Geomorphology 295 (2017) 507–528

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Are restored side channels sustainable aquatic habitat features? Predicting the potential persistence of side channels as aquatic habitats based on their fine sedimentation dynamics

Jérémie Riquier[a,*], Hervé Piégay[a], Nicolas Lamouroux[b], Lise Vaudor[a]

[a] Université de Lyon, CNRS, UMR 5600 - Environnement-Ville-Société, Site ENS de Lyon, Lyon, France
[b] IRSTEA – UR MALY, Villeurbanne, France

ARTICLE INFO

Keywords:
Channel design
Floodplain restoration
Floodplain sedimentation
Hydrological connectivity
Riverine wetland

ABSTRACT

The restoration of side channels (also referred to as abandoned channels, former channels, floodplain channels, or side arms) is increasingly implemented to improve the ecological integrity of river-floodplain systems. However, the design of side channel restoration projects remains poorly informed by theory or empirical observations despite the increasing number of projects. Moreover, feedback regarding the hydromorphological adjustment of restored channels is rarely documented, making it difficult to predict channel persistence as aquatic habitats. In this study, we analyze the spatial and temporal patterns of fine sediment deposition (< 2 mm) in 16 side channels of the Rhône River, France, restored in 1999–2006 by a combination of dredging and/or partial to full reconnection of their extremities and as a by-product of an increase in minimum flow through the bypassed main channels. We develop prediction tools to assess the persistence of restored channels as aquatic habitats, using between five and seven monitoring surveys per channel (spanning 7–15 years after restoration). Observed channel-averaged sedimentation rates ranged from 0 to 40.3 $\text{cm}\cdot\text{y}^{-1}$ and reached 90.3 $\text{cm}\cdot\text{y}^{-1}$ locally. Some channels exhibited a significant decline of sedimentation rates through time, whereas others maintained rather constant rates. Scouring processes (i.e., self-rejuvenation capacity) were occasionally documented in 15 channels. Six of the 16 studied channels appeared to be self-sustaining. The 10 others accumulated more and more fine sediment deposits after restoration. Parametric modeling of sedimentation rates suggested that among these 10 channels, four have long life-durations (i.e., more than a century), three have intermediate life-durations (i.e., likely between three and nine decades), and three others have short life-durations (i.e., likely between two and five decades). Observed channel-averaged sedimentation rates can be predicted from the frequency and magnitude (i.e., maximum shear stress) of upstream overflow events and the maximum intensity of backflow events (i.e., maximum backflow capacity). These predictors reflect the dominant role of side channel geometry (i.e., morphology of the upstream alluvial plug, slope conditions) in controlling their flooding regime. These models applied successfully to a wide range of channel morphologies and can be used to quantify a priori the likely effects and the sustainability of side channel restoration.

1. Introduction

Side channels (e.g., secondary side channels, backwater channels, sloughs, oxbow lakes) are ubiquitous landforms of shifting river channels. Two major phases govern the geomorphic evolution of these channels from aquatic to terrestrial stages: an initial bedload infilling followed by longer term fine sediment deposition. This sequence, established initially for meander cutoffs (e.g., Gagliano and Howard, 1984; Constantine et al., 2010; Toonen et al., 2012), also applies to channelized reaches of former multi-branched river-floodplain systems, where side channels were isolated from the main channel with submersible longitudinal dykes.

In the early stages (i.e., following cutoff or avulsion processes), active side channels are permanently connected with another river segment at both extremities. They can transport and trap bedload material until the establishment of an alluvial plug, which usually occurs at the upstream end. The establishment of a plug is not inevitable. For example, active side channels can sometimes maintain their permanent upstream connection with another river segment as stable bifurcation (e.g. Kleinhans et al., 2013) or an engineered bottom sill can prevent bedload entering the intake and thus plug formation (e.g. Simons et al., 2001). The angle of diversion of the flow separating the main channel

---

* Corresponding author at: CNRS UMR 5600 - ENS de Lyon - 15, parvis René Descartes, BP 7000, 69342 Lyon Cedex 07, France.
E-mail address: jeremie.riquier@ens-lyon.fr (J. Riquier).

http://dx.doi.org/10.1016/j.geomorph.2017.08.001
Received 16 February 2017; Received in revised form 1 August 2017; Accepted 1 August 2017

and the cutoff channel is a critical factor in explaining plug establishment (Gagliano and Howard, 1984; Shields and Abt, 1989; Piégay et al., 2002; Constantine et al., 2010; Dieras, 2013). When compared to low diversion angles (e.g., chute cutoffs), high angles (e.g., neck cutoffs) often promote lower shear stresses and a quick establishment of an upstream sediment plug, which in turn results in less bedload transport in the cutoff inducing shorter plugs and a greater remnant water volume after the disconnection (Constantine et al., 2010). Plug establishment in meander cutoffs can take from a few months to about a decade (Gagliano and Howard, 1984; Hooke, 1995; Gautier et al., 2007; Dieras, 2013). In many channelized rivers, where formerly active side channels were artificially disconnected from the main river channel at their upstream end and sometimes at both ends by the establishment of submersible longitudinal dykes (e.g., Hohensinner et al., 2014 - Danube, Austria), this first stage is usually curtailed and a second stage (discussed below) would then be much longer (Dépret et al., in press).

Once disconnected from the main channel at low flow at their upstream end, backwater channels are progressively filled by fine-grained material (from sand to clay) and gradually evolve into terrestrial environments. Their persistence as aquatic habitats is then mainly a function of fine sediment deposition rates driven by allogenic successional processes. Channel-averaged rates reported in the literature range from 0 cm·y^{-1} in a former braided channel of the Rhône River (Citterio and Piégay, 2009) to 18 cm·y^{-1} in an oxbow lake of the Sacramento River (Stella et al., 2011). Several important controls can explain these differences, including sediment concentration, trapping efficiency, and scouring capacity of the channel. These last two factors are significantly affected by side channel geometry.

Differences in geometry can be linked to cutoff types or types of channel abandonment. Sedimentation rates can vary according to the geomorphologic origin of side channels (Piégay et al., 2000, 2008; Citterio and Piégay, 2009), which is inherited from the fluvial dynamics during cutoff (e.g., slope conditions, depth, width). For example, former braided channels often experience lower rates than abandoned meanders because they have a steeper slope and a lower hydraulic capacity. Dieras (2013) estimated that meander chute cutoffs filled about 10 times faster than meander neck cutoffs, primarily because the remnant aquatic area after the establishment of the plug was already very low in chute cutoffs so that they are quickly filled with fine material. Similarly, Dépret et al. (in press) demonstrated that artificially abandoned side channels in the Rhône River (i.e., closed with submersible dykes at their upstream end) have a much longer persistence in comparison to natural side channels that were disconnected by a sediment plug. Indeed, the artificial and imposed premature closing of their upstream end by submersible dykes has truncated the initial bedload infilling phase of the side channels.

Side channel fine sediment deposition rates evolve through time according to their flooding regime, that is, the frequency and magnitude with which upstream overflow events (i.e., lotic functioning) and backflow events (i.e., passive inundation of channels from their downstream end) occur. Upstream overflow events reflect the potential of fine sediment scouring and backflow events reflect the potential for fine sediment deposition (Citterio and Piégay, 2009). Fine sediment deposition rates also decrease quickly in intensity through time as a result of plug(s) accretion and/or overall side channel accretion (Hooke, 1995; Gautier et al., 2007; Kondolf and Stillwater Sciences, 2007; Riquier, 2015).

Once fully isolated from the main channel, allogenous processes are gradually replaced by autogenous ones (e.g., internal production of organic matter) and depositional infilling occurs at lower rates (Bravard et al., 1986; Rostan et al., 1987; Reckendorfer et al., 2013). Morphodynamic processes in the main channel (degradation/aggradation or contraction/enlargement) influence fine sediment deposition rates in side channels by decreasing or increasing their trapping efficiency, their scouring capacity, and/or directly affecting water depth in side channels independently of fine sediment accumulation through base level changes (Bravard et al., 1997; Piégay et al., 2000, 2008; Riquier, 2015). As a consequence, the persistence of side channels as aquatic habitats has previously been shown to vary between a few years and several centuries (Gagliano and Howard, 1984; Amoros et al., 2000; Constantine et al., 2010; Dieras, 2013).

Over recent decades, numerous projects involving side channel restoration have been implemented to improve the ecological functioning of highly regulated river-floodplain systems (e.g., Theiling, 1995 — upper Mississippi, USA; Reckendorfer et al., 2005 — Danube, Austria; Simons et al., 2001 — Rhine, Netherlands; Baptist et al., 2004 — Waal and Rhine, Netherlands; Jacobson and Galat, 2006 — lower Missouri, USA; Stammel et al., 2012 — upper Danube, Deutschland; Lamouroux et al., 2015 — upper and middle Rhône, France). However, designs for side channel restoration projects are poorly informed by theory or empirical observations, despite massive investments (Jacobson et al., 2004; Shields et al., 2009). Only a few studies have reported detailed hydromorphological responses of side channel restoration (Jacobson et al., 2001, 2004; Amoros et al., 2005). Consequently, the development of practical predictive tools to promote effective side channel restoration remains a major challenge.

In this study, we analyzed fine sedimentation dynamics in 16 restored side channels of the Rhône River (France) to (i) describe and classify sedimentation patterns and rates; (ii) model the accumulation dynamics of observed fine sediment deposition; (iii) model the influence on sedimentation rates of quantitative descriptors of the flooding regime of channels that managers can modify; and (iv) provide estimates of the potential persistence of restored side channels as aquatic habitats.

2. Materials and methods

2.1. Study sites

Over the past two centuries, the cumulative effects of human actions (e.g., embankment construction, dam building) have deeply affected the physical and ecological integrity of the Rhône river-floodplain system (Roux et al., 1989; Olivier et al., 2009). A large restoration project started in the late 1990s to recover the diversity of floodplain habitats and communities (Lamouroux et al., 2015). Between 1999 and 2006, 24 side channels were restored in four different reaches of the Rhône River that are bypassed by hydropower plants. Three of these reaches were located in the French upper Rhône (Chautagne, Belley, and Brégnier-Cordon; Fig. 1) and one in the middle course of the river, just downstream of Lyon (Pierre-Bénite). Restored side channels were dredged, either locally or over their entire lengths, with or without upstream and/or downstream plug removal, in order to increase the volume of aquatic habitats and to improve groundwater-channel exchanges (Riquier et al., 2015). In addition, minimum regulated flows were increased in the bypassed main channels, sometimes influencing water levels in the side channels (Lamouroux et al., 2015). Of the 16 restored channels monitored (see Table 1 for a list of the selected side channels and Fig. 1 for maps), five were active side channels with permanent upstream and downstream surface connections after restoration (100% flow exceedance) and 11 were backwater channels with permanent connections at their downstream ends only (i.e., plugged at their upstream ends, but they do pass water and sediment with some range of exceedance frequency; for details of restoration works, see Lamouroux et al., 2015 and Riquier et al., 2015).

The hydrology of the main river channels varied among the four studied reaches (Fig. 2) depending on the management of dams. In the Rhône, each bypassed reach includes a diversion dam that redirects flow into an artificial canal that feeds a hydroelectric power plant (see Fig. 1B and C). The old riverbed (so-called *old Rhône*, hereafter bypassed main channel or bypassed reach) receives a minimum flow, except when it is used to evacuate floods that exceed the maximum operating flow of the plant. Downstream of each power plant, the canal