

Monitoring of Coastal Dynamics in French Guiana from 16 Years of SPOT Satellite Images

A. Gardel† and N. Gratiot‡

†Laboratoire Régional de télédétection
Unité ESPACE, IRD Guyane,
BP 165, Rte de Montabo, Cayenne
97323, Guyane Française, France
gardel@cayenne.ird.fr

‡Laboratoire d'écologie littorale,
Unité ELISA, IRD Guyane,
BP 165, Rte de Montabo, Cayenne
97323, Guyane Française, France
gratiot@cayenne.ird.fr



ABSTRACT

GARDEL, A. and GRATIOT, N., 2006. Monitoring of coastal dynamics in French Guiana from 16 years SPOT satellite images. *Journal of Coastal Research*, SI 39 (Proceedings of the 8th International Coastal Symposium), 1502 - 1505. Itajai, SC, Brazil, ISSN 0749-0208.

The Guianas coast, northwest of the mouth of the Amazon river, experiences a very strong supply of muddy sediment that entails major coastal modifications at seasonal to annual timescales. Mud supply is predominantly in the form of mud banks migrating alongshore from the Amazon to the Orinoco. In this paper, focus is placed on the geomorphic change that has affected the 60 km stretch of coastline between Cayenne and Kourou (French Guiana) from 1986 to 2002. The remote sensing analysis demonstrates an overall erosion of 60 km² of sea-front mangrove swamps. A new mud bank migrating towards Kourou since 1991 has led to a significant reduction in erosion and has even enabled the commencement of mangrove colonization. A spatio-temporal matrix applied to both the vegetated and inter-tidal parts of the mud bank highlights the interplay between mud bank migration and mangrove colonization.

ADDITIONAL INDEX WORDS: *Mud bank, mangrove, cohesive sediment, remote sensing.*

INTRODUCTION

The Guianas coast from Amapá, in Brazil, to the Orinoco River delta in Venezuela (Figure 1) is the longest muddy coast in the world. The longshore sediment flux along this northeastern coast of South America is driven by the seasonal supply of mud from the Amazon river. The Amazon discharge has been estimated at 1.2×10^9 tons.y⁻¹ (MEADE *et al.*, 1985). Fifteen to twenty percent of the sediment supply migrates northwestward along the Guianas coast, half of this load ($1-1.5 \times 10^8$ tons.y⁻¹) migrating in highly turbid suspensions in the coastal waters, while the other half (1×10^8 tons.y⁻¹) migrates in the form of huge mud banks (WELLS and COLEMAN, 1978) whose formation occurs along the northwestern coast of Amapá State in Brazil (ALLISON *et al.*, 2000). The mud banks then migrate along the French Guiana, Surinam and Guyana coasts until the Orinoco delta in Venezuela (WARNE *et al.*, 2002). The mechanisms of this migration are complex, and are hinged on sediment supply and hydrodynamic forcing. Migration is driven essentially by trade wind-generated waves which attain their peak activity between December and March (WELLS and COLEMAN, 1978). The Guyana Current is deemed to be too far offshore to be effective in the transport of coastal mud (RODRIGUEZ and MEHTA, 1998).

The morphology of the mud banks appears to be variable. They range in length from 10 to 60 km, are 20 to 30 km wide, spaced 15 to 25 km apart and are up to 5 m thick (FROIDEFOND *et al.*, 1988; ALLISON *et al.*, 2000). Their rates of migration are also quite variable, from less than 0.5 km.y⁻¹ to more than 5 km.y⁻¹ (AUGUSTINUS, 1987; EISMA *et al.*, 1991; FROIDEFOND *et al.*, 1988). In French Guiana annual rates were estimated (FROIDEFOND *et al.*, 1988) at about 1.0 km.y⁻¹. A recent study by Gardel and Gratiot (2005) has recorded rates of migration twice higher (2.2 km.y⁻¹) during a 12-year survey of a mud bank using satellite data. This work also highlighted large variability in rates of migration (from 1 to 3 km.y⁻¹).

This paper focuses specifically on the French Guiana coast. The coastal morphology of French Guiana largely reflects the influence of mud supply from the Amazon river. The coastal plain has a width of 10-30 km, and is backed inland by the Basement Complex formed by the Guyana Shield. From the shoreline to the Guyana Shield, the landscape is composed of a succession of morphological units. The young coastal plain, of Holocene age, is situated between an older, 10-20 km wide

Pleistocene coastal plain that abuts the Shield, and the highly dynamic modern muddy shoreline. This humid coastal plain is interrupted in places by linear relict Holocene beach ridges (old cheniers). The modern shore evolves permanently. It can be muddy or sandy depending on the presence or absence of a mud bank. Mud bank phases are characterised by large-scale development of mudflats and mangrove-colonized tidal flats. The colonization of mudflats by mangroves is not systematic. It occurs following mud consolidation driven by prolonged low-tide exposure of mud

(WELLS and COLEMAN, 1981) and by massive tidal deposition of seeds. In the wake of such colonization, *Avicennia germinans* forms exclusive sea-front stands, although *Laguncularia racemosa* commonly occurs in the initial phases of colonization. Inter-bank phases are dominated by erosion and commonly by the occurrence of sandy (chenier or non-chenier) shores, as described from the Surinam coast by AUGUSTINUS (1979). Erosion can have a considerable impact, commonly engendering major morphological modification of the coast. Large areas of mangroves can totally disappear under wave action as shown in Figure 2.

The aim of this paper is to apply a satellite image-based method, recently developed by Gardel and Gratiot (2005) to the monitoring of geomorphic change along the 60-km stretch of mangrove-colonized coastline between the cities of Cayenne and Kourou (Figure 1). Sixteen SPOT images and one LANDSAT image covering the period 1986-2002 are used to monitor the evolution of this part of the French Guiana coast. All the images were geo-coded and integrated in a GIS (Geographic Information System) in order to extract mangrove limits at every date. This allowed a global analysis of the coastal dynamics and a quantification of mangrove erosion and new colonization. A matrix representation of the relative evolution of mangroves since 1986 highlights the direct interaction between mud bank evolution and mangrove behaviour.

DATA AND METHODS

High resolution satellite images such as SPOT and LANDSAT are well adapted to the monitoring of highly dynamic coastal features such as those of the Guianas coast. Their multi-spectral resolution in the visible and infrared domains offers a good tool for the identification of mangrove forests. At the observation scale provided by these satellite

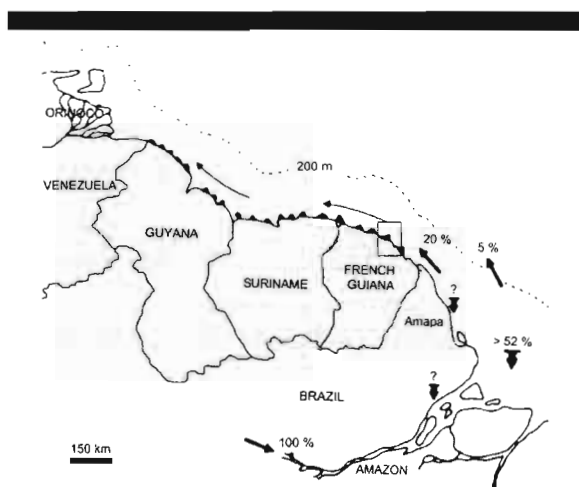


Figure 1. The Amazon-influenced South American coast (adapted from Eisma et al., 1991). Dots along the coast represent positions of mud banks monitored between French Guiana and Venezuela by Delft Hydraulics (1962).

images, mangrove features are homogeneous (due to the monospecific and same-age character of mangrove forests) and can thus be easily discriminated. The set of data contains sixteen SPOT images from 1986 to 2002 and a LANDSAT image acquired in September 2002 that completes and updates the set. All images were geometrically processed and geographically formatted in WGS84 UTM N22 projection. These initial treatments were realized using ER Mapper (©) software version 6.21. The geo-coded images were then integrated in a GIS software (GeoConcept ©). The set of images, their dates of acquisition, their coverage rates and the corresponding tidal levels are reported in Table 1.

A manual method based on interpretation of satellite images has been chosen to extract mangrove limits. The stable shoreline has also been extracted. The stable shoreline limit corresponds to the first Holocene sandy ridge. This structural limit is observed to be stable for the duration of the survey covered by the images. At present, this Holocene sandy ridge is subjected to erosion in the inter-bank areas.

In the GIS, the shoreline has been cut out in ten sectors uniformly-spaced 4 km apart. The evolution of mangroves is measured in each sector and at every date. This step is effected using topological analysis between sectors and mangrove surfaces.

A matrix method was developed for the monitoring of mud bank migration (Gardel and Gratiot, submitted). This method

Table 1. *Some characteristics on the remote sensing images acquisition.*

Date	time UT	Tidal height (m)	Coverage rate %
10-20-86	14h16	1,28	100
11-17-91	14h13	2,40	50
10-02-93	13h56	1,14	55
08-30-94	14h12	2,28	85
10-16-95	13h49	2,35	90
10-26-95	13h57	1,14	80
09-28-96	13h55	0,86	90
09-02-97	14h20	0,97	45
06-20-98	13h57	2,11	40
09-06-98	13h57	0,74	90
05-09-99	13h45	2,65	40
02-07-00	14h16	1,20	70
07-02-01	13h49	1,58	100
10-14-01	13h49	1,40	40
12-14-01	14h16	1,28	70
08-05-02	14h15	1,78	60
09-19-02	12h30	1,05	100



Figure 2. photograph of a mature mangrove swamp undergoing erosion (courtesy of M.T. Prost).

allows for a relevant spatio-temporal monitoring of inter-tidal mud bank limits, but also mangroves, and, more generally, the evolution of all mathematical combinations of coastal features.

RESULTS

Mangrove Dynamics

The available data set does not cover the entire studied shoreline stretch at each date (see Table 1). For this reason, the sector analysis cannot be strictly applied to cover every date.

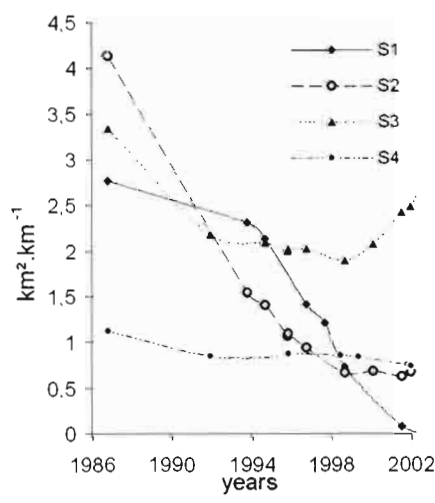
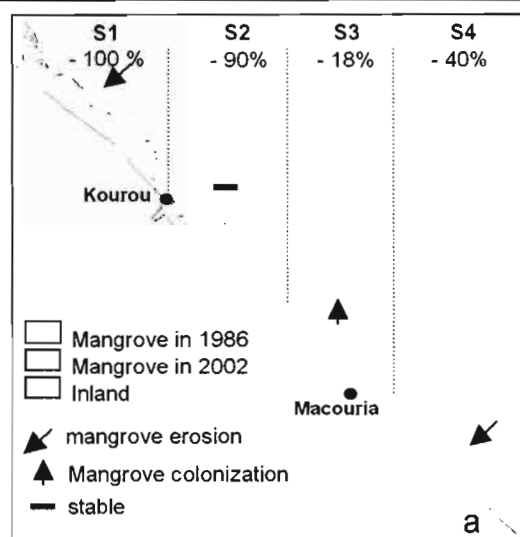


Figure 3. a Evolution between 1986 and 2002 and present trends in mangrove dynamics by sector (S1-S4); 3b. mangrove surface areas per kilometre alongshore per annum.

Over the 16-year study period, the coast underwent marked morphological modifications. Initially, it was covered by a large mangrove forest established on a stabilized mudflat. At present, much of this mangrove forest has been eroded by waves. Globally, between 1986 and 2002, 60 km² of mangrove was eroded. However, the mangrove evolution of the ten uniformly spaced sectors is not similar and four main sectors (S1-S2-S3-S4) can be distinguished (Figure 3a).

In sector S1, the mangrove forest, which had a cross-shore width of 3 km in 1986, had totally disappeared by 2002, entailing a loss of 30 km². Figure 3b highlights the remarkably constant erosion rate of this sector since 1994. Erosion still continues today (2003), affecting the relict chenier behind the eroded muddy deposits.

Southeastward of the Kourou River (S2), erosion has also been intense and 90% (19 km²) of the initial mangrove area has disappeared. A narrow fringe of mangroves less than 100 m wide persists in front of the relict chenier. Mangrove erosion has resulted in the formation of a large embayment in this sector. In contrast to the previous sector (S1), no erosion has occurred in this sector since 1998.

S3 suffered erosion to the tune of 10 km² until 1991. The coast then remained relatively stable for 10 years. Mangrove recolonization began in 2000 and had attained 7 km² by the end of 2002. Globally, this part of the coast has undergone a mangrove retreat of about 20%.

S4 also suffered erosion until 1991, followed 3 years later by limited mangrove growth. This sector has been affected since 1998 by a phase of erosion and the mangrove surface area has decreased slightly.

The mangrove retreat along the 60-km stretch of coastline differs significantly from one sector to another, S3 and S4 sectors even showing colonization trends since the end of 1990s. The arrival of a new mud bank in front of S4 in 1991 is believed to be a major event conditioning mangrove behaviour.

Influence of Mud Banks on Mangrove Changes

The matrix representation (Figure 4a) provides an original spatio-temporal representation of the inter-tidal kinetiks of mud banks. As highlighted by Gardel and Gratiot (2005), the migration rate experienced three phases. Up to 1996, the mud bank migrated at a celerity less than 2.0 km.y⁻¹. This mean rate increased to about 2.5 km.y⁻¹ from 1996 to 2000 before slowing down to about 1.5 km.y⁻¹. At the end of 2002, the main part of the intertidal area had reached S2 sector. Over the studied period, the inter-tidal area became larger and more elongated. In the last dates, the inter-tidal cross-shore and longshore extension reached 3.5 km and about 20 km, respectively. This trend is related to the slow-down measured since 2000.

The same matrix representation is applied to the mangroves. Mangrove evolution relative to the coastline in 1986 is presented in Figure 4b. The main sectors (S1-S2-S3-S4) described previously are reported in Figure 4b. The black vertical line between S1 and S2 corresponds to the Kourou river mouth. Globally, and as seen in section IIIa, the mangroves have suffered intensive erosion (grey to white shades in Figure 4b). However, two peaks of colonization are recorded (white crosses on Figure 4b). The first occurred in 1997 in sector S4 and the second occurred in 2000 in sector S3. These two peaks of colonization are closely related to the migration of the mud bank. They both occurred in the back part of the bank, two and a half years after the passage of the maximal inter-tidal extension (-).

DISCUSSION AND CONCLUSIONS

This analysis using GIS and an image-based matrix method offers a relevant perception of the dynamics of mangroves along the Cayenne-Kourou coastline between 1986 and 2002. Overall, erosion and mangrove growth are closely linked to mud bank location and migration. For instance, sector S1 has

experienced the longest inter-bank duration since the early 1990's and has simultaneously suffered the most intensive mangrove retreat (100%). However, although correlations can be established between mud bank dynamics and mangrove evolution, the influence of the former on the latter does not always appear clearly. This is not very surprising because mangroves and inter-tidal mud are governed by physical and biological processes at different space and time scales. Mangrove dynamics exhibit a more or less cross-shore pattern of erosion or colonization while inter-tidal mud is subjected to alongshore migration, mostly under the influence of waves. The two and a half years delay between the passage of the maximal inter-tidal extension and the beginning of colonization (see Figure 4b) highlights the complex and long-term interplay between mud bank and mangroves. The increase of the cross shore inter-tidal mud extension first protects the coast from waves, allowing for the onset of soil consolidation processes. The transport of seeds by tidal currents or creeks and their arrival at low-tide exposure of the mudflats is then a critical condition for the deposition of seeds and the initiation of colonization.

The relationship between inter-tidal mud bank and mangroves is more evident when inter-bank and bank areas are examined independently. Results presented in Figure 4c demonstrate the existence of three distinct periods. From 1986 to 1995, vegetation suffered erosion in both inter-bank and bank areas; the following 1995-2001 period was very active for both erosion process in inter-bank areas and colonization in bank areas; finally, mangrove colonization ceased in 2001 while erosion rates rose back to a hundred m.y⁻¹ in inter-bank areas. The different phases are well correlated with the variability of mud bank migration rates quantified by Gardel and Gratiot (2005). This demonstrates a high time dependency of both mud bank and mangrove dynamics on a more global forcing

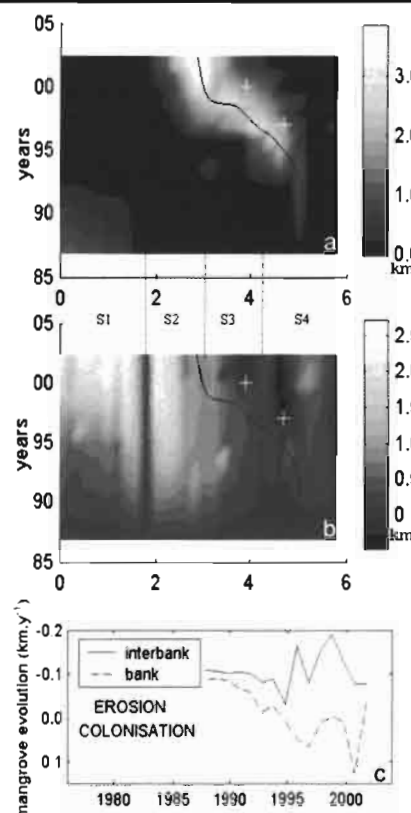


Figure 4a. matrix representation of the inter-tidal mud bank evolution (1986-2002) and evolution of the maximal inter-tidal extension (-). 4b. matrix representation of the relative evolution of mangroves since 1986. White crosses represent colonization spots. 4c. temporal evolution of mangroves, discriminating bank and inter-bank areas on Figure 4a.

context and on the duality between the inter-bank areas (black areas in Figure 4a) in erosion (see Figure 4b) and bank areas that are the potential zones of mangrove colonization.

Future research should focus on reasons for the variability of mud bank migration rates and its incidence on mangrove dynamics. Low-frequency tidal constituents are very likely to be a determinant factor in the consolidation process (Wells and Coleman, 1981) while wind stress (intensity and direction) variations at local and synoptic scales may significantly modify wave forcing.

ACKNOWLEDGEMENTS

This work was supported by CNES/IRD contract n°02/CNES/0814/00. PNEC (Programme National d'Environnement Côtier) provided some of the SPOT images. We wish to thank Météo France for the wind data and Edward J. Anthony for the fruitful discussions and his review of the manuscript.

LITERATURE CITED

- ALLISON, M.A.; LEE, M.T.; OGSTON, A.S.; and ALLER, R.C., 2000. Origin of Amazon mudbanks along the northeastern coast of South America. *Marine Geology*, 163, 241-256.
- ANTHONY, E.J.; GARDEL, A.; DOLIQUE, F. and GUIRAL, D., 2002. Short-term changes in the plan shape of a sandy beach in response to sheltering by a nearshore mud bank, Cayenne, French Guiana. *Earth Surface Processes and Landforms*, 27, 857-866.
- AUGUSTINUS, P.G.E.F., 1978. The changing shoreline of Surinam (South America). The Netherlands, University of Utrecht, Ph.D. thesis, 232p.
- AUGUSTINUS, P.G.E.F., 1987. The geomorphologic development of the coast of Guiana between the Corentyne river and the Essequibo river. In: John Wiley and Sons (ed.): *International Geomorphology. Part. I*, pp.1281-1292.
- BOYE, M., 1962. Les palétuviers du littoral de la Guyane française, ressources et problèmes d'exploitation. *Les Cahiers d'Outre-mer*, 15, 271-290.
- DELFT HYDRAULICS LABORATORY, 1962. Demerara coastal investigation. Report on siltation of Demerara Bar Channel and coastal erosion in British Guiana. Delft, 1-240.
- EISMA, D.; AUGUSTINUS, P.G.E.F. and ALEXANDER, C.R., 1991. Recent and subrecent changes in the dispersal of Amazon mud. *Netherlands Journal of Sea Research*, 28, 181-192.
- FROIDEFOND, J.M.; PUJOS, M. and ANDRE, X., 1988. Migration of mud-banks and changing coastline in French Guiana. *Marine Geology*, 84, 19-30.
- FROIDEFOND, J.M.; GARDEL, L.; GUIRAL, D.; PARRA, M. and TERNON, J.F., 2002. Spectral remote sensing reflectances of coastal waters in French Guiana under the Amazon influence. *Remote Sensing of Environment*, 80, 225-232.
- GARDEL, A. and GRATIOT, N., 2005. A satellite imagery-based method for monitoring mud bank migration rates, French Guiana, South America. *Journal of Coastal Research*, 21, 720-728.
- KIRBY, R., 2000. Practical implications of tidal flat shape. *Continental Shelf Research*, 20, 1061-1077.
- MEADE, R.H.; DUNNE, T.; RICHEY, J.E.; SANTOS, U.M. and SALATI, E., 1985. Storage and remobilisation of suspended sediment in the lower Amazon River of Brazil. *Science*, 228, 488-490.
- NEDECO, 1968. Surinam transportation study: report on hydraulic investigation. The Hague, Netherlands, 293 p.
- RODRIGUEZ, H.N. and MEHTA, A.J., 1998. Considerations on wave-induced fluid mud streaming at open coasts. In Black, K.S.; Paterson, D.M. and Cramp, A. (eds.) *Sedimentary processes in the intertidal zone*. Geological Society, London, Special Publications, 139, 177-186.
- WARNE, A.G.; MEADE, R.H.; WHITE, W.A.; GUEVARA, E.H.; GIGEAUT, J.; SMYTH, R.C.; ASLAN, A. and TREMBLAY, T., 2002. Regional controls on geomorphology, hydrology and ecosystem integrity in the Orinoco Delta, Venezuela. *Geomorphology*, 44, 273-307.
- WELLS, J.T. and COLEMAN, J.M., 1978. Longshore transport of mud by waves: northeastern coast of South America. *Geologie en Mijnbouw*, 57, 353-359.
- WELLS, J.T. and COLEMAN, J.M., 1981. Periodic mudflat progradation, northeastern coast of South America: a hypothesis. *Journal of Sediment Petrology*, 51, 1069-1075.