Geomorphology 230 (2015) 125–137

Contents lists available at ScienceDirect

Geomorphology

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

Morphological evolution of a rural headwater stream after channelisation

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A R T I C L E I N F O

Article history:
Received 19 May 2014
Received in revised form 14 November 2014
Accepted 18 November 2014
Available online 22 November 2014

Keywords:
Channelisation
Historical cross sections
Sediment budget
Fine sediment
Uncertainties

A B S T R A C T

In recent decades, stream valleys have been profoundly modified by the construction of weirs and dams and by channelisation. Channelisation modifies the morphology of streams and induces changes in their energy regime and sediment transport capacity. These types of changes in the channel morphology have to be quantified to allow the implementation of management strategies to regulate sediment transfer. However, studies over an entire stream using historical comparisons remain scarce, and the associated uncertainties have not yet been resolved.

In this study, the sedimentary response to channelisation on a medium time scale (42 years) of a French river known as the Ligoire is investigated. This river is the main channel of a small rural headwater catchment that has been channelised over 21 km. We have used the historical cross sections before and after channelisation and the current ones, and the objectives of this study were as follows: (1) to develop a methodology of cross section superposition and the associated uncertainties; (2) to quantify the erosion and aggradation processes in the bed and on the banks along the bed profile; and (3) to calculate a sediment budget for the entire stream and determine the relative contributions of the banks and the streambed to this budget.

A comparison of the cross sections before and after the channelisation shows that the morphology of the stream has been completely altered: the main channel length was reduced by 10%, the bankfull width was increased on average by 63%, and the slopes were smoothed. A total of 60,000 m^3 of sediments was excavated during the channelisation works.

Our results indicate that erosion is the dominant process: over 63% of its length, the streambed was incised by 0.41 m on average; and over 60% of its length, the banks were eroded by 0.20 m on average. The successive patterns of erosion and deposition along the stream are the result of the cumulative effects of channelisation and of the presence of weirs and artificial knickpoints in the Ligoire channel.

The vertical uncertainty of the elevation of the historical cross section is an important parameter for controlling the areas and sediment budget values. Using Monte Carlo methods, we found that 1000 sediment budgets from different profile shiftings are necessary to obtain a variation coefficient below 0.1%. The overall mean stream sediment budget for the period 1970–2012 is -9358 $\pm$ 412 m^3, with 66% originating from the banks and 34% from the streambed. Relative to the Ligoire watershed surface, the stream sediment yield is 2.71 $\pm$ 0.12 $m^3.km^{-2}.y^{-1}$.

The approach developed in this study is easily replicable and relatively cheap and provides an integrated quantified, overview of the morphological adjustments after channelisation works on a stream.

1. Introduction

To allow for the transformation of extensive agriculture into intensive agriculture, most rural watersheds in lowland areas of Europe have been completely remodelled since the early twentieth century (Stoate et al., 2001). Changes generally included reparcelling of the land, modification of the drainage, and elimination of landscape elements (such as hedges and wetlands) that had dampened liquid and solid fluxes (De Groot et al., 2002; Van der Zanden et al., 2013). Stream valleys have been profoundly modified through the construction of weirs and dams and by channelisation. The latter process modifies the morphology of a stream to reduce the frequency and magnitude of floods, drain new agricultural land, favour navigation, and reduce erosion in the channel (Brookes et al., 1983). The different methods of channelisation include the recalibration, realignment, or rectification of meanders, damming, or levee construction, bank protection, and bed cleaning (Brookes, 1985).

In the 1980s, certain studies (Brookes, 1985; Simon and Hupp, 1987) mentioned that channelisation operations can cause serious and almost systematic morphosedimentary dysfunctions. Indeed, increasing the slope gradient and associated transport capacity of a stream (Wilcock, 1991) leads to bed scouring and bank erosion in the high-energy sections (Surian and Rinaldi, 2003; Simon and Rinaldi, 2006), resulting in

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http://dx.doi.org/10.1016/j.geomorph.2014.11.011
0169-555X/

the transport of eroded sediment downstream and its accumulation in low-energy reaches (Nakamura et al., 1997; Kroes and Hupp, 2010). This aggradation primarily involves fine sediment, which may clog the streambed (Landwehr and Rhoads, 2003), deteriorate the physico-chemical water quality (Shields et al., 2010), and degrade aquatic habitats (Steiger et al., 2005). In addition, changes in land use can result in an increasing supply of fine sediment and, thus, accentuate the aggradation phenomenon (Walling and Amos, 1999; Collins and Walling, 2007). Moreover, the suspended sediment deteriorates water quality though pollutants adsorbed on the fine fractions, such as heavy metals, nutrients, organic contaminants, or pesticides (Kronvang et al., 2003; Walling et al., 2003; Ballantine et al., 2009).

These environmental problems have led to the development of different approaches to quantifying the production, transport, and deposition rates in each of the geomorphological units of a watershed. One of the most frequent approaches is the sediment budget, which has been widely employed as a sediment management tool (Dietrich et al., 1982). These budgets help establish sustainable management strategies for sediment transfer (Walling and Collins, 2008). Furthermore, these budgets show that the sediment contribution from the banks of a channel on a decadal time scale in temperate rural catchments is ~10% in the case of streams slightly impacted by human influence (Walling et al., 2002) but can reach more than 50% in channelised streams (Wilson et al., 2008; Day et al., 2013; Palmer et al., 2014). Thus, the sediment emanating from a channelised river can represent a large proportion of the total sediment yield from a landscape (Simon and Rinaldi, 2006). This contribution varies with the size and extension of the modifications to the fluvial corridor (Malavoi and Adam, 2007), but it also varies based on changes to the watershed (Schilling et al., 2011).

This type of dysfunction has been observed over almost 300,000 linear kilometres in the USA (Schoof, 1980), 40,000 km of streams in Great Britain (Brookes et al., 1983), and tens of thousands of kilometres of streams in France (Malavoi and Adam, 2007). Nevertheless, the quantification of the morphosedimentary impact of channelisation on such streams and the contribution of the channels to the sediment budget commonly remain underdocumented (Heitmuller, 2014). Moreover, although most qualitative studies dealing with the impact of channelisation only focus on the channelised reach, channelisation also causes morphological readjustments in upstream and downstream adjacent reaches.

In fact, regular and comprehensive monitoring of the morphology of a stream is difficult (Sear and Newson, 2003), as it requires the deployment of high-spatial-resolution instrumentation over several decades, which limits the number of available studies (Gomez et al., 2007; Heitmuller, 2014). To overcome this lack of monitoring, the impact of channelisation on the stream banks and bed morphology is commonly quantified by retrospective studies. The pre-works morphology is generally extracted from aerial photographs (or occasionally from historical cross sections) and then compared to the current morphology by means of recent aerial photographs (Kesel and Yodis, 1992; Sipos et al., 2007; Segura-Beltrán and Sanchis-Ibor, 2013), newly measured cross sections (Terrio and Nazimek, 1997; Rinaldi and Simon, 1998; Kiss et al., 2008; Heitmuller, 2014), or airborne LiDAR topographic surveys (Rhoades et al., 2009; De Rose and Basher, 2011; Day et al., 2013; Kessler et al., 2013). Still, retrospective studies based on airborne methods are mostly restricted to evaluating morphological changes in stream banks and do not provide the three-dimensional morphology of the channel. Therefore, Gregory (2006) recommends the use of cross sectional surveys at different time steps for the quantification of changes affecting the river bed and banks. However, in many cases, the uncertainties of the measurements are not clearly defined, and furthermore, the use of historical cross sections over a medium time scale remains scarce.

In this context, the objective of this study is to investigate the morphosedimentary response to channelisation on a medium time scale (42 years) of a stream in a small headwater within a lowland catchment that has been strongly impacted by agricultural practices. The main objectives of the investigation consist of (i) developing a methodology for comparing cross sections and assessing the associated uncertainties; (ii) quantifying erosion and aggradation processes in the bed and on the banks along the channel profile; and (iii) calculating the sediment budget for the entire stream and determining the relative contribution of the banks and the streambed to this budget.

2. Study area

The Ligoire drainage basin is an 82-km^2 watershed located in the southwestern part of the Paris sedimentary basin; its length is 19 km from southwest to northeast, and its elongation ratio is 0.52 (Fig. 1). The area is hilly, but it has a moderate relief. The slopes have an average gradient of 5%, and elevations range from 60 m asl at the catchment outlet to 143 m asl, which is the highest point of the divide at the northeastern edge of the basin.

The geology of the Ligoire basin is characterised by an east–west trending anticline. The incision of the anticline during the Quaternary period led to the outcropping of Cretaceous rocks. In the Ligoire valley, these geological formations are represented in the stratigraphic order by micaceous chalks including flintstones (middle Turonian, C3b), by early Turonian argillaceous chalk with flints (C3a), and by late Cenomanian marlstone (C2). These formations are overlaid by sandy micaceous limestone with flints (late Turonian), Senonian clays and flints, Tertiary sandy-clay deposits, and Quaternary aeolian loess. Land use consists mainly of intensive agriculture, and 75% of the basin surface is covered by crops (corn, wheat, and rapeseed).

The drainage network comprises 107 km of streams. The two main streams are the Ligoire trunk channel and its main tributary: the Riolle. The Ligoire is 21 km long, issues from a spring in the northeast of the basin at an elevation of 131 m asl and joins the Esves River at an elevation of 58 m. In 1970, to enable the transformation from extensive agriculture into intensive agriculture, the main channel of the Ligoire was entirely straightened and resectioned over 21 km, and artificial knickpoints have been implemented along the stream. The longitudinal profile of the channel bed is punctuated by several artificial knickpoints, such as masonry weirs, riprap infill of fords, and bridge pillars (Fig. 2). The most remarkable is found at the Verger mill, where a dam impedes sediment transfer to the downstream reach and enhances sediment deposition along a 1200-m reach upstream. Except for this 2-m-high dam, the drops over most of the obstacles do not exceed a few tens of centimetres.

Many of the morphological, sedimentary, biological and chemical dysfunctions described in the introduction are observed in the Ligoire River.

3. Material and methods

In France, many stream channelisation projects were carried out in the first half of the twentieth century (Bravard et al., 1999). Usually, the stream morphology was surveyed by means of cross sections, longitudinal profiles, and linear drawings on the cadastral maps of the period. These morphological data were used as a basis for designing the new morphology of the channelised stream. Information of this type shows strong potential to provide accurate data, and these data were used in the present study to quantify the hydraulic, morphologic, and sedimentary impact of the realignment and resectioning of the main stream. In this study, we analysed the changes in the stream morphology for two periods: (i) before and after the channelisation and (ii) after the channelisation and currently.

3.1. Stream morphology before and after the channelisation

Topographical data before and after the channelisation were extracted from surveys of the stream cross section carried out by the Public Works Department of the Indre-et-Loire province. A total of 135 cross sections were measured along the main channel. These data were