Suspended sediment yields in the Amazon basin of Peru: a first estimation

JEAN LOUP GUYOT[1], HECTOR BAZAN[2], PASCAL FRAIZY[1], JUAN JULIO ORDONEZ[3], ELISA ARMIJOS[4] & ALAIN LARAQUE[5]

1 *IRD – LMTG (Institut de Recherche pour le Développement – Laboratoire des Mécanismes de Transfert en Géologie), Casilla 18-1209, Lima 18, Peru*
jean-loup.guyot@ird.fr

2 *UNALM – FIA (Universidad Nacional Agraria La Molina – Facultad de Ingeniería Agrícola), Avenida La Molina s/n, Lima 12, Peru*

3 *SENAMHI – DGH (Servicio Nacional de Meteorología e Hidrología – Dirección General de Hidrología), Casilla 11-1308, Lima 11, Peru*

4 *INAMHI, Iñaquito700 y Corea, Quito, Ecuador*

5 *IRD – OBHI (Institut de Recherche pour le Développement – OBHI), Centre Martinique-Caraibe, BP 8006, 97259 Fort de France Cedex, France*

Abstract The Amazon basin represents 76% of the area of Peru. From north to south, the Andean tributaries of the Amazonas River in Peru are: the Napo River (100 520 km^2, 6 300 m^3 s^{-1}), the Marañón River (360 550 km^2, 14 700 m^3 s^{-1}) and the Ucayali River (360 490 km^2, 13 800 m^3 s^{-1}). The total suspended sediment yield exported from Peru to Brazil by these rivers is about 450×10^6 t year^{-1} for the 2004-2006 period (12% from the Napo River, 40% from the Marañón River and 48% from the Ucayali River). As the Amazon floodplain traverses the Andean piedmont and reaches its mouth, sediment yield increases along the Napo and Marañón rivers. This suggests the occurrence of erosion processes in the lowlands as observed in Ecuador, rather than the occurrence of sedimentation as observed along the Madeira River in Bolivia. At all the study stations, discharge and suspended sediment yield show a very high degree of seasonal variation.

Key words hydrology; suspended sediment; Amazon basin; Peru

INTRODUCTION

With a very large drainage basin area of 6.1×10^6 km^2 (Goulding *et al.*, 2003), and a mean annual discharge estimated at 209 000 m^3 s^{-1} (Molinier *et al.*, 1996), the Amazon basin is the largest river system in the world. Due to its large extent, the Amazon basin experiences significant climate variability (Marengo, 2004). At Óbidos, the lowest gauged station on the Amazon River in Brazil, annual data for the 1903–1999 period indicates a generally increasing discharge trend for the century (+9%), and a recent period (1988–1999) of decrease (Callède *et al.*, 2004). Several suspended sediment yield budgets have been published for the Amazon in recent decades (Gibbs, 1967; Meade *et al.*, 1979, 1985; Dunne *et al.*, 1998; Filizola, 2003), but the time variability (based on 10-day sampling) during a 10-year period (1995–2004) was recently published thanks to the HYBAM observatory (http://www.ore-hybam.org). At Óbidos, the trend in suspended sediment yield trend for the 1995–2004 period is not correlated with discharge, and seems to show increasing yield in recent years (Guyot *et al.*, 2005). For the large Central Brazil floodplain in the period 1998–2003, comparison of suspended sediment budgets at upstream and downstream gauging stations reveals negative values (–20%), which suggests that sedimentation on the Amazon floodplain is important (Filizola, 2003; Laraque *et al.*, 2005).

In the Andean countries of the Amazon basin (Colombia, Ecuador, Peru and Bolivia), hydrological data from large rivers was scare, and suspended sediment yield data non-existent before the advent of PHICAB and HYBAM projects. PHICAB data collected in the Amazonian floodplain of Bolivia (the Beni and Mamoré rivers, Llanos de Mojos) in the period 1982–1990 also reveal a decreasing suspended sediment yield (–50%) from the Andean piedmont (upstream) to the Brazilian frontier (downstream), again suggesting large-scale sedimentation along the floodplain (Guyot *et al.*, 1996), as observed in Brazil. However, HYBAM data for the period 2000–2003 in the Ecuadorian floodplain, from the Andes to the Peruvian border along the Napo River, indicates an increase in sediment load in the downstream direction (+80%) and suggests erosional rather than depositional processes dominate in the floodplain (Laraque *et al.*, 2004).

In Peru, the Amazon drainage basin extends over 977 900 km^2 (76% of the country area), from the Andean Cordillera to the Amazon floodplain, and it supplies 98% of the water resources of the country. Regular ADCP discharge measurements began in 2001 on the Amazonas River and its main tributaries (the Marañón, Huallaga, Ucayali, and Napo rivers) as part of the HYBAM project (IRD-SENAMHI-UNALM, http://www.mpl.ird.fr/hybam). At the Tamshiyacu (TAM) gauging station located near Iquitos city, the Amazonas River drains a basin area of 726 400 km^2 (53% in the Andes) and had a mean annual discharge of 31 700 $m^3\ s^{-1}$ for the period 1969–2006, but also exhibits a clear trend of declining flows; see Fig. 1 (Espinoza *et al.*, 2006).

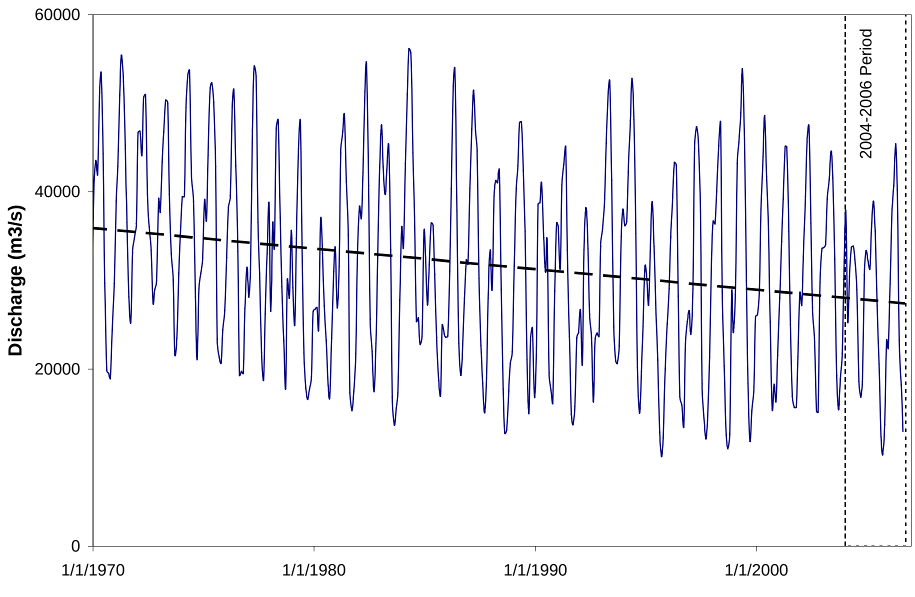

Fig. 1 Monthly discharge for the Amazonas River at Tamshiyacu (1969–2006).

In this paper, we present the first estimates of suspended sediment yield in the Amazon basin of Peru, which are based on the HYBAM data for the 2004–2006 hydrological cycles, that represent a relatively low flow period.

DATA AND METHODS

For this study, hydrological data for seven gauging stations were analysed (Table 1 and Fig. 2). These included the two HYBAM stations of Rocafuerte (ROC, located in Ecuador near the Peru border) and Chazuta (CHA, located in Peru), and five SENAMHI gauging stations in Peru: Bellavista (BEL), Borja (BOR), San Regis (SRE), Requena (REQ) and Tamshiyacu (TAM). These gauging stations drain large basin areas ranging from 27 390 to 733 470 km^2. The extent of the drainage basins was delimited using SRTM data. With 90% of their basin areas located in the mountain range, the Borja and Chazuta stations monitor the Andean outlet for the Marañón and Huallaga rivers, and represent 82% of the Andean part of the Marañón basin at the San Regis station. The Marañón and Ucayali rivers, which have a similar drainage basin area, join upstream of Iquitos to form the Amazonas River in Peru, which is called the Solimões River downstream in Brazil. Tamshiyacu is the first gauging station on the Amazon River mainstream. The two gauging stations on the Napo River monitor the water input in Peru (Rocafuerte) and the output of the Napo River to the Amazonas River (Bellavista).

Table 1 Gauging station characteristics, Amazon basin of Peru.

Station Code	Gauging station	River	Lat. (deg.)	Long. (deg.)	Total area (km^2)	Andean area (km^2)	(%)	Mean discharge (m^3 s^{-1})	(L s^{-1} km^{-2})	Period of data
ROC	Rocafuerte	Napo	–0.92	–75.40	27 390	18 810	69	2 210	81	2001–2006
BEL	Bellavista	Napo	–3.48	–73.08	100 520	18 810	19	6 270	62	1989–2006
BOR	Borja	Maranon	–4.47	–77.55	115 410	104 800	91	4 670	40	1986–2006
CHA	Chazuta	Huallaga	–6.57	–76.12	58 930	53 120	90	2 900	49	2003–2006
SRE	San Regis	Maranon	–4.51	–73.95	360 550	193 580	54	14 730	41	1986–2006
REQ	Requena	Ucayali	–5.03	–73.83	360 490	198 380	55	13 800	38	1984–2006
TAM	Tamshiyacu	Amazonas	–4.00	–73.16	733 470	392 010	53	30 060	41	1986–2006

For all the gauging stations, water level is measured twice a day by HYBAM (ROC and CHA) or SENAMHI (BEL, BOR, SRE, REQ and TAM) observers. Since 2001, discharge measurements have been undertaken at all these stations by Acoustic Doppler Current Profilers (ADCP) using the same HYBAM protocol (Filizola & Guyot, 2004). To date, 100 discharge measurements have been made: 21 at ROC, 11 at BEL, 13 at BOR, 6 at CHA, 16 at SRE, 15 at REQ and 19 at TAM. These data permit us to establish good rating curves for all the stations. Daily discharge is calculated using the HYDRACCESS software (http://www.mpl.ird.fr/hybam/outils/hydraccess.htm).

Mean discharge data for the observation period are listed in Table 1. For the first time, discharge data for the main tributaries of the Amazonas River in Peru are available. Specific discharge varies from 40 L s^{-1} km^{-2} for large basins to 80 L s^{-1} km^{-2} for the smallest basin of the equatorial area in the north of the study area (Napo River). The time series of discharge data for the Tamshiyacu station (1986–2006) has been extended to the period 1969–2006 using the ENAPU (Empresa Nacional de Puertos) data of Iquitos (Fig. 1). For this period, mean annual discharge values have decreased by about 0.8% per year (Espinoza *et al.*, 2006).

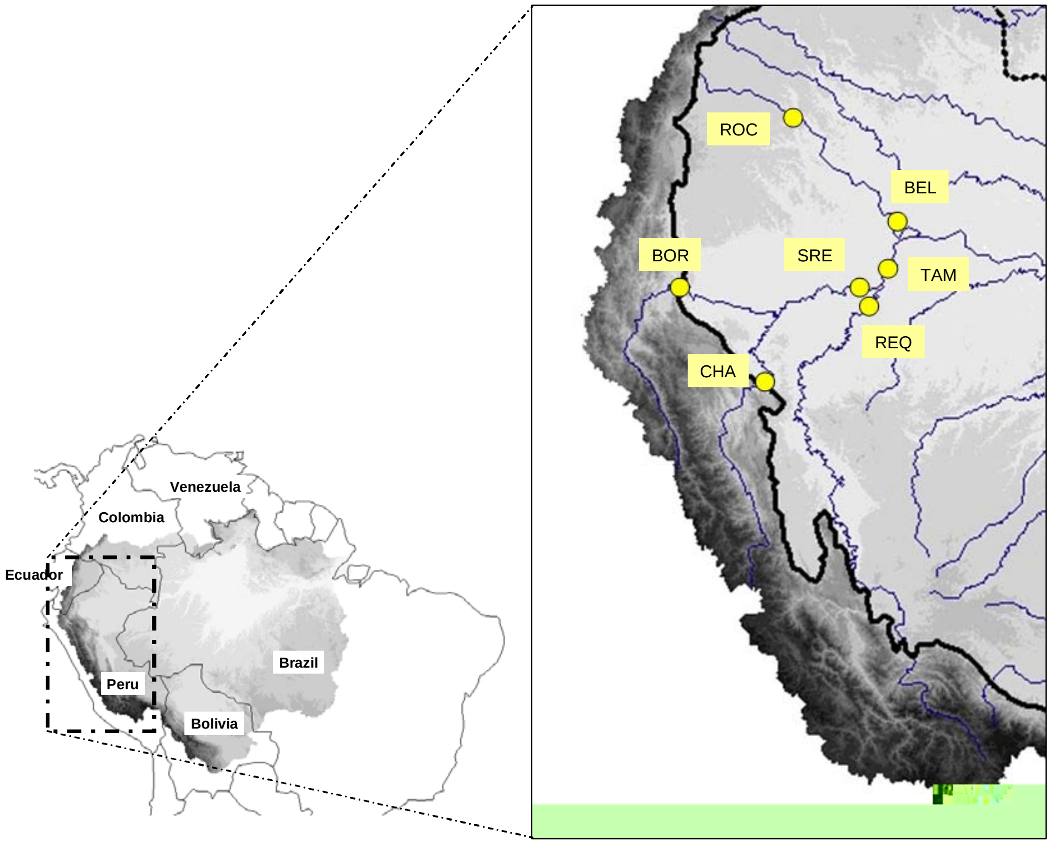

Fig. 2 Location of the gauging stations in the Amazon basin of Peru; relief data from SRTM (see Table 1 for station codes).

For all the stations, surface suspended sediments were sampled in the middle reach of the river by observers every 10 days. Except for the ROC station in Ecuador, where collection was initiated in 2001 (Laraque *et al.*, 2004), suspended sediments sampling in Peru began in 2004. To date, more than 500 samples have been analysed for the 2004–2006 period for all the stations (Table 2). During field campaigns, suspended sediments were sampled at different depths in three verticals, in order to calibrate the surface suspended sediment samples collected by observers. Using this information, 10-day suspended sediment yields are calculated using HYDRACCESS software, as described by Guyot *et al.* (2005) for Brazilian rivers.

RESULTS

Results presented in this study represent the first evaluation of suspended sediment transport in this part of the Amazon basin. For the 2004–2006 hydrological cycles (Table 2), discharge data varies somewhat from long-term averages (Table 1), with lowest discharges observed at Tamshiyacu (–9%) and Requena (–22 %), and a highest discharge observed at San Regis (+9%).

Table 2 Discharge and suspended sediment data for the Amazon basin of Peru in the period 2004–2006.

Station Code	Gauging station	River	Mean discharge ($m^3 s^{-1}$)	Number samples	Suspended sediment ($mg L^{-1}$)	($10^6 t year^{-1}$)	($t km^{-2} year^{-1}$)
ROC	Rocafuerte	Napo	2 210	72	270	21	770
BEL	Bellavista	Napo	6 270	76	260	49	480
BOR	Borja	Maranon	4 780	89	620	103	890
CHA	Chazuta	Huallaga	2 820	51	340	42	710
SRE	San Regis	Maranon	16 230	90	310	168	470
REQ	Requena	Ucayali	11 260	83	520	205	570
TAM	Tamshiyacu	Amazonas	27 500	86	450	413	560
Total				547			

Mean suspended sediment concentrations exhibit relatively little variation between the study sites, and ranged from 260 mg L^{-1} for the Napo River to 620 mg L^{-1} for the Marañón River at Borja, the outlet of the Andes. Mean erosion rates are also very similar, varying from 480 to 890 t km^{-2} $year^{-1}$, with the highest values observed for the Andean basins (ROC, BOR, CHA), and the lowest in the Amazonian floodplain.

Along the Napo River, the suspended sediment yield increases from Rocafuerte (21 x 10^6 t $year^{-1}$) to Bellavista (49 x 10^6 t $year^{-1}$, +130%), and provides evidence of erosion in this lowland basin, and sediment sources located outside of the Andes. Similar results were obtained in Ecuador by Laraque *et al.* (2004), from where the suspended sediment yield increased by 80% from the Andean piedmont to Rocafuerte (from 14 to 24 x 10^6 t $year^{-1}$). In this area, the sediment source is probably the Tertiary alluvial megafan of Pastaza and/or by the remobilisation of fine fluvial deposit, behind tectonic uplift (Bès de Berc *et al.*, 2005). For the Peruvian part of the Napo basin, between Rocafuerte and Bellavista, the mean erosion rate is approximately 400 t km^{-2} $year^{-1}$.

For the Marañón River, the suspended sediment yield observed at San Regis (168 × 10^6 t $year^{-1}$) represents a little more (+16%) than the combined sediment output from the Andean gauging stations (BOR+CHA, 145 × 10^6 t $year^{-1}$). This can be explained by two factors:

– sediment yields from other Andean tributaries, such as the Morona and Pastaza rivers located north of Borja have not been gauged (Borja and Chazuta basins represent only 82% of the Andean domain above San Regis),
– sediment contributed from the Pastaza alluvial megafan by the Pastaza and Tigre rivers which flow to the Marañón River.

Although the lack of data for the Pastaza and Tigre rivers introduces some uncertainty, it appears that the upstream and downstream data for the Marañón River basin do not reveal significant floodplain sedimentation of the sort observed in the Beni or Mamoré river basins of Bolivia (Guyot *et al.*, 1996).

A very high degree of seasonal variability in discharge was recorded in the present study (Fig. 3). For Andean stations, such as Borja, the high water season is characterised by frequent and short floods. At Borja, daily values varied 13-fold from 1 350 $m^3 s^{-1}$ (12/12/05) to 17 370 $m^3 s^{-1}$ (06/06/04). In the floodplain, the Marañón River at San Regis has a classic Amazonian hydrograph with a high flow period from November to June, but with two maxima: the first from November to January, and the second from March to June. Low water is observed from August to October, and also in February. Daily discharge values vary five-fold from 5 170 $m^3 s^{-1}$ (30/09/05) to 26 170 $m^3 s^{-1}$ (04/05/06). The same observations are valid for the Tamshiyacu station which has a similar hydrograph, with extreme values ranging from 9 320 $m^3 s^{-1}$ (06/09/05) to 47 100 $m^3 s^{-1}$ (07/05/06) for the same period. Low values observed in 2005 correspond to the lowest discharge recorded for the whole observation period in Peru, and also at some stations in Brazil (Ronchail *et al.*, 2006).

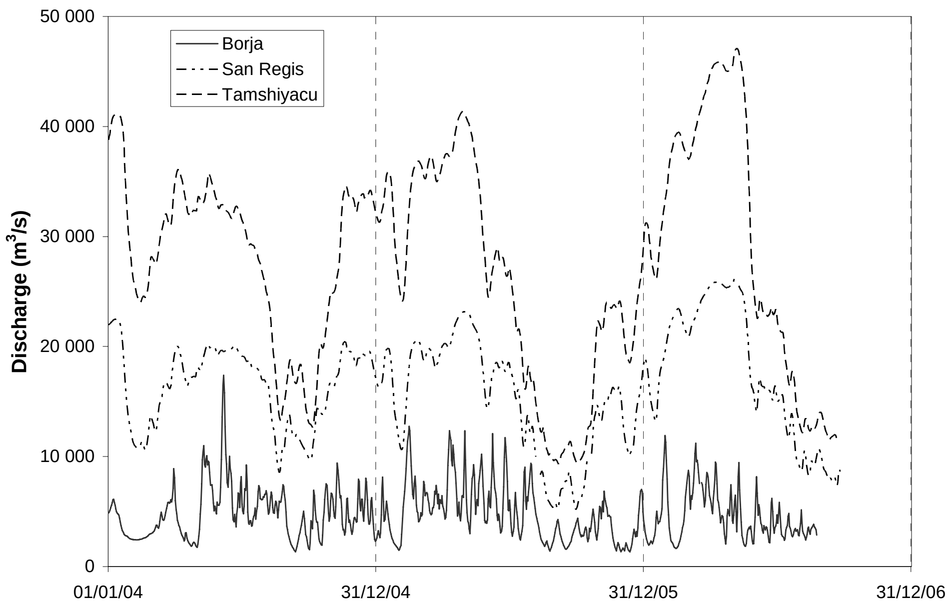

Fig. 3 Daily discharge for the Marañón (Borja and San Regis) and Amazonas (Tamshiyacu) Rivers in the period 2004–2006.

For the three stations along the Marañón–Amazonas River, the suspended sediment concentrations range from 70 to 2400 mg L^{-1} during the annual hydrological cycle at Borja, from 60 to 820 mg L^{-1} at San Regis, and from 110 to 850 mg L^{-1} at Tamshiyacu. Figure 4 demonstrates that the suspended sediment yield has a more strongly seasonal regime than the discharge.

At Borja on the Marañón River, extreme daily sediment yield values have a more than 100-fold variation and range from 15 600 t d^{-1} (25/08/05) to 1 570 000 t d^{-1} (09/04/06). Downstream, at San Regis, the suspended sediment yield regime is very similar, and extremes daily values vary over a 22-fold range from 58 500 t d^{-1} (10/10/05) to 1 280 000 t d^{-1} (21/03/05). At Tamshiyacu on the Amazonas River, there is a 20-fold range in daily suspended yields with extreme values varying from 135 000 t d^{-1} (11/10/05) to 2 680 000 t d^{-1} (01/04/05).

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CONCLUSION

Results presented in this study relate to the 2004–2006 period and represent the first evaluation of suspended sediment transport in the western part of the Amazon basin (Ecuador and Peru). The suspended sediment yield of the Amazonas River in Peru is around 450×10^6 t year^{-1}, with 12% coming from the Napo River basin, 40% from the Marañón River basin, and 48% from the Ucayali River basin. The sediment budget along the Napo River allows an erosion rate for the Pastaza alluvial megafan in Peru of ~400 t km^{-2} year^{-1} to be estimated. This information will be completed and/or corrected in the future with new data acquired through the HYBAM programme.

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