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Characterization of confluences in free meandering rivers of the Amazon basin

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ABSTRACT

Past studies on river confluence dynamics are mostly based on a limited number of experimental and field data that mainly represent the morphodynamic, hydrodynamic, and sedimentary processes of alluvial river channels with limited planform activity and concentrated solely around the confluence region. The present contribution is novel and focuses on the study of the planimetric configuration of confluences in tropical free meandering rivers located in the upper Amazon catchment. Confluences are environmental controls that impose convective instabilities in all the associated channels, namely the main stretch channel upstream of the confluence (M), the tributary (T), and the main post-confluent channel (MT). By performing a wavelet analysis on channels' curvature, we quantify the extent of the transitional region. Our results indicate that the strength of these transitional instabilities are in some degree dependent on the confluence width ratio (β); such that for $\beta > 0.45$, marked instabilities are developed. These instabilities induce the following general changes and in the planimetric configurations of the aforementioned channels: [i] the arc-wavelength in the confluent (M and T) and post-confluence channels increase in the transitional region, and [ii] the peaks on the curvature of MT channel decrease with respect to the M channel, thus resembling a constructive effect in the superposition of the meander trains.

Although most of the confluence angles are acute, regardless the width-ratio, some instances of obtuse angles of confluence are observed. They are associated with $\beta \geq 0.80$, where possibly the confluence is forced to become accordant. Our results show that no evident cause–effect relationship is found between the angle of confluence and the length of the transitional region; however, some degree of dependence is seen between the confluence angle and the arc-wavelength of the post-confluence channel (i.e., higher values of the arc-wavelength corresponds to normal confluence angles).

1. Introduction

River confluences are ubiquitous features in river networks. They represent entities at which rapid changes in flow, sediment discharge, and hydraulic geometry must be accommodated (Best, 1988), inducing thereby step changes in channel size, slope, and bed composition (Ferguson and Hoy, 2008). Past research in this topic has shown that the main parameters that influence the dynamics of confluences are the momentum ratio between the combining flows and the three-dimensional geometry of the junction, namely the degree of discordance (defined as the relative depth of incision of the confluent thalwegs; (Kennedy, 1984)) and the planform confluence angle (Boyer et al., 2006), although some researchers (e.g., Biron et al. (2002)) suggest that curvature of the incoming channels should also be taken into account. Geologically, river confluences are locations with different sedimentary facies that could provide significant insights into the paleomorphology of river systems (Best, 1988; Carey et al., 2006; Unde and Dhakal, 2009) and represent prime petroleum-exploration targets (Ardies et al., 2002; Best and Rhoads, 2008).

Best, (1986), Biron et al. (1996), Boyer et al. (2006), Rhoads et al. (2009), and Ribeiro et al. (2012) proposed conceptual models for the hydrodynamic, bed morphodynamic, and sedimentary processes that take place in river confluences. These models progressively identified six different zones at confluences: [i] zone of stagnation, [ii] flow deflection zone, [iii] flow separation zone, [iv] zone of maximum velocity, [v] zone of flow recovery, and [vi] zone of shear (and the existence of a second zone of shear for pronounced bed discordance cases); and determined that the extent and location of these zones vary with the junction angle, the degree of discordance and the hydrological variability in the momentum flux ratio of the confluent rivers. From the morphological standpoint, channel confluences can be broadly divided into three elements: [i] distinct, and commonly steep, avalanche faces that form at the mouth of each of the confluence channels; [ii] a region of pronounced scour within the center of the junction; and [iii] bars of

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sediment that are formed within the post-confluence channel (Best, 1988). Earliest research (e.g., Mosley, 1976; Ashmore and Parker, 1983; Best, 1986; Best, 1988) determined that a positive correlation exists between the maximum scour depth and the confluence angle.

Contrary to the Playfair's Law (Playfair, 1956) that stated that fluvial confluences are mainly morphologically accordant, namely having negligible degree of discordance, past studies have demonstrated that they are mainly discordant (e.g., confluences having tributary beds higher than those of the main channel). This issue was attributed to differences in channel-forming discharges and diversity in the geology and sediment size of the bed and the banks (Kennedy, 1984). Based on the Playfair's Law, it is assumed that two streams exhibit nearly identical rates of entrenchment near their junction (Niemann et al., 2001).

Confluence flow structures show some resemblance to those in meander bends, but modified because of the abrupt change in tributary direction as well as general difference involving the presence of a free-shear layer between the confluent flows. In addition, the introduction of asymmetry in terms of velocity ratio reduces sensitivity to junction angle and the strongest changes in secondary circulation strength arise from the introduction of bed discordance, and even low magnitude discordance may have a significant, although localized, effect (Bradbrook et al., 2001). Sediment research at confluences (Unde and Dhakal, 2009; Ribeiro et al., 2012) indicates that [i] tributary sediments impact on the main stream, thus punctuating the downstream trend in sediment size decrease; [ii] the size of the tributary is an important factor for tributary impact on the main stream; and [iii] the particle size decreases from the active flow bed toward the banks and bars.

(Ribeiro et al., 2012) stressed the fact that current understanding of channel confluences is based on experimental (Mosley, 1976; Qing-Yuan et al., 2009; Thomas et al., 2011), field (Richards, 1980; Rathbun and Rostad, 2004; Lauer et al., 2006; Parsons et al., 2007; Ashmore and Gardner, 2008; Kabeya et al., 2008; Laraque et al., 2009; Peixoto et al., 2009; Rhoads et al., 2009; Unde and Dhakal, 2009; Hackney and Carling, 2011), and numerical models (Bradbrook et al., 2000a, 2000b, 2001; Boyer et al., 2006; Roca et al., 2009; Constantinescu et al., 2011; Ribeiro et al., 2012) that surprisingly represent a small number of investigated configurations. Moreover, these configurations exemplify small scale rivers, i.e., less than 10 m wide (Parsons et al., 2008). To the best of our knowledge, such studied configurations do not include confluences in free meandering rivers. Ribeiro et al. (2012) and collaborators also stated that although these studies have provided valuable insight into the dynamics of confluence zones, they do not represent the full range of channel confluences encountered in nature that vary in, e.g. planform and slope of the confluent channels, confluence angle, discharge and momentum ratios, bed material, and sediment supply. Likewise, Parsons et al. (2007, 2008), based on the analysis of field data from large rivers (e.g., Parana, Ganges), warned that caution must be applied in assuming that processes observed in small channels can be scaled up linearly with increasing channel size. This limitation in the representativity of natural confluence configurations is particularly critical for the case of tropical rivers, such as those located in the Amazon catchment, for which even limited knowledge exists (McClain, 2001; Latrubesse et al., 2005; Townsend-Small et al., 2007).

River confluences are the mixing of three waters: two distinct river waters and one groundwater, even if this latter is generally obscured by the higher discharge of the rivers (Lambs, 2004). Probably, this active interface leads to a high concentration of biota in their proximities (Benda et al., 2004; Rice et al., 2008; Duncan et al., 2009; Peixoto et al., 2009; Osawa et al., 2010). For the case of the Amazon system, for instance, this aspect of the confluences has paramount importance, in the sense that confluences may have a role in its ecosystem structure. To date, this dimension of confluences is yet obscure for its role as sources of morphological heterogeneity at the scale of entire networks and is not well understood (Benda et al., 2004).

Meandering rivers, dune profiles, water waves, and sedimentary coastlines exhibit similar quasi-periodic behavior (Howard and Hemberger, 1991) and, similar to water wave trains that result from the combining of several different waves, confluent meandering rivers approach the confluence as meander trains having different energy, amplitude, and wavelength. Confluences have received only sporadic attention from geomorphologists and that this attention has generally been restricted to a speculative interpretation of changes past junctions in particular catchments (Ferguson and Hoy, 2008). Thus, this paper is aimed to answer the following research questions: [i] what are morphodynamic processes that develop at free meandering river confluences, not only at the confluence but also considering both the confluence and post-confluence channels?, and [ii] what are meandering planimetric parameters that characterize these confluences? These research questions are answered by analyzing the actual and estimated sizes of the channels connected to the confluences. Additionally, we introduce the application of wavelet transforms on the analysis of the confluence's geomorphology. Wavelets have been successfully used in the past to analyze river morphodynamic signals such as bedforms (Catano-Lopera et al., 2009; Singh et al., 2011; Gutierrez et al., 2013) and meander morphometrics (Abad, 2009; Gutierrez and Abad, 2014). Wavelet transforms are applied to the curvature of the meandering rivers' centerline and subsequently the transitional changes of the curvature frequencies imposed by the main channel over the tributary and by the tributary over the main channel are analyzed. Section 2 explains the data and methodology used in the study, Section 3 presents the obtained results, and Section 4 discusses these obtained results, which are presented in a broader context in Section 5.

2. Data and methodology

2.1. Data

Each confluence of meander trains involved the digitalization of 40–60 bends to obtain representative statistics of the data as suggested by Howard and Hemberger, (1991). The planimetric geometry of meandering rivers is typically described in terms of the curvature (C). This parameter is obtained by discretizing the channel centerline in equally spaced points, and it is expressed in local or intrinsic coordinates (Hickin and Nanson, 1991; Howard and Hemberger, 1991; Marani et al., 2002; Legleiter and Kyriakidis, 2006; Motta et al., 2012). Thus, by performing a coordinate conversion from geographical coordinates (e.g., Easting, Northing) to local coordinates (e.g., s, the streamwise coordinate and n, the normal coordinate), a set of curvature ($C(s)$) data from the M, T, and MT centerlines (sampled at 0.5B, B, and 1.5B, where B is the mean channel width), were obtained. Thus, the reach length L is estimated as the maximum s. Subsequently, normalized curvature ($C^* = C \times B_M$) and normalized local abscissa ($S^* = s/B_M$) were estimated (B_M is the mean channel width for the M reach).

In order to analyze the sensitivity of the wavelet transform to different sampling periods, sets of data sampled at 0.5B, B and 1.5B were obtained. Past research in meandering morphometrics has demonstrated that discretization of meanders at spacing of approximately one channel width is suitable to avoid noise from curvature signals (Hooke, 1984; Legleiter and Kyriakidis, 2006). This analysis was necessary to analyze the curvature of the main channel comprising the M and MT channels because the mean channel width varies, in some cases, markedly from the pre-confluence to the post-confluence stretch.

The confluences comprise three elements (Fig. 1): the main channel stretch located upstream of the confluence (M), the tributary stretch (T), and the main channel stretch located downstream of the confluence (MT). Arc-wavelength (λ), mean width (B), and reach length (L) of the aforementioned stretches are also included. The mean width is estimated by dividing the area occupied by the river banks and the downstream and upstream limits of the reach by the reach length (measured along the centerline). The arc-wavelength is quantified by performing the wavelet analysis to the meanders curvature. A detail description of the procedure is described in Section 2.2. In addition, the confluence angle (ψ) is estimated using the two channel curvatures immediately upstream of the confluence (see Fig. 1).