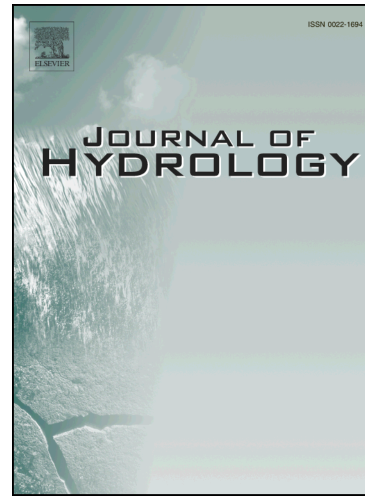

Research papers

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A reassessment of the suspended sediment load in the Madeira River Basin from the Andes of Peru and Bolivia to the Amazon River in Brazil, based on 10 years of data from the HYBAM monitoring programme

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Abstract

The Madeira River is the second largest tributary of the Amazon River. It contributes approximately 13% of the Amazon River flow and it may contribute up to 50% of its sediment discharge to the Atlantic Ocean. Until now, the suspended sediment load of the Madeira River was not well known and was estimated in a broad range from 240 to 715 Mt yr^{-1}. Since 2002, the HYBAM international network developed a new monitoring programme specially designed to provide more reliable data than in previous intents. It is based on the continuous monitoring of a set of 11 gauging stations in the Madeira River watershed from the Andes piedmont to the confluence with the Amazon River, and discrete sampling of the suspended sediment concentration every 7 or 10 days. This paper presents the results of the suspended sediment data obtained in the Madeira drainage basin during 2002-2011. The Madeira River suspended sediment load is estimated at 430 Mt yr^{-1} near its confluence with the Amazon River. The average production of the Madeira River Andean catchment is estimated at 640 Mt yr^{-1} (±30%), the corresponding sediment yield for the Andes is estimated at 3,000 t km^{-2} yr^{-1} (±30%), and the average denudation rate is estimated at 1.20 mm yr^{-1} (±30%). Contrary to previous results that had mentioned high sedimentation rates in the Beni River floodplain, we detected no measurable sedimentation process in this part of the basin. On the Mamoré River basin, we observed heavy sediment deposition of approximately 210 Mt yr^{-1} that seem to confirm previous studies. But while these studies mentioned heavy sedimentation in the floodplain, we showed that sediment deposition occurred mainly in the Andean piedmont and immediate foreland in rivers (Parapeti, Grande, Pirai, Yapacani, Chimoré, Chaparé, Secure, Maniqui) with discharges that are not sufficiently large to transport their sediment load downstream in the lowlands.

Keywords

Amazon Basin, Madeira River, Suspended Sediment Load, Andes erosion rate, Erosion sedimentation denudation, Annual fluxes

1. Introduction

Suspended Sediment Load Estimates in Previous Works

The Madeira River, with a drainage basin of 1,368,400 km^2 and an annual discharge of approximately 26,500 m^3.s^{-1}, is the second largest tributary of the Amazon River. Although its mean annual flow is only approximately 13% of the Amazon River flow (Molinier, 1996), it may contribute up to 50% of the Amazon River sediment discharge to the Atlantic Ocean (Laraque et al., 2005). At its confluence with the Amazon River in Brazil, the first estimates of the Madeira River suspended sediments load (SSL), using data from the CAMREX project, varied from 400 to 600 Mt yr^{-1} (Richey et al., 1986; Ferreira et al., 1988; Martinelli et al., 1993).

Dunne et al. (1998) proposed a sediment load of 715 Mt yr^{-1} for the Madeira River based on modeling of sediment transfer in the Amazon basin using CAMREX sediment data and ANA hydrological information. Using Brazilian ANA data prior to 1999, the SSL at Fazenda Vista Alegre (FVAL, the downstream gauging station of the Madeira River, figure 1) was estimated at approximately 240 Mt yr^{-1} (Bordas, 1991; Filizola and Guyot, 2009). However, using the first available data from the HYBAM network in Brazil over the 1998-2003 period, the SSL at FVAL was estimated at approximately 500 Mt yr^{-1} (Laraque et al., 2005). These different estimates clearly illustrate a dependency of the results on sampling conditions (methodology and frequency, for example).

From 1982 to 1990, the PHICAB project (a French-Bolivian research program on hydrology of the Amazonian basin of Bolivia) installed a first gauging network to quantify discharge and geochemical and sediment transfers in the Madeira River drainage basin from the Andes to the Brazilian border (Roche et Fernandez, 1988). The SSL results indicated massive erosion in the Andean part of the Beni

(Guyot et al., 1988) and Mamoré (Guyot et al., 1994) catchments, varying from 300 to 20,000 t km^{-2} yr^{-1}. The sediment export from the Andes was estimated at 500-600 Mt yr^{-1}, resulting in a mean suspended sediment yield (SSY) of 3,200 t km^{-2} yr^{-1} (Guyot et al., 1996). The PHICAB data in Bolivian Andean nested watersheds indicate that the erosion rates are mainly controlled by slope and lithology (Aalto et al., 2006). However, using data of piedmont stations from Ecuador to Bolivia (under different climatic conditions), Andean erosion rates appear to be mainly controlled by rainfall seasonality (Pepin et al., 2013). During the transfer along the Bolivian Amazonian floodplain (locally called “Llanos”), the PHICAB data indicated that approximately 50% of the sediment load was trapped by the floodplain.

Based on floodplain sediment cores and ^{210}Pb dating in the Beni River basin, Aalto et al. (2003) asserted that sedimentation in the floodplain occurred in pulses caused by extreme floods linked to cold El Niño Southern Oscillation (ENSO) events and proposed a sediment budget including heavy sedimentation (approximately 100 Mt yr^{-1}) for the Beni River in the distal floodplain between Rurrenabaque (RURR on figure 1) and Riberalta.

After a 4-year study of water and sediment exchanges between a meander and its associated floodplain on the Beni River downstream from RURR (using topographical surveys, sedimentation rate estimates from ^{210}Pb and sediment trapping systems), Gautier et al. (2010) proposed another sediment budget for the first 100 km of the Beni River downriver from Rurrenabaque, including heavy sedimentation as in Aalto’s sediment budget (approximately 100 Mt yr^{-1}), but attributed this sedimentation to the river bed instead of the distal floodplain.

From field, geophysical and borehole data, Baby et al. (2009) estimated the SSL deposition in the Madeira River Basin at an average of 110 Mt yr^{-1} over the last ten million years. During the same period, the denudation rate in the Cordillera Oriental was estimated to be between 0.3 and 0.92 mm.yr^{-1} from the thermo-chronometer data of Barnes et al. (2006).

The modern sedimentary fluxes in the Madeira Basin will likely be significantly impacted by several hydroelectric dams in Brazil, Bolivia and Peru (Finer & Jenkins, 2012) that will be constructed along the Madeira River main tributaries in upcoming years. On the Madeira River, the two first dams are being operated, and the first one (the Santo Antonio dam) has been in operation since 2012. Precise knowledge of the sedimentary fluxes prior to dam installation is extremely important for quantifying and understanding future environmental changes induced by hydroelectric dams.

Objectives

In this paper, we present the results of suspended sediment transfer in the Madeira drainage basin based on the continuous monitoring of discharges and SSL during nine hydrological cycles from 2002 to 2011 obtained by the HYBAM network at a set of 11 gauging stations from the Andes piedmont to the confluence with the Amazon River (figure 1). In particular, we aim to provide the most complete analysis of the modern sedimentary fluxes within the Madeira River basin, setting a baseline for future works that will assess the impact of hydroelectric operations and other environmental changes in upcoming years. To achieve this objective, in this paper, we analyze the contribution of the Madeira River Basin SSL to the Amazon, the Andean erosion rates, the localization of sedimentation in the Amazonian lowlands, and finally, we compare our results with estimates from previous papers.

2. The Madeira Basin

The Madeira River drainage basin extends over three countries (Peru: 8%, Bolivia: 52%, and Brazil: 40%) from 3.36 to 20.50 degrees south latitude and from 58.53 to 72.42 degrees west longitude (figure 1). The basin is divided into four geomorphological units: the Andes (16%), the Brazilian shield (33%), the Amazon plain (locally called “Llanos”) (48%), and the Fitzcarrald Arch formation (3%), which is located between the Andes and Amazon plain in the Madre de Dios River basin in Peru

(Guyot, 1993). In the Llanos, it was possible to separate the floodplains (9%) from the areas that never flooded (39%), locally called “Tierra Firme” (table 1).

In the Andes (16% of the basin), the altitudes vary from more than 6,400 masl at the Cordillera Real summits in Bolivia to 600 masl (south) and 200 masl (north) in the Amazonian lowlands. This plain is drained by three major rivers; from north to south, they are the Madre de Dios, Beni and Mamoré Rivers. When these rivers reach the Brazilian shield near the Brasil-Bolivia border, their elevation is 110 masl for the Beni River at Cachuela Esperanza (CACH) and 120 masl for the Mamoré River at Guayaramerin (GUAY).

Geology

The Andean orogeny in South America started during the mid-Cretaceous and is still active. Consequently, the adjacent retro-foreland basin of the Andean mountain belt developed since 100 Ma. The transcontinental Amazon drainage basin with connection to the Atlantic Ocean is relatively young; it is related to the faster mountain building and denudation rates in the Andes of the Late Miocene (23 to -5.3 Ma BP) and the consecutive transition from filled to overfilled conditions in the retro-foreland basin (Mora et al., 2010; Roddaz et al., 2010; Hoorn et al., 2010). However, the modern Amazon network was only fully established after the Pliocene (5.3 to 2.6 Ma BP) uplift of the Fitzcarrald Arch (Espurt et al., 2007, 2010).

A large proportion of the Andean sediment transport is retained in the retro-foreland system, which can be divided into several sub-basins that are delimited by structures resulting from north–south variations in Andean deformation (Kley et al., 1999; Gil et al., 2001; Espurt et al., 2008). The Bolivian Madeira drainage basin includes the southernmost of these sub-basins, which corresponds to a geomorphic region commonly referred to as the Beni plain. This basin was clearly formed in response to flexural subsidence driven by the thrusting and loading of the Andean retroarc orogenic wedge (Oriental Cordillera and Subandean foothills), whose forward propagation was approximately 74 km during the last 10 Ma (Baby et al., 1997; 2009).

Climate and hydrology

The mean annual rainfall over the Madeira lowlands shows a latitudinal gradient from 2,500 mm in the north to 1,000 mm in the south (Roche et al., 1990). In the Andes, there is no clear relationship between annual rainfall and altitude, and rainfall depends mainly on orography and exposure to the moist trade winds. A strong spatial variability is observed, with rainfall varying from 200 mm yr^{-1} at high altitude or on the leeward side of a mountain to 6,000 mm yr^{-1} at the eastern flank of the Andes (Espinoza et al., 2009a; Espinoza et al., 2015).

At a seasonal time scale, the Madeira River basin is characterized by a south tropical rainfall regime with a marked dry season during the austral winter, which is more intense inside the Andes, and a wet season during the austral summer (Roche et al., 1990; Ronchail and Gallaire, 2006). Indeed, approximately 75% of the annual rainfall is recorded from December to March (Espinoza et al., 2009a). The wet season is related to the presence of the South America Monsoon system, which brings humidity from the Atlantic Ocean and the Amazon rainforest (Vera et al., 2006).

In the Andes and its piedmont, the seasonal rain distribution determines hydrographs of multi-peaked floods that fuse together downstream to contribute to the large annual tropical type flood. The flood is more smoothed, flattened and delayed in the Mamoré and Itenez Rivers because of longer courses and greater catchment areas, as well as in wet years because of the lateral extension of broad flooded areas. During wet years, the flooding can extend over areas on the order of 100,000-150,000 km^2 in the *Llanos de Mojos* region, located in the Mamoré basin between the Andean foreland and Guayaramerín (Roche et Fernandez, 1988).

Several studies describe that a small fraction of interannual rainfall variability in the Madeira basin can be related to the ENSO in the Andean region (Aceituno, 1988; Ronchail, 1995; Vuille, 1999; Garreau et al, 2003) or to tropical or subtropical Atlantic sea surface temperature in the lowlands (Ronchail et al., 2005). In the Andean basins, many authors assert that El Niño years generally tend to be dry, whereas La Niña years are often associated with wet conditions (Vuille, 1999; Garreaud and

Aceituno, 2001; Ronchail and Gallaire, 2006). When considering the floods at RURR that exceed a discharge threshold of 6,000 $m^3 s^{-1}$, four of eight cold ENSO events resulted in strong floods (in 1971, 1974, 1999 and 2011). However, the other four cold ENSO events showed lower-than-average floods (in 1976, 1989, 2000 and 2008). We also observed one strong flood in a warm ENSO event in 1973 and three strong floods during non-ENSO years (1968, 1984 and 2001).

By analyzing rainfall trends in Bolivia, Seiler et al. (2013) showed that total rainfall increased from 1965 to 1984, mainly during the winter season (18%), and decreased afterward (10%). The authors attributed these changes to fluctuations in the Pacific Decadal Oscillation (PDO). Moreover, by computing the discharge trend in the Madeira River for the 1974-2004 period, Espinoza et al. (2009b) showed a significant diminution in discharge, particularly during the low-water period, especially at the Porto Velho and Fazenda Vista Alegre stations. That tendency was later confirmed for the extended 1967-2013 period (Molina-Carpio et al., 2017).

3. Data and Methodology

The HYBAM network

The HYBAM international network (www.ore-hybam.org) was created in 2003, in continuity with previous PHICAB and HiBAm projects in Bolivia and Brazil. The main objective of this network is to obtain new and freely available data, with better precision and accuracy, over a long period of time (more than 10 years) for the monitoring of the hydrology, geochemistry and sediment load of the main Amazonian rivers. To manage this network, the French Research Institute for the Development (IRD) is associated in Brazil with the Water National Agency (ANA), the University of Brasilia (UnB) and the Federal University of Amazonas at Manaus (UFAM). In Bolivia, it is associated with the National Meteorological and Hydrological Service (SENAMHI) and the University Mayor San Andrés (UMSA) in La Paz.

Gauging stations

The gauging stations previously used in the PHICAB project (1982-1990) were renovated between 2002 and 2004 to ensure the stability of the staff gauges. Most stations were kept at the same locations as during the PHICAB period, but a few stations were installed in new locations. The Angosto del Bala station on the Beni River was replaced by the Rurrenabaque station (RURR). The Abapó station on the Grande River was replaced by El Paraiso (PARA), located approximately 8 km upriver in a rocky and more stable section. The Miraflores station on the Madre de Dios River was first rehabilitated in 2002, and then, it was replaced in 2004 by the El Sena station (SENA), which is located on a more accessible site on the road from La Paz to Cobija. Both stations were observed simultaneously during one year. The stations of Palermo, Dos Estrellas and Portachuelo that were successively and briefly operated during the PHICAB period on the Beni River upstream of Riberalta were replaced by the Peñas Amarillas station (PENA), located on the road from La Paz to Cobija.

Extraction of the drainage basin limits

The watershed delimitation was performed by the *Hydrology* tool of ArcGis software (ESRI ©) based on the SRTM90 (Shuttle Radar Topography Mission – Farr et al., 2007) Digital Elevation Model (http://www2.jpl.nasa.gov/srtm/). The delimitation between the Andes and plain was defined under Google Earth according to the landscape and slope profile. The delimitation of the Fitzcarrald arch was based on the 300 m elevation limit from SRTM90. The Brazilian shield delimitation was defined from a selection of the outcrops older than Mesozoic age on geological maps of the Brazilian geological service (CPRM) and the Bolivian geological institute (SERGEOMIN). The floodplain area was retrieved from dual-season GRFM mosaics collected by the J-ERS L-band SAR satellite.

Water level and discharge monitoring

The water levels are read on staff gauges 2 or 3 times a day by observers from SENAMHI (Bolivia) or ANA (Brazil). Since the first discharge measurement was realized in 1994 with an ADCP on the

Solimões River, the HYBAM network has adopted the use of ADCP on its network (Filizola et Guyot, 2004; Filizola et al., 2009). Coupling the ADCP with a Garmin 18/5Hz GPS sensor allows for the correction of moving bottom errors and provides an estimate of the bottom velocity. All field data are managed by Hydraccess software (www.ore-hybam.org/index.php/eng/Software/Hydraccess), which is a free package developed by HYBAM to manage a hydrological database and offers a large range of standard treatments and data analysis (Vauchel, 2007). For the first time on the Madeira River basin, the quality and precision of the field measurements have produced reliable rating curves and discharges on the entire set of stations. Even non-univocal stage-discharge relationships caused by variable backwater as observed at FVAL (Meade et al, 1991), are treated in Hydraccess software using the Manning-Strickler equation.

Field measurement of SSL

The SSL field measurements are undertaken during field surveys simultaneously with ADCP discharge measurements. To account for the vertical and lateral gradients of suspended sediment concentrations (SSCs) over the river cross-section, 3 to 5 point samples are taken on 3 to 5 verticals, with an equidistant spacing of the samples along the depth and of the verticals along the width of the river (figure 2). Point sampling is preferred to depth-integrated sampling because it gives access to the SSC vertical profiles and information on the relationship between surface and section-averaged concentrations.

The treatment of the measurement is realized with HydroMESAD software (Vauchel, 2010), which combines discharge and velocity information from the ADCP measurements with sample locations and concentrations to calculate a weighted-average SSC for the cross-section.

Sampling strategy for measuring and calculating the SSL

In any case, the calculation of SSL at a gauging station over a long period of time requires a representative sampling of the SSC in the river, and the calculation methods depend on the frequency of this sampling. When making use of infrequent time-series (less than one SSC value per month), the typical method for calculating SSL is to fit power-rating curves expressing SSL = a . Q ^{b}, where *a* and *b* are fitted parameters. However, these parameters can vary considerably according to season and to rising or falling discharge. Even in good conditions at mountain or piedmont stations, gauged SSL values can frequently vary by a factor 10 to 100 for the same discharge, and the calculated SSL is only valid when averaged over a long period of time. Under poor conditions, such as plain stations, where tributaries bringing high sediment concentrations mix with tributaries bringing black waters from the floodplain, the power-rating curve method becomes difficult to use and is often erroneous (figure 3), as there is no longer any clear relationship between discharge and SSL (Filizola et al, 2011b).

The ideal method would be to realize full SSL measurements (documenting the cross-section of the river both laterally and vertically for SSC and discharge) on a sufficiently frequent time step (ideally daily) so that it makes sense to interpolate the average SSC from one value to the next one. We could then use the so-called averaging method: whenever there is an available value for discharge (Q), we obtain SSL by multiplying Q by the simultaneously measured SSC (if any) or by the SSC interpolated between two successive values. However, the cost of such an endeavor on 11 stations in a difficult environment would be so high that it would be impossible to consider it in the HYBAM network.

The method that was finally implemented in the HYBAM network is a less demanding version of the ideal one. We instructed the station observers to take a water sample from the surface of the river:

- Close to the bank but at a location with sufficient depth and water current every Monday morning in Bolivia.
- At the center of the river every 1st, 11th and 21st of the month in Brazil.

The surface sample is not representative of the entire cross-section SSC, and the relationship between *Surface SSC* and *Average SSC* must be rated, as illustrated in the next paragraph (figure 4).

The HYBAM staff conducted 2 to 3 campaigns of discharge and SSL measurements per year for each gauging station at low, medium and high water. At measurement time, 3 samples are taken at the same location where the observer typically takes the weekly or ten-day samples. In this manner, we can compare the *Surface SSC* from the observer to the cross-section *Average SSC* from the measurement and fit an average/surface relationship. *Surface SSC* values are then converted to *Average SSC* using this relationship, and the averaging method (SSL = Q . SSC) is used to calculate SSL, interpolating SSC when necessary. All the calculations are made using the Hydraccess software.

Average SSC = f(*Surface SSC*) rating curves and uncertainties

Because of difficulties associated with access to the stations during the rainy season and because of budget limitations, the HYBAM staff have not been able to make many SSL field measurements for high SSC values, especially at piedmont stations where the floods are rapid and SSC peaks are difficult to sample. As a result, the dataset of *Surface SSC* vs. *Average SSC* shows an asymmetric distribution, where most of the points have low or average SSC values and few points have high SSC values. After analysis of the entire dataset, we chose to fit power-rating curves expressed as $SSC_{average} = a . SSC_{surface}{}^{b}$ (where *a* and *b* are fitted parameters) because these curves are sufficiently flexible to fit to the entire dataset, they do not give exaggerated weights to high values, and they cross the axes at the origin (figure 4).

The main part of the uncertainty in a pair of *Surface* and *Average* values comes from the uncertainty in the *Surface* value. The average SSC resulting from a weighted average of 15 samples is at least rather stable. However, at the surface, sampling repetitions and turbidity data have shown that the concentration is highly variable because sand particles come to the surface only occasionally and in pulses. A significant uncertainty could not be avoided even if we always took three surface samples at the observer location to obtain a more stable value.

The reduced major axis (RMA) technique was applied to account for the uncertainty in the two variables to be rated (Isobe et al., 1990). We also used the resampling bootstrap technique (Wehrens et al, 2000) to minimize the effect of outlier values. Finally, we calculated the confidence interval limits at 95% for each power-rating curve (figure 4). The lower and upper *Average SSC* limits were then used to calculate lower and upper SSL limits at each station, making it possible to characterize the uncertainty due to the rating of *Average SSC* = f(*Surface SSC*).

Data screening and completing

The entire discharge and SSC dataset from the 11 gauging stations has been screened and completed whenever needed. A few gaps in the water level time-series could be completed by estimates from neighboring upriver or downriver stations through correlative methods. 11% of the discharge data and 3.8% of the SSC were obtained from corrected or completed daily data

The HYBAM network makes routine use of the MODIS products on the entire Amazonian basin using the GetModis/Mod3r software (Espinoza Vilar et al, 2012). Intensive field sampling and measurement campaigns have shown that the optical properties of the main Amazonian rivers are sufficiently stable to monitor surface SSC efficiently from satellite data (Martinez et al. 2015). The SSC time-series of gauging stations installed on sufficiently wide (more than 300 m) rivers have been systematically compared to MODIS satellite estimates (Martinez et al., 2009; Espinoza Vilar. et al., 2013). In some cases, a few corrections and completions were made. When there was sufficient proximity between stations and only small sources of sediments from the intermediate catchment, the SSL data coherence was further validated by comparing the flux of matter from one station to the other (an example is given in figure 5).

Limitations of the averaging method at piedmont stations and proposed correction

At lowland stations, the SSC sampling time interval of 7 to 10 days has generally proven to be adequate. However, at piedmont stations, the 7-day time interval is not sufficiently short to interpolate between two successive SSCs, as flash floods can occur in a few days between two successive samplings, which greatly affects the SSC. To estimate how an insufficient sampling frequency can affect the SSL results, simulations were made at stations with daily SSC (observed or simulated) by calculating the SSL both from the daily time-series and from 7-day subseries. The results show that for stations such as RURR, PVIL or PARA, the deviations between SSL calculated from 7-day and daily SSC can reach ±30% for an annual value depending on whether the SSC sampling is simultaneous with discharge peaks. However, at an interannual time scale (10 years), we estimated that the average underestimation rate is approximately 5%. For these reasons, the results of the mean annual SSL calculations with the averaging method presented in this document have been increased by 5%.

4. Results and discussion

Hydrological context

At Porto Velho (PVEL) on the Madeira River, we have continuous discharge data since 1967. The annual discharges show multidecadal oscillations, with a clear tendency toward increasing discharges before 1982 and a general trend toward decreasing discharges after 1982, as observed by Espinoza et al. (2009b), but with many irregularities and no clear trend since 1994 (figure 6).

As we compare in this paper the SSL obtained by PHICAB (1984-1989) and by HYBAM (2002-2011), it seemed interesting to analyze if these two observation periods presented comparable discharges. At PVEL, the mean annual discharge was 19,500 $m^3 s^{-1}$ on the PHICAB period and 17,700 $m^3 s^{-1}$ (9% less) on the HYBAM period. On the other stations, in comparison with the PHICAB period, the mean annual discharge observed during the HYBAM period was very similar in RURR, PVIL, CAMI and SENA, and lower (17% in average) at PSIL, GUAY and PRIN, due to lower than average discharges on the Mamoré and Itenez-Guaporé rivers during the HYBAM period.

SSL seasonality

Figure 7 shows the propagation of SSL on the Beni River from the piedmont station RURR to the plain station CACH, and downstream to the Madeira River PVEL station. The pulses of SSL observed at the piedmont stations can still be seen at the plain stations. However, they appear to be diminished when they occur at the beginning of the rainy season and amplified when they occur at the end of the flooding period. We hypothesize that at the beginning of the rainy season, a fraction of the sand contained in the suspended sediment pulses from the Andes is stored in the bed of the plain rivers that still have relatively low discharges. Later in the rainy season the discharges of these plain rivers increase with local runoff from the floodplain, and allow for sand transportation that adds to the silt and clay (washload) coming from the piedmont stations and to bank erosion.

The mean monthly SSL on the Beni – Madeira reach from RURR to FVAL demonstrates that the maximum SSL occurs during January and February (JF) at RURR, January to March (JFM) at PENA and CACH, and February to March (FM) at PVEL and FVAL (figure 8). The SSL flow begins to increase almost simultaneously at all stations in November, but it lasts approximately two months more at downstream stations PVEL and FVAL. This lag is probably due to the slow channel routing in the plains, and to the greater concentration time of the plain watersheds.

At the Andean piedmont stations (RURR, PVIL, PARA), the JFM SSL represents 65% of the annual sediment load, whereas it is only 41% of the annual load at the floodplain stations (CACH, GUAY, PVEL, and FVAL), as observed by Guyot el al. (1988, 1994).

The time lag between the piedmont stations and plain stations likely indicates a buffering in sediment transport. The Andean sediments come in pulses to the piedmont, the fine particles are directly transported, and the coarse particles can deposit partly in the riverbeds in the lowlands during JFM and are transferred slowly from January to June whenever sufficient discharge is available. The plain rivers need the energy from the floodplain local runoff for sand transportation. At the same time, bank erosion is an alternative source of sediments if the available sediment stock is less than the river can transport.

Mean annual SSL budget

Table 2 shows the results calculated from our Hydraccess database for river discharge and SSL.

It presents a high variability in discharge, SSC and SSL for the different stations. The values of specific discharge (Qspec) are highest at PVIL, whose watershed receives high precipitation due to the presence of a rainfall hotspot (Roche et al, 1990; Espinoza et al, 2009a; 2015). Apart from that hotspot, rainfall generally decreases from north to south, and we observe a similar gradient in Qspec from north (SENA, RURR, CACH) to south (PARA is especially low at 4 $l\ s^{-1}\ km^{2}$), as observed in the PHICAB period by Guyot (1993). In this aspect of specific discharges, our results consolidate the previous results as they are obtained on a longer observation period and with better rating curves provided by the use of the ADCP.

For SSC, table 2 is based on more than 4,000 samples of suspended sediments. The highest SSCs are observed at piedmont stations, such as RURR and especially PARA. The lowest SSCs are observed at GUAY on the Mamoré River, likely due to a high deposition rate of the Andean coarse sediments in the foreland and a strong dilution of the Andean white waters by black waters from the floodplain.

The PHICAB results for SSL are consistently less than the HYBAM results (see table 2), mainly because the SSL calculations for PHICAB were performed using surface SSC, which was converted from section averaged SSC by the equation $SSC_{Section} = 1.10\ SSC_{Surface}$ (Guyot, 1993). However, the recent SSL measurements made by HYBAM allowed us to obtain *surface-section* rating curves (figure 4), which indicate that this PHICAB equation strongly underestimates the section SSC, resulting in a general underestimation of SSL from 25% to 50%. This underestimation partially or entirely explains the higher SSL values observed for the HYBAM period at SENA, PENA, CACH, PVIL, and PARA.

Estimation of the Madeira River SSL contribution to the Amazon

From table 2, we obtain three estimates for the Madeira SSL, two from PVEL and FVAL and the third one from the sum CACH + GUAY to represent the confluence of the Mamore and Beni Rivers. As the main sediment source is the Andes, we assume that sediment inputs from local tributaries draining the Brazilian shield are extremely low. To support this assumption, we used the former PHICAB stations Caracoles on the Orthon River and Vuelta Grande (respectively CAR and VGR on figure 1) on the Itenez – Guaporé River to obtain an estimate of the possible SSL input from the intermediate catchments.

At Vuelta Grande, Guyot et al. (1996) estimate SSL at 1.7 Mt Yr^{-1} and SSY at 5 t km^{-2} yr^{-1}, considering that the totality of the watershed area of 354,300 km^2 is contributing to SSL. However, in the south of the catchment area, the Izozog swamps region is considered to be endorheic, and neither the discharge nor the sediment load from the Andes that enter this area ever reach the Itenez – Guaporé River. If we consider that the main part of the sediment load of this watershed comes from the Brazilian shield, with an area of approximately 147,000 km^2, we obtain an estimate of 12 t km^{-2} yr^{-1} for the Brazilian shield SSY, very close to the value observed at the Pontes e Lacerda station (16 t km^{-2} yr^{-1}), on the high Guaporé river in Brazil (Guyot et al., 1996). At Caracoles on the Orthon River, Guyot et al. (1996) estimate SSL at 1.77 Mt Yr^{-1} and SSY at 55 t km^{-2} yr^{-1} considering a watershed area of 32,300 km^2. These data make it possible to assess a Tierra Firme (never flooded plain) SSY estimate.

Using this SSY estimate for Tierra Firme catchments, we calculate the sediment input from the intermediate catchments between CACH + GUAY and PVEL at 3 Mt yr^{-1} and between PVEL and FVAL at 8 Mt yr^{-1}. In this manner, our three estimates for the Madeira SSL at FVAL are 419 Mt yr^{-1} from CACH + GUAY, 449 Mt yr^{-1} from PVEL and 421 Mt yr^{-1} from FVAL. As a result, we estimate that the Madeira River SSL at FVAL is approximately 430 Mt yr^{-1}. This value is similar to the estimate of Meade et al. (1979) at 400 Mt yr-1, to the CAMREX value of 400 to 600 Mt yr-1 (Richey et al., 1986; Ferreira et al., 1988; Martinelli et al., 1993) and to the first HYBAM estimate of 500 Mt yr-1 (Laraque et al., 2005). But is higher than the values of 240 Mt yr-1 from studies based on the quarterly ANA data (Bordas, 1991; Filizola et Guyot, 2009) or more recently realized by Leite et al. (2011).

In any case, the confidence intervals in our values (±30%) do not allow us to conclude whether there is some erosion or sedimentation between CACH+GUAY, PVEL and FVAL, as proposed by Laraque et al. (2005).

The Madeira River contributes 35% to 54% of the Amazon River SSL at Óbidos according to different sources, if we consider the lower and upper estimates respectively of 754 Mt y^{-1} (Martinez et al., 2009) and 1200 Mt y^{-1} (Meade et al., 1985) for the Amazon River SSL.

<u>Estimation of the Andean erosion rates</u>

With the new HYBAM data, we inferred the SSL and SSY for the ungauged Andean catchments, as shown in the next three paragraphs, to better understand the production, deposition and transportation processes (table 3).

At the SENA station on the Madre De Dios River, it is difficult to estimate the Andean SSL contribution, as the Andean part of the catchment area is only 35% of the total area, with 28% *Tierra Firme*, 35% *Fitzcarrald Arch* and 2% floodplain. However, the SSYs measured by PHICAB on the Orthon River at Caracoles for *Tierra Firme* and *Fitzcarrald Arch* are approximately 55 t km^{-2} yr^{-1}. On this basis, we estimate the contribution of the non-Andean part of the catchment area to be 6 Mt yr^{-1}. Assuming the absence of sedimentation processes between the Andes limit and SENA station, the Andean contribution to SENA SSL would be 139 – 6 = 133 Mt yr^{-1}, providing us with an upper SSY estimate of 3208 t km^{-2} yr^{-1} for the Andean part of the SENA watershed. Such an assumption appears to be consistent, as on the Beni River, our data do not show sedimentation processes between *piedmont* RURR and *Tierra Firme* PENA stations. This assessment of Andean SSY at SENA is coherent with the estimates obtained for the south and north neighboring catchments; to the south, we estimated the Andean SSY at 2,745 t km^{-2} yr^{-1} at RURR and 3,497 t km^{-2} yr^{-1} at PVIL, whereas to the north, the Andean SSY values have been estimated at 2,680 t km^{-2} yr^{-1} for the Ucayali River and 4,020 t km^{-2} yr^{-1} for the Pachitea River (Santini et al., 2014).

At PENA station on the Beni River, the only ungauged Andean catchment area is the Madidi River watershed. Due to large confidence intervals on the SSL values at RURR and PENA, it was not possible to estimate the Madidi River contribution by the difference PENA – RURR. We used the average SSY of the neighboring Andean watersheds at RURR and SENA to estimate the Madidi River Andean SSY.

At the CAMI and PSIL stations on the Mamoré River, the ungauged Andean watersheds are numerous. Between the Beni River at RURR and the Ichilo River at PVIL, we find the Maniqui, Secure, Chapare and Chimoré Rivers from north to south. The Andean SSY values of these watersheds were estimated from SSY gauged at PVIL, as the rainfall and land use conditions on these Amazonian slopes are similar. Between the Ichilo River at PVIL and the Grande River at PARA, we find the Yapacani and Pirai Rivers from north to south. Their Andean SSYs were estimated from the PHICAB SSY value given for the Pirai River at Angostura (Guyot et al., 1994). Finally, the SSY of the Parapeti River Andean watershed at San Antonio del Parapeti (SANT) was similarly taken from the PHICAB SSY value.

The gauged and estimated SSYs for the Andean watersheds range from 2,080 to 3,497 t km^{-2} yr^{-1}. The lower limit is obtained from the gauged Pirai watershed. Considering a sediment density of 2.5 t m^{-3}, the gauged SSY values lead to denudation rates between 1.1 and 1.4 mm yr^{-1}. These denudation rates are slightly higher than those mentioned by Pepin et al. (2013). They do not take into account the particular organic carbon which was estimated at 0.6% for the Beni, at 1.9% for the Mamoré and 2.6% for the Madeira Rivers according to Moreira-Turcq et al. (2003).

Based on our calculations of the ungauged catchments, we computed in table 4 the total contribution of the Andean watersheds

Over the 2002-2011 period and including the endorheic catchment of the Parapeti River, the average production of the Madeira River Andean catchment can be estimated at 640 Mt yr^{-1} (±30%), the corresponding sediment yield for the Andes can be estimated at 3,000 t km^{-2} yr^{-1} (±30%), and the average denudation rate can be estimated at 1.20 mm yr^{-1} (±30%). PHICAB data (Guyot et al., 1996) estimated the total SSL exported by the Andean basins in Bolivia at 500-600 Mt yr^{-1} and the SSY for the Andean catchment area at approximately 3,200 t km^{-2} yr^{-1}. Given the confidence interval, the HYBAM estimates are not significantly different from the PHICAB values.

The sediment yields calculated by HYBAM for the Andean basins of the Madeira River vary from 2,000 to 3,500 t km^{-2} yr^{-1} (tables 3 and 4). If we compare these rates with those of other Andean basins in the region, the Andean basin of the Ucayali River in Peru, which is adjacent to the Madre de Dios River basin to the northwest, is the only one that has higher erosion rates, which vary from 2,700 to 4,000 t km^{-2} yr^{-1} (Santini et al., 2014), while rivers draining the Fitzcarrald Arch (high Jurua and Purus rivers in Brazil), presents erosion rates from 150 to 500 t km^{-2} yr^{-1} (Filizola et Guyot, 2009). The other Amazonian Andean basins of the region have lower sediment yields: to the north in the Andean basin of the Marañón River in Peru (from 1,000 to 2,000 t km^{-2} yr^{-1} in Armijos et al., 2013a) and Ecuador (from 600 to 1,200 t km^{-2} yr^{-1} in Armijos et al., 2013b) and to the south in the Andean basin of the La Plata River (2,000 t km^{-2} yr^{-1} in Pepin et al., 2013). Identically, the Andean basins of the region draining toward the Pacific Ocean have lower erosion rates than the Madeira Andean watershed in Colombia (1,000 to 1,700 t km^{-2} yr^{-1} in Restrepo and Kjerfve., 2004), Peru (700 to 2,000 t km^{-2} yr^{-1} in Morera et al., 2013) and Chile (10 to 1,800 t km^{-2} yr^{-1} in Pepin et al., 2010), and also in the Andean Altiplano endoreic basin of Bolivia (20 to 640 t km-2 yr-1 in Guyot et al., 1990).

For others mountainous regions in the world, Alpine and Pyrenean rivers present erosion rates varying from 300 to 1000 t km^{-2} yr^{-1} (Dumas, 2008; Mano et al., 2009; Lopez Tarazon et al., 2009), while in the Maghreb region, this values are around 400-500 t km^{-2} yr^{-1} (Probst et Amiotte Suchet, 1992). For the large rivers draining the Himalayan chain, mountainous basin of the Ganges and

Brahmaputra Rivers present respectively erosion rate of 1200 and 800 t km^{-2} yr^{-1} (Abbas and Subramanian, 1984; Goswami, 1985), while large rivers of East and Southeast Asia present erosion rates from 200 to 1500 t km^{-2} yr^{-1} (Wang et al., 2011). In this context, erosion rates observed on the Andean basins of the Madeira River seem to be one of the largest observed in the world.

Estimation and location of sedimentation in the Amazonian plains

If we consider the sedimentation rate for the entire Madeira River basin in table 4, 33% of the Andean SSL is deposited in the basin. Such large sedimentation rates are also observed to the north in the Ucayali River basin in Peru, where 42% of the Andean SSL does not reach the Amazon River (Santini et al. 2014), and in the high Purus River basin in Brazil, where 30% of the pre-Andean Fitzcarrald Arch SSL does not reach the low Purus River (Filizola et al., 2011a). Large rivers from the Himalaya mountain present such deposition rates, as observed along the Brahmaputra River in India where 55% of the SSL is trapped between Farakka and Calcutta (Goswami, 1985), and also along the Ganges river (Abbas and Subramanian, 1984).

Table 4 reports a large contrast between the Beni and Mamoré Rivers. At CACH, the Beni River discharge contains 55% of Andean water, and its SSL is equivalent to the Andean production. However, at GUAY, only 26% of the Mamoré River discharge comes from the Andes, and only 20% of the Andean sediment production is exported by the Mamoré River at GUAY, reflecting massive sedimentation processes in the basin.

Unlike previous PHICAB results, our results on the Beni River catchment do not show sedimentation between Rurrenabaque and Riberalta. At RURR, the mean annual value for SSL (192 Mt yr^{-1}) is slightly less than that at PENA (208 Mt yr^{-1}) and less than that at CACH - SENA (346 - 139 = 207 Mt yr^{-1}). Thus, the total Andean SSL production of the Beni River catchment appears to match the SSL registered at the CACH station during the 2002-2011 observation period. Even considering the ±30% uncertainty, our results indicate that heavy sedimentation rates (up to 30% or 50%), as indicated in the past by PHICAB, are not probable.

In contrast, our data indicate high sedimentation rates for the Mamoré River catchment. The SSL values at CAMI (36 Mt yr^{-1}), PSIL (46 Mt yr^{-1}) and GUAY (62 Mt yr^{-1}) do not reflect the SSL of PARA + PVIL (187 + 16 = 203 Mt yr^{-1}). Additionally, PARA + PVIL represents only a part of the sediment production of the Andean part of this catchment, as many Andean tributaries (from north to south: Maniqui, Secure, Chaparé, Chimoré, Yapacani, Pirai and Parapeti) are not gauged by the HYBAM network. Taking into account these ungauged Andean catchments SSL estimates (as reported in table 3), we obtain a sedimentation rate of 80% for the Mamoré basin, and approximately 210 Mt yr^{-1} is deposited on average in the Andean piedmont and foreland.

We already knew from PHICAB that the Parapeti SSL was lost in the Izozog swamps. Our data show that the same is true for the Grande River, whose SSL does not appear at all at CAMI. The SSL results of CAMI, a new HYBAM station that was not monitored by PHICAB, shows us that most of the present sedimentation in the Madeira basin does not take place in the *Llanos de Mojos* floodplains as previously thought, but in the Andean piedmont and immediate foreland.

Our results also show a major contrast between the RURR and PARA Andean watersheds. Both watersheds produce similar SSL (approximately 190 Mt yr^{-1}). However, the Beni River at RURR has an average discharge of approximately 2,000 m^3 s^{-1} to transport its sediment load, whereas PARA has a discharge of only 260 m^3 s^{-1} (8 times less). As a result, it is not surprising that the Grande River SSL does not reach CAMI. ***The transport capacity of the rivers compared with their suspended sediment concentration is likely the main factor that controls sedimentation in the Amazonian foreland***. If we compare the drainage pattern of the Madre de Dios, Beni and Mamoré Rivers, we observe that for the two first rivers the Andean tributaries converge to form a strong river at its exit from the Andes. In contrast, the Mamoré River is formed by a whole set of tributaries that exit the Andes separately and converge farther in the plain. These small tributaries, especially those located south of the Ichilo River, whose watershed is located in a relatively dry region and whose SSC values are very high, have not enough energy to transport their sediments after the slope break when they reach the piedmont and enter the plain.

Concerning the Beni River between Rurrenabaque and Riberalta, Aalto et al. (2003) proposed a sediment budget with strong values of sedimentation: 19 Mt yr^{-1} in the proximal plain and 79 Mt yr^{-1} in the distal plain. Their study was based on a ^{210}Pb analysis of 80 cores 65-160 cm deep taken in sediment deposits along the Beni River at distances of 50 – 1200 m from the channel. The authors interpret these specific deposits as being probably delta-shaped sediments of small crevasse-splays formed during failure of the levees. In a first paper, Gautier et al. (2007) contradict this theory, and mention that “the use of satellite images and field survey does not reveal evidences of levee and crevasse-splay formations, and the very rapid migration of the meander bend renders the building of levees difficult”. According to these authors, the ‘episodic deposits’ identified by Aalto are probably related to sedimentation phases in the ox-bow lakes during floods, or could result from meander migration. In any case, our results do not confirm the strong values of sedimentation estimated by Aalto et al. A possible explanation for this difference could be the difficulty to spatially extrapolate a sedimentation value from 80 cores taken along a 400 km floodplain.

Gautier et al. (2010) proposed another sediment budget for the first 100 km of the Beni River downstream of RURR, based on the study of the area during period 2002-2006, and making use of an assemblage of tools: topometric and bathymetric surveys on one typical meander, sedimentation rate estimations from ^{210}Pb cores and sediment trapping systems. Strong values of sedimentation are proposed: 100 Mt yr^{-1} in the active bed, 10 to 12 Mt yr^{-1} in the active proximal floodplain, and 5 to 6 Mt yr^{-1} in the ox-bow lakes. These values of sedimentation are in contradiction with the HYBAM data, and it seems that the sedimentation estimate of 100 Mt yr^{-1} in the river bed results from an error in the extrapolation from the 5.5 km active meander studied in the paper to the whole 100 km reach. Actually during the 4 years of monitoring, the active meander sediment budget presented in the paper shows a net erosion instead of sedimentation.

5. Conclusion

This study, based on more than 4,400 samples of suspended sediments over the observation period 2002-2011, allows us to estimate the Madeira River SSL at FVAL at approximately 430 Mt yr^{-1} (±30%). The average production of the Madeira River Andean catchment area (including the Parapeti River) can be estimated at 640 Mt yr^{-1} (±30%), the corresponding sediment yield for the Andes can be estimated at 3,000 t km^{-2} yr^{-1} (±30%), and the average denudation rate can be estimated at 1.20 mm yr^{-1} (±30%). The HYBAM data estimate the mean annual SSL deposition at 210 Mt yr^{-1}, mainly in the southern Andean piedmont and foreland of the Mamoré basin, where extreme deposition rates are observed in rivers (Parapeti, Grande, Pirai, etc.) that have not enough discharge to transport the sediments across the plain. A schematic view of the SSL fluxes in the Madeira River Basin is given at figure 9.

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Tables

Table 1: HYBAM Gauging station characteristics (drainage basin extracted from SRTM, altitude data from Google Earth).

River - Gauging station	Code	Latitude	Longitude	Altitude	Drainage basin		Specific drainage basin (km2)				
		(degree)	(degree)	(m)	(km2)	(%)	Andes	Fitzc. Arch	Br. Shield	Tierra Firme	Floodplain
Madre de Dios - El Sena	SENA	-11.4702	-67.2368	140	118,459	9	41,463	33,193		41,088	2,706
Beni - Rurrenabaque	RURR	-14.4410	-67.5351	190	69,943	5	69,943				
Beni - Peñas Amarillas	PENA	-11.5488	-66.6737	130	108,590	8	73,525			27,325	7,741
Beni - Cachuela Esperanza	CACH	-10.5374	-65.5846	110	280,916	21	114,988	44,842	43	105,953	15,090
Ichilo - Puerto Villarroel	PVIL	-16.8371	-64.7921	190	7,683	1	4,576			2,960	147
Grande - El Paraiso	PARA	-18.9173	-63.4672	460	57,821	4	57,821				
Mamore - Camiaco	CAMI	-15.3358	-64.8668	150	128,778	9	76,188			48,991	3,599
Mamoré - Puerto Siles	PSIL	-12.8043	-65.0032	130	229,292	17	90,076			106,574	32,641
Mamoré - Guayaramerin	GUAY	-10.8124	-65.3430	120	611,713	45	98,648		164,694	263,475	84,896
Madeira - Porto Velho	PVEL	-8.7700	-63.9104	50	975,379	71	213,636	44,842	186,685	422,630	107,587
Madeira– Faz. Vista Alegre	FVAL	-4.8972	-60.0253	10	1,309,697	96	213,636	44,842	423,892	513,422	113,905
Madeira - Amazon confluence		-3.3732	-58.7570	5	1,368,431	100	213,636	44,842	455,140	538,198	116,616

Table 2: Discharge and suspended sediment data

HYBAM 2002-2011											PHICAB 84-89
River / HYBAM Gauging Station	**Code**	**SSC Obs. Period**	**Q ($m^3 s^{-1}$)**	**Qspec ($l s^{-1} km^{-2}$)**	**Samples (units)**	**SSC ($mg l^{-1}$)**	**SSL ($10^6 t yr^{-1}$)**	**CI95- (%)**	**CI95+ (%)**	**SSY ($t km^{-2} yr^{-1}$)**	**SSL ($10^6 t yr^{-1}$)**
Madre de Dios - El Sena	SENA	2002-2011	5,661	48	316	633	139	-17%	19%	1,173	71
Beni - Rurrenabaque	RURR	2002-2011	2,014	29	665	1,986	192	-27%	27%	2,745	212
Beni - Peñas Amarillas	PENA	2003-2011	2,958	27	314	1,298	208	-26%	37%	1,915	122
Beni - Cachuela Esperanza	CACH	2002-2011	9,083	32	488	940	346	-16%	19%	1,232	191
Ichilo - Puerto Villarroel	PVIL	2002-2011	571	74	520	552	16	-50%	100%	2,083	9
Grande - El Paraiso	PARA	2002-2011	258	4	388	12,828	187	-37%	60%	3,234	138
Mamoré - Camiaco	CAMI	2005-2011	2,092	16	323	489	36	-17%	19%	280	
Mamoré - Puerto Siles	PSIL	2005-2011	4,241	18	319	334	46	-33%	52%	201	47
Mamoré - Guayaramerin	GUAY	2002-2011	7,114	12	481	225	62	-16%	19%	101	66
Madeira - Porto Velho	PVEL	2002-2011	17,620	18	350	556	441	-5%	5%	452	257
Madeira - Fazenda Vista Alegre	FVAL	2002-2011	26,510	20	242	365	426	-32%	23%	325	306

Data for PVEL and FVAL for the PHICAB period are from DNAEE Brazil

Table 3: Andean SSL calculation for ungauged catchments

Catchment Area	Station	Andean Watershed	Total area (km^2)	Andean area (km^2)	SSY ($t\ km^{-2}\ yr^{-1}$)	Andean SSL ($Mt\ yr^{-1}$)	Denudation ($mm\ yr^{-1}$)
Beni	SENA	Madre de Dios	118,459	41,463	3,208	133	1.28
	RURR	Beni	69,943	69,943	2,745	192	1.10
	PENA	Madidi	108,590	3,582	2,976 *	11	
Mamoré	PARA	Rio Grande	57,821	57,821	3,234	187	1.29
	PVIL	Ichilo et Sajta	7,683	4,576	3,497	16	1.40
	CAMI	Pirai, Yapacani	128,778	11,642	2,080 *	24	
	CAMI	Chimoré	128,778	2,151	3,497 *	8	
	PSIL	Chaparé, Secure, Maniqui	229,292	13,888	3,497 *	49	
	SANT	Parapeti	7,458	7,458	2,590	19	

* Estimated from gauged catchments in the HYBAM or PHICAB period. Denudation rates are estimated considering a sediment density of 2.5 $t\ m^{-3}$.

Table 4: Contribution of the Andean watersheds to the discharge and SSL observed at the outlet of the main catchment areas.

			Discharge			SSL		
Code	River	Station / Catchment	Outlet ($m^3 s^{-1}$)	Andes contribution ($m^3 s^{-1}$)	Andean % (%)	Outlet (Mt yr^{-1})	Andes contribution (Mt yr^{-1})	Outlet % (*) (%)
CACH	Beni	Cachuela Esperanza	9,083	4,960	55%	346	336	103%
GUAY	Mamoré	Guayaramerin	7,114	1,876	26%	62	303	20%
PVEL	Madeira	Porto Velho	17,619	6,836	39%	441	638	69%
FVAL	Madeira	Fazenda Vista Alegre	26,508	6,836	26%	426	638	67%

(*) Outlet % is the percentage of Andean SSL that reaches the outlet of the main catchment area.

Figure captions

Figure 1: Location of the HYBAM gauging stations and geomorphological units in the Madeira River basin (see station codes in table 1).

Figure 2: Example of HydroMESAD output of one SSL field measurement at the PENA station.
Gray dashed lines show the limits of the influence zones considered for the weighted average SSC calculation.

Figure 3: The Mamoré River at Guayaramerín, 2002-2011, example of the relationship between SSL and discharge.
We observe a substantial variation in SSL around the general trend, and the trend disappears for discharges over 10,000 m3 s-1.

Figure 4: The average suspended sediment concentration as a function of the surface suspended sediment concentration assessed during gauging campaigns at RURR (20 gauging) and CACH (18 gauging).
Solid lines refer to fitted power-curves, and dashed lines refer to the confidence interval limits (α = 95%).

Figure 5: SSL Transfer between CACH + GUAY, PVEL and FVAL at a 10-day time-step during the 2009-2010 hydrological year. The graph shows a great similarity and coherence between SSLs of the 4 stations and is a confirmation of the good quality of the data during this year.

Figure 6: Annual average, min and max discharges at PVEL on the Madeira River, and hydrological context of PHICAB and HYBAM observation periods.

Figure 7: SSL propagation on the Beni – Madeira River reach for the 2005-2007 period, based on daily values

Figure 8: SSL seasonality on the Beni – Madeira River reach, computed on the 2002-2011 period, based on mean monthly values calculated on the 2002-2011 period

Figure 9: Schematic map of the SSL budget in the Madeira River Catchment Area. Black lines and arrows represent SSL transfer from the Andean basins to the Amazon River. Vertical black arrow symbolizes deposition in the piedmont area of the Mamoré Andean basin.

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- A new estimation of the Madeira River water and sediment budget is proposed
- The Andean basins produce a suspended sediment flux of 640 Mt yr^{-1}
- The Madeira River contributes 430 Mt yr^{-1} of suspended sediment to the Amazon River
- 33% of the Andean suspended sediments are trapped in the Mamoré Basin Piedmont
- Sediment routing in the foreland is controlled by water supply and concentration