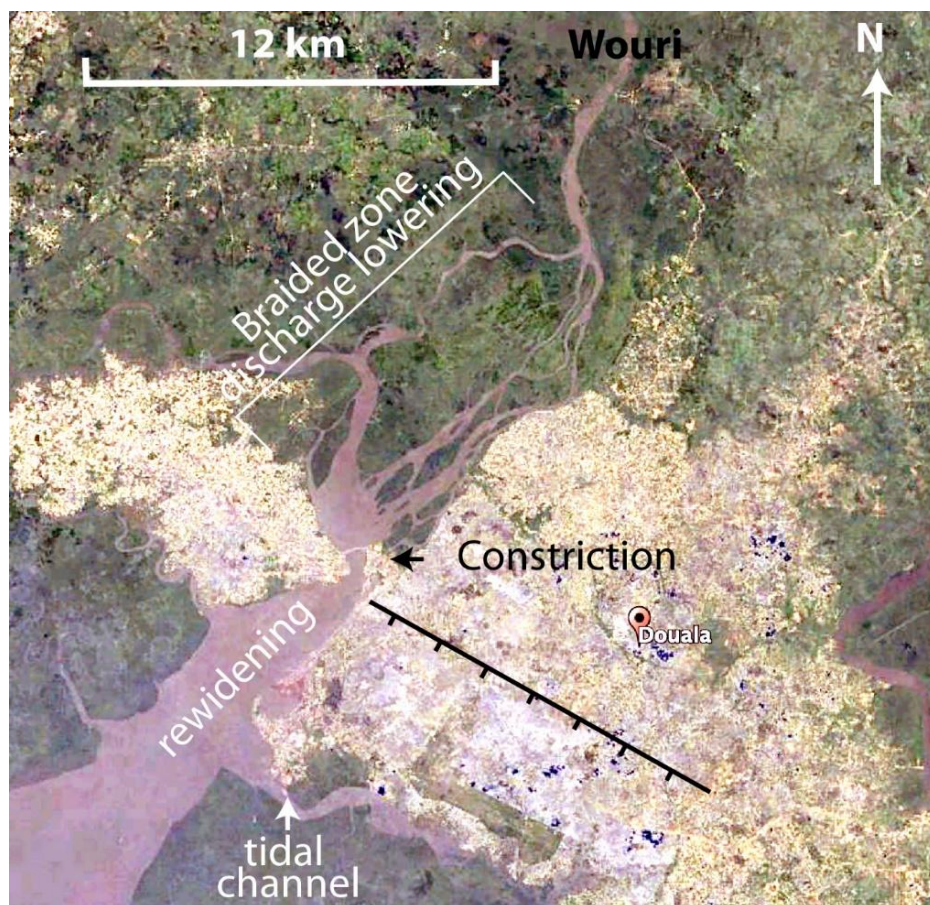


Figure 6: Mouth of the Wouri River, characterized by a braided pattern upstream, recalibrated after the Wouri bridge before flowing into the Mouths of Cameroon.



Figure 7: Case of sand collection in the Wouri estuary.

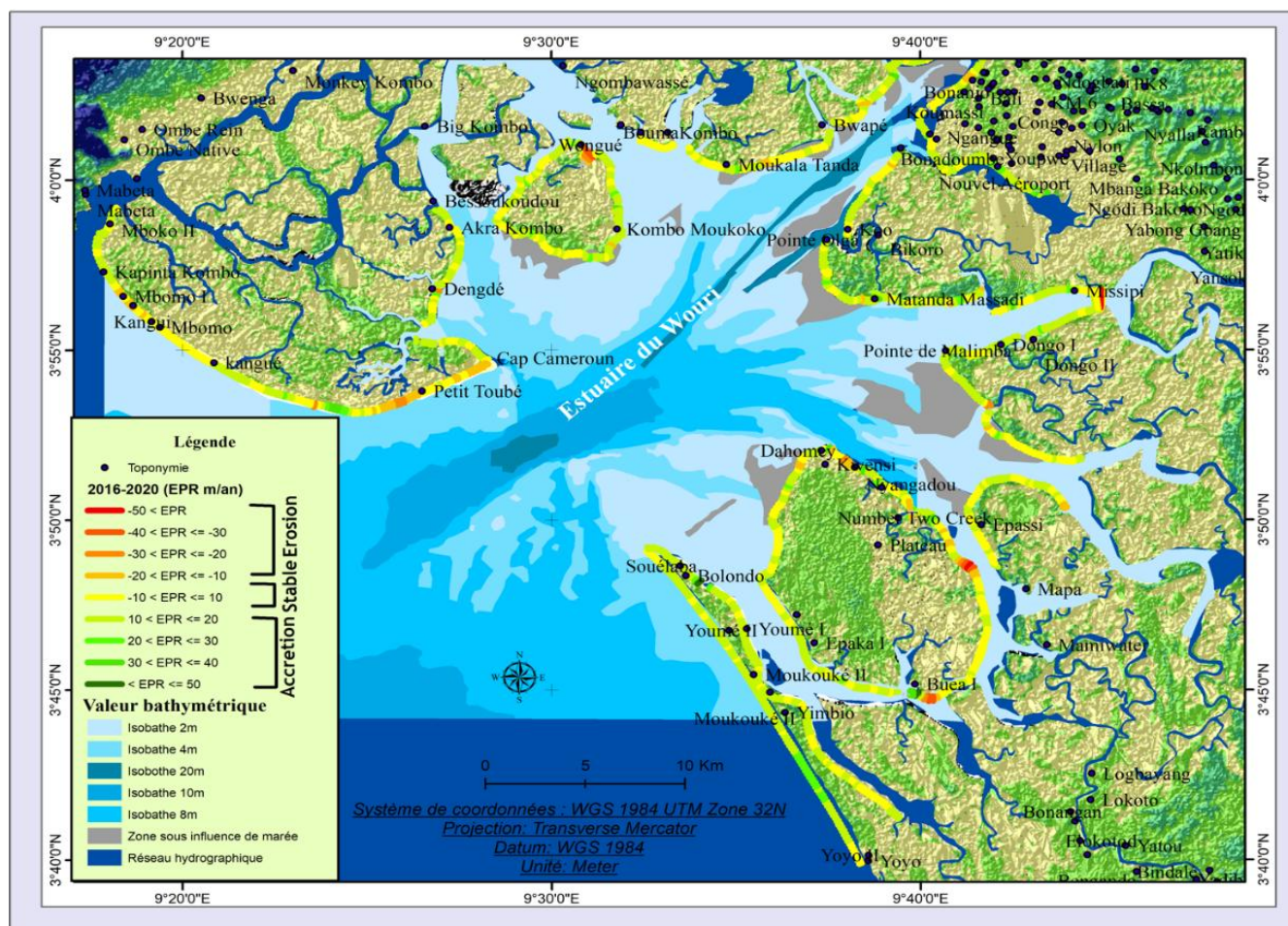


Figure 8: Coastline dynamics expressed as End Point Rate (EPR, m/year) in the Wouri estuary between 2016 and 2020, obtained with DSAS.

Table 2: Coastline recession and accretion rates (m/year) between 2016 and 2020, obtained with DSAS.

Coastline dynamics	Statistic	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Erosion	Mean EPR (m/year)	-16	-19	-39	-8	-21	0
Accretion	Mean EPR (m/year)	11	10	14	9	23	42
Eroding transects		42	9	35	4	41	0
Accreting transects		83	62	195	20	63	110
Stable transects		67	37	178	31	100	91
Total transects		192	108	408	50	204	207



Figure 9: Evidence of coastal retreat in the village of Cap Cameroun in the Wouri estuary. Photo credit: Mbevo, March 2024.

4.2. Landscape and morphodynamics outside the Mouths of Cameroon: a watershed approach

4.2.1. Landscape characterization of watersheds outside the Mouths of Cameroon

Beyond the estuary, the surrounding watersheds exhibit a mosaic of fragmented natural formations and widespread anthropogenic land uses (Fig. 10). The 2020 Landsat classification reveals significant differences in land cover among the basins, including savannah, secondary forest, mixed vegetation, agricultural land, and agro-industrial plantations.

The Wouri and Moungo watersheds are dominated by savannah and mixed vegetation in the West Cameroon highlands, where intense agriculture and long-term vegetation degradation prevail. The Dibamba watershed also shows degraded vegetation, largely due to its proximity to Douala and its historical role as a source of timber and fuelwood (Höhn and Neumann, 2018). In contrast, the Sanaga watershed contains the largest areas of secondary vegetation and is the most anthropized, featuring extensive agricultural land, plantations, and a dense road network.

The origin of degraded vegetation varies: in the Wouri and Moungo, it is linked to agricultural highlands and long-term degradation, while in the Dibamba, it stems from metropolitan pressure and resource extraction. In the Sanaga, some savannah areas are remnants of former plantations rather than natural vegetation.

Secondary forest distribution also differs. In the Sanaga, it dominates a transformed landscape with plantations and agriculture. In the Wouri, it is more developed in southern sectors, away from degraded highlands. In the Moungo, it occurs mainly on northwestern slopes, while in the Dibamba, it remains limited and fragmented. Mixed vegetation is more characteristic of the Wouri and Moungo, forming a complex mosaic of forest, savannah, and cultivated land.

Land-use classes reflect distinct degradation trajectories. In some basins, degraded vegetation results from long-term agricultural use, while in others, it reflects metropolitan pressure or plantation legacies. This distinction matters because similar land-cover classes may correspond to different environmental processes and management priorities.

Agro-industrial plantations are concentrated in the Sanaga and Moungo, with oil palm and rubber as major units. In the Dibamba, plantations are limited and near Douala. Agricultural land is most developed in the Sanaga, Wouri, and Moungo. Overall, the outer basins are heterogeneous: the Sanaga is the most transformed, the Dibamba is metropolitan-influenced, and the Wouri and Moungo combine highland agriculture, mixed vegetation, and plantation dynamics.

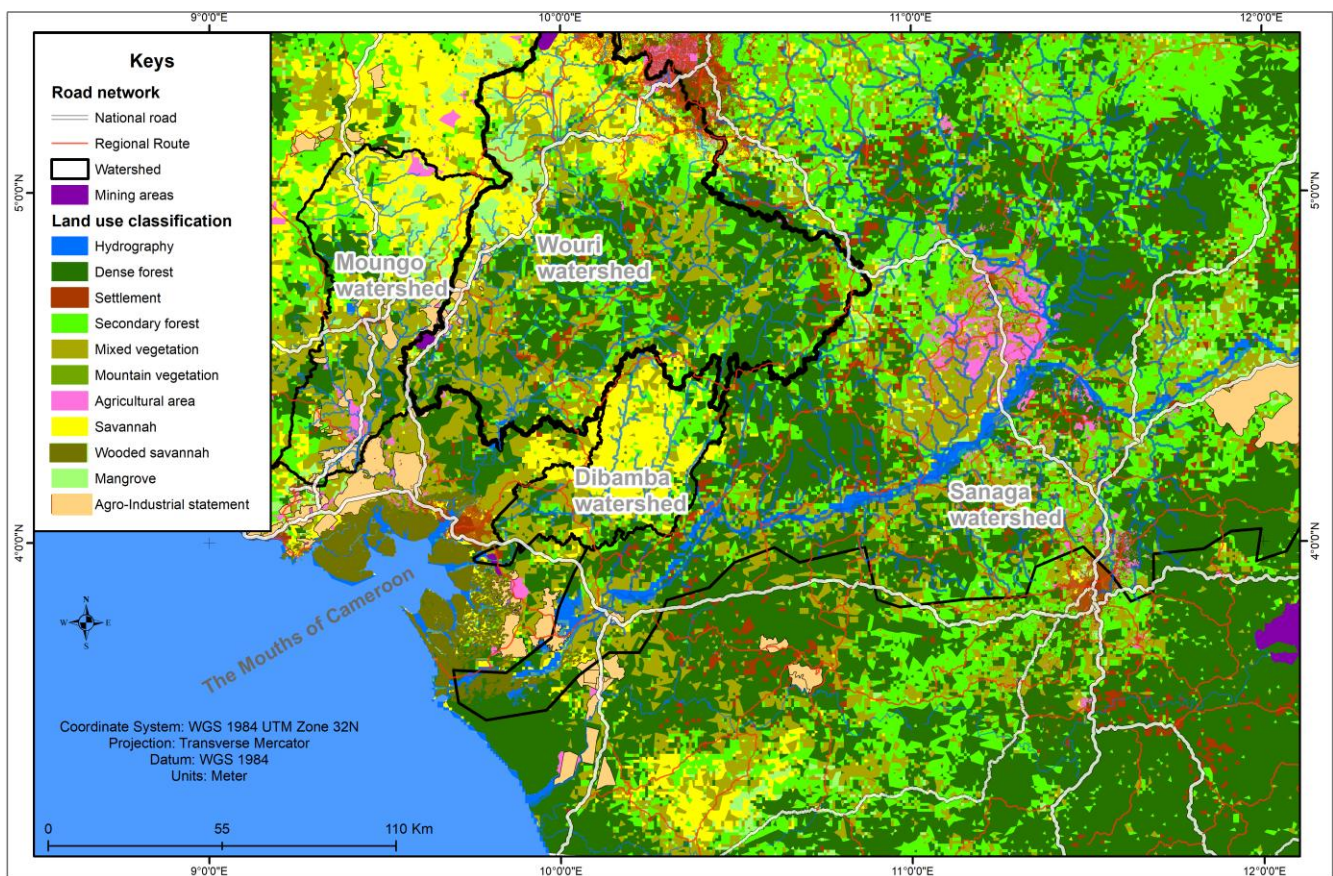


Figure 10: Landscape composition outside the Mouths of Cameroon.

4.2.2. The diversified morpho-landscape characteristics of the watersheds outside the Mouths of Cameroon

The outer watersheds connected to the Mouths of Cameroon are characterized by strong topographic and geological contrasts, largely controlled by the Cameroon Volcanic Line (CVL) (Fig. 1). This volcanic alignment borders the estuarine system and crosses part of the Moungo, Wouri, and northwestern Sanaga watersheds (Zogning, 1989; Tchindjang, 2021). It creates a marked contrast between volcanic reliefs, dissected highlands, lower sedimentary sectors, and the low-lying estuarine plain. Mount Cameroon, rising to 4,095 m, forms the most prominent relief on the northwestern margin of the estuary. The four watersheds also differ strongly in size: the Sanaga basin exceeds 140,000 km², whereas the Wouri covers about 21,600 km², the Moungo about 4,200 km², and the Dibamba about 2,400 km² (Dubreuil et al., 1975; Darnault, 1947; Olivry, 1986). These differences imply contrasting capacities for water and sediment production, as well as different degrees of connection to the estuary.

The Sanaga watershed is by far the largest basin considered here, covering more than 140,000 km² and draining much of the Adamawa and West Cameroon highlands before reaching the coastal basin (Fig. 11). The Sanaga River is about 918 km long and formerly flowed directly into the Wouri estuary until 1896, before its main outlet shifted southeast of the present estuarine system (Morin and Kuété, 1988). Its present connection with the Mouths of Cameroon is mainly indirect and occurs during exceptional flood periods. Its Precambrian basement formations and altered clayey to sandy-clayey materials give it a high sediment production potential, with a substantial fraction of fine sediment originating from western tributaries (Dubreuil et al., 1975; Ndam Ngoupayou et al., 2016). This explains why the Sanaga remains important for the broader sedimentary context of the Mouths of Cameroon even though it is only partly connected to the present estuary.

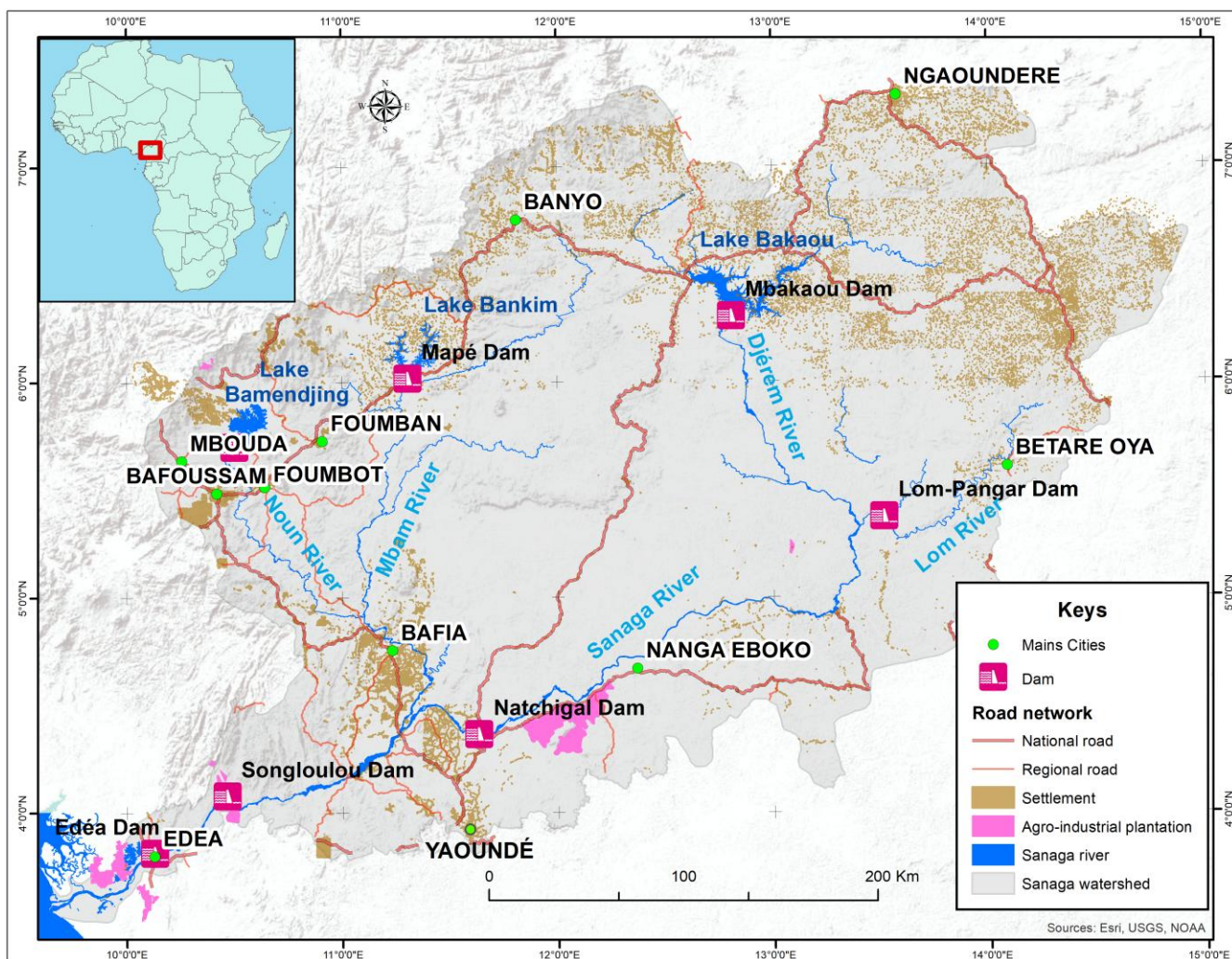


Figure 11: Sanaga watershed area.

The Wouri watershed forms the main direct hydrological link between the western highlands and the inner estuarine system (Fig. 12). It drains agricultural highlands, secondary forest areas, and volcanic reliefs before entering the estuary near Douala. Its main tributaries connect topographically active highland sectors with the low-lying estuary, making the Wouri a key pathway for water, sediment, and anthropogenic pressures entering the northern Mouths of Cameroon. Primary forest is now rare and mainly restricted to difficult-to-access slopes and riparian sectors, which reinforces the interpretation of this basin as a long-term degraded but still highly connected sediment source. This direct connection explains why changes in land use and sediment production in the Wouri basin can rapidly influence the estuarine environment around Douala.

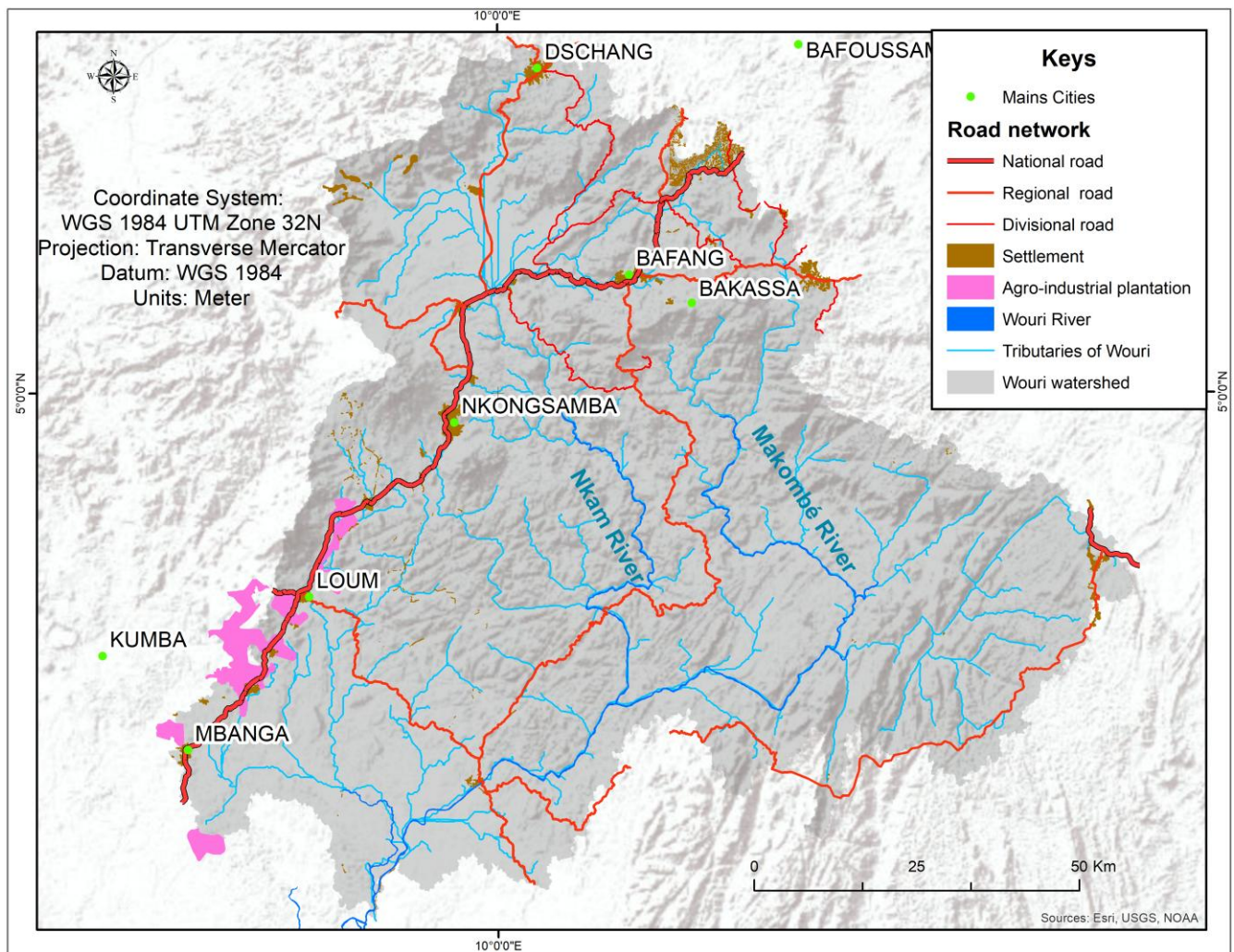


Figure 12: Wouri watershed.

The Dibamba watershed is smaller but strategically important because of its proximity to Douala (Fig. 13). It drains western highland reliefs and lower Meso-Cenozoic sectors before entering the southeastern part of the estuary. Its lower course lies close to the expanding urban area of Douala, where road development, land conversion, timber extraction, and sand extraction exert direct pressure on the river corridor. Although its total contribution is smaller than that of the Wouri or Sanaga, its local impact on the southeastern estuary is significant because anthropogenic disturbance is concentrated near the estuarine outlet.

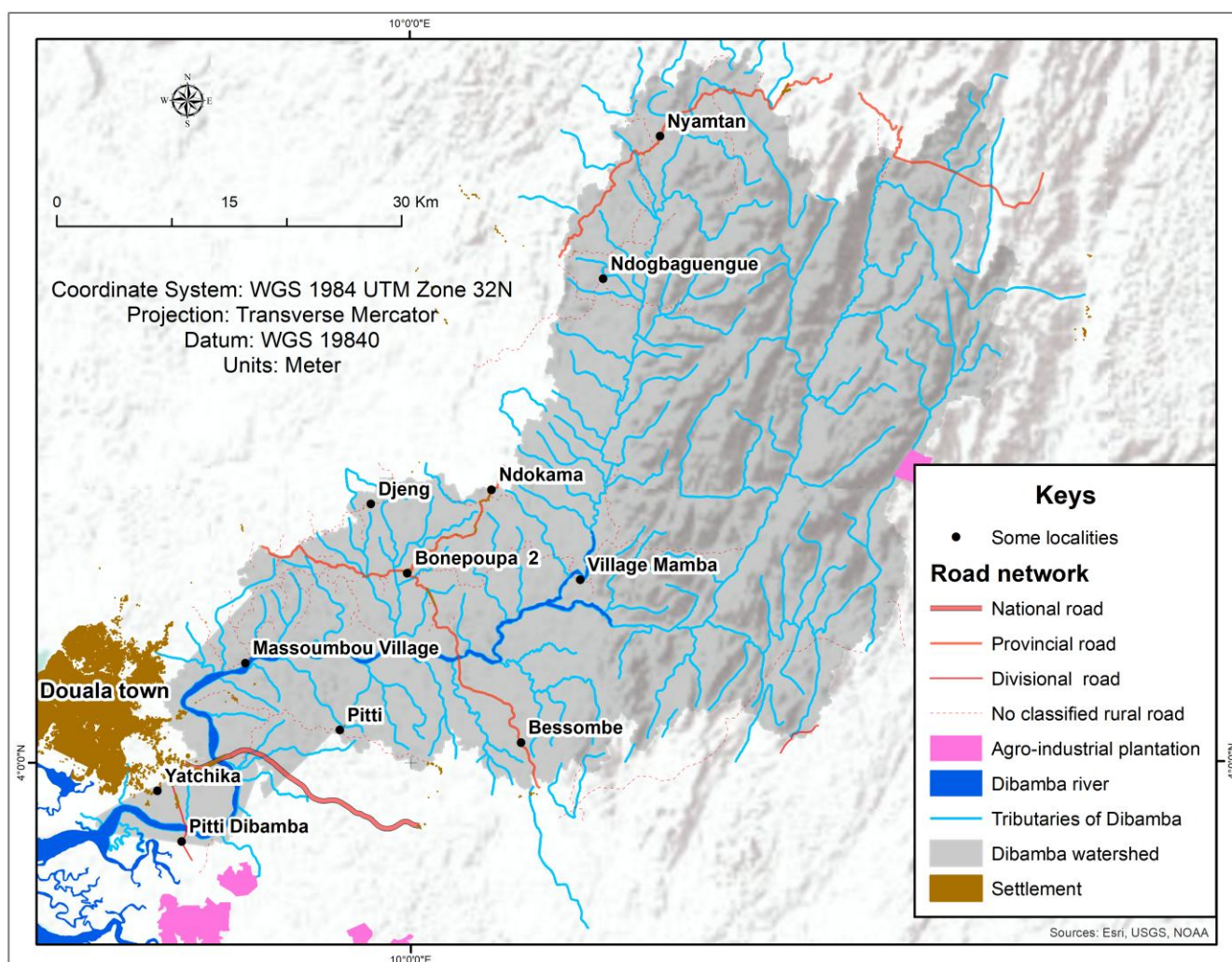


Figure 13: Dibamba watershed.

The Mounjo watershed provides a contrasting configuration, linking volcanic relief, fertile agricultural land, agro-industrial plantations, and mangrove-dominated lower reaches (Fig. 14). It drains the slopes of Mount Cameroon and adjacent mountain systems before entering Mudeka Bay and subdividing into small channels near the Wouri estuary. This basin therefore connects upland agricultural and agro-industrial processes with deltaic and estuarine environments, making it important for understanding how land-use changes outside the estuary may influence downstream ecological and sedimentary conditions.

Taken together, these four watersheds differ markedly in size, geology, relief, land use, degree of anthropization, and type of connection to the estuary. These contrasts explain why the Mouths of Cameroon must be interpreted not only as an inner estuarine system, but also as the downstream expression of differentiated watershed dynamics.

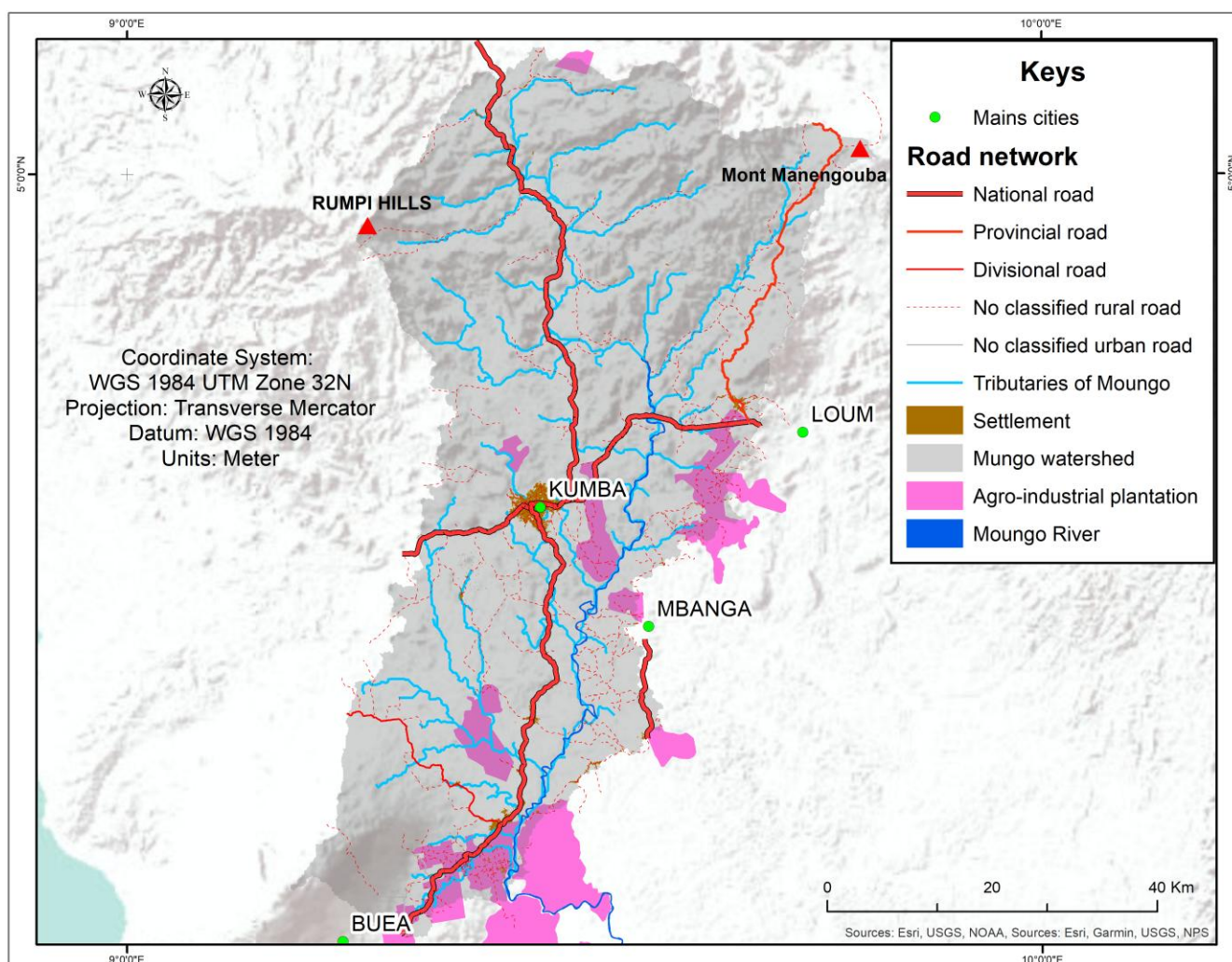


Figure 14: Mounjo watershed.

5. Discussion

5.1. Drivers of landscape change

The landscape dynamics observed in the Mouths of Cameroon result from the interaction of several drivers operating at different spatial scales. Inside the estuary, the main driver is the rapid demographic and spatial growth of Douala, which acts as the principal economic pole of the region. This expansion is linked not only to natural population growth, but also to strong migratory attraction and increasing demand for land, resources, and infrastructure (Dongmo, 1980; CWCS, 2007; Nsegbe et al., 2014). The rapid spread of urban neighborhoods over former mangrove and forested areas, therefore, represents one of the clearest manifestations of demographic and economic pressure on the estuarine landscape.

This urban growth has direct environmental consequences. In the inner estuary, it is associated with deforestation, wetland degradation, pollution, and biodiversity loss (Didier et al., 2016; Ngoran et al., 2015; Din et al., 2017). The land-use changes documented between 1975 and 2020 should therefore not be interpreted as a simple land-cover transition, but as part of a broader process of urban expansion driven by the concentration of people, infrastructure, and economic activities around Douala (Mbaha et al., 2012; Mbaha and Tchounga, 2020).

Resource use by local communities also contributes to landscape transformation. In island and coastal communities, fishing remains a major livelihood activity, but it depends heavily on mangrove wood for fish smoking (Nfotabong Atheull et al., 2009; UICN, 2013). At the same time, the urban economy of Douala extends this pressure beyond the built-up area through demand for fuelwood, charcoal, timber, sand, and other natural resources, including through informal economic activities (Fonteh et al., 2009; Roubaud, 2014). Landscape change in the estuary is therefore driven both by direct urban expansion and by the material demands of formal and informal economic activities.

These pressures are not limited to the physical expansion of the built environment. Douala acts as a regional demand center that connects urban growth with resource extraction in the estuary and adjacent watersheds. Fuelwood, charcoal, timber, sand, fish products, and agricultural commodities all link the city to surrounding rural and island communities. This helps explain why landscape transformation extends beyond the urban footprint itself and affects mangrove margins, river corridors, and watershed landscapes.

Outside the estuary, agro-industrial plantations represent a major driver of land transformation. Palm oil and rubber plantations have reorganized large parts of the surrounding watersheds, especially in the Sanaga and Moungo basins. Their expansion reflects not only local land-use decisions, but also broader economic and political trajectories, including the development of plantation agriculture and market-oriented production systems (Gerber, 2008; Tchindjang et al., 2016).

Agro-industrial expansion should also be interpreted as a historical and economic trajectory rather than only as a land-cover category. Plantation landscapes reflect former land concessions, market-oriented agricultural development, and, in some places, the persistence of inherited or ageing plantation structures. This legacy is particularly important in the Sanaga and Moungo watersheds, where present-day land-cover patterns partly record past phases of plantation expansion. More broadly, these processes fit with the proximate and underlying drivers of tropical deforestation, in which market demand, land tenure, infrastructure, and local livelihoods interact with governance and economic pressures (Geist and Lambin, 2002).

The watershed-based analysis shows that these transformations are spatially differentiated. The Wouri and Moungo watersheds are strongly influenced by the West Cameroon highlands, where agriculture, vegetation degradation, and active slope dynamics are closely associated (Morin, 1982b, 1994; Tchawa, 1991). The Dibamba watershed is more directly affected by the metropolitan influence of Douala, including road development, timber and fuelwood extraction, and sand mining along its lower course (Höhn and Neumann, 2018). The Sanaga watershed appears as the most extensively anthropized outer basin, with secondary vegetation, agro-industrial plantations, agricultural land, and a dense road network (Nguiffo and Sonkoué Watio, 2015). These contrasts show that the Mouths of Cameroon are not only transformed from within, but also embedded in a broader regional system of land-use change.

Taken together, these drivers indicate that landscape change in the Mouths of Cameroon is not controlled by a single process. It results from the combination of demographic growth, migration and land pressure, resource-dependent livelihoods, urban demand for raw materials, and agro-industrial transformation in adjacent watersheds. This multi-driver framework is essential for interpreting why similar forms of degradation may have different causes and implications from one basin to another.

5.2. Controls on coastline morphodynamics

Coastline morphodynamics in the Mouths of Cameroon result from the combined influence of natural hydro-sedimentary processes and human interventions. The estuary receives water and sediment from several rivers, while its outer sector is affected by marine currents, swells, and longshore sediment transport (Morin and Kuété, 1988; Ondo et al., 2018). This combination favors complex patterns of sediment redistribution and helps explain why erosion, stability, and accretion coexist over short distances.

Human activities disturb this balance. Dredging along the access channel to the Port of Douala removes large volumes of sediment and modifies channel morphology (Abaté, 2020; Fossi Fotsi, 2022). Sand extraction, especially along the lower Dibamba and in other estuarine sectors, further reduces sediment availability and can create local deficits, a problem also recognized in other sand-dependent coastal systems (Bendixen et al., 2019). Similar effects have been documented in other urbanized deltaic and estuarine systems, where dredging, channel deepening, and sea-level rise modify sediment budgets and channel morphology (Cox et al., 2021; Cox et al., 2022). These interventions are directly linked to the economic functioning of Douala, especially port maintenance and construction demand.

However, anthropogenic disturbance does not act on a passive coastal system. The estuary is naturally dynamic, with sediment inputs from rivers, redistribution by coastal currents, and deposition in channels, mudflats, mangrove margins, and shallow coastal sectors. Such low-gradient estuarine systems are especially sensitive to changes in sediment balance, tidal flow, and ecosystem structure (Anthony, 2015; Temmerman et al., 2013). The shoreline patterns observed between 2016 and 2020 therefore reflect a shifting balance between sediment supply, hydrodynamic redistribution, and human extraction or reworking of sediments.

The surrounding watersheds add another level of control. Land-use change, deforestation, agriculture, and plantation development may increase erosion and sediment export in some basins, while hydraulic regulation, especially on the Sanaga, may reduce downstream sediment transfer (Ndam Ngoupayou et al., 2016; Raburu and Okeyo-Owuor, 2006; Zeng et al., 2018). The Wouri and Moungo watersheds, with steep highland sectors and intense agricultural use, are likely to contribute sediment pulses during high-flow periods. The Dibamba, because of its proximity to Douala and local sand

extraction, represents a more localized but highly disturbed system. The Sanaga combines high sediment production potential with partial disconnection from the estuary and upstream regulation.

However, the lack of continuous measurements of suspended load and river sediment budgets prevents a robust quantification of these opposite effects. The present morphodynamic interpretation should therefore be understood as a qualitative assessment of interacting controls rather than as a closed sediment-budget calculation.

These differentiated controls explain why the estuary cannot be interpreted only through local shoreline processes. Its morphodynamics result from interactions between river inputs, marine forcing, urban-port interventions, sand extraction, and watershed-scale land-use change. The observed coexistence of retreating, stable, and accreting sectors is therefore the spatial expression of multiple interacting controls rather than the result of a single dominant process.

The presence of stable or accreting sectors should therefore not be interpreted as evidence of a system in equilibrium. Rather, it indicates that sediment supply still compensates for erosion locally, at least over the short 2016-2020 interval. This balance may be fragile because continued dredging, increasing sand demand, sea-level rise, and ongoing watershed transformation may progressively reduce the capacity of the estuary to buffer disturbance.

5.3. Ecological degradation and pollution

Ecological degradation in the Mouths of Cameroon is closely linked to vegetation loss, mangrove degradation, and multiple sources of pollution. Mangroves and coastal forests are not only landscape units; they play a functional role in sediment trapping, soil stabilization, reduction of tidal flow energy, and protection against erosion (Krauss et al., 2003; Ellison and Zouh, 2012; Temmerman et al., 2013). Their degradation therefore has both ecological and geomorphological consequences.

The vulnerability of these ecosystems is illustrated by the Mabé Mangrove Reserve, where more than 1,160 ha may have been lost over thirty years, representing about 14% of the territory (Mbevo, 2019). Such losses are particularly important in sectors such as Cap Cameroun, where mangrove degradation and shoreline retreat occur together.

Mangrove loss is driven by several interacting pressures. Fishing communities depend on mangrove wood for fish smoking, while nearby urban populations generate additional demand for fuelwood and other wood products (Nfotabong Atheull et al., 2009; IUCN, 2013). Agricultural activities and agro-industrial plantations on the margins of the estuary further contribute to vegetation clearing. The disappearance or degradation of mangroves reduces sediment-trapping capacity, weakens bank stability, and increases the vulnerability of the estuary to erosion (Alongi, 2002; Ellison, 2008; MINEPDED, 2018).

Because mangroves trap sediment and reduce tidal-flow energy, their degradation may directly alter the balance between accretion and erosion. Mangrove loss should therefore be interpreted not only as an ecological issue, but also as a geomorphological factor contributing to coastal vulnerability.

Pollution adds a second layer of ecological stress, especially in the northern part of the estuary around Douala and the port. Urban growth, industrial activities, poor waste management, recurrent flooding, and informal settlement expansion contribute to water, soil, and air pollution (Ngoran et al., 2015; Onana et al., 2021). These pressures affect wetlands, aquatic habitats, and biodiversity, and may also influence fisheries and local livelihoods (Didier et al., 2016; Ngongang et al., 2021; Clarisse et al., 2023).

The watershed perspective shows that ecological degradation should not be treated as a purely local estuarine problem. The Dibamba watershed is strongly affected by proximity to Douala, road development, timber extraction, and localized plantation activity. The Sanaga watershed shows advanced transformation of formerly forested landscapes into secondary vegetation, agricultural land, plantations, and road networks (Nguiffo and Sonkoué Watio, 2015). In the Wouri and Moungo watersheds, long-term degradation of vegetation cover in highland and agricultural sectors may affect downstream hydrological and sedimentary functioning (Morin, 1994; Höhn and Neumann, 2018).

The estuary should therefore be understood as the downstream receptor of cumulative pressures generated across the surrounding basins. Terrestrial degradation, river-borne pollution, urban-port activities, sand extraction, and mangrove loss converge in the Mouths of Cameroon. Ecological degradation and pollution are thus not separate issues, but interconnected expressions of the same environmental transformation affecting the estuary and its watersheds.

Even if the exact pathways and magnitudes of pollutant transfer remain insufficiently quantified, this downstream-receptor perspective is important because it prevents ecological degradation from being interpreted only as a local mangrove or urban problem. Instead, it links estuarine degradation to cumulative terrestrial, fluvial, industrial, hydraulic, and port-related pressures operating across the entire watershed-to-coast continuum.

This cumulative perspective also helps connect ecological degradation with morphodynamic change. Loss of vegetation cover, reduced sediment trapping, pollution, and extraction activities can act together to weaken shoreline

resistance and aquatic habitats. The ecological issue is therefore inseparable from the geomorphological evolution of the estuary and from the socio-economic dependence of local communities on estuarine resources.

5.4. Climate vulnerability, adaptation, and management implications

The Mouths of Cameroon are particularly vulnerable to climate change because they combine low coastal elevations, a gently sloping estuarine environment, dense human occupation, active shoreline change, and already degraded ecosystems (IPCC, 2021). Sea-level rise may intensify saltwater intrusion, submerge shallow areas, and favor the inland migration or retreat of mangrove belts (Wong et al., 2014). These effects are especially important in low-gradient estuaries, where small vertical changes can produce large horizontal shifts in shoreline and wetland position (Nicholls and Cazenave, 2010).

Climate vulnerability is not limited to sea-level rise. More intense rainfall events may increase runoff, erosion, sediment mobilization, and channel instability (Tamoffo et al., 2023). These processes could affect navigation, fisheries, waterfront infrastructure, and low-lying settlements. Climate change should therefore be understood less as an isolated driver than as an amplifier of existing pressures, including urbanization, vegetation degradation, dredging, sand extraction, and pollution.

The watershed-based perspective is essential here. The ability of the estuary to adjust to climate stress depends partly on the condition of the surrounding basins. Where vegetation cover is degraded, slopes are intensively cultivated, or sediment transfer is altered by hydraulic regulation, the downstream response to climate change may be intensified or modified. Adaptation should therefore be considered across the full watershed-to-estuary continuum rather than only along the shoreline.

Management responses must combine ecosystem restoration, land-use regulation, monitoring, and livelihood-compatible strategies. Mangrove restoration is a priority because it can strengthen bank stability, improve sediment retention, support fisheries, and reduce coastal vulnerability (Kauffman and Donato, 2012; Friess et al., 2019). Riparian buffer zones, protection of sensitive wetlands, and stricter control of urban and agro-industrial encroachment would help preserve the natural regulatory capacity of the estuary (Apeaning Addo, 2015).

At the watershed scale, more sustainable agricultural practices, including agroforestry, soil conservation, and reduced land clearing in fragile areas, are needed to limit erosion and downstream degradation (Lal, 2015; Mbow et al., 2017). Hydrological and sediment monitoring should also be strengthened, because the lack of continuous sediment measurements currently limits the capacity to anticipate morphodynamic change (Anthony, 2015). Monitoring is particularly important in a system where sediment delivery depends on both natural processes and human interventions.

Management should also be spatially differentiated. The Sanaga, Wouri, Dibamba, and Moungo watersheds differ in size, relief, geology, land use, degree of anthropization, and connection to the estuary. The heavily transformed Sanaga requires broad land-use planning; the Dibamba calls for urgent control of metropolitan and extractive pressures; while the Wouri and Moungo require attention to highland agriculture, plantation dynamics, and sediment transfer. A single undifferentiated management strategy would therefore be insufficient.

Finally, long-term resilience depends on inclusive governance. Many households rely directly on fishing, wood resources, small-scale agriculture, or estuarine products. Because of this dependence on livelihoods, restrictive conservation measures are unlikely to succeed unless they are combined with viable alternatives. Regulated artisanal fishing, sustainable use of mangrove products, community-based restoration, and locally adapted ecotourism could help reduce pressure on ecosystems while maintaining livelihoods (Walters et al., 2008). Involving fishers, farmers, local communities, and traditional authorities is therefore essential to align environmental protection with socio-economic realities (Ostrom, 2009).

Overall, sustainable management of the Mouths of Cameroon requires an integrated approach linking coastal processes, watershed dynamics, ecosystem conservation, climate adaptation, and local livelihoods. The estuary should be treated as a socio-ecological system whose resilience depends on coordinated action from the upstream basins to the shoreline (Syvitski et al., 2009; Day et al., 2016).

6. Conclusion

This study shows that the Mouths of Cameroon form a highly diverse and rapidly transforming estuarine system. Within the inner estuary, landscape change is mainly expressed through the expansion of Douala and its port complex, the degradation of mangroves and coastal forests, the persistence of subsistence farming, and localized agro-industrial plantation dynamics. Beyond the estuary, the watershed-based approach reveals strong contrasts among the Sanaga, Wouri, Dibamba, and Moungo basins in terms of relief, geology, land use, anthropogenic pressure, and connection to the estuarine system. Shoreline morphodynamics result from the interaction between natural coastal and fluvial processes and increasing human pressures. Marine currents, fluvial inputs, and the sandy-clayey substrate contribute to a naturally dynamic environment, while dredging, sand extraction, urbanization, vegetation degradation, and plantation expansion intensify existing imbalances. This combined influence is expressed by the coexistence of eroding, stable, and accreting coastal

sectors over short distances between 2016 and 2020. The Mouths of Cameroon should therefore be considered as a vulnerable socio-ecological system in which geomorphological change, ecological degradation, pollution, climate exposure, and livelihood dependence are closely interconnected. The results underline the need for integrated management linking coastal processes, watershed dynamics, ecosystem restoration, land-use regulation, and local community involvement. More broadly, the study demonstrates the importance of a watershed-to-estuary perspective for understanding environmental change and supporting long-term resilience in low-lying tropical coastal systems. By combining estuarine observations with watershed-scale interpretation, this study provides a framework for moving from descriptive coastal change assessment toward integrated territorial planning in tropical estuarine environments.

Author contributions

P.M.F. contributed to conceptualization, methodology, mapping, analysis, fieldwork, and writing. **L.R.B.** and **F.E.** contributed to review and editing. **A.H.-F.** contributed to methodology, analysis, review, and editing. All authors approved the manuscript.

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