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The anthropogenic nature of present-day low energy rivers in western France and implications for current restoration projects

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ABSTRACT

As in other European countries, western France has seen an increase in river restoration projects. In this paper, we examine the restoration goals, methods and objectives with respect to the long-term trajectory and understanding of the contemporary dynamics of the small low energy rivers typical of the lowlands of Western Europe. The exhaustive geomorphological, paleoenvironmental and historical research conducted in the Seulles river basin (Normandy) provides very accurate documentation of the nature and place of the different legacies in the fluvial systems we have inherited. The sedimentation rate in the Seulles valley bottom has multiplied by a factor of 20 since the end of the Bronze Age and has generated dramatic changes in fluvial forms. Hydraulic control of the rivers and valley bottoms drainage throughout the last millennium has channelized rivers within these deposits. The single meandering channel which characterizes this river today is the legacy of the delayed and complex effects of long term exploitation of the river basin and the fluvial system. Bring to light that the "naturalness" of the restored rivers might be questioned. Our research emphasizes the gap between the poor knowledge of the functioning of these rivers and the concrete objectives of the restoration works undertaken, including dam and weir removal. Account of the long-term history of fluvial systems is required, not only to produce a pedagogic history of the "river degradation" but more fundamentally (i) to situate the current functioning of the fluvial system in a trajectory to try to identify thresholds and anticipate the potential turning points in a context of climate and land use change, (ii) to understand the role of morphosedimentary legacies on the current dynamics, (iii) to open the discussion on reference functioning or expected states and (iv) to open discussion on the sustainability of ecological restoration. To conclude, we point out the necessity to take into account the hybrid nature of low energy rivers in rural environments and to develop specific evaluation protocols which would include both biophysical processes and usual human activities which could be a way to share the evaluation and overcome conflicts between socioeconomic needs and environmental issues.

1. Introduction

Our inherited waterways have been profoundly altered by human intervention and the question of their physical restoration has been debated since the 1970s (Downs and Gregory, 2004). In Europe, this process is included in the context of the Water Framework Directive (WFD). Enacted in 2000 on a Europe-wide scale, this was implemented in France in 2004 and then complemented by the Law on Water and Aquatic Environments in 2006 which instituted the restoration of ecological continuity as a leading tool for the re-establishment of river quality and recent environmental laws and regulations, especially those by the "*Grenelle de l'Environnement*" Forum in 2009, support these same principles. Such regulatory measures, combined with the principles of ecological restoration (Clewel and Aronson, 2010), stimulate direct interventions on regulated rivers with the aim of re-establishing the fluvial dynamic necessary to guarantee biological diversity (Boon and Raven, 2012). Thus, following the United States (Bernhardt et al., 2005), there has been a significant paradigm change in river management in Europe since consideration of biodiversity is imposed alongside the management of water levels and quality (Sear and Arnell, 2006). In France, this is more specifically seen by the increase in projects of removal or leveling of structures built across rivers, such as weirs and dams, considered as obstacles to fish migration and sediment transport (e.g. Petts, 1984; Petts and Amoros, 1996; Petts and Gurnell, 2005). The rate of longitudinal discontinuity ("*taux d'étagement*") has become one of the emblematic targets for ecological restoration of the rivers in France. The "National plan for restoration of ecological continuity of waterways" (2009) identified 1200 high-priority works among 70,000 works inventoried as obstacles to water flow in France (ONEMA, 2013). This development of ecological management places channel

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dynamics at the center of management concerns, including in lowland waterways. The regions of northwest France are those for which such operations are today among the most advanced (Germaine and Barraud, 2013a, b). More than 2500 obstacles to fish and sediment movement have been inventoried along the channels in Lower Normandy (ONEMA, 2013). Of these works, 110 are considered a priority under the Grenelle de l'Environnement and 97 in Priority Zone 1 under the Eel Plan. This policy of channel restoration is essentially funded by the Water Agency of Seine–Normandy and applied by local authorities. Due to the development of hydromorphological issues, the number of river technicians has increased from 5 to 6 to more than 40 in 20 years, and the total annual budget for restoration operations is now 4.6 million euros (S. Weil, oral communication, 12/20/2013), evidencing the emergence of a business for river restoration (Lave et al., 2010; Lave, 2012; Small and Doyle, 2012).

Discussions of the objectives and means of ecological restoration of rivers have been widely developed in recent years (e.g. Downs and Gregory, 2004; Sear and Arnell, 2006; Darby and Sear, 2008; Egan et al., 2011; Morandi and Piégay, 2011; Boon and Raven, 2012; Kondolf, 2012; Lave, 2012). This article puts into perspective the hydrogeomorphological restoration projects in progress by examining their methods and objectives with respect to the long-term trajectory of low energy rivers and understanding of contemporary dynamics. It is based on geomorphological, paleoenvironmental and historical research that enables very accurate documentation of the nature and place of the different legacies in the fluvial systems. This involves consideration of indirect changes in the fluvial system due to human modification of catchments over the last few millennia (Brown, 1997; Gregory, 2006; Notebaert and Verstraeten, 2010) in order to go beyond the temporal scale of the Industrial Era that often serves as a point of departure for studies of contemporary channel dynamics. Indeed, the reflection of field managers on the reference states and/or functioning of rivers to be restored is often based on historical documentation rarely older than the 18th century (e.g., James et al., 2009; Malavoi and Bravard, 2010; Comiti, 2012; Rinaldi et al., 2013). This is crucial for the rivers studied because their low energy implies long-term morphological adjustments for which the controlling factors are difficult to identify in contrast with high energy streams which can rapidly adjust their morphology to changes in governing conditions, making them easier to track (e.g., Liébault and Piégay, 2002; Comiti, 2012). We aim to demonstrate the relevance of a holistic approach to these specific fluvial systems that includes the collection of baseline data (Downs et al., 2011) and understanding of the trajectories over the long-term to develop objectives for sustainable management (Brown, 1997, 2002; Downs and Gregory, 2004; Brierley and Fryirs, 2005; Froyd and Willis, 2008; Hughes et al., 2008; Higgs et al., 2014; Kondolf and Podolak, 2014). The extent to which present understanding of the low energy systems is, and could be, used is discussed and the requirements for future research identified.

2. Study area, methods and previous research

2.1. Low energy river systems in western France and the Seulles river basin

Lowland rivers in western France have a fluvial pattern typified by single-thread channels, sinuous and meandering, bounded by cohesive loamy alluvial plains (Nanson and Croke, 1992). They generally have dynamics typical of inactive meandering systems with a weak coarse bed load (Brierley and Fryirs, 2005). The Seulles River is an order 5 river, according to the Strahler classification, representative of the region because it is incised in the crystalline basement of the Armorican massif upstream and the westernmost part of the Paris Basin downstream. It is 70 km long and at its mouth, into the English Channel, has a mean monthly discharge of 2.5 $m^3 s^{-1}$ (9.7 $L s^{-1} km^{-2}$). Its catchment (430 km^2) is located about 20 km west of Caen (Fig. 1). It has a pluvio-evaporal oceanic climate with mean rainfall between 680 mm near the English Channel and 820 mm further upstream. The source is in the Armorican Massif characterized by a Bocage landscape (286 m asl). Upstream, the crystalline substrate (schists, sandstones and conglomerates) favors a higher drainage density and the river has a single fairly straight channel, < 5 m wide, with bed slope between 5 and 10‰ in a partly confined valley. Downstream, the river and its two main tributaries (the Thue and the Mue) cross onto a limestone plateau (Bathonian and Bajocian formations) with openfield landscape at an altitude between 50 and 80 m asl with steep-sided valleys. The bed slope strongly decreases, not exceeding 0.6‰, and the valley widens (70 to 150 m) generating a laterally unconfined low energy setting. Here, it has a single sinuous to meandering channel, 8 to 11 m wide, that intersects the main aquifers of Lower Normandy, which significantly temper the effect of rainy episodes on channel discharge (Fig. 2). The modern hydrological and sedimentary dynamics of this catchment are now well-known due to continuous monitoring (2009–2012) of hydrological and suspended sediment flow recorded at four points of the catchment every 6 min (Viel, 2012; Viel et al., 2013a, 2014a; Fig. 1). An evaluation of the specific stream powers was done at 11 points on the channels of the Seulles and its tributaries (Fig. 1). The values obtained range from 1.5 to 85 W m^{-2}. Values were highest upstream, between 35 and 85 W m^{-2}, while the downstream Seulles, the Mue and the Thue rivers have very low specific stream powers, generally less than 10 W m^{-2}, largely lower than the published value needed for geomorphological adjustment (34–35 W m^{-2}; e.g., Brookes, 1987; Bizzi and Lerner, 2015). Bedload transport is negligible in the total load. Measurements show that the catchment has a low level of specific erosion, estimated at 18 t $km^{-2} yr^{-1}$, mostly associated with the transfer of suspended sediment. Because, the lack of tributaries along the downstream section of the Seulles River, the annual contribution of the bank erosion to the sediment budget can be estimated from the sediment discharges measured at two successive stations (Fig. 1, Viel, 2012). These measurements were accompanied by qualitative evaluation of the degree of bank erosion along homogeneous sections and in situ monitoring of bank recession at four representative sites (Viel et al., 2013a). Estimation of the contribution of the hillslopes in the overall sediment flow in the Seulles catchment is based on detailed analysis of the hydrological connectivity and sedimentary cascade between cultivated slopes and channels (Viel et al., 2014a,b).

2.2. A brief history of the Seulles River and the small low energy rivers of Western Europe

Geomorphological research on the long-term dynamics of the Seulles fluvial systems was initiated with an exhaustive study of the sedimentary record in the Mue Valley (Lespez et al., 2008). That work was extended to include the entire catchment and the approach expanded to determine the Holocene catchment sediment budget using quantification methods developed in Western Europe (e.g., Notebaert et al., 2011). Holocene deposits are 1.5 thick upstream and 15 m downstream in the Seulles catchment. Sediment mass accumulation was estimated by calculating the volume mass of the sediment, determined by representative sampling of the different facies of the alluvial sedimentation. This generated a value of 1.18 t m^{-3} for the loams on the valley bottom with a quite uniform particle size (mode: 20–60 μm) that form more than 85% of the Holocene sedimentary record. The chronological framework was then established using AMS dates (Lespez et al., 2008, 2012, 2013). For recent centuries, historical archives provide information on hydraulic construction and have been complemented by studies of large-scale drawings, especially the *plan-terriers* and road maps (1/6000 and 1/8000), which are useful documents to evaluate the state of the river (Lespez et al., 2005, 2012).

Three to four main phases in valley bottom accumulation have been identified, based on the calculated aggradation and specific erosion rates (Fig. 3). In general, after the deposit of gravels, sands and sandy silts attributed to the last glacial period (Weichselian), we see a pattern of channel incision during the Preboreal. The first phase of Holocene sedimentation was dominated by authigenic sediments which indicate