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Dynamics of nonmigrating mid-channel bar and superimposed dunes in a sandy-gravelly river (Loire River, France)

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ABSTRACT

A field study was carried out to investigate the dynamics during floods of a nonmigrating, mid-channel bar of the Loire River (France) forced by a riffle and renewed by fluvial management works. Interactions between the bar and superimposed dunes developed from an initial flat bed were analyzed during floods using frequent mono- and multibeam echosoundings, Acoustic Doppler Profiler measurements, and sediment grain-size analysis. When water left the bar, terrestrial laser scanning and sediment sampling documented the effect of post-flood sediment reworking.

During floods a significant bar front elongation, spreading (on margins), and swelling was shown, whereas a stable area (no significant changes) was present close to the riffle. During low flows and falling limbs of floods, intense sediment reworking on the top of the bar and lateral scouring occurred. Hydrological variations controlled the sediment supply (in terms of phasing, quantity, and grain size) delivered by surrounding channels during floods and thus superimposed dune development. Their development was also linked to the sediment availability (armor layers, riffle proximity). Their relatively constant height highlights a preferential adaptation on dune length during floods.

The role of each morphological forcing parameters (riffle vs. channel widening and curvature) on the bar dynamics and evolution is stage dependent; the shape, dynamics, and long-term morphological evolution of the bar and of the river reach (surrounding islands, channel translation) mainly depends on the presence of the natural riffle.

1. Introduction

1.1. Background

In sandy-gravelly rivers, the development of bars is commonly observed. The height and width of these bedforms are of the same order of size as the water depth and channel width, respectively (Jackson, 1975). Bars can influence the morphological evolution of rivers through their interaction with the flow and sediment transport (Parker, 1976; Blondeaux and Seminara, 1985; Struiksma et al., 1985; Crosato and Mosselman, 2009; Hooke and Yorke, 2011; Kleinhans and Van den Berg, 2011; Eekhout et al., 2013).

In rivers, migrating bars and nonmigrating bars (corresponding to the free and forced bars of Seminara and Tubino, 1989; see review in Rodrigues et al., 2015) can be distinguished. The first type results from the instability of turbulent flows occurring on an erodible bed and depends mainly on the aspect ratio of the channel (Callander, 1969; Colombini et al., 1987; Seminara and Tubino, 1989; Tubino, 1991). Nonmigrating bars (or forced bars) are basically stationary within the bed and develop because of changes in the channel planform or variations of the channel width (Bittner, 1994; Repetto et al., 2002; Wu and Yeh, 2005). In this case, the separation of the flow associated with an energy loss favor sediment deposition and even lateral migration of bars coming from upstream (Claude et al., 2014). Nonmigrating bars can also be induced by the presence of a steady local perturbation (riffle, groyne, and vegetation). In this case, bar deposition occurs downstream of the forcing if the width-to-depth ratio is smaller than a value of resonance and upstream if the width-to-depth ratio is larger (Zolezzi and Seminara, 2001; Zolezzi et al., 2005; Mosselman et al., 2006).

The two types of bars (migrating and nonmigrating) can coexist in river channels (Lanzoni, 2000a,b; Wu et al., 2011). Crosato et al. (2012) showed that slowly growing nonmigrating bars can develop and replace migrating bars on a long-term perspective if discharge remains constant. Contrarily, Rodrigues et al. (2015) suggested that

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flow variations, specifically at low flows, can generate new migrating alternate bars.

Migrating mid-channel bars and their interactions with bed morphology have been studied extensively in the field (Leopold and Wolman, 1957; Ashworth et al., 1992; Bridge and Gabel, 1992; Richardson et al., 1996; Richardson and Thorne, 1998, 2001; McLelland et al., 1999; Reesink and Bridge, 2011) and experimentally (Ashmore, 1982, 1991; Ashworth, 1996; Federici and Paola, 2003; Reesink and Bridge, 2007, 2009). However, investigations performed on nonmigrating mid-channel bars and superimposed dunes are rare. The feedback loops that link dunes with migrating bars have been recently investigated in studies that highlighted contrasted hydrosedimentary processes according to the study context. For example, the presence of bars influences flow depth and sediment availability which will impact the development of dunes (Tuijnder et al., 2009; Claude et al., 2012, 2014). Villard and Church (2005) and Claude et al. (2012) observed on migrating bars on the Fraser River (Canada) and the Loire River (France), respectively, that the largest dunes can be found superimposed on bars suggesting that sediment supply or availability can sometimes govern dune size in a stronger way than water depth. This is in contrast with many field studies that attributed the largest dunes to reaches where water was deepest (Coleman, 1969; Thorne et al., 1993; Dalrymple and Rhodes, 1995; Ashworth et al., 2000) as reduced water depth causes a reduction in the boundary layer involved in dune development. In return, the dunes affect the bar formation and morphological evolution by modulating their vertical and lateral accretion (Bristow, 1987; Bridge, 1993; Ashworth et al., 2000; Villard and Church, 2005; Rodrigues et al., 2012, 2015).

The present study investigated the interactions between a nonmigrating bar and superimposed dunes. The bar considered is principally forced by the presence of a riffle and, in a lesser way, by an expansion area and by a low degree of curvature of the channel. Before the surveys, an initial smooth flat-bed made of a mixture of sands and gravels was ensured by fluvial management works. Surveys were performed just after works were carried out on the bar that ensured a monitoring of the bar response to the disturbance. This large data set allows us to study the bar response to the discharge fluctuation and to consider whether the development is purely stage related or also dependent on the antecedent morphology and local morphological factors.

As a general objective, this paper aims to understand and quantify the morphological evolution of a nonmigrating, mid-channel bar during flood events and after fluvial maintenance operations that ensured homogenized initial conditions in terms of topography and grain-size distribution. To reach this objective, two scientific questions are addressed.

Firstly, what is the influence of discharge variations on the dynamics of a nonmigrating bar associated with a steady perturbation (riffle) and covered by superimposed dunes during high-magnitude floods and over several flood events? More precisely, how sediment availability/supply influence bar elongation, spreading, and the development of superimposed dunes?

Secondly, how do discharge variations affect the relative weight of forcing parameters (riffle vs. expansion and curvature) responsible for a mid-channel, nonmigrating bar formation and dynamics and how, comparatively to other forced bars, do nonmigrating bars induced by a steady perturbation influence the morphological evolution of a river reach?

1.2. Loire River and study site

1.2.1. The Loire River

The Loire River is 1012 km^2 in length and drains a catchment area of 117,000 km^2 in France. At Orleans (638 km from the source), the river flows through sedimentary rocks of the Paris basin and shows a range of fluvial patterns from single channel (straight or meandering) to anabranching. For bankfull discharge rates, the width-to-depth ratio ranges between 50 and 150 (Latapie et al., 2014). Two climatic influences determine the regime of the Loire: rainfall coming from the Atlantic Ocean (mainly during winter) or rain storms in the upper mountainous reaches that occur during spring (Dacharry, 1996).

A severe incision of the main branch of the river, owing to a combined effect of the groynes for navigation (nineteenth to twentieth centuries) and intense sediment extraction (1950–1995), led to exposure of the bedrock, affecting the slope and thus the morphology of the Loire River. Bank erosion and lateral shifting is also constrained by artificial levees built for flood prevention (Latapie, 2011).

As a consequence, associated with a decrease in flooding, side channels and alluvial bars were rapidly colonized by woody vegetation that enhances sediment deposition (Rodrigues et al., 2006, 2007) and reduces habitat diversity and flow capacity during floods.

1.2.2. Study site

The study site of Mareau-aux-Prés (Fig. 1) is located about 10 km downstream of Orleans (649 km from the source), downstream of the confluence with the Loiret River that is a resurgence of the Loire River. At the Orleans gauging station, the average discharge of the Loire is 344 m^3 s^{-1} and its 2-year flood discharge is 1700 m^3 s^{-1}.

At Mareau-aux-Prés, the anabranching fluvial pattern is characterized by a set of islands present for several decades (Fig. 1). This reach is characterized by a contraction–expansion area with a channel width varying from 270 to 430 m between artificial levees preventing lateral erosion and lateral sediment supply. On the right bank, an artificial curvature deflects the main channel course toward the southwest, while a side channel flows straight near the left bank. This river reach has a sinuosity index of 1.04 and an average slope of 0.00023 m m^{-1} (Latapie, 2011). The water surface is locally modified caused by two natural bedrock riffles (Fig. 1) and a nonmigrating mid-channel bar consisting of siliceous sands, gravels, and pebbles that developed between these two riffles. This bar constitutes the central part of an asymmetrical bifurcation splitting two channels of different sizes (main and secondary channels; Fig. 1) as commonly shown in the literature (Miori et al., 2006; Zolezzi et al., 2006). During floods, flow coming from the main channel is divided by the small island 1 (Fig. 1B). The mid-channel bar was colonized by pioneer trees (*Salicaceae*) in 2005 and evolved rapidly as an island until 2012 (Wintenberger et al., 2015). In September 2012, fluvial management works (FMW) were carried out. They consisted of cutting down the vegetation, extracting the root systems, and lowering the average elevation of the island by exporting the bar sediments into the main channel. After this work, the alluvial bar was characterized by a flat surface of 26,700 m^2; no bedforms were present anymore, except for some small ridges and swales mostly oriented in the flow direction. Sediments were homogenized on the bar to a depth of 0.5 m, disturbing the initial spatial organization of grain size. Following the management works, the bar was submerged at a discharge value of 300 m^3 s^{-1} (Orléans gauging station, 10 km upstream).

2. Material and methods

During low flow stages and flood periods, data were collected to characterize the hydrodynamic, morphological evolutions, and the sedimentary conditions over the mid-channel bar. Before the submersion of the bar (October 2012), the topography was acquired and sediments were sampled as presented in Fig. 1. During the flood period from December 2012 to June 2013, 17 field surveys (from S1 to S17) were carried out for discharge values ranging from 400 to 1900 m^3 s^{-1} (Fig. 2). The discharge was given at the gauging station of Orléans by the DREAL Centre (environmental agency). These 17 surveys always consisted of a bathymetric survey in addition with flow velocity for 13 surveys (S1, S2, S3, and S9 excluded because of field conditions) and sediment sampling for six surveys (S10, S13, S14, S15, S16, and S17; see Figs. 2 and 10). At the emersion of the bar in June 2013, topography