Planform dynamics of the Iquitos anabranching structure in the Peruvian Upper Amazon River

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ABSTRACT: The upper reach of the Amazon River has a very dynamic morphology, with the highest rates of migration observed in the entire Amazon River. It has an anabranching channel pattern which alternates between a condition of single channel and anabranching structures; in particular, the anabranching structure near Iquitos City shows an interesting channel behavior. Its channels migrate at different rates, where there are processes of narrowing and widening, and also collision and development of new channels. The temporal evolution of the Iquitos anabranching structure is described during the period from 1985 to 2014. The study is carried out by using satellite images to track the migration patterns, which are contrasted to the underlying geological units in the valley. Bathymetry of the structure and several velocity transects were obtained during a field campaign prior to the 2012 historic flood event. This information allowed for numerical modeling in order to compute the hydrodynamic flow field that complements the temporal analysis, aiming to understand the planform migration patterns after the 2012 flood event. It is observed that the geological units play an important role in modulating the migration rates and planform development of the channels. The channels in the structure are in contention to be the main channel, which become the secondary channel after migration. This causes the channels to experience a rise in bed elevation and narrowing of the channel itself; if this trend continues for several more years, these channels will detach from the Iquitos anabranching structure, thus forming paleo-channels. This geomorphic process is important for horizontal and vertical soil heterogeneity along the floodplain. In general, the analysis shows a complex interaction between the underlying geological units, flow structure, morphology of the bed and planform migration.

KEYWORDS: anabranching rivers; river migration; geological modulation; Amazon River

Introduction

The Amazon River has a length of more than 6000 km from the Andean region in Peru to the Atlantic Ocean in Brazil. Several studies have been carried out regarding the geology (Räsänen *et al.*, 1998; Latrubesse and Franzinelli, 2002; Rebata *et al.*, 2006; Latrubesse *et al.*, 2010), river morphology and migration (Salo *et al.*, 1986; Kalliola *et al.*, 1992; Mertes *et al.*, 1996; Pexioto *et al.*, 2009; Rozo *et al.*, 2012; Frias *et al.*, 2015). To the best of our knowledge, most of the research related to river morphology and migration (except for a few authors, e.g. Frias *et al.*, 2015) was focused in the central region of the Amazon River, from the area of Colombia and Brazil up to the junction with the Negro River, and little research has been done in the Peruvian Upper Amazon River.

Rozo *et al.* (2012) carried out an analysis of migration in the Brazilian Amazon River, specifically in the reach from the junction with the Madeira River up to the junction with the Negro River, where they computed migration rates of 60 m yr 1,and highlighted the trend of increasing stability from the Upper Amazon, which has higher migration rates compared to the Central Amazon. This statement was verified by Kalliola et al. (1992), who utilized Landsat MSS images from 30 July 1979 and 19 September 1983, in which they computed migration rates of 400 m yr 1 in the region from the junction of the Marañon and Ucayali rivers, the beginning of the Amazon River, until the anabranchi°ng structure of Iquitos. Similar results were obtained by Salo et al. (1986). In the case of the Amazon River near Iquitos City, analyses like those car-ried out by Garcia and Bernex (1994) and Tuukki et al. (1996) explained how the Amazon River was formerly located next to Iquitos City and migrated in such a way that the Itaya River, a tributary of the Amazon, is located next to the city now. Research is therefore needed in the region where the Ama-zon River is very active from the morphological point of view, but past research was focused mostly in other reaches of the Amazon River.

Another characteristic of the region is that floods follow a monomodal pulse, as is characteristic of large rivers. Near Iquitos City, the water level peak occurs during March to May and the lowest during August to October, with estimations of about 90% of the floodplains inundated during peaks (Kvist

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and Nebel, 2001). River migration and floods both play an important role for sediments since they are deposited in the surrounding floodplains and point bars; flood processes build channel levees and overbank deposits, while floodplain sed-iment returns to the river through migration via bank erosion and meander cut-off (Bouchez *et al.*, 2012). Additionally, Salo *et al.* (1986) have hypothesized that the diversity of vegeta-tion generated by different ages of forest (a direct consequence of constant development of floodplains caused by migrating channels) triggers a high biological diversity.

The Peruvian Upper Amazon River shows an anabranch-ing configuration, where it alternates along its valley with a certain periodicity of its planform geometry from a single to a multichannel configuration (Frias *et al.*, 2015). Nanson and Knighton (1996) stated that anabranching rivers coex-ist with other types of channel patterns; some conditions for their existence are flood-dominated flow regimes and the pres-ence of banks resistant to fluvial erosion. Jansen and Nanson (2004) identified anabranching patterns as the most common planform configurations of the largest rivers in the world; Latrubesse (2008) stated that anabranching structures are characteristics of mega rivers (mean discharge >1700 m^3s^1).Anabranching structures are identified by main and secondary channels. Channels in anabranching structures are separated by islands that are more permanent and vegetated than what is observed in braided rivers. The main and secondary chan-nels have a meandering behavior (Mertes *et al.*, 1996; Rozo *et al.*, 2012); however, Abad *et al.* (2010) reported that they behave as non-developed meandering channels since they generally do not attain maturity due to their short length between bifurcation and junction points; thus they have pre-dominantly boundary effects along the secondary channels. Mid-channel bar formation and chute cut-offs were identified as the main formative mechanism of the anastomosing struc-ture in the studied region, in contrast to avulsion processes (Rozo *et al.*, 2012; Frias *et al.*, 2015). Mertes *et al.* (1996) per-formed an analysis with remote sensing data of the Brazilian reach of the river, where it is known as the Solimões River.

They identified three processes for planform changes in chan-nels: (i) main channel migration in bends; (ii) migration of channels in the floodplain; and (iii) change in form of islands; they reported that the main cause of planform evolution is changes in islands. Subsequently, Rozo *et al.* (2014) analyzed remote sensing data to classify the channel patterns developed in the Colombian area of the Amazon River, finding a lower migration rate compared to other studies in the region. Again, they stated that the main cause of multi-channel development is the mid-channel bar formation and chute cut-offs rather than avulsion. As a side note, Rozo *et al.* (2014) carried out an analysis to assess the effect of erosion and deposition linked to long-term variation of discharge, finding no correlation at all. Frias *et al.* (2015) found a correlation between sinuosity in anabranching channels and the floodplain rework, which is done mainly by secondary channels in anabranching struc-tures with mid to high sinuosity, and by the main channel in low-sinuosity cases.

Although work has been done to explain the nature of anabranching structure development (Frias *et al.*, 2015), some interesting planform dynamics are found in the Iqui-tos anabranching structure that are worth describing. Little research has been done regarding the hydrodynamics in anabranching structures; Frias *et al.* (2015) carried out the modeling of two structures and found that the width ratio of main to secondary channels was not representative of flow discharge partition, even though flow partition depends on the flow stage. In this paper the dynamics of the Iquitos anabranching structure are discussed: (i) migration and devel-opment of channels and islands (ii) temporal analysis of floods;(iii) hydrodynamics and morphology of the river bed; and (iv) the interaction between such processes.

Study Area

Figure 1(A) shows the floodplain of the Amazon River near Iquitos City. As observed, this city is surrounded by several rivers (Nanay, Momon, Itaya, and Amazon). The Iquitos anabranching structure is located about 100 km downstream of the confluence of Ucayali and Marañon Rivers, where the Peruvian Amazon River has its origin. Also, the Iquitos anabranching structure is located downstream of the Muyuy anabranching structure, which was studied by Frias et al.(2015). Iquitos City is currently located to the southwest of the anabranching structure (see Figure 1A); however, until the early 1990s (when the dynamics of the anabranching struc-ture caused the Amazon River to migrate to the north), Iquitos City was located along the left margin of the Amazon River. Nowadays, only a lake fed by the discharge of the Itaya

River is connected (by a former channel of the anabranch-ing structure) to the Amazon River, allowing fluvial access to Iquitos City. The scroll bars and paleo-channels left by the Amazon River near Iquitos City are observed in Figure 1(B). It seems that the Iquitos anabranching structure is migrating along the geological valley. The averaged slope of the val-ley, computed from a digital elevation model (DEM), is 18 cm km^{-1}, while the valley width at the anabranching struc-ture and average width of the main channel are 20 km and 1.3 km, respectively.

This structure is quite unique in the region since it shows competition in two apparent main channels, as opposed to the cases studied by Frias et al. (2015) where there was only one main channel and several secondary channels. The mean annual discharge of the Amazon River in the region is 30,700 m^3s^1 , a value obtained by Carranza-Valle (2012) from a gauging station placed 41 km downstream of Iquitos City. The discharge varies between 10 000 and 55 000 $m^3 s^1$ during the year.

Geological background

The Amazon basin is confined by the Andes to the west, the Guiana Shield to the north and the Brazilian Shield to the southeast (Mertes *et al.*, 1996; Rebata *et al.*, 2006). The geol-ogy of the region between Iquitos City and the confluence of Marañon and Ucayali rivers has been reported in previous works such as Räsänen *et al.* (1998), which also describes the geological units in the region: (i) Pebas formation; (ii) Porvenir unit; (iii) Nauta unit; (iv) Iquitos unit; (v) fluvial terraces; and (vi) alluvial deposits. The geological formations originated dur-ing three periods: (i) 18–12 My, lacustrine – the area formed the Pebas Lake, and there were fluvial deposits of Andean ori-gin; (ii) 12 My, estuarine – the sea erupted from the north and there was an increase of deposition of fluvial material of Andean origin; (iii) 8 My, fluvial – the Amazon River took its current path, and tectonic activity influenced the development of terraces and alluvial floodplains. Räsänen *et al.* (1998) pre-sented in their Figure 4.30 a map of the configuration of the geology units; this map has been recently updated by the Geo-logical Service of Peru (see Figure 1A). It has nearly the same distribution of formations as defined by Räsänen *et al.* (1998). It can be observed that the anabranching structure is confined by the Pebas unit on the left (formation resistant to fluvial erosion), which is composed of blue smectilic clay beds inter-calated with sand and lignite beds (Siiro *et al.*, 2005). On the right-hand side of the Iquitos anabranching structure, there is an alluvial floodplain (denoted as alluvial deposits by Räsänen *et al.* (1998), which was formed by scroll bars of migrat-ing channels. The geological characterization from Figure 1A shows that the Amazon River has a planform development and migration preferentially within the alluvial deposits belonging to the Holocene epoch, as clearly observed by the scroll bars and paleo-channels.

The Peruvian Navy analyzed the sediment size distribution of the bed material of the Amazon River, downstream from the confluence of channels IS-A0 and IS-A1. (see Figure 2). Results are similar to those reported by Nordin *et al.* (1980). The mate-rial is fine sand with a d_{50} around 0.3 mm. Also Nordin *et al.* (1980) notes that the sands found in the first 1300 km of the Amazon River have minerals that indicate a predominant Andean source.

Information and Processing Methods

Herein, three aspects of the anabranching structure are ana-lyzed: (i) planform migration; (ii) frequency of floods; and (iii) hydrodynamic flow field. Previous studies (Salo *et al.*, 1986; Garcia and Bernex, 1994; Mertes *et al.*, 1996; Tuukki *et al.*, 1996; Mertes and Dunne, 2008; Carneiro, 2009; Rozo and Castro, 2009; Rozo *et al.*, 2012, 2014; Meshkova and Car-ling, 2013; Frias *et al.*, 2015) have highlighted the importance of multi-temporal satellite imagery to assess the migration of rivers in the Amazon rainforest, where little or no field data are available. The planform evolution observed in the Iquitos anabranching structure was studied using Landsat images for a period of 29 years. The set of Landsat images used for the analysis was selected from MSS, ETM, ETM and OLI sensors to have the widest set of images with the quality required for the study in the interval of time selected. The main criterion was that the cloud coverage should be low enough (a max-imum cloud coverage of 20%) to allow the tracking of river bank position. The methodology for the satellite image analy-sis is the same as described by Frias et al. (2015). The NDVI (normalized difference vegetation index) better discerns the land from water in Landsat imagery. See Frias et al. (2015) for further information about the NDVI technique. Figure 2(A–F) presents the historical evolution of the Iquitos anabranching structure from 1985 to 2014. In this figure, two consecutive images were superimposed, in order to allow the definition of three main regions: (i) permanent water, which corresponds to zones in the channel that did not change; (ii) deposition areas; and (iii) erosion areas. The evolution of channel width averages was calculated by dividing their area by the length of the channel studied. The result of such computations is pre-sented in Figure 2(H). An important assumption to be noted is that sand bars are considered to be water. This is due to the fact that the water stage varies greatly depending on the time the image was taken. The Service of Hydrography and Navigation of the Peruvian Navy maintains a gauging sta-tion (close to the mouth of the Itaya River) in Iquitos City. Its records were utilized to obtain the stage in the anabranch-ing structure. Figure 2(G) describes the temporal variation of the water stage in the anabranching structure from 1968 to 2014; it is observed that the low-discharge periods occur from August to October, while the high-discharge periods are from March to May. It is clear that the low-discharge periods are becoming more severe over the years and the amplitude of the low-discharge period is increasing. For the high-discharge periods, the trend is not as notorious as for the low-discharge ones; however, it is quite clear that the flood events are well registered, with the most recent in 2012.

In addition to the remote sensing analysis, the Peruvian Navy in collaboration with the Earth Processes and Environmental Flows group of the University of Pittsburgh collected bathymetry and velocity data along the channels of the Iqui-tos anabranching structure during June 2011 (see Figure 3(A)). The bathymetry survey was carried out using a single-beam echo sounder (SyQwest Batty 500, controlled by Hypack soft-ware) in transects spaced 500 m, and 250 m in small channels. Velocity transects were measured with an acoustic Doppler current profiler (ADCP, Workhorse Rio Grande 600 KHz RD Instruments); velocity transect labels starting with '14' were measured on 14 June, whereas velocity transect labels start-ing with '15' were measured during 15 June (Figure 3(A)). The bathymetry data was obtained using the depth measure-ments and the linear distribution of the water surface elevation between the gauging stations at Tamshiyacu (upstream of Iqui-tos City), Iquitos and Sinchicuy (downstream of Iquitos City). The average water slope is 3.22 cm km^{-1} and was computed with information from two gauging stations: one located one in Iquitos and another located 21 km downstream in the Ama-zon River. Measurement corresponds to May, the time of high water levels in the Amazon River. This value is similar to that reported by Trigg et al. (2009), who reported a maximum water slope of 3.29 cm km^{-1} in the Solimões River during the peak flow period.

The water discharges of the channels were: (i) Amazon River upstream of the Iquitos anabranching structure – 29 063 m^3s^{-1} (ii) Itaya River (cross section 15-14, see Figure 3(A)) -20 m^3s^{-1} ; (iii) Nanay River (cross section 15-10, see figure 3(A)) – 1743 m^3 s^{-1}.Since only a few cross-sections of velocity data were per-formed (mostly to obtain water discharges), a hydrodynamic model was used to compute the flow field in all the chan-nels. The flow field is solved for steady flow conditions using Telemac-2D, the module of the Telemac-Mascaret system that solves the shallow-water equations (Hervouet, 2007). It uses the finite element method on an unstructured mesh. The mesh utilized was conformed by 106 000 triangular elements, with sides of 40 m on average. Since flow in the Amazon River is subcritical, water level (83.97 m above sea level) and dis-charges along the Amazon, Itaya and Nanay rivers have been used as inlet and outlet boundary conditions, respectively. The k- model was selected as the turbulent model, similarly to Frias et al. (2015). Velocities measured with ADCP were utilized to calibrate the numerical model, and the friction coefficient of the bed was adjusted until the modeled veloc-ities were similar to those measured in the field campaign. The water surface gradient and elevation were calibrated using information from the gauging stations. More details on the implementation of Telemac-2D model for anabranching structures can be found in Frias et al. (2015).

Analysis of Results

Planform evolution

From the processing of satellite images, the following mor-phology changes are identified:

- 1985–1989, channels IS-A0 and IS-A1 have similar widths (averaging 1100 m); by year 1989, the inlet of channel IS-A2 is detached from the structure IS-A1 (see Figure 2(A)). For this period, IS-A1 migrates to the northwest in direction of IS-A0 and there are several depositional regions along the upstream portion of the Amazon River. Note that during this period, the Iquitos City was located at the left of the Ama-zon River. The left-hand channel of the Amazon River is colliding into the Iquitos formation (Qp-i); thus the channel cannot migrate further west and the bend starts to present an upstream skewness – a clear characteristic of geologic modulation or horizontal soil heterogeneity (Motta et al., 2012). Note that the Nanay River (to the north of Iquitos City, see Figure 1(A)) is located at the edge of the Pebas For-mation (N-p); thus the Nanay River cannot migrate further northwest. At the confluence with the Amazon River, IS-A0 and the Nanay River described low migration rates.
- 1989–1995, channel IS-A1 collides into channel IS-A0 (see Figure 2(B)). A detailed look into the satellite images leads us to infer that the collision occurred during the flood of mid 1994; consequently, IS-A0 starts a widening process, while IS-A1 starts a narrowing process (see the trend started by 1995 for both channels in Figure 2(H)). This indicates that flood events might trigger abrupt planform changes.
- 1995–2000, channels IS-A0 and IS-A1 experienced widen-ing and narrowing processes respectively. Such processes are due to the redistribution of water discharge; thus more water flows through IS-A0. During this period, IS-A0 is being converted into the main channel and IS-A1 into a secondary channel. This seems to be the first step for the formation of paleo-channels. IS-A1 keeps moving towards IS-A0 until it collides with the Nanay River; thus a new channel, IS-A3, was formed (see Figure 2(C)). As observed in Figure 2(H), IS-A3 starts a widening process due to the increase of water discharge. Channel IS-A0 also gets wider (as a consequence of higher discharge running through IS-A3) by eroding the right bank, having an average width of about 2000 m by 1998, reaching an apparent equilib-rium condition by the rest of this period. On the other hand, channel IS-A1 keeps narrowing due to the planform config-uration, and less and less water runs through the channel. The incipient development of IS-A4 is observed during this period in the point bar developed by the sharp bend of IS-A1. A detailed analysis of satellite images in the period leads to formulate the hypothesis that the flow takes advan-tage of the scroll bars developed by the migration of IS-A1. Under certain stage conditions, IS-A4 is not visible.

- 2000–2005, IS-A4 is a well-defined channel by year 2000, IS-A0 starts a narrowing process (see Figure 2(H)). IS-A1 keeps the narrowing trend started by 1995 and is approx-imately 620 m wide by year 2003. Conversely, IS-A3 and IS-A4 maintain a widening trend. Note that the confluence of the Nanay and Amazon rivers has been translated further upstream due to the collision of IS-A0 into the Nanay River (compare the position in Figure 2(A) and (D)).
- 2005–2011, channel IS-A3 is almost twice the width in 2003 compared to its original width the previous year; see Figure 2(E) (the main areas of widening are the inlet and out-let of the channel). IS-A0 narrows suddenly from year 2001 to 2003. IS-A0 and IS-A3 width values are very close (again a competition of two main channels).
- 2014, IS-A0 and IS-A1 keep the same narrowing rate and by year 2012 both channels are around 200 m wide. By year 2014, the main channel is again along the alignment of IS-A0 channel. The trend shows that IS-A0 and IS-A1 may disappear in the near future and that the structure no longer will be conformed by large secondary channels, but by very short ones separated by small islands. Thannels, but by very short ones separated by small islands. Thus the Iqui-tos anabranching structure might present higher migration rates in the future.

The modulation of geological formations and the competition of channels are the main mechanisms for the evolution of the Iquitos anabranching structure. Every time a channel col-lides to a formation resistant to erosion, not only are migration rates decreased but also other channels start colliding in the following years.

Historical floods in the region

Aalto et al. (2010) have studied the accumulation of sedi-ments in floodplains on the Bolivian side of the Upper Amazon basin and found that deposits develop in a episodic pattern, correlated to the cold phase of El Niño Southern Oscillation (ENSO) events. Furthermore, these events correspond only to large, rapid-rise floods. In Iquitos City the historical record of floods is well documented given the impact that they have in this riverine city. Figure 2(G) shows the water surface eleva-tion at the Iquitos gauging station from 1968 to 2014. Gentry and Lopez-Parodi (1980) pointed out the marked increase on the height of the annual flood crest in the Amazon in the decade 1970–1980, which is clearly seen in Figure 2(G). Since the 1980s, the Amazon basin experienced an intensi-fication of hydrological extremes, which particularly affected its Andean rivers (Espinoza et al. (2013). However, there are records of exceptional inundations during the years 1859, 1892, 1895 and 1900 (Sternberg, 1987); more recently, floods were reported in years 1986, 1993, 1999, 2006 and 2009 (Espinoza et al., 2009, 2013; Takasaki et al., 2004); extreme high discharges were recorded during years 1989, 1999 and 2009; an unprecedented flood started in January 2012, causing an extreme discharge in April 2012 of 55 420 $m^3 s^{-1}$ (which is the highest value recorded in the Peruvian Ama-zon river) that affected 140 000 people and triggered a state of emergency to be declared by the Peruvian authority (Espinoza et al., 2013). Figure 4(A) shows the extent of the 2012 flood event in Iquitos City. The area enclosed by the red region was the only dry portion; everything else was mostly covered by water. Figure 4(B) shows Iquitos City and the Nanay River, where the water flow was running along the channel and the floodplain. Figure 4(C) shows a portion of Iquitos City where streets were covered by water. Besides the floodplain deposits produced during floods, the increased stream power in the channels produces a greater modification of the banks, thus changing the planform geometry of the river (Buraas et al., 2014).

From the five recent flood events reported from years 1985 to 2014, four agree with the peaks shown in Figure 2(G). Only the flood event reported in 2006 does not match with a peak in the water surface elevation record of Iquitos gauging sta-tion. This shows that it is possible to have some flooding in Iquitos City below stage 88 m, which may indicate that there is overbank flow in the anabranching structure and the surround-ing meandering channels with the consequent implications of morphological work. Based on the available literature and the data recorded at Iquitos gauging station, we can say that a high discharge is not always related to a flood event in this zone, but an extreme discharge will produce an extreme flood event, as was described in Espinoza et al. (2013). Little is known about the hydrological (e.g. precipitation patterns), hydraulic (e.g. flow patterns) and morphological (river pat-terns) parameters that might trigger flooding in Iquitos City. As observed before, the planform morphology of the Amazon River near Iquitos City has experienced drastic changes from 1985 to 2014, leaving some questions unanswered: (i) What is the influence of the river planform morphology on produc-ing flood events in Iquitos City and its surrounding floodplain area? (ii) Is it possible to have extreme flood events in Iquitos City in the absence of extreme hydrologic events? Of course, floods in the surrounding area of the anabranching structure (and in Iquitos City) are not only caused by the flow in the Amazon River but also by discharges from the Nanay, Momom and Itaya rivers.

Hydrodynamics and bed morphology before thehistoric flood of 2012

As observed in Figure 2(E) and (F), there was a drastic change in the main channel of the anabranching structure after the historic flood of 2012. Figure 3(A) shows that the secondary channels IS-A0 and IS-A1 have a higher bed elevation than the main channel (see also Figure 3(B)). At the entrances of IS-A0 and IS-A1 channels, the bed morphology forms a step of about 10 m height. The reach of the Amazon River shown in Figure 3(B) has an average bed slope of 14 cm km^{-1} and the channels IS-A0 and IS-A1 have larger values, 100 cm km^{-1} and 24 cm km^{-1} respectively; slope is computed following the centerline of the channel. Also, near the confluence points of the secondary channels, IS-A0, IS-A and IS-A4, with the main channel of Amazon River, the bed of the main chan-nel is observed to have zones of lower elevation (see junction points depicted in Figure 3(B)). In the confluence points, the difference of bed elevation between the main channel and the secondary channels produces a sharp drop of 10 m or more.

To understand the influence of flow patterns and sediment transport in the morphodynamic adjustment of the anabranch-ing structure (especially after the historical 2012 flood event), the results from the numerical model described in the previous section are shown in Figure 5. The difference in velocity mag-nitudes in the channels is noticeable (see Figure 5(A)); while the velocity magnitudes for channels IS-A3 and IS-A4 are in the range of 1–2 ms^{-1} , the velocity magnitudes for channels IS-A0 and IS-A1 are less than 1 ms^{-1} . It is noticed that the velocity vectors in channel IS-A4 are almost perpendicular to those at the entrances of channels IS-A0 and IS-A1 showing low flow rates. The importance of the bifurcation angles for the distribution of flow has been studied earlier; for exam-ple, Hardy et al. (2011) analyzed numerically the effect of angles and orientation of flow prior to arriving at the bifur-cation zone. They found that larger angles tend to increase the velocity downstream in both channels; however, such a finding may not apply here since they used bifurcating channels of the same width, where the transference of momentum played a major role. The behavior of the distribution of veloc-ities observed at the entrances of IS-A0 and IS-A1 provides evidence that the driving cause of flow in such channels is the gradient of the water surface between their inlet and their out-let rather than momentum transference from channel IS-A4. Based on the numerical results, the slopes in channels IS-A0 and IS-A1 are 6.7 and 3.22 cm km^{-1}, respectively; the slope in the Amazon River in the reach is 3.34 cm km 1. The dis-charge in such secondary channels is adjusted to exert a loss of energy equal to the difference of levels between their inlet and outlet. Since IS-A0 and IS-A1 are narrow, they exert a higher flow resistance and have lower velocities; it can be observed that the discharge on them is in proportion to the water surface slope (see Figure 5). An important factor modu-lating the water surface slope is the channel length; planform migration increases the length and thus reduces the water sur-face slope and its capacity to transfer momentum. This may have a direct impact in the bed morphology at the inlets of IS-A0 and IS-A1. Strong velocity gradients are generated where the bed morphology is affected; thus negative shear stress gradients produced a decrease on the sediment transport capacity, and consequently, promoted sedimentation in the area. Specific stream power was computed (see Figure 5(B)) and the magnitude is in agreement with the values obtained downstream, in the Solimões River (Latrubesse, 2008). The higher values are found at the centre of the main channel (IS-A3) and in the second wider channel (IS-A4); a strong gra-dient is observed at the entrances of IS-A0 and IS-A1. Note the match between specific stream power gradient and bed gradient (Figures 5(B) and 3(A)). Sediment transport measure-ments were not performed in the field campaign; however, the Meyer-Peter and Muller formulation was used to estimate bedload transport rates (Figure 5(C)). In channels IS-A3, and IS-A4, there is bedload transport rates are considerable; how-ever, in channels IS-A1, there is little bedload transport due to the reduced velocity along this channel. Similarly, the sus-pended transport load (Figure 5(D)) was estimated by vertical integration of the Rousean sediment distribution profile (Gar-cía, 2008); herein the Einstein formulation was used to obtain the near-bed concentration. As observed, there is an input of suspended sediment into channel IS-A1; however, due to the reduced velocity field, there is a deposition of sediments along the channel. Both the reduced bedload sediment transport rates and deposition of fine sediments along channel IS-A1 produce the inactivity of this channel and thus the formation of paleo-channels.

Discussion

The Landsat images from 1985 to 2014 show that the Iqui-tos anabranching structure is very dynamic, with channels developing, colliding and tending to disappear. Channel IS-A3 originated when the initial main channel IS-A0 migrated and collided with the last 6 km of the Nanay River before its junc-tion with the Amazon River (see Figure 2(B)). Mertes *et al.* (1996) and Rozo *et al.* (2012) discussed that chute cut-offs pro-duce the formation of new channels, as observed in channel IS-A4 during the late 1990s. With the exception of channel IS-A3, channel width changes rapidly for all channels since 2005; the case of IS-A1 is the most illustrative: it has a nar-rowing process and its width decreased by around 80% in the period 1998–2012. The slow width variation observed in channel IS-A3 is because it was originally part of the Nanay River, which lies over the Pebas formation and which is more resistant to fluvial erosion (see Figure 1(A), where the Pebas formation is labelled as N-P). The trend of changes in chan-nel width (see Figure 2) shows that in the near future the only remaining channels will be IS-A3 (main channel in 2011) and IS-A4, since IS-A0 and IS-A1 are experiencing narrow-ing and sedimentation processes; thus, IS-A0 and IS-A1 will be good examples of paleo-channel formation. The overbank flow, caused during floods, plays an important role in the exchange of sediment between the floodplain and the river. An example is shown by Dunne *et al.* (1998) in which they analyzed the Brazilian region of the Amazon River and found that the transference of sediment to the floodplain through overbank flow and deposition in bars exceeded the amount of sediment taken to the river through erosion. Given that the pattern of floods in the region of the Iquitos anabranching structure is well documented, the supply of sediment to the floodplain through diffuse overbank flow could be estimated in a future work.

The results from the numerical model presented in Figure 5(A–D), combined with the erosion and deposition regions obtained from the Landsat images (in particular Figure 2(E)), allow us to make the following observations. Although channels IS-A3 and IS-A4 are subject to similar flow conditions, the resistance to erosion of the Pebas formation in the left bank of IS-A3 restricts the migration; that is not the case for IS-A4, which is migrating to the west. Also, the numerical simulation showed a strong velocity gradient (because of the difference in velocity magnitudes) at the beginning of IS-A0 and IS-A1 (see Figure 5(A)). The implications of this may be found in the bed morphology as is observed in Figure 3(C), where the entrances to IS-A0 and IS-A1 have a high gradient step. Such a difference in bed elevation may be explained by the fact that the reduction in velocity diminishes the capacity of sediment transport; this may be observed in the computed sediment transport capacity (see Figure 2(C)). The origin of higher bed elevation along channels IS-A0 and IS-A1 is as fol-lows: since the flow in IS-A4 has a larger sediment transport capacity it carries more sediment, but at the area of lower velocities located at the inlets of IS-A0 and IS-A1, sediments start to be deposited. The sediments are slowly transported downstream into the secondary channels IS-A0 and IS-A1, increasing their bed elevation as observed in Figure 3(C). More research is needed to characterize the conditions suitable for the formation of paleo-channels.

Conclusions

The dynamics of planform migration of an anabranching struc-ture in the Upper Amazon, near Iquitos City, Peru, were analyzed using satellite images, field measurements and a hydrodynamic numerical model. The study covers the period 1985–2014. An important finding of the morphodynamic analysis is the role played by the geology in the migration of the anabranching structure. Such a condition leads to the not migrate or migrate more slowly. The consequent collisions result in the reconfiguration of the structure, and new chan-nels in the structure may be observed (see case of channel IS-A3). The bathymetry obtained from the 2011 field cam-paign (before the 2012 flood event) shows secondary channels IS-A0 and IS-A1 (which formerly competed between them-selves to be the main channel during the 1980s and early 1990s; see width evolution in Figure 2(H)) to have a bed eleva-tion higher than the main channel, IS-A3 (see Figure 3(B)). The numerical model finds a high gradient in velocity magnitude at the inlet of both secondary channels, triggering dispositional processes that continuously rise the bed elevation of these sec-ondary channels. The water surface gradient decreases as the channel migrates and the channel length increases between the points of bifurcation/junction, thus reducing the capacity of the channel to transport water and sediments. This is a pos-sible explanation for the origin of the more elevated bed in channels that were formerly main channels. It is clear in IS-A1 that, as the bed is rising, the channel keeps narrowing and, if the trend follows as in the previous years (see Figure 2(H)), the channel will be abandoned, becoming a paleo-channel. A high correlation between shear stress and the bed elevation is observed in Figures 5(C) and 3(A), where zones of higher shear stress appear to have deeper bed configurations.

The Iquitos anabranching structure shows complex interac-tions between the geological units in the floodplain where varying resistance to erosion modulates the migration rates of the channels. Historical analysis of the planform morphody-namics of this anabranching structure shows the formation of new channels and the formation of paleo-channels. The inter-action between the orientation of the secondary channels with respect to the main channel, the hydrodynamics developed in these channels, its relation to the bed evolution, and the narrowing process requires further studies to fully understood. Moreover, there is a need to develop morphodynamic models for anabranching structures that could describe the interaction of main and secondary channels.

Acknowledgements— Two anonymous reviewers and the Editor, Dr Stuart Lane, are thanked for providing detailed observations that helped to improve this manuscript significantly. Thanks to the Center for Latin American Studies (CLAS) of the University of Pittsburgh for providing field research grants to Dr Abad and PhD students. Thanks to officers and technical personnel from the Peruvian Navy, especially to Bruno Peralta, Cesar Ferrer, Luis Gutierrez and Carlos Holguin. Thanks to the officers that were enrolled in the River Hydraulics course, 2011 (held in Iquitos City and taught by Dr Abad), who helped to per-form these measurements as part of their hydraulic training. Thanks to CONACYT-Mexico for partially supporting Dr Alejandro Mendoza during his post-doctoral period at the University of Pittsburgh. Thanks to Helena Rowland for proofreading the manuscript and providing technical comments.

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