Sediment yields and erosion rates in the Napo River basin: an Ecuadorian Andean Amazon tributary

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Abstract This paper presents the first results obtained by the HYBAM project in the Napo River drainage basin in Ecuador during the period 2001–2002. Three gauging stations were installed in the basin to monitor suspended sediment yields, of which two are located in the Andean foothills and the third station on the Ecuador–Peru border in the Amazonian plain. At the confluence of the Coca and Napo rivers, the suspended sediment yield transported from the Andes Mountains is 13.6 10^6 t year^{-1} (766 t km^{-2} year^{-1}). At the Nuevo Rocafuerte station 210 km downstream, the suspended sediment yield reaches 24.2 10^6 t year^{-1} for an annual mean discharge of 2000 m^3 s^{-1}. These values indicate intensive erosion processes in the Napo Andean foreland basin between the Andean foothills and the Nuevo Rocafuerte station, estimated to be 900 t km^{-2} year^{-1}. These high rates of erosion are the result of the geodynamic uplift of the foreland.

Keywords Amazon Basin; Andes; Ecuador; erosion; hydrology; Napo River; suspended sediment

INTRODUCTION

Most (95%) of the sediment discharged to the Atlantic Ocean by the Amazon River comes from the Andes Mountains although the range only covers 12% of the surface area of the Amazon basin. The eastern half of Ecuador, which comprises the eastern slopes of the Andes and the foreland, covers around 135 000 km^2. This represents less than 3% of the total surface area of the Amazon basin. The foreland corresponds to the edge of the humid, equatorial plain of the Amazon, which continues in Peru and Brazil. This is the region in which the Andes present the most important tectonic activity characterized by intensive volcanic and seismic activity.

The international HYBAM programme (Hydrological and Geodynamic Research Program on the Amazon Basin), in which France, Brazil, Bolivia, Ecuador and Peru are taking part, is carrying out global studies on the climatological, hydrological, sedimentological, geochemical and geodynamic aspects of the Amazon basin. The overall objective of the project is to understand how the Amazon basin functions and to study the link between this and its geodynamics. The studies aim to identify the spatial distribution of the erodable zones, and of the transfer and deposit of sediments. One of the other purposes is to estimate the processes of each, linked with the phenomenon of upward movements in the Andes and subsidence in the Amazonian depression. Starting in January 2001, a network of seven reference stations was launched in Ecuador, supported by the IRD and INAMHI Institutions, to study the processes of the transfer of solid material from the eastern side of Ecuadorian Andes, by means of the study of its principal basin, the Napo River (Fig. 1).

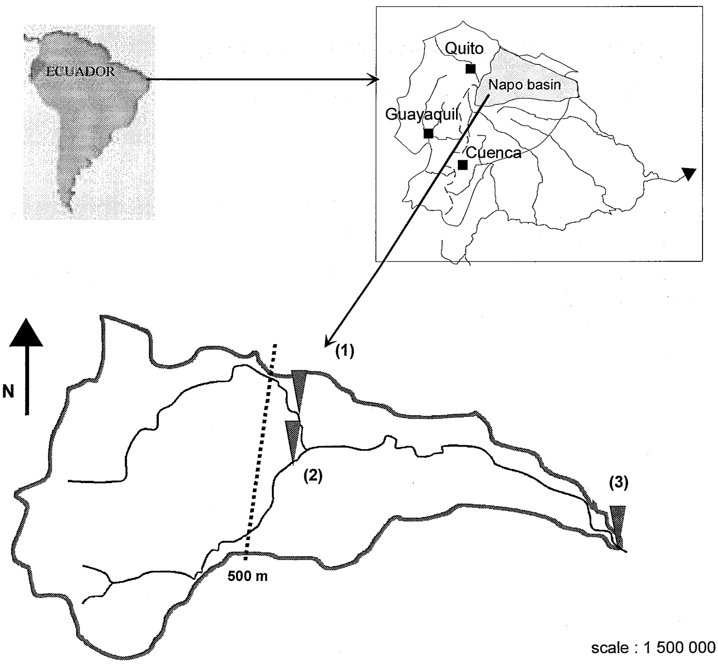

Fig. 1 Location of the Napo basin and its reference stations (see number explanation, Table 2).

THE STUDY AREA

The high precipitation (mean annual rainfall 2900 mm) has a heterogeneous spatial distribution. The 2-fold pluviometric and hydrological regime of the upper basin tends to become one in the lower basin (Moreno & Tapia, 2001). Recorded at daily intervals, these very irregular regimes are characterized by flash floods, reflecting their extreme sensitivity to rain events. The Napo basin covers an area of 26 860 km^2, i.e. equivalent to 20% of the eastern part of Ecuador. It is situated between the southern latitudes of 00°01′ and 01°10′ and the western longitudes of 77°20′ and 78°30′ (Perez Suasvana, 2000; Armijos, 2001).

The Napo River is 1300 km long and starts in the Ecuadorian Andes at an altitude of more than 5000 m. After the first 460 km, the river leaves Ecuador at an altitude of 189 m and enters Peru, where it forms the left tributary of the fluvial axis of the Marañon/Amazon at Iquitos. Figure 1 is a schematic presentation of the basin with the location of the three gauging stations used on the two main rivers. The figure also shows the altitude limit of 500 m, to indicate the boundary between the Andean and Amazonian regions.

DATA AND METHODS

Three reference stations were selected in Ecuador: San Sebastian and Fr. De Orellana, which control the output of the Andes, and Nuevo Rocafuerte which closes the basin at the outlet from Ecuador. One of the three stations was opened at the beginning of 2001 (San Sebastian on the Coca River) and the others (Fr. De Orellana and Nuevo Rocafuerte on the Napo River), have kept limnimetric records since 1980 but needed calibrating. The gauging curves were established over only two hydrological cycles using a 1200 kHz ADCP (Acoustic Doppler Current Profiler) (RDI, 1999). At these stations, samples of water and suspended matter (SM) were also taken every 10 days. The relations between these surface SM concentrations and the average of the cross section were established using several complete solid discharge measurements taken during an entire annual flow season (Laraque *et al.*, 2003) (Figs 2 and 3).

Using a point sampling protocol, in each solid gauging section, n samples were taken over all the depth of p vertical lines uniformly distributed over the area of the section (with $n > 3$, $p < 5$). The point-to-point concentrations were weighted by the velocities corresponding to the sampling points. The samples were filtered using 0.45 µm cellulose acetate filters to separate the suspended matter. There were thus two years' (2001–2002) data available on both water discharge and SM load from the three stations. These data allowed us to calculate the first annual fluxes of SM in the principal sub-basins of the Napo River and to compare the balance of the transport between the stations.

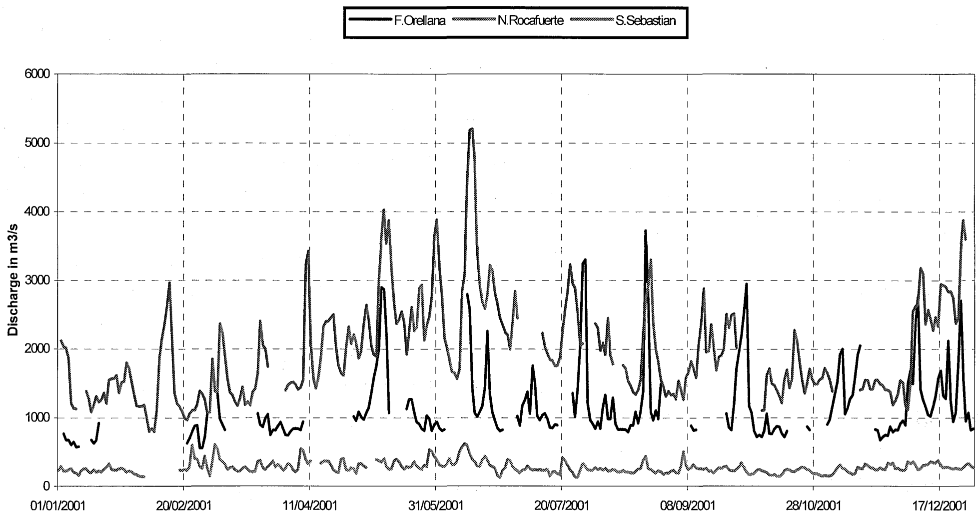

Fig. 2 Daily hydrographs of the Coca River at Sebastian, and of the Napo River at Fr. De Orellana and Nuevo Rocafuerte stations (year 2001).

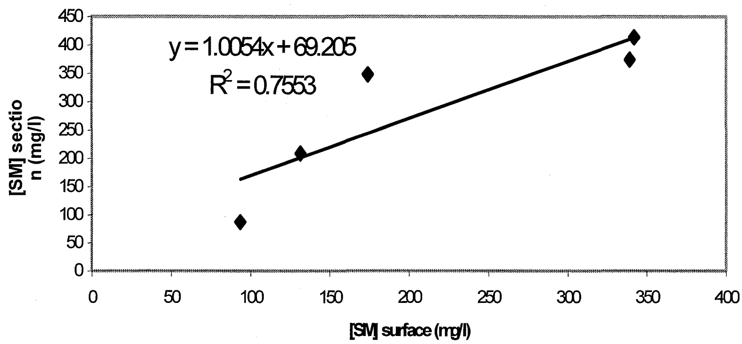

Fig. 3 Relation between surface SM load *vs* mean SM load in the section of the Napo River at Nuevo Rocafuerte station.

RESULTS AND DISCUSSION

Table 1 presents the first annual hydrological balance of the basins under study for the period 2001–2002. The mean annual discharge of the Napo River at Nuevo Rocafuerte was 2000 $m^3 s^{-1}$, which corresponds to an annual volume of 63 km^3. The specific discharges indicate a high degree of spatial irregularity, from 47 l s^{-1} km^2 in the basin of the Coca at San Sebastián to 99 l s^{-1} km^2 for the Napo River at Fr. De Orellana.

The SM load concentration varied from 10 to 2800 mg l^{-1} from one station to another and with the seasons. The ratio between the highest and lowest daily values decreased downstream: San Sebastian (161), Fr. De Orellana (146) and Nuevo Rocafuerte (31) as a function of altitude, of the increase in the size of the area drained and of the geographical origin of stream flow (only mountains or mountains and plain). These sediment concentration ratios were much higher than the highest ratios for extreme daily discharges: San Sebastian (4.9), Fr. De Orellana (6.7) and Nuevo Rocafuerte (6.6). Table 2 presents the first computations of the specific sediment fluxes for the years 2001 and 2002.

The rates of specific sediment yield (QSs) varied between 557, 1260 and 901 t km^{-2} $year^{-1}$, respectively for the Napo at F. Orellana, Coca at San Sebastian, and Napo at Nuevo Rocafuerte, for basin areas ranging from 5270 to 27 000 km^2. The maximum QSs correspond to the Coca River basin, which is the principal provider of the sediment, although it has the lowest specific stream flow (Qs) of the basins studied. Its annual fluxes of SM are similar to those of the Napo basin at Fr. De Orellana station, whose surface area is two times bigger. The Andean part of this basin produced 13.6 x 10^6 t $year^{-1}$ of SM, but a total of 24.2 × 10^6 t $year^{-1}$ leave the Ecuadorian Napo Basin downstream. The area between the stations of Fr. De Orellana and San Sebastian, both located at the foot of the Andes, and the station at Nuevo Rocafuerte, covers 9146 km^2. Thus, this area provided a net gain of 10.6 × 10^6 t of SM to the outlet of the basin, which corresponds to 45% of the Napo River sediment yield at Nuevo Rocafuerte. The specific sediment yield from the lower part of the basin was about 1160 t km^{-2} $year^{-1}$. This rate seems very high, considering there are almost no uplands in this intermediary area, which is protected by a dense forest cover. The high erosion rate here corroborates the very active uplift tectonics evidenced geomorphically (Bès de Berc *et al.*, 2004).

Table 1 Details of the drainage basins studied with location of gauge sites.

Gauging station	River	Latitude	Longitude	Altitude (m)	Drainage area (km^2)	Annual mean discharge: ($m^3 s^{-1}$)	(mm $year^{-1}$)	(l s^{-1} km^{-2})
San Sebastian	Coca	00°20'30"S	77°00'21"W	285	5272	247	1478	46.9
F. Orellana	Napo	00°28'15"S	76°58'38"W	262	12443	1234	3127	99.2
Rocafuerte	Napo	00°54'18"S	75°25'48"W	189	26861	1996	2343	74.3

Table 2 Sediment fluxes and specific export in the Napo basin from mean SM concentration in the sections (year 2001–2002).

River and gauging station	Q annual ($m^3 s^{-1}$)	Mean annual SM (mg l^{-1})	Fluxes of SM (10^3 t $year^{-1}$)	(t km^2 $year^{-1}$)	Surface area (km^2)
Coca at San Sébastian = 1	247	399	6644	1260	5272
Napo at Fr. De Orellana = 2	1234	158	6929	557	12443
Napo at Nuevo Rocafuerte = 3	1996	285	24195	901	26861
Intermediate area = 3 – 2 – 1	515		10622	1161	9146

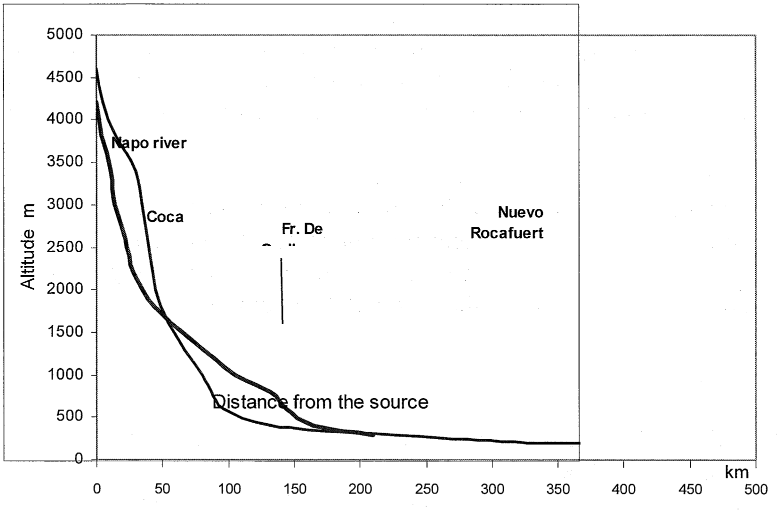

Fig. 4 Longitudinal profiles of the Napo and Coca rivers.

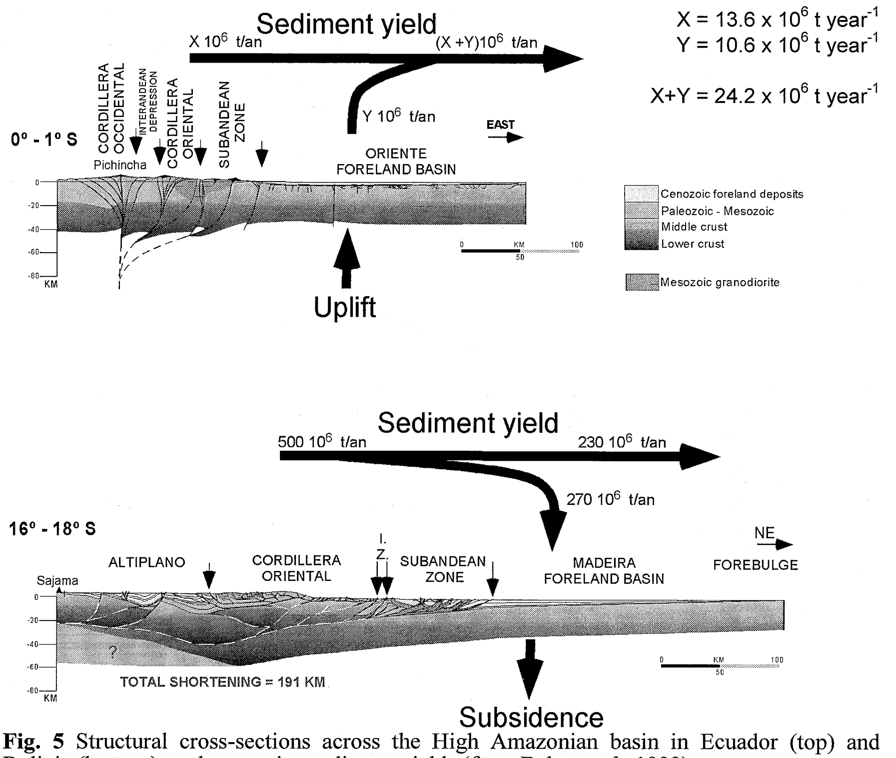

Fig. 5 Structural cross-sections across the High Amazonian basin in Ecuador (top) and Bolivia (bottom), and respective sediment yields (from Baby *et al.*, 1999).

A process of remobilization of fine material occurs along the 200 km section between Fr. De Orellana and Nuevo Rocafuerte. The slope of this section of the river is still high

(35.5 cm km^{-1}, Fig. 4), i.e. more than 10 times higher than in the rest of the Amazon basin, where the slope varies between 3 cm km^{-1} and 0.3 cm km^{-1} in its central depression. The steep slope explains the relatively rectilinear course of the Napo River as it leaves the Andes. The opposite condition has been observed at the foot of the Bolivian Andes (Guyot *et al.*, 1996; Baby *et al.*, 2004), where the streams meander through an area undergoing subsidence (slope < 3 cm km^{-1}) and deposit more that half of their load of suspended matter (Fig. 5). This study enabled us to confirm the observation made by Baby *et al.* (1999), that "in Ecuador, the Oriente basin is uplifting by transpressive tectonics influence and no Pliocene and Quaternary sedimentation has been recorded. It is actually in process of erosion and the sediments are transported towards the east and the southeast".

CONCLUSION

The first results of this study on the Napo basin show that it exports annually a total of 63×10^9 m^3 of water and 24×10^6 t of SM. Around 45% of the solid fluxes result from the remobilization of fluvial sediments along the 200 km section between the foot of the Andes and the Ecuador exit. This part of the basin presents a slope of 35 cm km^{-1}, which is high for this part of the Amazon plain river. These results confirm those of other studies on geodynamics (Burgos *et al.*, 2004) that were conducted over a longer period, and which show that since the end of the Neogene period and during the Quaternary, under the influence of the Andes uplifts, the foreland basins now present a zone of sediment transfer and erosion of deposits that were deposited at a time when the slopes were less steep.

Acknowledgements We would like to thank participants in HYBAm/Ecuador project from Ecuador and France, and their institutions of origin: INAMHI, INOCAR, IRD.

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