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Impact of land degradation from mining activities on the sediment fluxes in two large rivers of French Guiana

Gallay Marjorie [1, *], Martinez Jean-Michel [2], Allo Sebastien [3], Mora Abrahan [4], Cochonneau Gerard [2], Gardel Antoine [5], Doudou Jean-Claude [6], Sarrazin Max [7], Chow-Toun Franck [8], Laraque Alain [2]

[1] Univ Guyane, IRD GET UMR 5563, UR 234, Cayenne, Guyane Francais, France.
[2] GET UMR CNRS IRD UPS UMR 5563, Toulouse, France.
[3] Off Natl Forets, Brigade Nat, Cayenne, France.
[4] Tecnol Monterrey, Ctr Agua Amer Latina & Caribe, Escuela Ingn & Ciencias, Monterrey, Mexico.
[5] LEEISA, USR Mixte CNRS UG IFREMER, Cayenne, France.
[6] OBHI, Cayenne, France.
[7] IMAGO, Cayenne, France.
[8] Univ Paris 07, UMR PRODIG 8586, Paris, France.

* Corresponding author : Marjorie Gallay, email address : marjorie.gallay@gmail.com

Abstract :

We analyzed two contrasting catchments located among the world's largest unspoiled tropical rainforests impacted by mining in the northeastern coastlands of South America. We used the following: (a) mining, agricultural, and urbanized areas to compare the land use evolution with suspended sediments and sediment yields; (b) field monthly river suspended sediments in the two catchments (2004-2015: n = 154); (c) MODIS remote sensing water color technique in the Maroni basin to complete (n = 387) and extend field suspended sediment sampling from 2000 to 2015; (d) hydroclimatic statistical analysis conditions and sediment concentrations to identify the long-term trends, the abrupt changes in time series and to analyze if the environmental and anthropogenic factors control sediment yield regional variations. No significant long-term changes were observed in precipitation or water discharge with the Mann-Kendall test. However, the mean suspended sediment concentration has increased significantly (239%) in the Maroni River with a breakpoint in 2009 and decreased (33%) in the Oyapock River (breakpoint in 2008). These differences are explained by the larger percentage of deforestation because of mining activities in the Maroni (0.37%) than in the Oyapock (0.06%) catchment. In the Maroni River, the increasing sediment yield trend (2000-2015) coincide significantly ($r2 = 0.97$; $p < 0.0001$) with the increase of 400% of mining areas, whereas no significant relationship with the runoff was found. In the Oyapock River, the runoff explains the sediment yield decreasing trend ($r2 = 0.82$; $p < 0.0001$) and no relationship with the land use change was found.

Keywords : land degradation, mining, MODIS, runoff, sediment yields

1. INTRODUCTION

At a global scale, there are only few rivers that have not undergone alterations in their hydrological and morphological processes or water quality because of changes in land use and hydrological or climatic conditions in their catchments (Milliman *et al.*, 2008; WWAP, 2015; Pekel *et al.*, 2016). As reported by Pékel (2016), water discharge and global sediment loads to the ocean are decreasing, mainly due to the increasing number of dams worldwide and global water demand (WWAP, 2015). At the same time, erosion processes are increasing within catchments due to land-use conversion increasing rates (Shi & Wang, 2015, Shi *et al.*, 2016; Zhao *et al.*, 2017).

Over the past decade, the tropical region was the only climate domain exhibiting a significant decrease trend of forest loss, with 2,101 km² per year (Hansen *et al*., 2013). Demographic, economic and social changes impose considerable pressure on forest cover (Valentin *et al*., 2008), water resources and leaving conditions, in spite of they are hotspot of biodiversity and freshwater ecoregions (Mittermeier *et al*., 1998; Abell *et al*., 2008). Several examples of how deforestation and land use changes can alter the natural dynamic of water in the tropic can be found in the Amazon region, specifically in the Tocantins and Araguaia rivers, where Coe *et al*. (2009) have shown that deforestation changes in the basin increase the water discharge. Similarly, Hettler *et al*. (1997) concluded in Papua (New Guinea) that mining has increased the sediment loads in rivers by approximately 5-10 times over the natural background, with very high deposition rates in the creeks, channels and floodplains.

On the other hand, it is well know that changes in sediment flux balance have direct implications for water quality and freshwater habitats. It is well known that turbidity reduces the amount of light that can penetrate the water column, affecting the photosynthetic processes, the production of dissolved oxygen (Boyd, 2015) and the visibility of aquatic organisms, which also affect their most basic needs such as hunting for food, reproduction and eggs and larvae development (Alabaster & Lloyd, 1982; Dedieu *et al*., 2015). Similarly, the flux of sediments is a suitable indicator of the concentration of bacteria, nutrients and pollutants in waters (Pourabadehei & Mulligan, 2016). For example, in several French Guiana rivers and streams, Mercury (Hg) concentration in bottom sediments was correlated with fine sediments (30 to 100 µm) (Guedron *et al*., 2009).

The Maroni (MAR) and Oyapock (OYA) river basins are located on the northeastern Guiana Shield, in French Guiana. Despite this area has the world´s largest forest cover (more than 98%), both basins have been increasingly impacted by small-scale gold mining activities in the last 20 years. In addition to contamination, the impact of gold mining also includes deforestation, removal of soils, increase of suspended material in rivers, changes in the hydrological cycle and in rivers geomorphology due to sedimentation, flow modifications, changes in landforms and land degradation (Laperche *et al.* 2014). However, although the changes in the riverine regimes seem to be an obvious consequence of gold mining, there are no scientific studies that clearly relate the increase in the suspended material in rivers with the land use changes due to small-scale gold mining activities. Therefore, the aim of this study is to monitor, using field and satellite data, the evolution of suspended sediment fluxes in Guiana Shield MAR and OYA rivers and assess if the change in sedimentary loads and yields are associated with deforestation and removal of soil layers caused by an increase in the mining activities in both basins. These rivers represent an excellent case of study because they are affected by deforestation as well as legal and illegal gold mining activities (Alvarez-Berríos & Aide, 2015; Rahm *et al*., 2015).

2. MATERIALS AND METHODS

2.1. STUDY AREA

The MAR and OYA rivers are located in the northeastern part of the Guiana Shield in South America (Figure 1). The MAR River is 612 km long and its catchment covers an area of 66,814 km² between Surinam (57%) and French Guiana (43%) (Hiez & Dubreuil, 1963). The OYA River is 404 km long and its catchment covers 33,614 km², which are partly distributed between Brazil (51%) and French Guiana (49%). All this region is considered as part of the largest unspoiled tropical rainforests in the world with 97% of its area being classified as "primary forest" (Renoux *et al.*, 2003), with substantial freshwater reserves not influenced by dams (FAO, 2003; Keenan *et al*., 2015). It also has one of the world´s lowest erosion rates with 2 meter eroded per million years (Théveniaut & Delor, 2004).

Small fluctuations in altitude (<700 m) are observed along both rivers resulting in a gentle slope (<1%) (Palvadeau, 1998). Also, both rivers have a succession of about 100 rapids. In the MAR River the last rapid is at Saut Hermina (SH), whereas in the OYA River, the Saut Maripa (SM) is the most important rapid, with a 4 km length and 8 m slope. The climate of the zone is equatorial, with a strong rainfall gradient (2,970 mm average annual rainfall) from the Atlantic Ocean westward that is controlled by the movement of the Inter-Tropical Convergence Zone (ITCZ). The climate comprises two rainy seasons (December-February and April-July) and a dry season (August-November) (Héritier, 2011). The one hundred year flood with the law of Gumbel at SH was in 2008 (8,790 $m^3.s^{-1}$), whereas at SM it was in 1989 (4,919 $m^3.s^{-1}$) (BD Hydro: http://hydro.eaufrance.fr/).

Both basins are composed of three rock complexes: the Imataca Archean gneiss (3.4-2.7 Ga), the Lower Proterozoic volcano-sedimentary terrains and granite-greiss rocks (2.3-1.9 Ga), and the Middle Proterozoic continental deposits and magmatic rocks (1.9-1.5 Ga) (Négrel & Lachassagne, 2000). Climatic and geodynamic conditions over the Guayana Shield since the Cretaceous have induced an extensive development of 50–100 m thick laterite (red clays compact little permeable) masking the substratum with generally slow vertical drainage (Théveniaut and Delor, 2004). During the important rainfall events, the latosol (2 m) allows the infiltration of the water in the ground. When this horizon is destroyed, the vertical infiltration of the rainwater is limited and allows the saturation of the superior horizons, which can then generate side flows.

2.2. LAND USE CHANGES

To identify the changes in land use in both catchments, two datasets were used:

1) The artificial and agricultural areas inventory produced by the National Forest Service of French Guiana in 2005, 2008 and 2011 (ONF, 2011; 2013) and the National Park of French Guiana (data of Camopi and Trois Sauts villages in 2011), which are based on photo interpretation of regional aerial photographs taken by the BD ORTHO®IGN (www.geoguyane.fr), SPOT, Pleiades, Landsat and Sentinel 2 satellite images.

The term “artificial areas” combines urbanized, industrial and green areas. The term "agricultural areas" concerns all the areas around main villages. On the opposite to an undisturbed area, the term “disturbed area” can be defined as an area with anthropic activities (agricultural, artificial or mining activities), that is not a natural rainforest. For comparison with the evolution of Sediment Yields during the study period, a linear interpolation and extrapolation of the surface was assessed for the years 2002 and 2014 in the MAR basin, assuming a regularly increasing trend in urbanization. In the OYA basin, we used the same land use surface in 2005, 2008 and 2011 for the Trois Sauts and Camopi Amerindian villages assuming an absence of important change during the last decade.

2) Forest areas impacted by mining activities were identified in the Guiana Shield (Guyana, Surinam, French Guiana and the North of Brazil) in 2000, 2008 and 2014 by ONF (Office National des Forêts) and ONFI (International French Forest Service) in French Guiana, SBB (Foundation for Forest Management and Production Control) in Suriname and SEMA (Secretaria do Estado de Meio Ambiente do Amapá) in Brazil, in collaboration with the World Wildlife Fund (WWF) (Debarros & Joubert, 2010; Rahm *et al.*, 2015), using high resolution satellite images (SPOT, Landsat and RapidEye images, see supplementary document). The mining surfaces of each sub-catchment were issued from an extraction of the complete shape file.

Mining activities areas can correspond to primary gold mining (hard rock mining) or alluvial gold mining (extracting gold from the creaks, rivers and streams). Gold mining sites are characterized by vegetation and abiotic land cover elements, such as bare soil, water (pits), vegetation, regrow fath and in specific cases degraded forest. Infrastructures (human settlements, runaway, roads, etc.) and agriculture in the vicinity of gold mining sites are not considered.

2.3. FIELD DATA

Water discharge and rainfall data

The principal gauging station of the MAR catchment is Langa Tabiki (LT), which drains 91% of the basin (60,930 km²). For the OYA catchment, the main gauging station is SM draining 74% of the basin (25,120 km²). The OYA and MAR rivers show similar annual cycles, with a high water discharge period from May to July and a low water period from October to December.

Data of water discharge (Q) were calculated with the Hydraccess software (Vauchel, 2004) using discharge rating curves from mechanical current meter coupled with an Acoustic Doppler Current Profiler (ADCP 1200 kHz from RD Instruments). Since 2001, river level measurements were collected automatically every half hour using satellite telemetry (limnimetric 'Cloe' type sensors until 2001 and 'Argos' type sensors since 2004). All gauging stations in French Guiana were installed in 1952-1953 by Institut de Recherche pour le Développement (IRD) (ex-ORSTOM) (Sondag *et al.*, 2010) and the rating curve used was created by ORSTOM and completed with the DEAL service in charge of the stations since 2004.

All precipitation (P) data were provided by Meteo France services, including rain gauge data from 1978 to 2015 at Maripasoula (MPS), Papaïchton (PPI), Grand-Santi (GS), and Apatou

(APT) stations within the MAR catchment, and Saint-Georges de l'Oyapock (STG) and Camopi (CM) stations over the same period within the OYA catchment.

Suspended Sediment Concentration data

In this study, we used 4 datasets of suspended sediment concentrations and 2 datasets of turbidity values. The first dataset *(1)* comprises Surface Suspended Sediment Concentrations (SSSC) measured and processed monthly since 2004 within the framework of the SNO-HYBAM observation service program in the OYA and MAR basins: 154 water samples were collected along the border of rapids at SM station in the OYA basin and 154 samples were collected with a little boat at 475 m from the right riverbank at SH station in the MAR basin. The sampling locations of the SNO-HYBAM in the OYA River at SM and in the MAR River at SH is explained by the fact that there is no sea tide influence.

The second dataset (*2*) includes 81 SSSC measurements performed during consecutive campaigns in 2015 along the MAR River at virtual stations location. As discussed later, during the collection of these data, the water surface reflectance was also measured.

The third dataset (*3*) comprises Suspended Sediment Concentrations (SSC) performed at surface and within the water column (depths of 40% and 80%) to estimate the Average Suspended Sediment Concentrations (ASSC*)*. These measurements were carried out from 2014 to 2015 over all the hydrological year (Figure S1): 323 water samples were collected in 2L Niskin bottles at SH station (MAR River) across the river (166, 475, 772 and 940 m from the right riverbank to the left bank during 33 sampling campaigns) and 36 water samples were collected in the same bottles at SM (OYA River) across the river (115, 292 and 487 from the right riverbank to the left during 4 sampling campaigns). Turbidity data were also measured at the same time in order to establish the relationship with the SSSC (Figure S2).

The fourth dataset (4) includes turbidity values punctually measured by the French Guiana National Amazonian Park (PAG) at the stations MPS (n=91; 2012-2015) in the MAR basin and CM in the OYA basin (n=36; 2007-2012) with a Turbidimeter WTW 600 in the Middle of the cross section.

Datasets (*1*) and (*2*) were used to calibrate and validate field and satellite-derived SSSC estimates, dataset (*3*) was used to calculate river sediment discharge and dataset (*4*) was chosen in order to compare turbidity data with SSSC data because of their good relationship. All suspended sediment concentrations were determined by drying and weighing the sediment caught on sieves and membrane filters using Millipore 0.45-µm pore-sized cellulose filters according to Laraque *et al.* (2013).

Estimation of Suspended Sediment Loads (S_L)

To assess the Suspended Sediment loads (S_L), we computed the ASSC from the sampling campaigns allowing to relate HYBAM water surface samples to samples collected in the water column. A very good lineal relationship was found between ASSC and SSSC in both rivers, allowing to compute ASSC from surface samples using the equations presented in Figure S3.

S_L values were then calculated multiplying the ASSC by the daily water discharge (Q_j) and then dividing by the corresponding monthly discharge (Q_m), providing an estimate of the daily SSC (Laraque *et al.*, 2009; Laraque *et al.*, 2013). Monthly and annual concentrations were then calculated (in t.month^{-1} and in t.yr^{-1}) multiplying by the number of days.

Determination of Sediment Yield and Runoff

In order to compare the study sites with other catchments, we calculated the sediment yield (S_y) and the water runoff (R), which are the sediment load (S_L) and the water discharge (Q), respectively, normalized by the drainage area at the hydrological main station. The cumulative double mass plots display the relationship between R and S_y. If S_L and Q present a similar trend, then the slope of the curve will not change, but if S_L increases or decreases, then the erosion/transport/deposition processes are changing (Walling, 2006).

2.4. MONITORING SSSC WITH MODIS

Field surface reflectance/SSSC retrieval model

We developed a reflectance/SSSC retrieval model based on sampling and compared it with a model directly calculated from matched MODIS reflectance/SSSC sample data in the MAR River. We realized spectral radiometric measurements with TriOS-RAMSES spectroradiometers (Figure S4) at the river surface during water sampling (n=81 for the MAR and n=10 for the OYA). The radiometers were mounted on one side of a small boat with the acquisition geometry recommended by Mobley (1999) and Remote sensing surface reflectance $R_{rs}(\lambda)$ values were then calculated using the protocol described by Mueller *et al.* (2003). Unlike the MAR River, several factors such as very low reflectance values, the width of the river and the strong cloud coverage, did not allow to develop a robust MODIS reflectance/SSSC retrieval model in the OYA River.

MODIS remote sensing images

In this study, we have used the MODIS products MOD/MYD09A1 and MOD/MYD09Q1 derived from data collected by Terra and Aqua satellites. These products represent 8-day composites delivered at spatial resolutions of 250 m (Q1 product) and 500 m (A1 product). We determine the mean reflectance value at a virtual station with the MOD3R software according to the method described in Martinez *et al*. (2009), which has been applied in river and lake studies in the tropic (Espinoza Villar *et al.*, 2012; Espinoza Villar *et al*., 2013; Robert *et al.*, 2016).

The matched MODIS surface reflectance/SSSC sample data were obtained by comparison of MODIS 8-day composite reflectance in the red channel (640-680 nm) and daily water samples collected by HYBAM since 2004. MODIS was used to create height virtual monitoring stations along the MAR River only four are detailed below: Saut Hermina (SH), Gran Creek (GR), Tapanahoni (TPI) and Abattis Kotika (KO). MODIS images were not used in the OYA River because the river width is too low for the 250-meter MODIS. The minimum section wide required for MODIS detection is about 300 m with no islands or sand banks.

2.5. STATISTICAL ANALYSIS

SSSC retrieval model accuracy assessment

To compare field-based and satellite-derived SSSC estimates, we used the BIAS statistical method and Root Mean Square Error (RMSE) metrics, which were calculated as follow:

$$BIAS = \sum_1^n \frac{y_i - x_i}{n}$$

$$RMSE = \sqrt{\frac{1}{\mathrm{n}} \sum_{\mathrm{i}} \frac{{y_i - x_i}^2}{y_i}}$$

where y_i and x_i are field-based and satellite-derived estimates of SSSC, respectively, given as percentages and n is the number of data.

Finally, the relative difference is calculated as the difference between the maximum and the minimum annual value expressed in percentage.

Water discharge, precipitation and SSSC trends

Trends in precipitation (P: period 1978-2015) and water discharge (Q: period 1952-2015) were analyzed in terms of mean, maximum and minimum values at daily, monthly and annual scales using the Mann-Kendall test (Mann, 1945; Kendall, 1975) and the SSSC were analyzed at daily scale (period 2000-2015). The Mann-Kendall test (MKT) is a non-parametric test that is recommended by the World Meteorological Organization (Zhang *et al.*, 2008; Wang *et al.*, 2013). MKT is applied to check the presence of long-term monotonic changes, to determine if the time series reflect increasing or decreasing trends (Shi & Wang, 2015; Buendia *et al.*, 2016; Shi *et al*., 2016). This test does not depend on the magnitude and statistical distribution of the data and provides three parameters: the S statistic, Kendall's tau (τ) correlation and the significance level ($p \leq 0.05$). A positive value of S indicates a positive trend, whereas a negative value stand for a negative trend.

Furthermore, in order to detect potential breakpoints in the long-term daily time series of SSSC, we applied Pettitt's change point test methods (Pettitt, 1979), which is a non-parametric technique widely used to detect "change" or "no change" at a given point in time for continuous observations (Shi & Wang, 2015; Shi *et al.* 2016).

3. RESULTS

3.1. LAND USE CHANGES

In the OYA catchment, deforestation induced by small-scale gold mining covered 387 ha in 2000, 1,542 ha in 2008 and 1,874 ha in 2014 (0.06% of the catchment), representing an increase of 384% over the period (Table I). Camopi area (CM) is the most exposed to deforestation in the catchment (sub-catchments 600 and 612: 1547 ha in 2014) (Figure 2). In comparison, artificial and agricultural areas represented 2,479 ha in 2011 (STG, CM and TS villages). Ignoring areas downstream SM station, artificial and agricultural areas represented 328 ha.

In the MAR catchment, deforestation induced by mining activities covered 4,821 ha in 2000, 17,609 ha in 2008 and 24,463 ha in 2014 (0.37% of the catchment), including the 200 ha downstream the SH station and showing an increase of 407% between 2000 and 2014 (Figure 2). Of a total of 34 sub-catchments, 18 were disturbed in 2014, 10 in 2000 and 17 in 2008. Most of the gold mining areas were located on the Surinam border region. The most impacted sub-catchments in 2000 were sub-catchments 521, 522, 504 and 503. Between 2000 and 2008, substantial increase of small-scale mining activities occurred (from 244% to 694%) in sub-catchments 501, 502, 503, 504, 512, 521, and 522. Between 2008 and 2014, mining activities increased (from 143% to 352%) in sub-catchments 501, 502, 503, 512, 514 and 524 and decreased (from 80% to 96%) in sub-catchments 504, 522, and 521.

In comparison, artificial and agricultural areas represented 15,848 ha in 2011 (STL, GS, APT, PPI, MPS, SA villages). Ignoring areas located downstream SH station, artificial and agricultural areas represented 3,913 ha in 2005 and 5,959 ha in 2011.

3.2. RIVER DISCHARGE AND RAINFALL

At the SM gauging station, the mean annual river discharge was 867 $m^3.s^{-1}$ from 2000 to 2015. The range of daily water discharge was between 64 and 4,033 $m^3.s^{-1}$ in November 2009 and May 2015, respectively (Table IIa). The mean annual precipitation recorded by all rain gauges in the catchment varied from 2,685 mm to 3,645 mm in 2014 and 2010, respectively.

At the LT gauging station, for the 2000-2015 period, the lowest river discharge was 84 $m^3.s^{-1}$ (December 2004) and the highest was 8,790 $m^3.s^{-1}$ (June 2008:100-year flood event), for an average of 1,831 $m^3.s^{-1}$. The mean annual precipitation recorded by all rainfall gauging stations in the MAR catchment vary from 1,486 mm to 2,776 mm in 2015 and 2013, respectively (Table IIb).

No significant changes ($p \leq 0.05$) were found from the MKT, for maximum and mean data, in daily, monthly, and annual precipitation (1978-2015), at the 4 raining stations in the MAR basin (MPS, PPI, GS, APT) and at the 2 raining stations in the OYA basin (CM and SM). A positive trend in minimum precipitation of monthly data were observed at GS (P_{GS} : τ= 0.14, p<0.0001) and PPI stations (P_{PPI} : τ=0.08, p=0.02) as well as at SM (P_{SM}: τ=0.10, p=0.000) and CM stations (P_{CM}: τ=0.28, p<0.0001). Also, no significant change in the monthly and annual discharge were found for both catchments at the 2 main gauging stations LT and SM.

3.3. SUSPENDED SEDIMENT DYNAMICS

Oyapock River catchment

In the upper OYA River, between 2007 and 2012, the CM station presented a mean turbidity of 11 NTU with a range between 0.53 and 55 NTU (Figure 3). In the lower OYA River at SM, the minimum value of SSC for the period 2004-2015 was 2 $mg.l^{-1}$ (December 2004 and November 2009) and the maximum value recorded was 22 $mg.l^{-1}$ (January 2010). The mean value was 9.5 $mg.l^{-1}$ (Table S1).

The daily SSSC showed a general decreasing trend (MKT values of -0.18; p=0.001) for absolute difference of 1 to 5 $mg.l^{-1}$ (Table III). A significant breakpoint in January 2008 was observed. The relative difference from 2004 and 2015 was -17% for annual mean SSSC values, -26% for maximum values, whereas no difference was found for minimum values. From 2008 to 2015, relative differences were of -33%, -28% and -33% for mean, maximum and minimum values, respectively.

Maroni River catchment

Satellite data were used to extend and complete SSSC field observations over the Maroni River. Figure 4 compares two retrieval models based on two independent reflectance/SSSC datasets: 1) The field-based surface reflectance/SSSC matches estimates collected during sampling campaigns, and 2) monthly estimates MODIS surface reflectance/SSSC SNO-HYBAM match from 2004 to 2015. Both reflectance/SSSC datasets show significative (p<0.0001) relationship (r^2=0.87 for n=81 and RMSE of 25% for MODIS; r^2=0.85 for n=65 and RMSE of 30% for field reflectance), confirming the ability of satellite data to robustly assess SSSC values along the MAR River on a long-term basis. A slight BIAS of 8% (p=0.006) was found using both retrieval models, which is likely caused by the largest SSSC range covered by satellite datasets and the lower accuracy associated with the determination of satellite/SSSC matchups.

In the MAR catchment, all stations presented a significant increasing trend (p<0.0001) in SSSC, as assessed using the MKT (Table III). The eight stations created with the exception of GS (August 2007) and TPI (November 2005) showed a significant break with the Pettitt's test (p<0.0001) between November 2009 and August 2010. In upper reaches, general increasing trends, as revealed by τ, was smaller at PPI station (0.25). Largest long-term changes were observed in the downstream reaches at GR (0.43), SH (0.40) and TPI stations (0.39).

To infer SSSC and turbidity interannual and seasonal variability (Figure 5), only two stations in upper MAR (MPS and GS) and three in lower MAR (TPI, GR and SH) are showed. At the last field station in MAR basin at MPS, turbidity varied from 7 NTU to 320 NTU (n=91; 2012-2015), with a mean of 30 NTU.

From MODIS estimates and downstream GS station, the range of the mean annual SSSC values was 8-19 mg.l^{-1} from 2000 to 2015, showing an increase of 145% between 2002 and 2015. The increase in the maximum annual SSSC was about 440% for the same years (range between 11 and 60 mg.l^{-1}).

At TPI station, downstream of the most important tributary of the basin, the range of mean annual concentration was between 6 and 22 mg.l^{-1}, showing an increase of 247% from 2000 to 2012. The increase of maximum annual SSSC was about 214% comparing the year 2000 with the years 2007 and 2015 (range between 19 and 61 mg.l^{-1}).

At GR station, the range of mean annual concentration was between 7 and 29 mg.l^{-1}, presenting an increase of 305% from 2000 to 2013. The increase of maximum annual SSSC was 337% between 2000 and 2011(range from 14 to 61 mg.l^{-1}).

At the lower station of SH (using MODIS-derived estimates and field samples, Table S1), the mean annual SSSC values between 2000 and 2009 ranged from 11 to 21 mg.l^{-1} and subsequently increased to 17-36 mg.l^{-1}, showing an increase of 230% between 2001 and 2013.

Similarly, from 2001 to 2015, the annual maximum SSSC increased from 19 to 84 $mg.l^{-1}$ (+336%), and between 2002 and 2013, the annual minimum SSSC reached a range from 3 to 24 $mg.l^{-1}$, suggesting an increase of about 807%.

3.4. SEDIMENT LOADS, SEDIMENT YIELD AND RUNOFF TRENDS

For the OYA River at SM, the range of monthly S_L values was between $0.59x10^3$ and $86x10^3$ $t.month^{-1}$, with a mean of $24x10^3$ $t.month^{-1}$. Maximum values of S_L occurred in May-June during the high water stage, and the lowest values occurred in October-November during the low water stage (Figure S5). Annual S_L varied from $212x10^3$ to $478x10^3$ $t.yr^{-1}$ (Table S1), with a mean of $304x10^3$ $t.month^{-1}$. Sediment yield (S_y) ranged from 8 to 19 $t.km^{-2}yr^{-1}$, whereas annual runoff varied between 28 and 44 $l.s^{-1}km^{-2}yr^{-1}$. Inspection of the cumulative double mass plot indicates a decreasing trend at SM after 2008 (Figure 6).

For the MAR catchment at SH station, the range of monthly S_L values was between $1x10^3$ and $406x10^3$ $t.months^{-1}$, whereas the annual S_L values ranged from $530x10^3$ to $2{,}510x10^3$ $t.yr^{-1}$ (Table S1). A first peak in S_L generally occurs in January-February at the beginning of the rising water stage, and a second peak usually appears in May during the high water stage. S_y ranged from 9 to 41 $t.km^{-2}yr^{-1}$ and the annual runoff varied from 16 to 43 $l.s^{-1}km^{-2}yr^{-1}$. At SH, the cumulative double mass plot shows that S_y started increasing after 2003 with a strong acceleration after 2009 (Figure 6).

3.5. RELATIONSHIPS AMONG THE DATA

Annual SSSC were further analyzed in order to infer the dependence of sediment fluxes on water discharge and precipitation-related variables, using the Spearman correlation matrix.

In the OYA River at SM, we observe that S_y was significantly ($p \leq 0.05$) correlated with runoff (r=0.82) (Table IVa). Similarly, mean and maximum SSSC were also well correlated with runoff (r=0.61 and r=0.49, respectively). However, the highest correlation coefficients were obtained correlating minimum SSSC with Q_{min} (r=0.80) and with Q_{mean}/Q_{max} ratio (r=0.68).

In the MAR River at SH, we observed that S_y was significantly correlated ($p \leq 0.05$) with precipitation at MPS (r=0.61) and PPI (r=0.57), and with maximum water discharge (r=0.50). Mean and maximum SSSC were correlated with precipitation at MPS (P_{MPS}), with correlation coefficients of 0.53 and 0.52, respectively) (Table IVb). Minimum SSSC showed a correlation with Q_{min} (r=0.52). Similarly, unlike the OYA River, no relationships were found between runoff, mean and maximum SSSC values.

4. **DISCUSSION**

4.1. LAND USE CHANGES AND DISTURBANCES ON SEDIMENT YIELD

We did not observe significant long-term changes in precipitation or water discharge in the MAR and OYA rivers. Results suggest an absence of relationship between the changes in SSSC with climatic and hydrological data in both basins. Thus, we compared S_y trends with the mining, agricultural and urbanized areas since 2000. Figure 7a shows the absence of relationship between the decrease of S_y with land use areas in the OYA catchment. Conversely, in the MAR catchment, Figure 7b provides a strong evidence of relationship between S_y with the land use degradation, especially with gold mining surfaces ($r^2=0.97$; $p<0.0001$). Indeed, S_y and mining surfaces increased 400% from 2000 to 2015.

In both catchments, urbanized and agricultural areas consist of a very weakly part of the total area with no industrial companies or farming (<1%). According to Keenan *et al.* (2015)**,** Suriname and French Guiana represent an important preserved area with the world´s highest reported forest cover of any country; 95% of their forests are "primary rainforest". Land degradation, as represented by artificial and agricultural areas was significantly lower in the OYA catchment than in the MAR catchment in 2011 (2,479 ha and 15,848 ha, respectively). Agricultural areas consist in mainly traditional slash-and-burn systems (shifting cultivation), without mechanized agriculture (Renoux *et al*., 2003; Rossi *et al*., 2010).

In the MAR basin approximately 16,682 ha located in Surinam and 8,058 ha in French Guiana border regions were cleared for mining activities in 2014 (0.37%). For the OYA basin, the cleared areas represent 0.06% of the catchment area; 1,547 ha were cleared in French Guiana for only 327 ha in Brazil. Mining activities use hydraulic methods for remove soils and bottom sediments in rivers (Cremers *et al*., 2013). One hectare of forest is cleared and high-pressure water hoses are used to remove soil and pump the water-soil mixture into a sluice box. Gold particles are then trapped in the sluice box, and the mine tailings, including gravel, sand, and clay, flow into abandoned mining areas, adjacent forest areas or into the river. Similar operations are carried out in rivers.

Between 2008 and 2014, the increase in the mining areas occurred almost exclusively in Suriname and French Guiana in comparison with Brazil. Rahm *et al.* (2015) estimated in 2014 that 53,669 ha within Surinam, 24,282 ha within French Guiana, and 2,125 ha within the Amapa region (Brazil) were impacted by small-scale gold mining. This contrasting situation may be explained by the legalization in 2011 of all small-scale mining activities in Surinam, also by repeated military expeditions launched to destroy illegal mining sites in French Guiana and stricter regulations imposed in the 1990's by Brazil to limit local expansion of gold mining (De Theije, 2014; Dezécache *et al*., 2017).

4.2. LONG TERM TREND OF SEDIMENT CONCENTRATIONS AND LOADS IN THE MARONI AND OYAPOCK RIVERS

French Guiana rivers have very low SSSC values, which are related to the extremely low erosion rates of the Precambrian Guiana Shield. Undisturbed rivers (with rainforest and no human activities) show SSSC values varying between 4 and 25 $mg.l^{-1}$ (Eisma & Van der Marel, 1971; Jouanneau & Pujos, 1988; Lointier, 1995; De Mérona de *et al*., 2000). During the year 2015, 94% of SSSC values measured in the OYA River at SM fall within a range of concentrations of 0-10 $mg.l^{-1}$, and most were between 5-10 $mg.l^{-1}$. Few values were as high as 10 $mg.l^{-1}$, and only one reached 20 $mg.l^{-1}$. Significant decreases in annual mean and maximum SSSC values were observed for the period 2004-2015, with a breakpoint in 2008. The changes in the long term trend may be explained by the exceptional high runoff occurred in 2008, which may have washed out the riverbed, decreasing the amount of sediments available to be transported. The years 1989 (Lointier, 1995) and 2008 (our study) presented very similar S_y values (e.g. 20 and 19 $t.km^{-2}yr^{-1}$, respectively) and runoff values (47 and 44 $l.s^{-1}km^{-2}yr^{-1}$, respectively). Furthermore, we assessed an average S_L value of $303x10^3$ $t.yr^{-1}$. This assessment is slightly lower than that of Lointier (1995), who estimated a S_L value of $450x10^3$ $t.yr^{-1}$ for the same basin. These different results may be explained by the highest discharge of one hundred flood occurring during the years 1989-1990, the difference of the equation used here to estimate the S_L (which implies a correction of the SSSC with the ASSC) and the decrease of SSC over the time.

In the MAR catchment at SH, we compared our SSSC results with previous data acquired by Jouanneau & Pujos (1988), which analyzed SSSC frequencies at the SH station in 1984-1985. From 114 surface water samples collected, they assessed that concentration frequencies for ranges of 5-10 $mg.l^{-1}$, 10-20 $mg.l^{-1}$ and above 20 $mg.l^{-1}$ were 48%, 39% and 3%, respectively. In 2015, our results show that the concentration frequencies for ranges of 5-10 $mg.l^{-1}$, 10-20 $mg.l^{-1}$, 20-30 $mg.l^{-1}$, 30-40 $mg.l^{-1}$ and above 40 $mg.l^{-1}$ were 7%, 26%, 22%, 13% and 32%, respectively. Thus, in 2015, 67% of SSSC values measured at SH station were above 20 $mg.l^{-1}$, whereas the values above 20 $mg.l^{-1}$ were only 3% thirty years ago. River discharge measured in 1984-1985 by Jouanneau & Pujos (1988) was lower than for 2015 (1475 versus 1830 $m^3.s^{-1}$). However, between July 1989 and July 1991, Lointier (1995) compared SSSC in the MAR, OYA and Comté basins, observing no relationship between SSSC with hydraulic conditions. Finally, Vigouroux *et al.* (2005) have shown that rivers in French Guiana with SSSC up to 20 $mg.l^{-1}$ present a high anthropogenic influence.

Furthermore, we observed in the MAR River, for similar runoff values in 2001 and 2015 (32 and 35 $l.s^{-1}km^{-2}yr^{-1}$, respectively), very different S_L and S_y values (743x10^3 – 2,510x10^3 $t.yr^{-1}$ and 12 - 41 $t.km^{-2}yr^{-1}$, respectively). In comparison, Eisma *et al*. (1971) estimated a S_L value of 1,400x10^3 $t.yr^{-1}$ with SSSC values from 4 to 12 $mg.l^{-1}$ and for a mean discharge of 5,500 $m^3.s^{-1}$. Jouanneau & Pujos (1988) estimated a S_L value of 600x10^3 $t.yr^{-1}$ in 1984-1985, for SSC ranging from 0.8 to 27.4 $mg.l^{-1}$ at the border of the channel at LT. On the other hand, Lointier (1995) calculated a S_L value of 1,300x10^3 $t.yr^{-1}$ between 1989 and 1991 at LT station with a mean discharge of 1,840 $m^3.s^{-1}$ during these years. Finally, our assessment of S_y is very similar to that showed by Sondag *et al*. (2010), who reported a mean value of 21 $t.km^{-2}yr^{-1}$, which was determined from HYBAM water samples collected between 2004 and 2008.

Roche (1982) assessed runoff and soil erosion in small headwater catchments ranging in area from 1 to 1.5 ha that were covered by primary rainforest. This author calculated S_y between 20 and 80 $t.yr^{-1}km^{-2}$ and resulted in wash loads that ranged from 4 to 38 $t.yr^{-1}km^{-2}$ and bedloads that ranged from 9 to 40 $t.yr^{-1}km^{-2}$. Using the S_y values assessed by Roche (1982), we calculated that undisturbed wash load and bedloads for the OYA River might vary between 98x10^3 and 935x10^3 $t.yr^{-1}$ and between 221x10^3 and 985x10^3 $t.yr^{-1}$, respectively. In the MAR River, undisturbed wash load and bedload may vary from 256x10^3 to 2,440x10^3 $t.yr^{-1}$ and from 578x10^3 to 2,570x10^3 $t.yr^{-1}$, respectively. It is worthwhile to note that the upper estimate of the undisturbed sediment flux is close to the S_L value that we calculated in 2015 for the MAR River. For the OYA River, the upper estimate of the undisturbed S_L value is twice as large as the actual annual maximum fluxes that we calculated, indicating that sediment fluxes in this catchment remain largely unaffected by anthropogenic activities. In contrast, the MAR River shows evidence of disturbances to sediment fluxes at the catchment scale.

In 2013, the highest turbidity values were observed at the upper station (MPS) of the MAR basin and lower values were observed at downstream stations. The same observation was carried out in the OYA basin, with 55 NTU (equivalent to 50 $mg.l^{-1}$) measured at CM in March 2011 and 12 $mg.l^{-1}$ at SM. These lower SSSC values relative to the upstream values may be explained by several factors such as the deposition of particles in the riverbed and the dilution effect associated with local tributaries. In French Guiana, other studies have made the same observation (Vigouroux *et al.,* 2005).

5. CONCLUSIONS

Gold mining has been an important cause of land use changes within the Maroni and Oyapock River catchments during the last decade and represented over 24,463 ha in the Maroni catchment and over 1,874 ha in the Oyapock catchment. Our study using MODIS remote sensing data and field measurements (RMSE: 25%) has shown that fifteen years of intensive mining activities have changed the background of SSC in the Maroni River, increasing significantly the sediment loads and yields since 2009. In 2015, at the main downstream station of SH, 67% of SSSC measurements were above 20 $mg.l^{-1}$, whereas the values above 20 $mg.l^{-1}$ were only 3% thirty years ago. No relationship between sediment yields with runoff was found in the MAR basin. However, interesting positive relationships of sediment yield with mining surfaces ($r^2= 0.97$ $p< 0.0001$) were observed. On the other hand, although the upper Oyapock River is suffering from increasing land degradation by mining activities, sediment fluxes in this catchment remain unaffected by anthropogenic activities. Moreover, a decrease in SSC and in the sedimentary loads and yields have been observed in the most downstream station of this catchment since year 2008. However, 82% of the variance in sediment load of the OYA River was explained by runoff, suggesting that natural processes remain important in this catchment. Finally, a critical boundary of 0.1% of deforestation in a catchment from mining activities is suggested to generate an impact on water SSC and turbidity values in the most downstream stations.

TABLES

Table I: Agricultural and artificial territories of main villages (2005, 2008, 2011) and deforestation from mining activities (2000, 2008, 2014) in the a) OYA and b) MAR catchments.

Table II: Discharge (Q), Runoff (R), Precipitation (P) at a) CM, SM in the OYA Catchment and b) MPS, PPI, GS, APT in the MAR Catchment.

Table III: Mann-Kendall test and Pettit's test used to determine the daily SSSC long term trend and the breakpoint in the OYA basin at SM and in the MAR basin at SH, LT, GR, BE, TPI, KO, GS, and PPI stations.

Table IV: Spearman correlation matrix of the a) OYA and b) MAR catchments properties: Mean annual runoff (R), maximum annual water discharge (Qmax), minimum annual water discharge (Qmin), mean annual water discharge divided by the maximum water discharge (QpK), total annual precipitation (P) for each station (APT-GS-PPI-MPS in the MAR and SM-CM in the OYA catchments), average daily suspended sediments concentration in a year (SSSCmean), maximum daily suspended sediments concentration (SSSCmax), daily minimum suspended sediments concentration (SSSCmin), annual sediment load (SL) and Sediment Yield (SY) for the stations SH and SM

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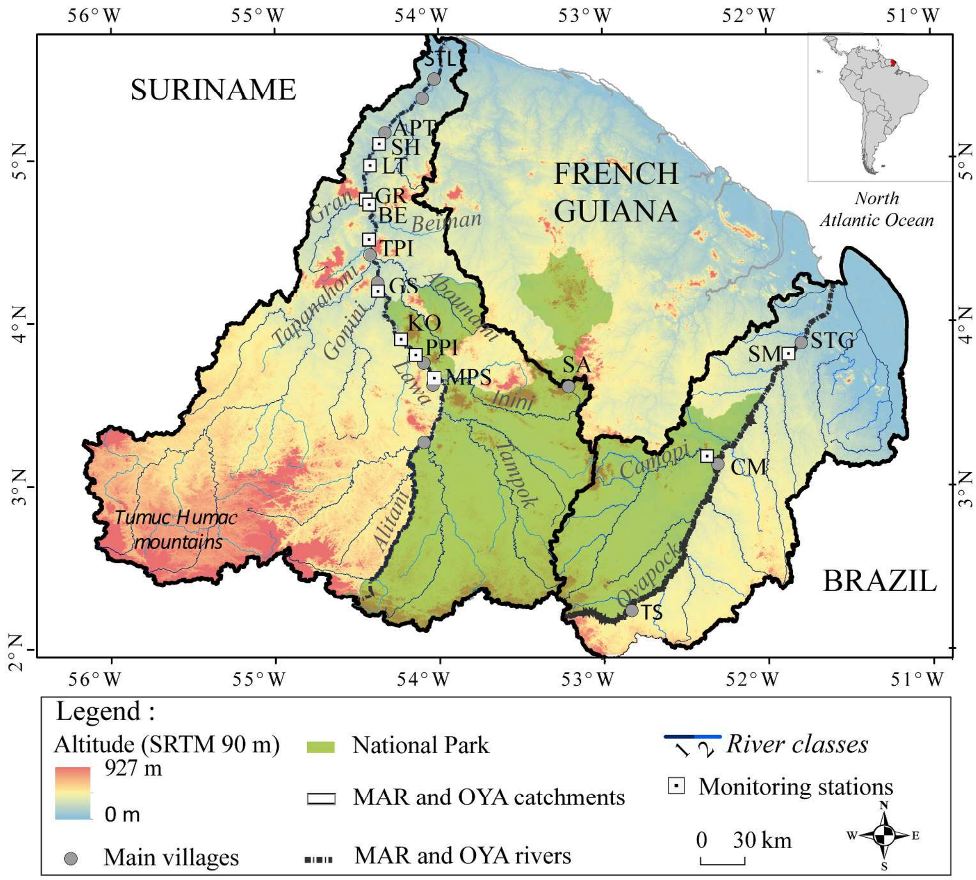

Figure 1 : Maps of the MAR and OYA catchments showing topography, main cities location (grey circle), water gauge stations (LT and SM), sampling (SM, SH, CM, MPS) and virtual stations (SH, LT, GR, BE, TPI, GS, KO and PPI).

721x653mm (120 x 120 DPI)

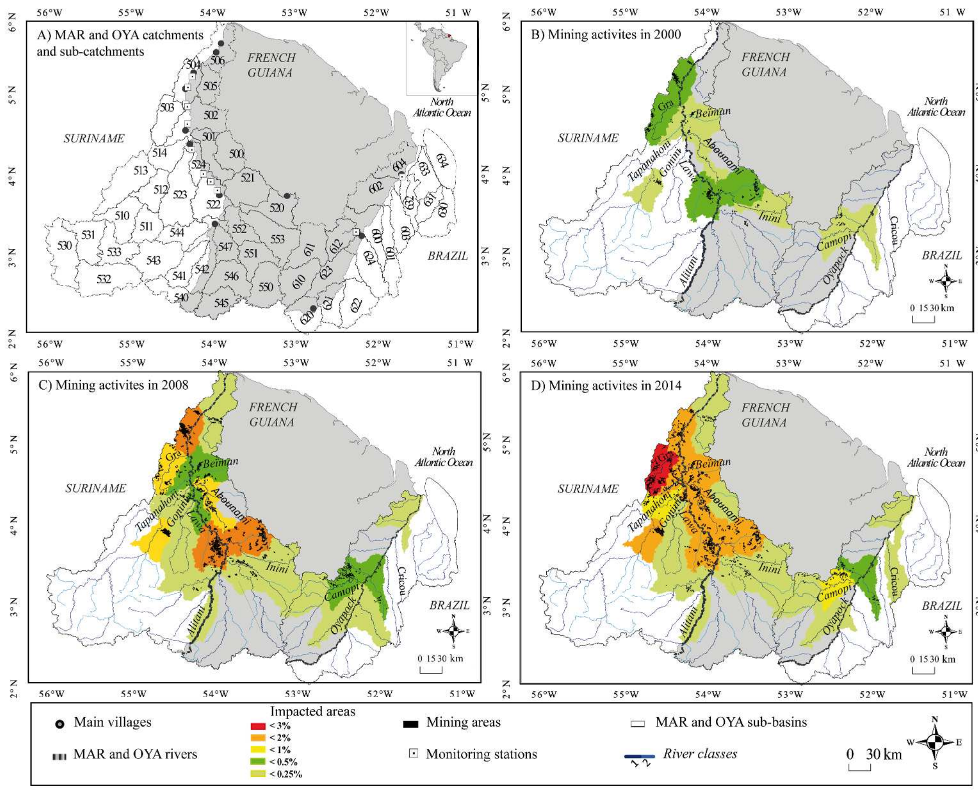

Figure 2 : Evolution of mining deforestation surfaces A) per sub-catchments in B) 2000, C) 2008, D) 2014 in percentage per sub-catchment, in the MAR and the OYA catchments.

1495x1190mm (120 x 120 DPI)

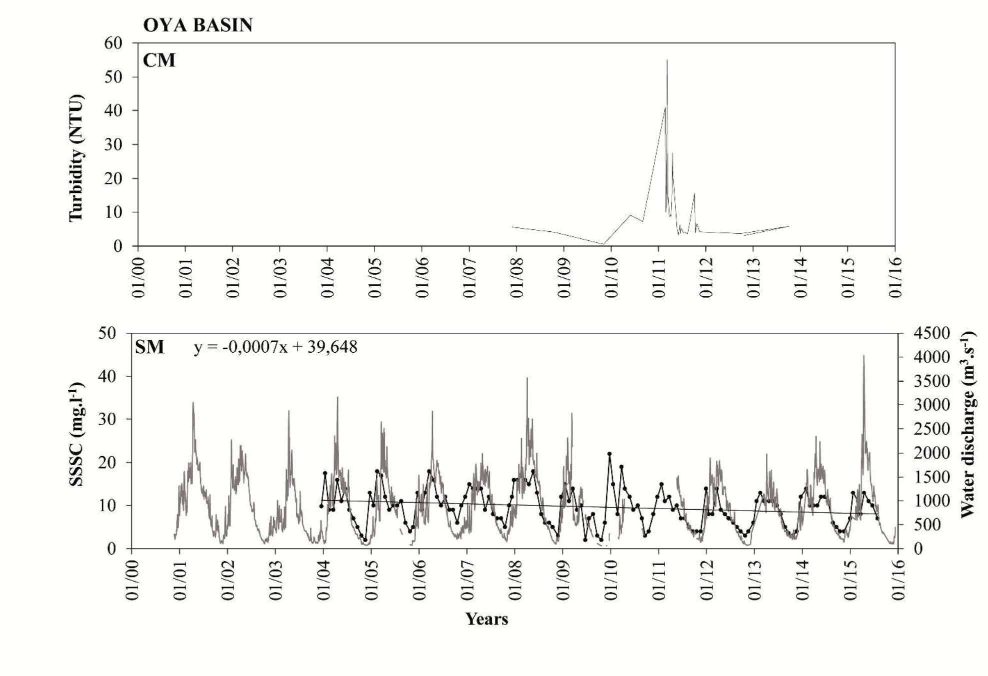

Figure 3: Comparison of river monthly SSSC in upper OYA River at CM and in the lower OYA River at SM. The grey line at SM correspond to the daily water discharge. All data came from SNO-HYBAM estimation excepted for turbidity data of CM station corresponding to field data of the French Guiana turbidity network.

424x292mm (300 x 300 DPI)

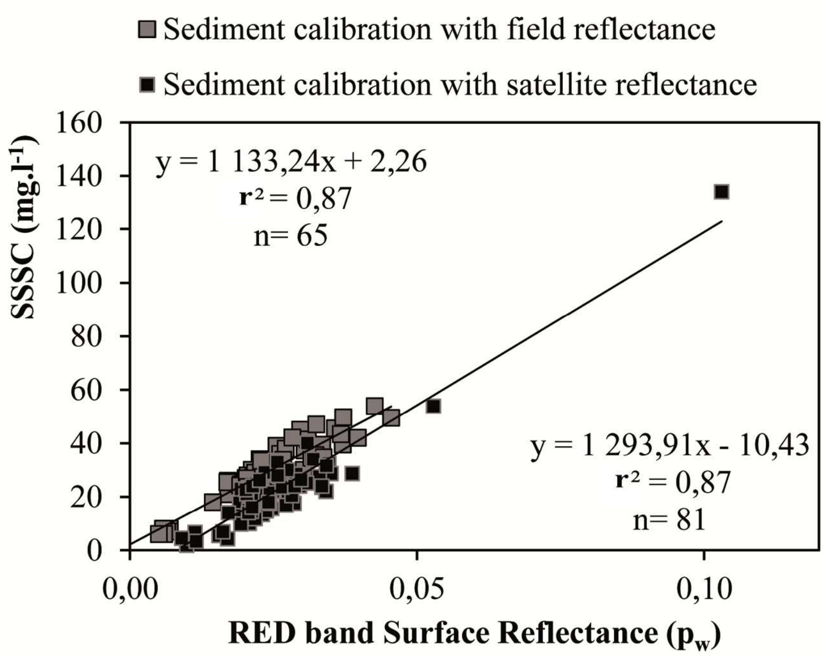

Figure 4 : Relationship between field spectral reflectance (grey squares) and MODIS spectral reflectance (black squares), for the MAR Catchment in the RED band.

380x297mm (120 x 120 DPI)

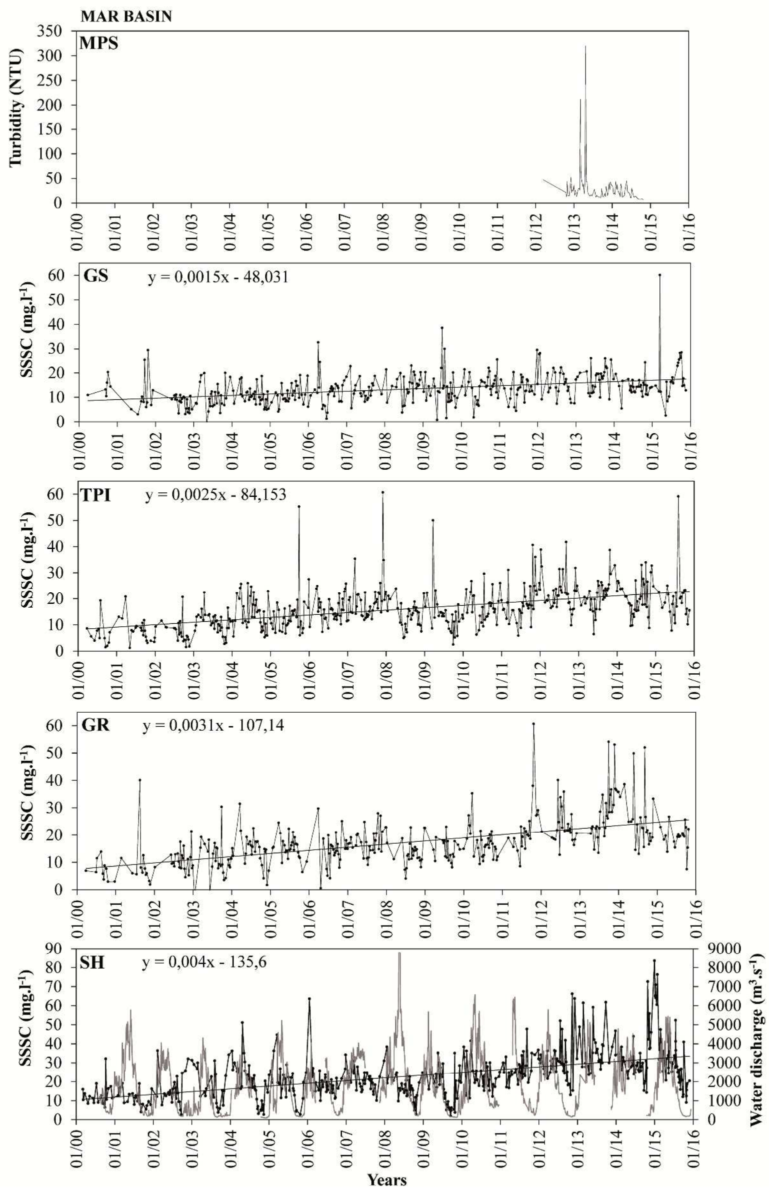

Figure 5: Comparison of river daily SSSC in the Lawa River at MPS and GS and in the MAR River at TPI, GR and SH. The grey line at SH correspond to the daily water discharge. All data came from MODIS estimation excepted for turbidity data of MPS corresponding to field data of the French Guiana national park.

435x626mm (200 x 200 DPI)

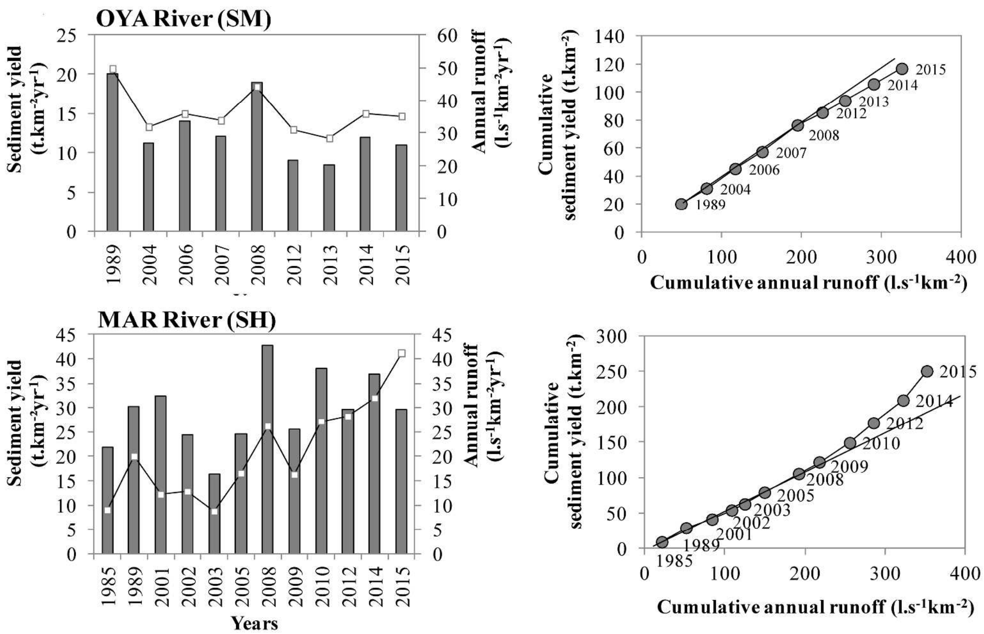

Figure 6 : Recent trends of Sediments Yields (black line), Annual Runoff (grey bar) and cumulative double mass plot of the OYA (SM) and MAR Rivers (SH).

824x528mm (96 x 96 DPI)

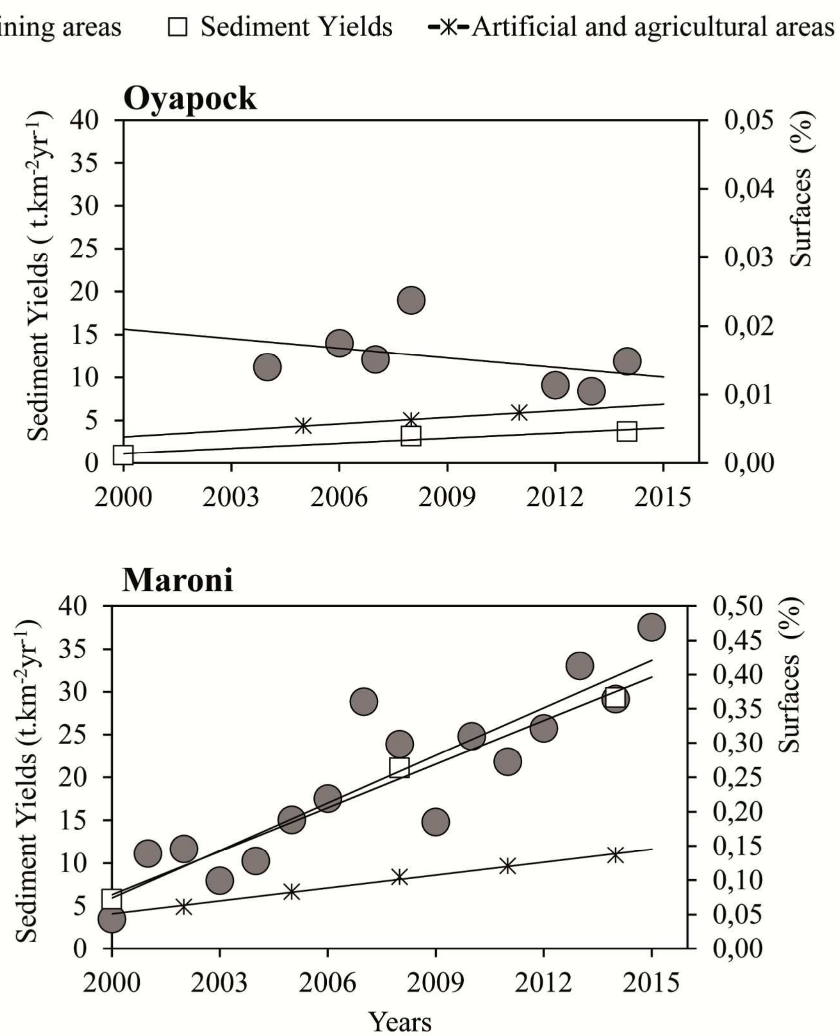

Figure 7 : Comparison of the Sediment Yields (Sy), mining areas, artificial and agricultural areas trends in the: a) OYA and b) MAR catchments. Areas are given in percentage relatively to the whole catchment surface area.

182x198mm (300 x 300 DPI)

Oyapock Catchment	Mining areas (ha)	Mining areas (%)	Artificial areas (ha)	Agricultural areas (ha)	total (ha)
In 2000	387	0.01			
In 2008	1 542	0.05			
In 2011			862	1 617	2 479
In 2014	1 874	0.06			
Increase (2000-2014) in %	384				
Increase (2000-2008) in %	298				
Increase (2008-2014) in %	22				
Maroni Catchment	**Mining areas (ha)**	**Mining areas (%)**	**Artificial areas (ha)**	**Agricultural areas (ha)**	**total (ha)**
In 2000	4 821	0.07			
In 2005			4 297	6 756	11 053
In 2008	17 609	0.26	4 976	8 770	13 746
In 2011			5 391	10 456	15 848
In 2014	24 463	0.37			
Increase (2000-2014) in %	407				
Increase (2000-2008) in %	265				
Increase (2008-2014) in %	39				
Increase (2005-2011) in %			20	35	30

Table I : Agricultural and artificial territories of main villages (2005, 2008, 2011) and deforestation from mining activities (2000, 2008, 2014) in the a) OYA and b) MAR catchments.

268x114mm (300 x 300 DPI)

a) Oyapock Catchment	**QJ ($m^3.s^{-1}$) at SM**				**R**	**P_{CM}**	**P_{SM}**	**P_{mean}**
Years	Median	Mean	Max	Min	($l.s^{-1} km^{-2} yr^{-1}$)	(mm)	(mm)	(mm)
2004	584	800	3 159	71	32	2 405	3 305	2 855
2005						2 624	3 771	3 198
2006	808	901	2 863	198	36	2 688	3 009	2 848
2007	765	850	1 987	147	34	2 990	3 167	3 079
2008	1 050	1 110	3 569	95	44	2 762	3 254	3 008
2009				64		2 859	3 306	3 083
2010						3 503	3 788	3 645
2011						2 708	3 466	3 087
2012	787	780	1 897	72	31	2 411	3 126	2 769
2013	711	714	1 975	189	28	2 597	3 131	2 864
2014	913	902	2 346	134	36	2 867	2 503	2 685
2015	652	882	4 033	96	35	2 708	3 265	2 987
mean	784	867	2 729	118	35	2 760	3 258	3 009
max	1 050	1 110	4 033	198	44	3 503	3 788	3 645
min	584	714	1 897	64	28	2 405	2 503	2 685

b) Maroni Catchment	**QJ ($m^3.s^{-1}$) at LT**				**R)**	**P_{MPS}**	**P_{PPI}**	**P_{GS}**	**P_{APT}**	**P_{mean}**
Years	Median	Mean	Max	Min	($l.s^{-1} km^{-2} yr^{-1}$)	(mm)	(mm)	(mm)	(mm)	(mm)
2000						2 526	2 659	2 432	2 591	2 539
2001	1 790	1 971	5 781	180	32	2 202	2 193	2 749	1 941	1 794
2002	1 173	1 489	4 068	170	24	1 987	2 094	2 594	2 489	1 675
2003	449	995	4 313	130	16	1 896	1 994	2 236	1 911	1 536
2004				84		2 296	2 258	2 277	1 970	2 277
2005	1 067	1 500	5 228	87	25	2 520	2 254	2 838	2 692	1 909
2006						2 555	2 754	2 890	2 822	2 733
2007						2 476	2 602	2 934	2 851	2 671
2008	2 195	2 603	8 790	199	43	2 666	2 793	2 527	2 450	2 007
2009	1 419	1 557	5 683	119	26	2 134	1 960	2 168	2 759	1 572
2010	1 786	2 317	6 584	268	38	2 667	2 617	2 729	2 604	2 013
2011						2 446	2 574	2 466	2 505	2 495
2012	1 654	1 802	5 794	138	30	2 340	2 430	2 142	2 465	1 736
2013						2 813	2 577	2 938	2 929	2 776
2014	1 918	2 136	4 799	199	37	2 395	2 234	2 190	2 244	1 714
2015	1 714	1 939	5 444	161	35	2 753	2 598	557	2 127	1 486
mean	1 516	1 831	5 648	158	31	2 417	2 412	2 417	2 459	2 058
max	2 195	2 603	8 790	268	43	2 813	2 793	2 938	2 929	2 776
min	449	995	4 068	84	16	1 896	1 960	557	1 911	1 486

Table II: Discharge (Q), Runoff (R), Precipitation (P) at a) CM, SM in the OYA Catchment and b) MPS, PPI, GS, APT in the MAR Catchment.

235x191mm (300 x 300 DPI)

	Mann-Kendall test			Pettitt's test		
Stations	S	Kendall Tau	*p*-value	K	t	*p*-value
$SSSC_{SM}$	-1840	-0.18	0.001	1849	10/07/2008	0,002
$SSSC_{SH}$	46812	0,40	< 0,0001	39397	14/01/2010	< 0,0001
$SSSC_{LT}$	16348	0,44	< 0,0001	12339	03/12/2009	< 0,0001
$SSSC_{GR}$	27895	0,43	< 0,0001	20457	01/01/2010	< 0,0001
$SSSC_{BE}$	31961	0,46	< 0,0001	24063	09/11/2009	< 0,0001
$SSSC_{TPI}$	43787	0,39	< 0,0001	30719	09/11/2005	< 0,0001
$SSSC_{KO}$	20423	0,29	< 0,0001	10608	05/08/2010	< 0,0001
$SSSC_{GS}$	13109	0,28	< 0,0001	16202	21/08/2007	< 0,0001
$SSSC_{PPI}$	10308	0,25	< 0,0001	8733	29/08/2010	< 0,0001

Table III: Mann-Kendall test and Pettit's test used to determine the daily SSSC long term trend and the breakpoint in the OYA basin at SM and in the MAR basin at SH, LT, GR, BE, TPI, KO, GS, and PPI stations.

268x83mm (300 x 300 DPI)

a) Oyapock Catchment

Variables	S_y	$SSSC_{SM}$ (mean)	$SSSC_{SM}$ (max)	$SSSC_{SM}$ (min)	Q_{max}	Q_{min}	Q_{pk}	R	P_{SM}	P_{CM}
$SSSC_{SM\ (mean)}$	**0.88**									
$SSSC_{SM\ (max)}$	**0.77**	**0.85**								
$SSSC_{SM\ (min)}$	0.28	0.46	0.25							
Q_{max}	0.46	0.22	0.27	-0.54						
Q_{min}	0.06	0.33	0.10	**0.80**	-0.52					
Q_{pk}	-0.28	-0.02	-0.16	**0.68**	**-0.94**	**0.72**				
R	**0.82**	**0.61**	**0.49**	0.03	**0.72**	-0.11	-0.53			
P_{SM}	0.07	0.12	0.47	-0.32	0.24	-0.17	-0.17	-0.01		
P_{CM}	0.47	0.37	0.20	0.18	0.40	0.11	-0.14	**0.66**	0.14	
P	0.19	0.27	0.48	-0.03	0.13	0.14	0.04	0.07	**0.90**	0.39

b) MAR Catchment

Variables	S_y	$SSSC_{SH}$ (mean)	$SSSC_{SH}$ (max)	$SSSC_{SH}$ (min)	Q_{max}	Q_{min}	Q_{pk}	R	P_{APT}	P_{GS}	P_{PPI}	P_{MPS}
$SSSC_{SH\ (mean)}$	**0.56**											
$SSSC_{SH\ (max)}$	**0.68**	**0.84**										
$SSSC_{SH\ (min)}$	**0.54**	**0.78**	**0.54**									
Q_{max}	**0.50**	0.15	0.07	**0.52**								
Q_{min}	0.16	0.19	0.02	**0.52**	**0.75**							
Q_{pk}	0.23	-0.19	-0.02	-0.35	-0.07	-0.67						
R	0.41	0.07	0.00	0.39	**0.94**	**0.83**	**-0.17**					
P_{APT}	0.15	0.23	0.16	0.23	0.40	0.42	-0.18	0.34				
P_{GS}	-0.31	-0.06	-0.19	0.13	0.32	0.59	**-0.48**	0.39	0.58			
P_{PPI}	**0.57**	0.24	0.26	0.39	**0.82**	**0.71**	**-0.12**	0.86	**0.35**	0.32		
P_{MPS}	**0.61**	**0.53**	**0.52**	0.48	**0.60**	**0.54**	**-0.04**	0.67	**0.45**	0.33	0.82	
P	0.17	0.17	0.12	0.40	**0.68**	**0.68**	**-0.31**	0.63	**0.78**	**0.81**	**0.64**	**0.59**

Table IV: Spearman correlation matrix of the a) OYA and b) MAR catchments properties: Mean annual runoff (R), maximum annual water discharge (Qmax), minimum annual water discharge (Qmin), mean annual water discharge divided by the maximum water discharge (QpK), total annual precipitation (P) for each station (APT-GS-PPI-MPS in the MAR and SM-CM in the OYA catchments), average daily suspended sediments concentration in a year (SSSCmean), maximum daily suspended sediments concentration (SSSCmax), daily minimum suspended sediments concentration (SSSCmin), annual sediment load (SL) and Sediment Yield (SY) for the stations SH and SM

207x151mm (300 x 300 DPI)