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A study of sediment transport in the Madeira River, Brazil, using MODIS remote-sensing images

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ABSTRACT

The Madeira River may contribute nearly half of the Amazon River sediment discharge to the Atlantic Ocean, showing the highest erosion rates in the Amazon Basin. However, few studies have assessed the Madeira River sediment budget and the transport processes occurring in the main stem of the river. In this study, MODIS space-borne sensors were used to analyze the suspended sediment transport processes along the main stem of the Madeira River. Field measurements of suspended sediment concentration, spectral radiometry and granulometry were performed during 10 cruises from 2007 to 2011. The relationship between the spectral reflectance and the surface suspended sediment concentration (SSSC) was analyzed using both field radiometric measurements and satellite data. Ten-day SSSC samples acquired by the HYBAM monitoring network were used to match satellite observations with field measurements performed from 2000 to 2011. Over 900 MODIS images of 6 different locations were processed to monitor the SSSC dynamics in space and time. Satellite reflectance was found to be significantly correlated with the SSSC. However, a seasonal dependency was demonstrated, most likely caused by a variable granulometric distribution along the annual cycle. The ratio between the red and near-infrared bands was found to be free of the seasonal dependency ($r = 0.79$, $N = 282$), and a SSSC retrieval model was built from the satellite data using a bootstrap resampling technique. The satellite-retrieved SSSC time series showed excellent accuracy over the 11-year period and at two different stations located 800 km from each other. The satellite data were averaged to analyze the SSSC pattern temporally and spatially along the entire Madeira River, which provided evidence of significant sedimentation and resuspension. The backwater effect caused by the two-to-three-month lag between peak water in the Madeira and Amazon Rivers was used to predict local sedimentation near the Madeira River mouth. Our results facilitated a precise assessment of such sedimentation, which demonstrated an SSSC decrease 400 km upstream from the Madeira–Amazon confluence.

1. Introduction

Sediment transport is of special significance in large tropical basins, which are known to concentrate approximately 50% of the world's solid fluxes from continental lands to the oceans (Latrubesse et al., 2005). Among these basins, the Amazon Basin exhibits high erosion rates in which most of the sediment is derived from the Andes and from large floodplains that can store and release sediment on different time scales (Meade, 1994). The size of the basin and the fact that the basin is moderately affected by anthropogenic activities make it a valuable case study for understanding erosion and sediment transport and their relation with past and present geomorphology (Baby et al., 2009) and climate (Martinez et al., 2009).

Most studies on the sediment budget of the Amazon Basin have focused on the Amazon River main stem, where the availability of hydrological data is better than in other areas of the catchment (Filizola and Guyot, 2004; Gibbs, 1967; Martinez et al., 2009; Meade et al., 1979). The Madeira River Basin drains approximately 25% of the Amazon Basin but may account for nearly half of the sediment fluxes released to the ocean (Guyot et al., 1996). The Madeira

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drainage basin forms the southwestern boundary of the Amazon Basin. It is limited to the southwest by the Cordillera Oriental, which supplies a large quantity of sediment to the rest of the basin and to the northeast by the Brazilian craton (Baby et al., 2009). Sediment yield data show that the upper basin hosts the most elevated erosion rates in the Amazon Basin, which are approximately 3200 t $\times$ km^{-2} $\times$ year^{-1} on average, with large variations ranging from 50 to 50 000 t $\times$ km^{-2} $\times$ year^{-1} (Guyot et al., 1996). The total mass of suspended sediment exported from the eastern Andes and sub-Andean drainage basins in Bolivia, excluding the Peruvian Madre de Dios subcatchment, has been estimated to be approximately 500–600 million t $\times$ year^{-1} (Guyot et al., 1996). Using a network of sampling stations for river sediment discharge assessment in Bolivia, Guyot et al. (1996) estimated that the current sedimentation in the Madeira foreland basin may be approximately 270 million t $\times$ year^{-1}.

Sediment transport monitoring is critical in the Madeira River Basin because the monitoring provides valuable information for economic activity that is dependent on river flows and sediment discharge, such as ship transport. Interestingly, the construction of two large hydroelectric power-generation dams in the upper reach of the Madeira River, upstream of Porto Velho, may affect the natural sediment transport. Concerns about the impact of these dams and the future behavior of sediment discharge as a function of regional climate change (Espinoza Villar et al., 2009) require the development of robust and cost-efficient monitoring methods adapted to large rivers. It has been shown that the optical qualities of water are closely linked to certain quality parameters, such as turbidity (Dekker et al., 2002; Mertes et al., 1993), algal pigment (Gohin et al., 2002; Schalles et al., 1998) and organic matter (Vodacek et al., 1995). Recent studies on the Amazon Basin have shown that space-borne global monitoring sensors can be used to efficiently monitor river sediment discharge along the Amazon River (Martinez et al., 2009) (Espinoza et al., 2012). In this study, we analyzed the optical properties of the Madeira River waters to develop a surface suspended sediment concentration (SSSC) retrieval algorithm based on MODIS satellite data. The SSSC estimates acquired over an 11-year period were analyzed to assess the sediment transport processes along the main stream of the Madeira River. Special attention was paid to the Madeira River mouth, where backwater effects originating from the confluence with the Amazon River cause sedimentation.

2. The study area

With an area of 6.2 $\times$ 10^6 km^2, the Amazon Basin is the world's largest catchment, delivering a water discharge of 6600 km^3 $\times$ year^{-1} (Molinier et al., 1996) and a sediment discharge of 800 million t $\times$ year^{-1} based on measurements at the last gauged station along the Amazon River that is not disturbed by sea tides (Martinez et al., 2009). Sediments are transported principally from the Andes, which surround 12% of the Amazon Basin. One of the most important tributaries is the Madeira River, which contributes 16% of the Amazon River water budget and approximately 50% of the sediment discharge (Filizola, 1999). According to the Sioli classification system (1957), the Madeira River is a white-water river that is rich in dissolved material and suspension solids.

The Madeira River drains an area of approximately 1.4 10^6 km^2 and has a mean annual discharge of 32 000 m^3 $\times$ s^{-1} (Molinier et al., 1993). This river is among the ten largest rivers in the world and was classified as a *mega river* (Latrubesse, 2008). The Madeira River is formed at the confluence of the Beni and Mamore Rivers near the border between Brazil and Bolivia. These rivers are of Andean origin and present high sediment loads of approximately 690 and 280 mg $\times$ l^{-1} at the river surface, respectively (Guyot et al., 1996). The lower load of the Mamore River results from low sediment load tributaries that drain the lowlands (e.g., the Guapore River) and strong sedimentation processes in the Andean Piedmont (Guyot et al., 1996). Downstream from the Beni-Mamore confluence, all of the tributaries are characterized by low sediment concentrations because they drain the Amazonian lowlands on the Brazilian Shield (Fig. 1). In Brazil, most of the tributaries from the Abunã River down to the Aripuanã River confluence flow into the Madeira River from its right bank as the Madeira River nears the Purus River catchment.

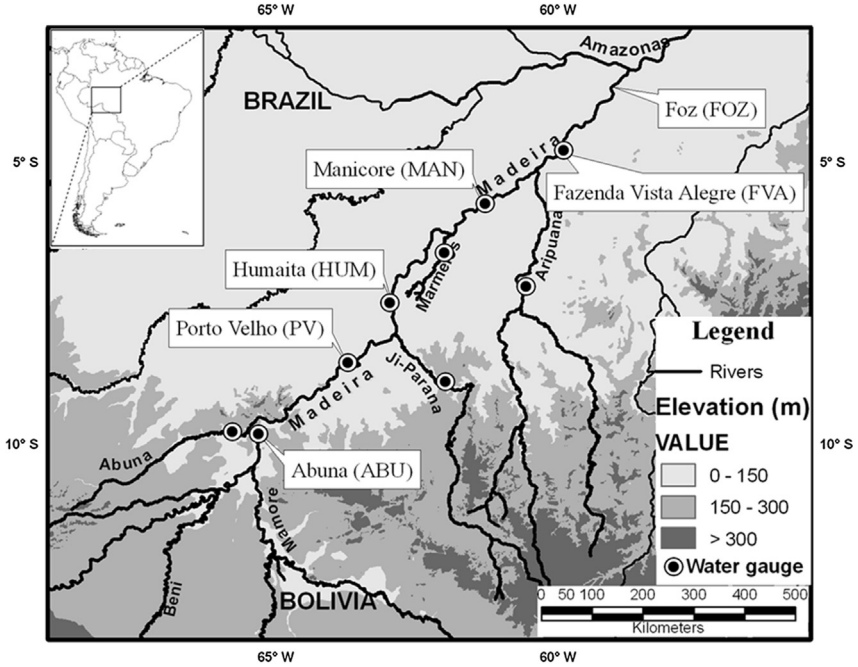

Fig. 1. A map of the Madeira River and the major tributaries showing the water-gauge stations along the river main stem maintained by the Brazilian Water Agency. The relief data were extracted from the SRTM digital elevation model.