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Assessing channel response of a long river influenced by human disturbance

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ABSTRACT

This paper describes an approach to assess channel changes of a long anthropogenised river (the Middle Loire River) over decadal timescales. Channel changes are evaluated along geomorphically homogeneous river reaches. The classic geomorphic parameters (active channel width, bed slope, grain size) are complemented with parameters extracted from a 1D hydraulic model: width–depth ratio, effective bed shear stress and specific stream power calculated for the biennial discharge assimilated to bankfull flow conditions. The delineation of reaches is undertaken by combining visual inspection with the implementation of simple statistical tests to corroborate discontinuities in flow and sediment transport. The 450 km long study area has been divided into 167 homogeneous reaches. The general trends observed over the last fifty years are narrowing of the active channel width and incision of the river bed. However, changes in bed level and active channel width are not consistently correlated. Channel changes at the reach scale are mainly controlled by the presence of former sediment extraction sites. Significant incision is observed at the peak of the in-stream sediment mining period. This was followed by channel recovery when extractions stopped. The 1D numerical model provides a more rigorous manner to derive hydraulic parameters. The effective bed shear stress made dimensionless by its critical value and the width–depth ratio helps to explain observed channel responses more effectively by relating patterns to geological units along the Middle Loire.

1. Introduction

Natural alluvial channels adjust their slope and shape in response to water and/or sediment inputs, whether as a consequence of climate change or anthropogenic influences. Since channel changes can have detrimental effects on flood extent, groundwater recharge and the stability of infrastructure and ecology (Bravard et al., 1999), better understanding of channel adjustments is crucial to predict future evolution and thus adapt river management strategies.

As river managers are working to understand and/or reverse channel changes, geomorphic reach scale assessments are being developed to support restoration interventions (e.g. Brierley and Fryirs, 2005; Kellerhals et al., 1976; Montgomery and Buffington, 1997; Rinaldi et al., 2013; Rosgen, 1994). These approaches tend to perform poorly on anthropogenised reaches as human influences such as channel embankments and gravel extraction have significantly altered some of the basic variables that go into most classification schemes.

Often, designation of reach boundaries can be subjective and difficult to reproduce (Miller and Ritter, 1996; Simon et al., 2007). In order to improve the detection of threshold conditions along the river continuum, statistical algorithms have been implemented to enhance the robustness of reach definitions (Leviandier et al., 2012; Orlowski et al., 1995). The use of statistical algorithms for detecting homogeneous patches along a continuum has been widely applied in hydrology, ecology and geography (e.g. Buishand, 1984; Clark et al., 2008; Clément and Piégay, 2003).

Whilst reach scale approaches are undeniably valuable, they generally contain limited analysis of vertical characteristics, with water depth often estimated on site (Rosgen, 1994), or using "hydraulic geometry" relationships (Leopold and Maddock, 1953), or a simple Manning Strickler equation, or more recently using hydraulic models (Armas et al., 2012). Site assessment is obviously not appropriate for long river reaches. Although empirical equations can provide an acceptable approximation, hydraulic models provide more robust information (see Aggett and Wilson, 2009; Armas et al., 2012; Zilani and Surian, 2012).

This paper uses multi-disciplinary tools to analyse channel changes among a relatively large river, the Middle Loire (France), that has been characterized by different channel types and influenced by human disturbances. The specific objectives are: (1) to delineate homogeneous river reaches using a visual distinction of changes approach and simple statistical tests, (2) to analyse channel changes observed on the Middle Loire River over the last 50 years and to assess if reaches delimited by natural features behave differently from "anthropogenized" ones, (3)

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to relate channel adjustments to hydraulic parameters computed with a 1D hydraulic model, and (4) to assess the influence of instream sediment mining on the evolution of the Middle Loire River.

2. Study area

The Loire River is the longest river in France with a length of 1012 km. Its drainage area covers 117,000 km^2, one fifth of France's area. Four major tributaries feed the river: Allier, Cher, Vienne and Maine. Bedload sediment inputs come mainly from the Allier and the Vienne. The reach studied is the Middle Loire, which extends from the confluence with the Allier River to the confluence with the Maine River. The downstream boundary was extended to the gauging station of Montjean-sur-Loire to facilitate hydraulic modelling, that is a distance of about 450 km (Fig. 1). The Middle Loire River is characterized by a section with a multiple channel configuration downstream of the confluence with the Allier River, a short meandering section upstream of Orléans and a multiple channel system with the presence of numerous vegetated islands and sand bars in the downstream section.

2.1. Hydrologic characteristics

The Middle Loire River has a highly variable hydrologic regime: very low discharge during the summer and high magnitude flows in winter and spring. Cumulative departure from the mean annual discharge for the period 1863–2011 is presented for Blois gauging station in Fig. 2a. Blois is representative of the hydrologic regime of the Middle Loire; it is located 250 km downstream of the confluence with the Allier River. The curve ascends during wet periods and descends during drier periods. Despite major flood events in 1846, 1856 and 1866, the end of the nineteenth century presents a relatively stable flow regime. Alternating wet (from 1905 to 1941 and from 1973 to 1984) and dry periods (1941–1964 and 1984-today) are evident.

The last major flood events on the Loire River were recorded in the second half of the nineteenth century. These extreme events had an estimated return period of 200 years and reached an estimated discharge of 7 200 m^3/s at Gien (Dacharry, 1996; Duband, 1996). Since then, other floods happened, but on a smaller scale. Dams built at the upstream end of the catchment have only impacted upon the 1996, 2003 and 2008 floods.

At Gien, located 564 km downstream from source, flood events with a return period of 2 years correspond to a discharge of 1600 m^3/s. Fig. 2b examines the flood frequency and magnitudes of flow recorded at Gien between 1936 and 2011. The data were compiled from peak annual discharges with a threshold of 1600 m^3/s. Floods above 2700 m^3/s (equivalent to an event with a ten year return period) have been relatively rare throughout the period (5 occurrences).

2.2. Geological settings

The Loire River basin is characterized by various lithological units influencing its layout and valley setting (Babonaux, 1970; Brossé, 1982). Upstream of Gien (Fig. 1), the north/south alignment of the river is associated with faults in the Hercynian socle (Alcaydé and Gigout, 1976; Debrand-Passard et al., 1998; Nelhig, 2010). On the Middle Loire, four geological units can be distinguished: Jurassic limestones from the confluence with the Allier River to 90 km downstream, then Tertiary formation (lacustrine limestones and alluvial formation) to downstream of Blois (located at a distance of 696 km from source), Cretaceous chalks to the confluence with the Maine River and Hercynian metamorphic rocks on the downstream section (Fig. 3). The first two geological units are characterized by similar mean slope ($s_{b1} \approx s_{b2} \approx 0.4$ m/km), whereas units 3 and 4 have a lower mean slope value ($s_{b3} = 0.29$ m/km; $s_{b4} = 0.18$ m/km).

The nature of sediment available is associated with crystalline and volcanic rocks from the upstream Loire, locally enriched by flint coming from sedimentary formations of the Parisian Basin. Sediments are dominated by coarse sands, quartz, feldspar and gravels (Macaire et al., 2013). Champion et al. (1971) investigated the thickness of alluvia in the substratum and reported layers varying between 3 m at Amboise (730 km from source) to 10 m at Cosne-Cours-sur-Loire (522 km from source) with an average value of 5 m. Alluvia thickness is the largest where the floodplain is wide and in confluences zones (Donsimoni et al., 2008).

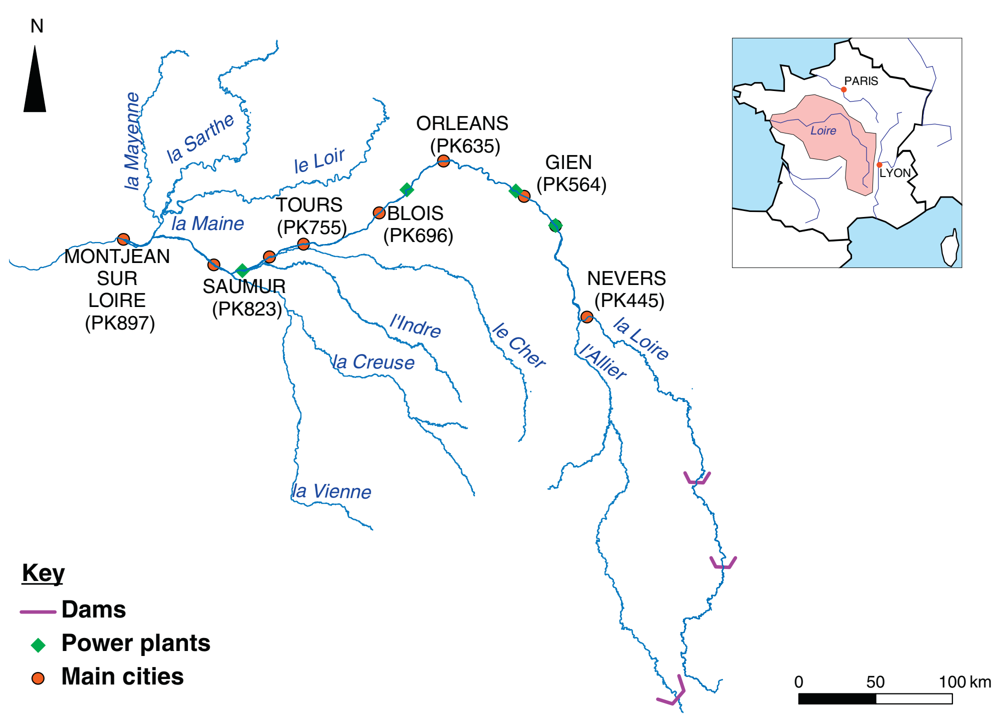

Fig. 1. Location map showing the study reach.