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Automated extraction of meandering river morphodynamics from multitemporal remotely sensed data

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ABSTRACT

We introduce PyRIS, an automated, process-based software for extracting extensive meandering and anabranching river morphodynamics from multitemporal satellite imagery, including a unique ability to quantify river bars dynamics. PyRIS provides three main computations: (i) detection of planform centerline including complex river patterns, (ii) computation of migration vectors between subsequent centerlines, and (iii) analysis of sediment bars dynamics. PyRIS was validated against several test cases in the Amazon River basin, specifically i) main channel extraction from the anabranching Amazon river, ii) migration analysis following a large cutoff on the Ucayali River and iii) detection of sediment bar migration on the Xingu River. Tests prove the capability of PyRIS to detect the main channel in anabranching structures and chute cutoffs. PyRIS can extract extensive morphodynamic information with unprecedented automation levels and reasonable computational effort (5 h for 28 Landsat images of a 240 km reach of the Xingu River on a 3.20 GHz Intel).

1. Introduction

Traditionally, the planform evolution of river meanders has been studied through analytical models (Ikeda et al., 1981; Johannesson and Parker, 1989; Seminara et al., 2001), field data (Leopold and Wolman, 1960; Lewin, 1972; van den Berg, 1995; Brewer and Lewin, 1998; Lewin and Brewer, 2001; Hooke, 2007; Hooke and Yorke, 2011) and numerical models (Howard, 1992; Sun et al., 1996; Asahi et al., 2013; Eke et al., 2014a). Only recently has the power of modern computers and the availability of geospatial imagery made it possible for researchers to investigate meander morphodynamics from remotely sensed data. In this paper we present a process-based software, PyRIS (Python–RIvers from Satellite), which allows for automated extraction of information on meander morphodynamics from multispectral remotely sensed data, by isolating individual physical processes occurring in evolving meander bends.

In the following sections, we provide some fundamental background on meandering river morphodynamics and then discuss the state of art of remote sensing applications in this research field.

1.1. A brief overview on river meander morphodynamics

Meandering is one of the most intriguing and highly dynamic processes occurring in alluvial riverine environments. The process of meandering occurs as freely evolving rivers with curvilinear planforms wander through their floodplains, carving the landscape and reworking its sediments through the mechanisms of river bank erosion and accretion (Edwards and Smith, 2002; Hooke et al., 2011; Hooke, 2003; Leopold and Wolman, 1960; Seminara, 2006). Eventually meandering rivers encounter planform constraints such as bedrock, valley sides or anthropogenic structures which condition their planform development. Large-scale sediment bedforms called point bars usually develop at the inner banks of meander bends (point bars), gently connecting the floodplain with the river bed (Kasvi et al., 2013; Legleiter et al., 2011; Nanson and Hickin, 1983). A steeper slope connects the channel bed to the outer, eroding bank of meander bends, where the flow depth is generally

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higher, as well as the streamwise velocity (Eke, 2013; Mosselman, 1998). Experimental, analytical and numerical modeling (Kinoshita and Miwa, 1974; Schuurman et al., 2016; Tubino and Seminara, 1990) indicate that under some conditinos point bars can coexist with alternate migrating bars, which can be viewed as river bed topography waves with scour and deposition patterns that alternate streamwise and spanwise at opposite banks. Alternate bars are shorter in length and migrate downstream whereas point bars do not (Blondeaux and Seminara, 1985; Colombini et al., 1987; Tubino, 1991).

The analysis of sediment bar dynamics in real meandering rivers has received relatively little attention in the past decades compared to their planform dynamics, for which a large body of theoretical and modeling work has been developed (e.g., Zolezzi et al., 2012). However, recent works started addressing the importance of sediment bars in a wide range of morphodynamic studies focused on real rivers, including effects of massive deforestation on sediment dynamics in the Amazon (Latrubesse et al., 2009), influence of point bar development on the mechanisms of meander migration (Eke et al., 2014b; Hooke and Yorke, 2011; van de Lageweg et al., 2014), effects of mid-channel bar development on planform stability and structure of meandering rivers (Luchi et al., 2010a; b), and alternate bar dynamics in channelised reaches (Adami et al., 2016). Reconstructions of sediment bar dynamics based on GIS analysis of historical maps and aerial imagery, supported by fieldwork, were proposed by Brewer et al. (2000); Gittins (2004) and the impact of sediment bars on river management was analyzed by O'Callaghan et al. (2013).

Meander bends undergo temporal amplification and translation (Eke et al., 2014a; Güneralp and Rhoads, 2009, 2011; Seminara et al., 2001), deformation (Kinoshita, 1961; Schwenk et al., 2015; Seminara et al., 2001) and eventually cutoff processes (Hooke, 2004; Schwenk and Foufoula-Georgiou, 2016) when they grow enough to cut themselves out (neck cutoff, e. g Camporeale et al.. 2008, see also Fig. 1a) or when they are overridden by secondary channels (chute cutoff, e.g. Constantine et al., 2009; Kasvi et al., 2013; Kleinhans & van den Berg, 2011). A spatially-distributed indicator of meander planform dynamics is the local migration rate, which represents the local rate of movement of the river centerline and corresponds to the average between the local rate of erosion of the retreating bank and the local rate of accretion of the advancing bank (Eke et al., 2014a; b).

Meandering rivers are commonly viewed as single-thread fluvial patterns, though several transitional styles of meandering actually exist, characterised by the presence of secondary and multiple channels (Fig. 1b). Some of the processes described earlier are of particular interest for large meandering rivers. In this study, we also focus on large rivers in the evaluation of PyRIS due to the lack of high spatial resolution data on small rivers spanning long time scales.

In particular, chute cutoffs are one of the dinstinctive characteristics of large active meandering rivers, whereby secondary, chute channels form and connect the upstream and downstram ends of a meander bend thorugh shorter paths that eventually become the main channel after flooding events (Constantine et al., 2010). These transitional meanders may present some similarities with anabranching river systems typical of the largest rivers on Earth like the Amazon river (Latrubesse, 2008), where the main channel splits into multiple sinuous branches which merge together repeatedly in space. The larger a meandering river, the more frequently an anabranching structure is apparent. In fact, the largest rivers on earth are mostly anabraching (Latrubesse, 2008). In contrast to many meandering rivers, anabranching channels are relatively stable in time with a number of channels oscillating in space due to the presence of semi-permanent vegetated islands (Nanson and Knighton, 1996; Carling et al., 2014). The main channel displays very low sinuosities (Amos et al., 2008). According to Nanson and Knighton (1996) anabranching channels are associated with a flow regime that is flood-dominated.

1.2. Remote sensing of river meanders

Most image processing and geospatial analysis tools make it possible to classify and analyse the earth surface through pixel-distributed indices that map vegetation (Carlson and Riziley, 1997), water (Feyisa et al., 2014; Gao, 1996; Xu, 2006; Pai and Saraswat, 2013) and lithology (Ninomiya, 2004). The combination of such indices allows for identifying river and water boundaries in a semi-automated fashion (Güneralp et al., 2013, 2014). A number of approaches for the extraction of channel centerlines (Fisher et al., 2013; Schwendel et al., 2015; Schwenk et al., 2016; Schwenk and Foufoula-Georgiou, 2015) and banks (Güneralp et al., 2014, 2013; Merwade, 2007; Pavelsky and Smith, 2008; Rowland et al., 2016; Schwenk et al., 2016) from river masks has been developed so far (tools for the extraction of channel planforms from topography data are also available, e.g. Sangireddy et al., 2016). The recently

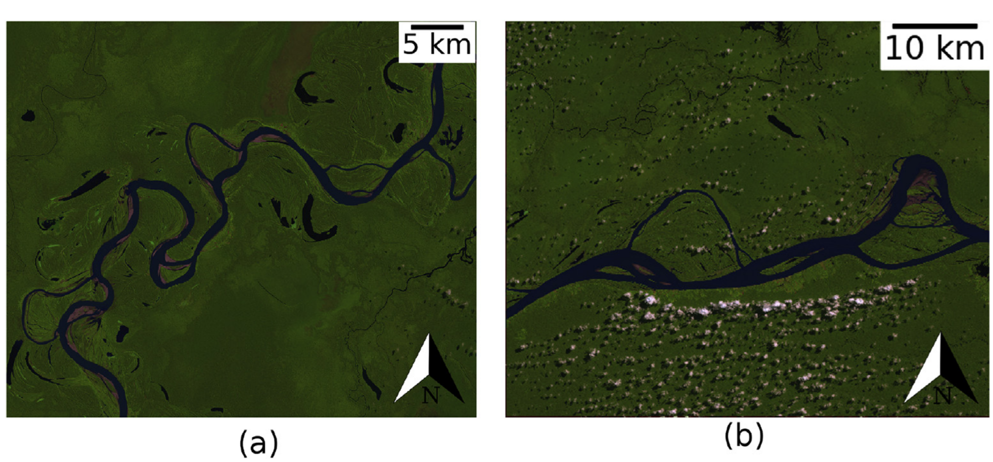

Fig. 1. Illustrative examples of river patterns. (*a*) False color map of the meandering Rio Huallaga (Brazil) with chutes. Abandoned meanders (cutoff residuals or oxbow lakes) provide evidence of morphological activity and planform development (Landsat false color composite based on LT05_L1TP_007064_20000730_20161213_01_T1_B(5,4,3). TIF image layers). (*b*) False color map of the anabranching Amazon River (Brazil, Landsat infrared composite based on LT05_L1TP_003062_20010721_20161211_T1_B(5,4,3). TIF image layers). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)