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A remote sensing-based classification approach for river mouths of the Amazon-influenced Guianas coast

Antoine Gardel¹ · Edward J. Anthony² · Valdenira F. Santos³ · Nicolas Huybrechts⁴ · Sandric Lesourd⁵ · Aldo Sottolichio⁶ · Tanguy Maury¹

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Abstract

The mouths of the rivers on the 1500-km-long Guianas coast, South America, are strongly influenced by large mud banks migrating alongshore from the Amazon River. To probe this influence, a river-mouth morphological classification scheme was carried out from satellite images, complemented by data from rare previous studies of estuarine hydrodynamics. The classification highlights a variety of morphological and dynamic river-mouth types that are further influenced by both fluvial water discharge and fluvial catchment rock type. Three basic types are identified: (1) river mouths diverted westward by capes and spits built from multi-decadal to multi-millennial accumulation of mud supplied by the Amazon; among these, mouths close to the Amazon are fixed by bedrock surrounded by mud; (2) small river mouths in French Guiana fixed by outcrops of Precambrian rocks that form headlands devoid of Amazon mud; and (3) large river mouths characterized by high water discharge that imparts an orientation normal to the coast; the largest two belonging to this type (the Essequibo in Guyana and the Maroni on the border between French Guiana and Suriname) exhibit infilled mouths that are transitioning towards deltas. These river mouths show a tropical seasonal estuarine circulation regime strongly influenced by Amazon mud. The influence of mud from the distant Amazon constitutes a unique aspect of the river mouths on the Guianas coast. Field and modelling studies in the future will be needed in order to achieve better characterization of the influence of Amazon mud on the estuarine circulation systems and of the distribution of sediment types within these river mouths, including sand supplied by the rivers.

Keywords River-mouth classification · Remote sensing of river mouths · Tropical estuary · Guianas coast · Amazon mud

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Introduction

River mouths occur at the confluence of a river system and the ocean. Most modern river mouths formed more or less deep estuaries that started infilling with sediments following the stabilization of global sea level about 6000 years ago (e.g. Boyd et al. 1992; Dalrymple et al. 1992). Sediment trapping occurs through specific estuarine processes resulting from interactions between river and sea (Dyer 1997; Wolanski 2007). Sediments accumulating in river mouths are commonly supplied by the river catchments, but in many situations, a significant part of the sediment supply is from marine sources. The plan-view morphology of river mouths reflects the influence of both sediment inputs and the way these inputs are organized by marine processes, notably waves and currents. Infilled river mouths can eventually develop into deltas characterized by subaerial alluvial plains

associated with further sediment accumulation in subaqueous delta fronts (Elliott 1978; Wright 1985).

Mud supply from the Amazon has had an overarching influence on the morphology, sedimentology, and dynamics of the 1500-km-long Guianas coast in South America (Fig. 1). About 20% of this mud (out of nearly 1 billion tons annually, Eisma et al. 1991) forms distinct massive banks, separated by ‘inter-bank’ zones, and mobilized by waves and currents towards the Orinoco River delta in Venezuela (Anthony et al., 2010). Between the Amazon and the Orinoco occur numerous smaller rivers draining the Guiana Shield. The objective of this study is to probe the influence of the large Amazon mud banks on these river mouths by proposing a simple geomorphic river-mouth classification based on remote sensing, an indispensable technique in the mapping and interpretation of landforms across regional to global scales. We also carry out a brief synopsis of similar mud-influenced systems and river mouths at the global scale.

Regional setting of river mouths on the Guianas coast

The Guiana Shield provides a common regional geological setting for rivers debouching on the South American coast between the Amazon and the Orinoco. As a result, these rivers share, in common, landscapes, ecology (Sieber et al. 2021), and environmental problems (Oyedotun and Ally, 2021). The northward orientation of all of these rivers towards the Atlantic Ocean (Fig. 1) is a product of the tectonic separation of South America and Africa that led to the opening of this ocean during the Cretaceous (Roddaz et al. 2021). The geological units of the Guiana Shield are quite diversified, and include granitoids, granites, granulites, gneisses, sandstones, greenstones, mafic intrusions, and dykes ranging in age from Jurassic to Archaean (Kroonenberg et al. 2016; Roddaz et al. 2021).



Fig. 1 Regional setting of rivers on the Amazon-influenced Guiana Shield coast between the mouths of the Amazon in the east and those of the Orinoco in the west. The main map shows the catchments of a selection of the larger rivers. The red imprints on the shoreline rep-

resent the alongshore-migrating mud banks and their mud plumes defined from 2017 MODIS satellite images. See text for explanation of river types 1 to 3

The catchment size and limits, hydrology and sediment fluxes of several of these rivers are still not completely determined. The actual sources of the Essequibo River, for instance, the largest of the Guiana Shield rivers, were only discovered in 2013. Table 1 summarizes the regional coastal context and some characteristics of some of these rivers. The orientation of the coast inherited from the creation of the Atlantic Ocean is south-north (S–N) in western Brazil, southeast-northwest (SE–NW) in French Guiana, essentially east–west (E–W) in Suriname, and SE–NW in Guyana (Fig. 1; Table 1). The Guiana Shield is influenced by a tropical-equatorial seasonal climate influenced by the north–south migration of the Intertropical Convergence Zone (ITCZ). A well-marked rainy season occurs from the end of December to July and a dry season from August to December. This seasonal contrast is matched by marked variations in river discharge, with a threefold to fourfold increase in the rainy season. The rainy season is generally interrupted by dry conditions during the month of March. Rousseau et al. (2019) showed that the seasonality index, i.e. the ratio between the highest monthly discharge divided by the lowest one, of the Maroni River, the second largest Guiana Shield river (Table 1), is much higher than that of the Amazon, thus highlighting the high seasonality of the freshwater input. This may be due to the much

smaller catchment of the Maroni, compared to that of the Amazon (catchment size: ~6.1 million km² and mean discharge: 200,000 m³), since a large catchment size can significantly dampen seasonal fluctuations in water discharge. Misir et al. (2013) have shown, from an analysis of the Essequibo's and the much smaller Demerara's discharges, that ENSO events play a key role in fluctuations, with La Nina phases leading to wetter years.

Onshore-directed northeast trade winds occur during the rainy season, whereas weaker offshore southwest trade winds prevail when the ITCZ is at its northernmost position during the dry season (Gratitot et al. 2007). The stronger northeast trade winds from January to April have mean velocities of 6.3–8.2 m/s. Waves on the Guianas coast arrive from an east to northeast direction in response to these predominant northeast trade winds. This results in a regional sediment transport direction that is globally E–W, i.e. from the mouths of the Amazon to those of the Orinoco, but the potential volumes and rates are highly variable. They are significantly influenced by the subtle alongshore variations of the orientation of the Guianas coast (Table 1), by mud bank size, bank and inter-bank phases, variability in wave approach, and river-mouth hydrology (Gratitot et al., 2007). Waves are higher and longer between October and May (mean wave heights of about 1 m and significant wave heights of 1.5 to

Table 1 Characteristics of a selection of rivers debouching on the Guianas coast, including the much larger Amazon and Orinoco for comparison: *CO*, regional coastline; *CA*, catchment area; *L*, river length (from Hydrosheds <https://www.hydrosheds.org/page/gloric>); *Q*, water discharge (from GRDC <https://portal.grdc.bafg.de>, and Suriname Water Resources Information System for rivers of Suriname* <https://www.swris.sr/data/rivers/>); *SI*, discharge seasonality index (from Hydrosheds); *TR*, tidal range (from www.shom.fr); *H*, average wave height in the vicinity of each river mouth (from Marine Copernicus, <https://resources.marine.copernicus.eu>); *R-M*, river-mouth type. #Under influence of the Essequibo (see text)

	CO	CA (km ²)	L (km)	Q (m ³)	R-M	SI	TR (m)	H (m)
Orinoco	SE-NW	941,400	2025	30,621	Delta	9.2	2	0.9
Barima	SE-NW	9250	280	301	1b	2.1	-	0.5
Waini	SE-NW	9400	365	338	1b	1.7	-	0.9
Essequibo	SE-NW	154,860	920	2104	3	2.6	3	0.5
Demerara	SE-NW	7450	350	283	#	2.5	-	0.5
Berbice	SE-NW	15,800	450	372	1b	2.8	-	0.8
Corentyne*	E-W	64,285	850	1570	3	4.7	-	1
Nickerie*	E-W	9985	390	178	1b	2.7	2.9	1
Coppename*	E-W	21,200	400	500	3	3.2	-	0.8
Saramaka*	E-W	9455	440	225	1b	3.3	-	0.8
Suriname*	E-W	16,830	48	426	1b	5.5	2.2	0.7
Commewijne*	E-W	5090	190	120	1b	2.1	-	0.7
Maroni	SE-NW	66,410	610	1682	3	8.8	3	1
Mana	ESE-WNW	12,200	320	320	1b	5.0	-	1
Iracoubo	ESE-WNW	1500	160	57	1b	10.3	-	1
Sinnamary	SE-NW	6550	290	319	1b	12.9	-	1
Kourou	SE-NW	1810	145	99	2	12.1	2.9	1
Cayenne	SE-NW	725	50	46	2	10.1	-	
Mahury	SE-NW	3615	170	240	2	6.2	3	0.8
Approuague	SE-NW	9160	335	463	1a	4.0	3.5	0.7
Oyapock	SE-NW	26,100	405	835	1a	9.9	~4	0.9
Uaçá	SE-NW	5000	165	300	1a	7.3	~4	0.9
Cassipore	S–N	6150	220	422	1a	6.38	~4.5	0.8
Amazon	SE-NW	6,112,000	6500	209,000	Delta	2.2	~5–8	1

2 m, and peak periods of 9 to 11 s), and weaker from June to September (Gratiot et al. 2007). Tides are semi-diurnal and rapidly diminish in range westward from the coast of Amapá in Brazil, from about 4–5 m to 2.5–3 along the rest of the Guianas coast during spring tides (Table 1). The westward migration of mud banks affects the coasts of French Guiana, Suriname, Guyana, and Venezuela, which, together, form the world's longest continuous stretch of muddy coast. The mud banks dissipate wave energy, whereas inter-bank zones are commonly characterized by a relatively mud-free shoreface, and wave energy is thus more efficiently transmitted to the shore in these zones. Mud concentrations exceeding several hundreds of g/l (Gratiot et al. 2007) occur alongshore, potentially affecting the sediment dynamics of numerous smaller Guiana river mouths. The alongshore mud supply from the Amazon has been so massive as to be a major mud source over geological time up to the present for the delta of the Orinoco River (Fig. 1) 1500 km to the northwest of the mouths of the Amazon (Peng et al. 2018). The alongshore-shifting bank and inter-bank zones interact with water discharge from the Guiana Shield rivers. This relationship largely determines the river-mouth morphology.

Materials and methods

Given the spatial scale of the Amazon-influenced coast, the large number of river mouths (22 of them have a catchment size greater than 3500 km²), and the problems of accessibility, we used satellite images as a basis for the morphological characterization of river mouths and to deduce patterns of plan-view river-mouth development associated with mud banks. Fifteen river mouths distributed across the Guianas coast were selected from Sentinel 1 and Sentinel 2 images. We used multispectral images (Sentinel 2: 13 spectral bands and 10- to 60-m spatial resolution) to distinguish between the ecological and landscape units of the coastal plain (mangroves, freshwater swamps, and cheniers, i.e. beach deposits abandoned inland within the muddy coastal plain) and land-use types (farmland, settlements). Due to the high cloud cover in the region, we supplemented the datasets with Sentinel 1 SAR images (spatial resolution 88 × 87 m). In addition to identifying the limits of the river mouths, patterns of circulation of both suspension-sized sediment and bedload were estimated from the remote sensing images (Abascal Zorrilla et al. 2020). Because of the problems of access and logistics one faces regarding in situ field monitoring of the muddy Guianas coast, we use proxy data from the Mahury and Maroni River estuaries in French Guiana to show the pervasive influence of Amazon mud on the dynamics of these river mouths. The seasonal and tide-induced patterns of estuarine circulation and mud transport under the influence of Amazon-derived mud banks have been recently

monitored in these river mouths (Orseau et al. 2017; Sotolichio et al. 2018; Ross et al. 2019), modelled (Do Anh et al., 2020), and analysed through remote sensing (Abascal Zorrilla et al. 2020).

Results

Figure 2 depicts a selection of Sentinel 1 satellite images of river mouths for which we have drawn up a simple classification comprising three basic types that are shown on the regional map of the Guianas coast (Fig. 1), as well as in Table 1:

- Type 1 corresponds to river mouths fronted by a mud cape or spit oriented northwestward or westward in the direction of the regional alongshore sediment transport. These capes and spits correspond to significant Holocene coastal accumulation of Amazon-derived mud and are composed of freshwater swamps and mangroves, but may also include cheniers (Anthony et al., 2019). Two sub-types can be identified: (a) mud capes partially built on, and engulfing bedrock that exerts a lithological control on the river channel, represented by the Cassipore and Uaçá Rivers in Amapá, Brazil, the Oyapock River between Brazil and French Guiana, and the Approuague River in French Guiana (Fig. 2a); (b) river mouths diverted to varying extents by large mud capes or spits with no bedrock influence, represented by the Sinnamary, Iracoubo (Fig. 2b), and Mana Rivers in French Guiana, the Suriname River, co-located with the much smaller Commewijne, in Suriname (Fig. 2c), and the Berbice River in Guyana (Fig. 2d); in some cases, the diverted river mouths debouching at the distal tip of a mud cape or spit are co-located with the non-diverted mouth of a larger river (see type 3 below). Examples include the Mana (mouth co-located with that of the Maroni), and the Saramaka (mouth co-located with that of the Copename, Fig. 2e). Sub-type (a) mouths form large gulfs expressed by the important muddy seaward advance of the cape shoreline but with an orientation that is fixed by bedrock, which crops out in places in the river channel down to the mouth. In sub-type (b), the entire alluvial cape or spit can stretch alongshore for tens of kilometres, except in the cases of the Suriname and Berbice Rivers the muddy cape diversion of which embodies significant seaward shoreline displacement rather than alongshore growth (Fig. 2c,d).
- Type 2 corresponds to river mouths fixed by headlands of Precambrian basement rocks, represented by the Mahury, Cayenne, and Kourou Rivers (Fig. 2a). These are rivers with small catchments (< 3500 km²). They occur only in French Guiana, the only territory on the 1500-km-long

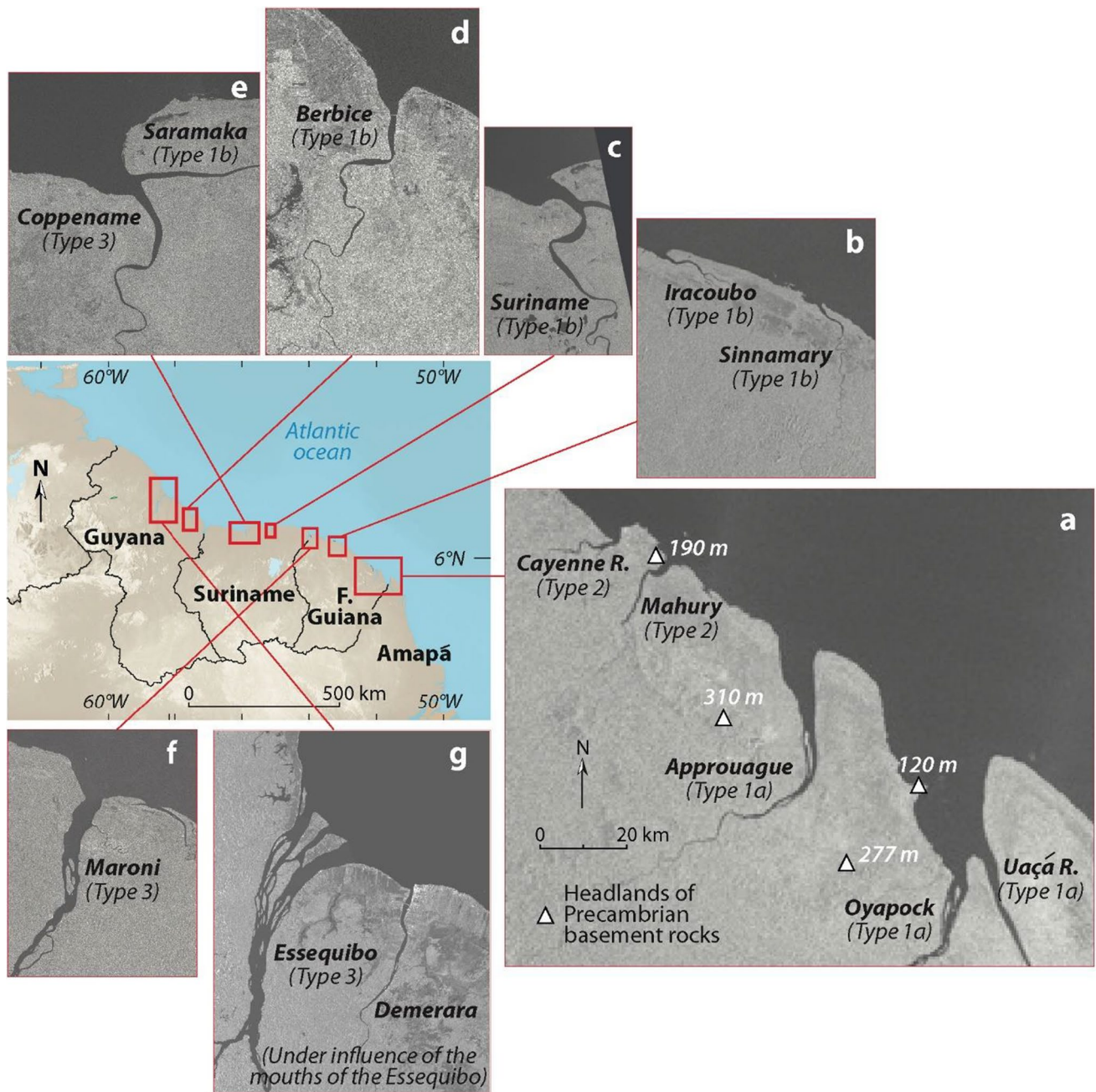


Fig. 2 Satellite images (2021 Sentinel 1, ©ESA) of a selection of Guiana Shield river mouths depicting their morphological plan-view diversity. The river mouths have been categorized into three types: (a) type 1a associated with large bedrock-engulfed muddy capes oriented nearly S–N in western Brazil and eastern French Guiana, and bedrock headland-controlled small type 2 river mouths in French Guiana;

(b, c, d) type 2 b alluvial river mouths variably diverted eastward by muddy spits or large mud capes, sometimes associated with larger type 3 river mouths (e); (f, g) type 3 river mouths oriented normal to the coast and associated with large rivers, from the French Guiana–Suriname border to Guyana

Guianas coast where the basement rocks locally crop out. Lithological fixing is limited to either the updrift bank (east, relative to the regional E–W regional sediment transport direction), cases of the Mahury and Kourou Rivers, or downdrift (west) bank as with the Cayenne River.

- Type 3 river mouths are free, unbounded features oriented normal to the coast and associated with relatively large-discharge rivers. Two sub-types are identified: (a) classic ‘trumpet’ or ‘funnel’-shaped estuaries, represented by the Coppename (Fig. 2e) and Corentyne Rivers in Suriname, and (b) river mouths showing substantial

sediment accumulation and a transitional morphology towards a delta, represented by the Maroni River between French Guiana and Suriname (Fig. 2f) and the Essequibo River in Guyana (Fig. 2g), the largest river on the Guianas coast after the Amazon and the Orinoco. As noted above, in some cases, the mouth of a large type 3 river is co-located with that of a much smaller rivers diverted alongshore by spits (Fig. 2e). A unique case of a non-diverted but co-located mouth of a small river is that of the Demerara close to the Essequibo (Fig. 2g).

Discussion

The plan-view morphology and sediment dynamics of the three Guiana Shield river-mouth types between the Amazon and the Orinoco are schematically summarized in Fig. 3. A feature common to all these river mouths is that they have developed in a context of significant accumulation of mud supplied by the former. In addition to this overarching mud supply, variation in type has also resulted from bedrock control and from the influence of large river water discharge in the cases of the bigger catchments. These three controls on river-mouth development form the basis of the discussion, followed by brief considerations of future perspectives of Guiana Shield river catchment changes under strong

anthropogenic impacts, and a global view of river-mouth systems associated with large alongshore mud supplies.

The overarching role of mud supply from the Amazon

Mud supplied by the Amazon over the last 5–6000 years has resulted in a Guianas coastal plain that can be up to 20-km wide, notably in eastern French Guiana and Amapá, and overlying a Precambrian basement with locally significant rock outcrops only in French Guiana (Anthony et al. 2010). This growth of the Guianas coastal plain has been assured by the welding of mud banks onshore over the last 5–6000 years (Augustinus 1978; Allison and Lee 2004; Wong et al. 2009; Anthony et al. 2010; Orseau et al. 2020). The regional-scale context in which these river mouths have developed significantly reflects this overarching Amazon influence, and all of the river mouths have infilled to varying degrees with Amazon mud.

The most pronounced morphological influence of Amazon mud on river-mouth development is associated with northward or westward diversion of type 1 river mouths by spits and capes. This morphological diversion is embedded in the development of the sedimentary Guianas coastal plain once these rivers exit from the crystalline and mafic bedrocks of the Guiana Shield. With this river-mouth type, bank welding in the course of the Holocene has led to two

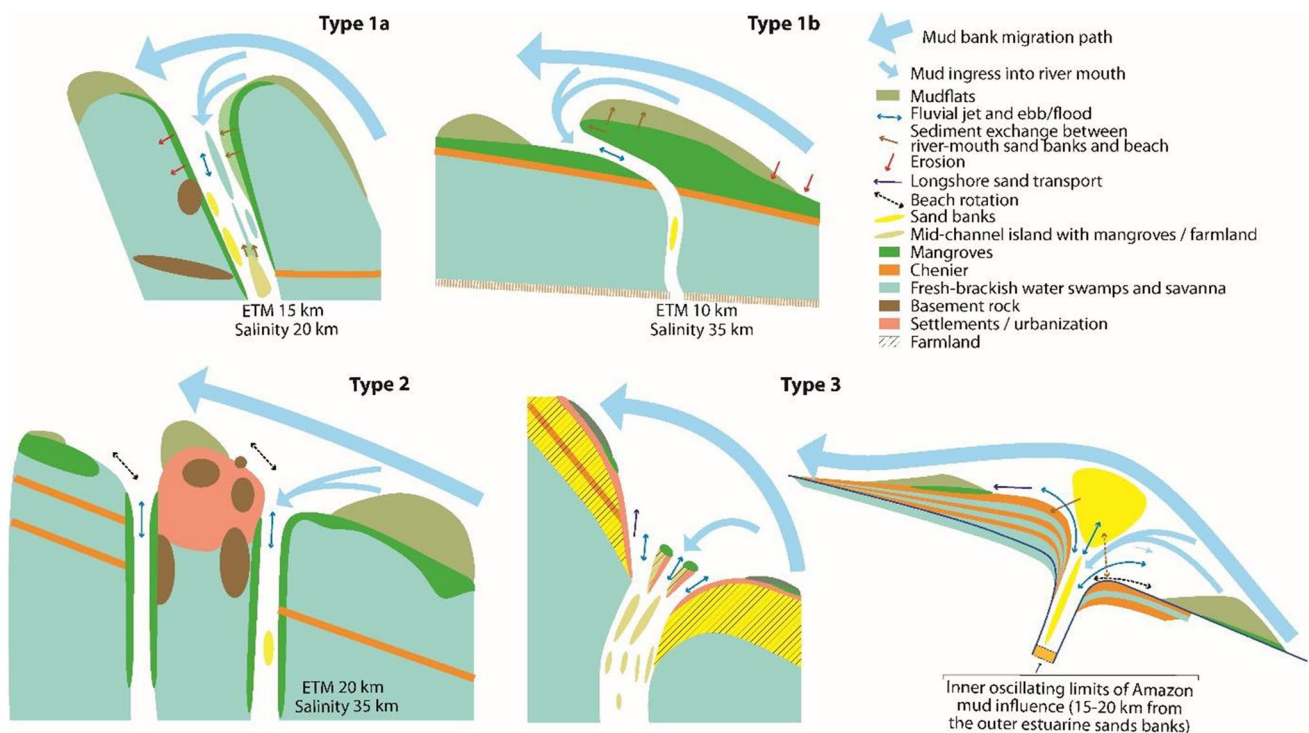


Fig. 3 Simple classification of Guiana Shield river mouths and schematic elements of their morpho-sedimentary dynamics

situations: significant gulf development as a result of north-westward to westward growth of the Guianas coastal plain, or alongshore deflection of the debouching river mouths. The former situation notably concerns the eastern sector of the Guianas coast in Amapá and eastern French Guiana, the area closest to the mouths of the Amazon where sub-type 1a river mouths prevail, and the latter sub-type 1b. Sub-type 1a river mouths form large gulfs subject to a large tidal range (up to 4 m at spring tides). These gulfs have developed following the important muddy seaward growth of the cape shoreline, but the overall S–N coastal orientation is fixed by bedrock, which crops out in places in the river channels down to the mouth. Northward extension of the mud capes bounding these river mouths is still going on, punctuated, however, by erosion. In this sub-type, both the proximity (tantamount to the availability of abundant Amazon mud) to the zone of mud-bank formation near Cape Cassiporé (Allison and Lee 2004), and the tidal range would appear to be complementary important controls. Both the abundance of mud and the large tidal range would lead to wave energy dissipation, favouring muddy accumulation. The relatively high river discharges, complemented by high tidal discharge resulting from the large tidal range, have kept these type 1a river mouths wide open (Fig. 2a). Type 1b river mouths have developed in a totally alluvial context. They are characterized by relatively small catchments (< 20,000 km²) and water discharges (< 450 m³/s) insufficient to maintain open river mouths at right angles to the coast (Anthony et al., 2013). As a result, these river mouths have been variably diverted alongshore by mud capes and spits. This deflection is mild for the largest type 1b river, the Suriname ($Q=426$ m³/s), but can extend for tens of kilometres for most of the smaller rivers. In this alluvial sub-type characterized by low to moderate discharge (< 500 m³/s), alongshore westward cape and spit deflection is clearly controlled by strong wave influence in a context of a smaller tidal range (spring tides of 2.5–3 m). This sub-type includes the marked alongshore mouth diversion of small rivers, such as the Saramaka (Fig. 2e), that join the mouths of much larger type 3 rivers located at the distal tips of these capes. In this sub-type 1b, alongshore deflection associated with the cape/spit extension process, appears to have been regulated by a compromise involving the following conditions: wave-induced refraction at the mouths of the rivers, freshwater river discharge and tide-water discharge from mangrove swamps that extend several kilometres along the banks of these diverted rivers, and, most important of all, regulation by inter-bank phases that periodically halt the extension of spits barring the smaller rivers. These inter-bank phases lead to the reworking of the distal fronts of these capes and spits. This can result in net seaward shoreline advance rather than pronounced cape elongation, as in the cases of the Suriname and Berbice Rivers (Fig. 2c, d).

The capes and spits can sometimes undergo significant retreat during prolonged inter-bank phases or when passing mud banks do not weld onshore. The erosion process can open up a gap alongshore, thus creating a new river mouth, as shown by the recent example of the Mana River (Fig. 4). Jolivet et al. (2019a) documented the demise, in the course of nearly 60 years (1955–2017), of the large mud cape of Pointe Isère. This erosion involved a loss of nearly 42 km² of coastal plain composed essentially of mangrove wetlands, and resulted in the eastward relocation of the mouth of the Mana. Pointe Isère had diverted the Mana westwards since at least the nineteenth century (Plaziat and Augustinus 2004). The gradual impingement of a large mud bank was accompanied, in 2011, by sealing of the ancestral mouth of the Mana by mud, and relocation of the present mouth of this river several kilometres east. Although we have documented here only one example of massive multi-decadal shoreline retreat affecting a mud cape, this is potentially an outcome that can affect all type 1 rivers (this was already observed for the Sinnamary mouth in the 1990s). The consequences of the change in the location of the mouth of the Mana have not been investigated but these may be expected to have significant repercussions on estuarine and river ecology and dynamics, and on the livelihoods of the coastal populations, especially those dependent on fishing and tourism, as shown by Jolivet et al. (2019b) for the settlement of Awala (Fig. 4).

The influence of bedrock on river-mouth development

It was stated in the foregoing section that the overall S–N coastal orientation of the large gulf-forming sub-type 1a river mouths is fixed by bedrock. This lithological control is more strongly expressed in type 3 river mouths. Although the three river mouths belonging to this category are associated with small catchments, the strong bedrock control has constrained their mobility, precluding the alongshore spit and cape diversion exhibited by type 1b alluvial river mouths. In the case of the Cayenne River, the pronounced Cayenne promontory, 20-km long and up to 10-km wide, leads to the offshore deflection of mud banks downdrift of the river mouth. Although the mouth of Cayenne River is not deflected, it has still been subjected to significant muddy accumulation associated with large-scale mangrove development in the downdrift lee side of the promontory. The important tidal influx associated with the extensive mangrove wetlands in this very wide river mouth enhances mud fluidization, and therefore contributes to the fixed position of the main river channel. The relationship with Amazon mud is rather different for the Mahury and Kourou Rivers. Their locations, respectively updrift of the Cayenne promontory and Pointe des Roches headland in Kourou, have implied that the mouths of these two small rivers are

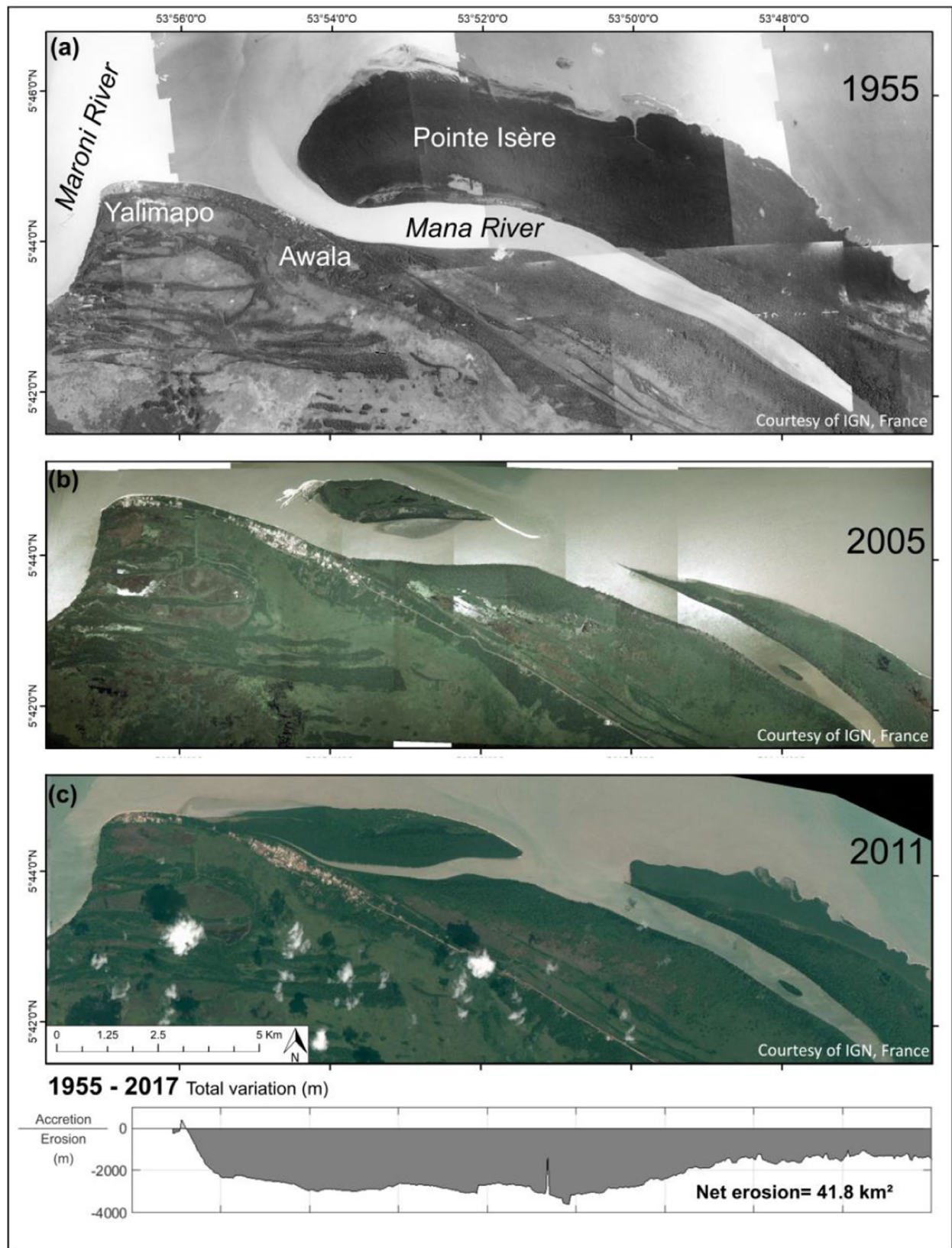


Fig. 4 An example of the drastic shoreline changes that have affected the mouth of the type 1b Mana River over 60 years. These changes have involved significant erosion of Pointe Isère, the large mud cape that had diverted the river westwards towards the mouth of the larger neighbouring Maroni River since at least the nineteenth century

potentially strongly influenced by the intrusion of Amazon mud. Both are associated, on their updrift eastern coasts, with pronounced growth of the muddy coastal plain. These two headlands of Precambrian basement rocks have been favourable sites for human settlements and the creation of the cities of Cayenne and Kourou. The two main ports in French Guiana (the commercial port of Degradés des Cannes in Cayenne and the European Space Agency's rocket and satellite-handling port of Pariacabo in Kourou) are located in these river mouths. In consequence, during the passage of mud banks, these small estuaries are massively silted up, necessitating important dredging operations to maintain the navigation channels to access the ports. Inter-bank phases are associated with the fluidization and natural desilting of these river mouths but the mud influence is still pervasive during these phases. Orseau et al. (2017) showed that the residual sediment transport in the Mahury estuary, largely dominated by Amazon mud, is landward during the dry season and variable during the rainy season, depending on the neap-spring tidal cycle. However, suspended sediment is easily expelled seaward during spring tides. Despite the situation of the Mahury and the Kourou directly in the pathway of mud banks, the two rivers have succeeded in maintaining wide, open mouths. This suggests that the combination of Atlantic waves, a large tidal influx, and freshwater discharge is important in maintaining fluid mud during bank phases, whereas wave-driven mud-bank migration and inter-bank phases moderate the long-term influence of Amazon mud.

The role of large river discharge

The morphological development outcomes of river mouths may be described in simple terms by considering the importance of river discharge (e.g. Ashton and Giosan, 2011; Anthony, 2015; Zainescu et al., 2021). River discharge, combined with tidal discharge, can prevent onshore welding of mud banks by rendering the mud highly fluid. Type 2 river mouths directly oriented by bedrock headlands are less concerned by the outcome of this hydrodynamic control. In type 3, alongshore muddy deflection of the mouths of rivers running northwards from the Guiana Shield to the Atlantic is precluded by the large water discharge from these rivers ($> 450 \text{ m}^3/\text{s}$, Table 1), complemented by the tidal discharge in their estuarine reaches. This large discharge acts as what has been described as a hydraulic 'groyne' (tantamount to a strong outflowing jet of river water) that liquefies and diverts offshore parts of a mud bank (Anthony et al. 2013). By preventing mud banks from welding onshore, this process contributes to the shielding of much smaller river mouths from the alongshore deflecting effect of mud spits formed from these banks, as in the case of the mouth of the Demerara River. This small river is located in the zone of 'hydraulic' influence of the mouth of the Essequibo (Fig. 2g). The

plan-shape morphology of type 3 river mouths conforms to the classic 'trumpet' or 'funnel'-shaped meso-macrotidal estuary. Notwithstanding, these river mouths are significantly impacted by the supply of Amazon mud as shown by Abascal Zorrilla et al. (2020), for the Maroni River, from analysis of surface suspended particulate matter (SPM) and the dynamics of the estuarine turbidity maximum (ETM) determined from OLI (Operational Land Imager)-Landsat 8 images. This study highlighted the influence of the well-marked seasonal river discharge regime and of tides, especially during the dry season. The ETM, located in the middle estuary during low flow conditions, shifts towards the mouth during high river flow, and under spring-tide conditions, or can even be pushed outside the mouth during the rainy season. Abascal Zorrilla et al. (2020) showed an increase in SPM, especially since 2017, accompanied by the extension of the ETM, that reflects the influence of a large impinging mud bank. This example, although limited to the Maroni River, albeit the second largest one among the Guiana Shield rivers, illustrates the pervasive influence of Amazon mud in the dynamics, and, as indicated below, long-term development of these rivers.

The two sub-types in this large river-mouth category are mainly differentiated on the basis of the degree of infill, which has been controlled by both Amazon mud and fluvial sediment supply, as Gardel et al. (2021) recently demonstrated also for the mouth of the Maroni. Growth of the Guianas coastal plain on either side of these river mouths has been regulated by mud-bank welding, promoted by mangrove development, and by the formation of cheniers from river-borne sand (Anthony et al., 2019). The mouth of the Essequibo has been significantly modified by empoldering and agricultural activities that is a hallmark of much of the coast of Guyana (Anthony and Gratiot 2012; Vaughn 2017; Mullenite 2020; Oyedotun and Burningham, 2021), compared to the still relatively pristine mouth of the Maroni River. At the mouth of the Maroni, active fluvial sand supply has contributed to the formation of cheniers on the down-drift Suriname side (Gardel et al. 2021). Mud welding on either side of the river mouth has resulted in coastal advance between cheniers. This fluvial sand supply is manifested by a sand-filled shallow estuary mouth.

These large, non-deflected river mouths offer a full and diversified range of morpho-sedimentary dynamics and sediment-transport pathways and interactions with the adjacent shoreline that is typical of large river mouths, but with the added significant dimension of Amazon mud in the estuarine dynamics (Fig. 3). The suspended sediment dynamics at the mouth of the Maroni clearly highlight the influence of Amazon mud (Abascal Zorrilla et al. 2020; Do Anh et al. 2020). The Maroni is a fine example for gauging the importance of this mud supply in long-term river-mouth development. In the course of the dry season, when river

discharge is low ($< 700 \text{ m}^3 \text{ s}^{-1}$), the mouth is uniformly turbid with high mud concentrations near the bottom (several g/l), reflecting the pervasive influence of Amazon mud. The high rainy-season discharge ($> 3500 \text{ m}^3 \text{ s}^{-1}$) is characterized by a marked vertical turbidity gradient and a salt-wedge circulation. This rainy-season salt-wedge structure has been important in blocking the river's sand load at the mouth. The large mud banks approaching the river mouth from the updrift French Guiana coast dissipate the NE to N trade-wind waves, contributing to preferential asymmetric accumulation of the estuarine sand bank closer to the west bank (Suriname). Active sand supply from this river mouth to the coast has been limited to the downdrift coast, and this has favoured the formation of numerous cheniers. The behaviour of the Maroni river mouth reflects an asymmetrical growth pattern that tends towards a delta characterized by both Maroni river sand and Amazon mud, fingerprinting the skewed (westward) growth pattern of much of the muddy, chenier-studded, coastal plain of the Guianas in the vicinity of Guiana Shield river mouths.

The increasing anthropogenic impact on Guiana Shield river catchments

In addition to potential fluctuations in mud-bank activity that are still poorly known, and the impact of which is particularly visible in the smaller cape- and spit-deflected river mouths, the morphology and dynamics of the Guiana Shield river mouths in the future will be determined by deforestation and eventual river damming. The catchments are mostly covered by dense equatorial forests that are still relatively protected compared to the Brazilian Amazon (Azevedo-Ramos et al. 2020; Ferrante and Fearnside, 2019). Gold-panning activities, often illicit, are, however, generating deforestation (Gallay et al. 2018; Dezechache et al. 2017). Increasing deforestation and dams in the future will affect the water and sediment discharges of rivers, both small and large, and the morphodynamic balance they have maintained thus far with Amazon mud supply (Anthony et al., 2021a).

Examples of river-mouth systems associated with large alongshore mud supplies

Mud may be transported in abundance from estuaries onto the global ocean, especially during high river discharge. This can contribute to enhancing turbidity levels both on the shoreface and alongshore, and it is not common to have important fine-grained sediment intrusion into estuaries from the open coast (Anthony et al., 2021b). Undoubtedly, the most significant example of this situation is that of the Guianas coast where this system has been nurtured by the combination of massive mud discharge from the Amazon and its alongshore transport over a distance of 1500 km. The

mud migration process has been aided by the favourable orientation of the coast relative to the regional trade-wind waves, by wind activity and by tidal currents. Similar lateral mud dispersal systems associated with river mouths have also been identified on other coasts (Anthony et al., 2021b). Important examples include the Ayeyarwady and the Salween, two high-discharge rivers in Myanmar and the mud supply of which is contributing to infill of the neighbouring Sittaung estuary, and the mouths of the Ganges and Brahmaputra which supply mud alongshore to the moribund deltaic lobes that host the Sundarbans mangroves. These are among the world's largest sediment-discharge rivers. Several small estuaries on the 500-km-long coast of West Africa between Sierra Leone and Guinea-Bissau are also interlinked by a mud supply system.

Conclusions

The rivers debouching on the 1500-km-long Guianas coast between the Amazon and the Orinoco River deltas are characterized by a river-mouth morphology that has been more or less significantly impacted by mud supplied by the Amazon. This mud has built up the Guianas coastal plain. The overarching component of the long-term coastal dynamics is the alongshore supply of mud from the mouths of the Amazon to those of the Orinoco by wave- and wind-generated currents. This mud influence is particularly manifested by alongshore deflection of the mouths of the smaller rivers by growth of the muddy coastal plain, the extent and direction of which may be constrained where bedrock crops out. This is the case with some of the cape-deflected river mouths in Brazil and eastern French Guiana. Stronger bedrock control associated with promontories is limited to small rivers in French Guiana. Where river discharge has not been strong enough to act as a hydraulic groyne on Amazon mud, river mouths are deflected alongshore by mud capes and spits for tens of kilometres. Large rivers with significant discharge, from the French Guiana-Suriname border to the Guyana-Venezuela border, are characterized by non-deflected river mouths that show various stages of development, from infilling estuaries to deltas. But this infill has also been nurtured by significant sedimentation of Amazon mud which contributes to the constitution and dynamics of the estuarine turbidity maximum in these large river mouths. The influence and changing dynamics of Amazon mud also impact human activities associated with these river mouths.

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