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The hydro-geomorphologic complexity of the lower Amazon River floodplain and hydrological connectivity assessed by remote sensing and field control

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ABSTRACT

Hydrological connectivity processes along the lower Amazon River floodplain at Lago Miratuba Floodplain (LMF) were analyzed based on remote sensing and field measurements. Connectivity processes are related to 12 geomorphic sub-units of the floodplain that are interconnected at different stage thresholds through channelized and overbank flow paths, while lakes act as reservoirs for flood waters, local rainfall, and water table saturation-seepage. Hydrological connectivity processes along the floodplain happen through complex internal routings of water flows over space and time, mainly along floodplain channels and breached levees. The contribution of *local recharge* (mainly rainfall) was decoupled from *river recharge* (river hydrological connection to floodplain) because precipitations and local runoff also recharge the floodplain. The hydrological connectivity of the 12 geomorphic units varied significantly from each other, because the inundation and the floodplain connections with the river were initiated at specific river stage thresholds for each sub-unit.

An interesting finding is that connections with the river for all units were initiated through channelized flows below the bankfull stage of the Amazon River. The connectivity processes over different geomorphic units are also not correlated with their minimum distance (shortest lines) from the river. This implies that a "flood pulse" model largely concerned with lateral connectivity (mostly through overbank diffusion) only partially explains the complex hydrological connectivity processes at a regional scale along the complex lower Amazon River floodplain. Thus, for hydrological connectivity assessments in the Amazon River floodplain, reach-by-reach scale studies have to be carried out, relating the hydro-geomorphologic processes (channelized flow routing paths, overbank diffusion, and local recharge) to the internal geomorphic variability and complexity of the floodplain.

1. Introduction

Existing works on large river floodplain hydrology assessing the links between geomorphology and hydrological connectivity had been developed in the Mississippi River, the largest meandering river (Hudson and Colditz, 2003; Hudson et al., 2012). However The largest axial alluvial rivers on the planet in water discharge are anabranching fluvial systems that contain the longest and widest floodplains (Latrubesse, 2008, 2015). The integration between the hydrological connectivity processes and the floodplain geomorphic mosaic on large anabranching river systems around the world is still incipient (Marchetti et al., 2013; Montero and Latrubesse, 2013; Stevaux et al., 2013). Among large rivers, the Amazon River could be considered a superlative case because of the massive volume of water and sediment seasonally exchanged through complex channel floodplain interactions (e.g. Alsdorf et al., 2010; Dunne et al., 1998; Richey et al., 1989; Wilson et al., 2007). Through channelized flow and overbank diffusion processes, a complex maze of interconnected network of lakes, channels, and swales over vast floodplains experience spatiotemporally heterogeneous patterns of inundations (Alsdorf, 2003).

Floodplain construction in the lower Amazon River is related to the evolution of the fluvial system since the last glacial maximum and also to the current anabranching channel processes and overbank deposition (Latrubesse and Franzinelli, 2002; Mertes et al., 1996). The importance in considering the morphosedimentary imprints in the floodplain evolution as a basis to understand the current floods and hydrological connectivity patterns is recognized (Latrubesse and Park, 2017). However, the extension and distribution of the floodplain area covered by seasonally flooding water along the Amazon River are still to be comprehensively understood from the geomorphic perspective. The floodplain of the Amazon River is not entirely inundated during the typical seasonal floods (Iriondo, 1982; Tricart, 1977). In the Brazilian territory, for

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example Mertes et al. (1996) estimated, based on geomorphologic maps of Iriondo (1982) that 44,000 km^2 of the floodplains and islands are inundated directly from the Amazon River, while 20,000 km^2 of remaining alluvial deposits may stay dry or recharged locally by ground water interactions, rain fall, or small local tributaries. The floodplain under the influence of river flooding is typically composed of a patch network of water saturated flat terrains and large shallow inter-connected round lakes (i.e. impeded lakes, Latrubesse, 2012). This water-saturated floodplain is a representative floodplain style of the lower Amazon River, typically observed downstream of the Madeira River confluence (Hess et al., 2003; Latrubesse, 2015). During the passage of the Amazon flood wave, different sectors of the floodplain experience complex spatiotemporal patterns of inundation depending on their bathymetric and hydraulic characteristics (Alsdorf et al., 2007) but also on the landforms that imprint the floodplain surface morphologies. Therefore, to understand the underlying flood routing patterns and hydrological connectivity over the floodplain geomorphic mosaic, individual floodplain hydrogeomorphic units (hereafter "geomorphic units" or "unit") should be identified in terms of their own hydrogeomorphic functions.

Traditional in-situ measurements in floodplains, which are restricted mainly by regular access, provide temporary, thus partial information on the hydrological connectivity processes for different geomorphic units. Monitoring the hydrological connectivity demands more continuous records of the inundation dynamics taking place over the floodplain. In this context, satellite remote sensing offers an efficient tool to overcome these limiting factors because it enables the multi-temporal observations of the hydrogeomorphic processes over the floodplain at a large extent (Mertes and Magadzire, 2008; Park and Latrubesse, 2014). Characteristically, optical remote sensing data have been widely used to monitor the water quality in the Amazon floodplain lakes, while Synthetic Aperture Radar (SAR) data have been utilized mainly to measure the hydraulic variables in floodplains (e.g. Hess et al., 2003; Jung and Alsdorf, 2010). In this study time-series optical remote sensing (MODIS), radar (PALSAR) data, water level data at gauge station, and measurements and observations during the field work conducted on June 2016 were integrated to characterize the hydrological connectivity processes in the Amazon floodplain. Specifically, using the Lago Miratuba Floodplain (LMF) along the lower Amazon, we mapped the seasonal water extent and quality variabilities, identified channel-floodplain connection thresholds, and verified our results using field measurements.

2. "Incomplete" floodplain of the Amazon River and Lago Miratuba Floodplain (LMF)

The lower Amazon River exhibits a vast floodplain. The largest extensions with flooded areas and lakes are located downstream of the Madeira River confluence (Fig. 1). At this reach the Amazon River transports a large amount of sediment load that could range between 600 to 1200 million tons per year (Mt/yr) at Obidos gauge station (e.g. Dunne et al., 1998; Filizola and Guyot, 2004; Meade et al., 1985). From the geomorphic perspective, valleys and sedimentary basins along the downstream reaches are partially filled up and thus presenting "incomplete" floodplain, which have not had enough time and sediment inputs to attain the equilibrium stage since the last deglaciation (Latrubesse, 2015). The widest and the most critical floodplain sedimentary sinks are located at lower section of the river, in between the confluence with the Madeira River and Obidos.

Lago Miratuba Floodplain (LMF) is located immediately downstream the confluence with the Madeira River, the largest tributary of the Amazon that delivers nearly 50% of the sediment load carried by the Amazon River (Filizola and Guyot, 2009; Meade, 1994). The LMF is delimited to the north by the Amazon River, west by the Madeira River, and south/east by uplands (Solimões Formation) with its total area around 1100 km^2 (Fig. 1). Hydrology of the LMF is under the influence of both the Amazon and Madeira Rivers. We select LMF because it is a representative area of "incomplete" floodplain in the Amazon that actively responds to the hydrological variability of the river through oscillations of the lake surface area and depth, and by storing water and trapping sediment.

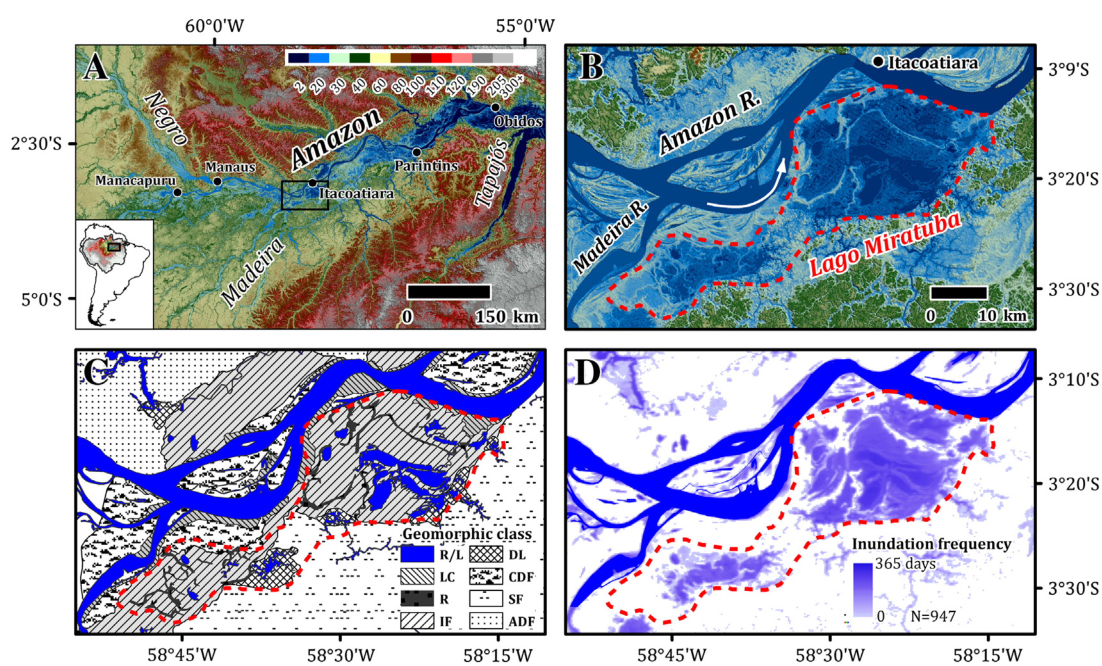

Fig. 1. A: Large scale map of the Amazon River (Manacapuru-Obidos) with major tributaries. Itacoatiara gauge station (3°8′34.48″S, 58°25′12.13″W) Manacapuru, Manaus, Parintins and Obidos are labeled. Background is the SRTM DEM. B: Study area (indicated in A) with Lago Miratuba floodplain extent portrayed in thick red dashed line. C: Geomorphic map of the study area following the classification of Latrubesse (2012): River and Lakes (R/L), Levee Complex (LC), Ridges (R), Impeded Floodplain (IF), Deltaic Lakes (DL), Channel-Dominated Floodplain (CDF), uplands (Solimões Formation-SF and Alter do Chão Formation-ADF). D: Inundation frequency map of Lago Miratuba. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)