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Increase in soil erosion after agricultural intensification: Evidence from a lowland basin in France

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ABSTRACT

Changes in agricultural practices impact sediment transfer in catchments and rivers. Long term archives of sediment deposits in agricultural plains of northwestern Europe are rarely available, however, for reconstructing and quantifying erosion and sedimentation rates for the second half of the 20th century. In this context, a multi-parameter analysis was conducted on sedimentary deposits accumulated in a pond created in the 11th century and draining a 24 km^2 cultivated catchment in western France. This catchment is representative of cultivated and drained lowland environments where agriculture has intensified during the last 60 years.

High-resolution seismic profiles and surface sediment samples ($n = 74$) were used to guide the collection of cores ($n = 3$) representative of the sequence of sediment accumulated in the pond. The cores were analyzed to quantify and characterize the evolution of sediment dynamics in the pond.

The first land consolidation period (1954–1960) was characterized by a dominance of allochthonous material input to the pond. This input represents an erosion of 1900–2300 t km^{-2} yr^{-1} originating from the catchment. Then, between 1970 and 1990, the terrigenous input decreased progressively and tended to stabilize. Eutrophication and associated primary production increased in the pond. These processes generated the majority of material accumulated in the pond during this period. Further land consolidation programs conducted in 1992 generated a new increase in soil erosion and sediment input to the reservoir. For the last 10 years, terrigenous input to the pond corresponds to a catchment-wide erosion rate between 90 and 102 t km^{-2} yr^{-1}. While a strong decrease is observed, it still represents a 60-fold increase of the sediment flux compared to the pre-intensification period. These large temporal variations of sedimentation rates over a few decades underline the dynamics of sediment transfer and raise questions about the sustainability of soil resources in lowland temperate environments.

Introduction

Soil erosion has been identified by the European Commission as one of the most important factors of environmental degradation (Jones et al., 2012). Human activities and the intensification of agricultural practices in Western Europe have induced a significant acceleration of soil erosion during the second half of the 20th century. Land management, as consolidation operations, hedge removals, stream re-sizing and the implementation of drainage networks have increased runoff and sediment connectivity between eroding hillslopes and the hydrosystems (Evrard et al., 2007). This higher connectivity between sediment sources and the rivers has facilitated the transfer of fine particles to aquatic environments. A continuous supply of fine particles to ponds and reservoirs contributes to their filling and modification of ecological niches (Kiffney and Bull, 2000; Waters, 1995). Fine particles were

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also shown to be very efficient in transporting organic, radioactive and metallic pollutants to and within hydrosystems (Ayrault et al., 2014; Chartin et al., 2013; Desmet et al., 2012).

For Europe, Cerdan et al. (2010) compiled existing data at the plot scale and estimated the mean sheet and rill erosion rates on arable land to be 360 t km^{-2} yr^{-1}. However, there is a lack of knowledge regarding the fate and export of sediment towards lowland drained areas (Vanmaercke et al., 2011). Very little research exists on transfers of sediment for water bodies in small catchments (<100 km^2) exposed to Atlantic climate conditions in Western Europe. In these basins, the connectivity between hillslopes and rivers is often high and they are therefore considered as privileged areas for the export of eroded material. However, very few data are available to quantify the specific sediment production of lowland drained areas. In the absence of long term measurement of water quality and suspended sediment dynamics in drained environments, sediment deposits provide a promising tool to reconstruct the effect of land use change on sediment yields and soil erosion over the last decades. Lake and reservoir deposits have been widely used in contrasted topographic/climatic settings to investigate the link between human activity, soil erosion and sediment production, generally over long timescales (ranging between 10^2 and 10^3 yrs) (e.g. Macaire et al., 1997, 2010; Massa et al., 2012). In agricultural regions, most investigations were realized on downstream floodplain deposits, and few studies focused on sediment accumulation in upstream reservoirs/ponds. For instance, Foster et al. (2003) and Foster and Walling (1994) analyzed reservoir deposits to establish the link between land use change and sediment production in a small catchment characterized by a rolling topography. Dearing and Jones (2003) demonstrated an acceleration of sediment delivery during the 1950–1960 period in this small grazing catchment and attributed this increase to land use change. To the best of our knowledge, the temporal evolution of sediment dynamics has not been reconstructed for lowland cultivated catchments. Existing studies are generally restricted to short time periods. Verstraeten and Poesen (2002) proposed for instance a methodology to quantify the export of material from small agricultural catchments in Belgium, by using the sediment records of 21 flood retention ponds, but their records are limited to a few years.

The lack of information on the evolution of sediment/erosion dynamics for lowland drained catchments is therefore mainly explained by the difficulty to find an old sedimentary reservoir characterized by a high sedimentation rate as to reconstruct the link between land use change, soil erosion and sediment production. In this context, the characteristics of sediment deposits accumulated in a pond draining a 24 km^2 cultivated catchment of central France have been investigated. The study area has been selected as it is representative of the agricultural drained plains of Western Europe. An original multi-parameter approach was conducted in order to reconstruct the evolution of sediment dynamics as a result of land use changes during the second half of the 20th century.

Materials and methods

Study site

The Louroux pond drains a small agricultural lowland catchment (24 km^2) located in the south-western edge of the Parisian basin (France), in the Loire Valley (Fig. 1a). It is characterized by smooth topography (mean slope of 0.44%) with an altitude ranging between 99 and 127 m (Fig. 1c). Six different lithologies are found in the catchment: Senonian flint clays (23%), Ludian lacustrine limestone (6%), Eocene siliceous conglomerate (1.4%), Helvetian shelly sands (18%), post-Helvetian continental sands and gravels (32%) and quaternary loess (18%). Soils are mostly hydromorphic and prone to crusting. They are classified as Epistagnic Luvic Cambisols (Froger et al., 1994; Rasplus et al., 1982). The area is dominated by an Atlantic climate with a mean annual rainfall of 684 mm (between 1971 and 2000).

For more than 50 years, the Louroux catchment – as the large majority of agricultural plains in Western Europe – has been affected by intense modifications of land use and agricultural practices (Antrop, 2005). Before World War II, the Louroux catchment was a large wetland with hedgerows, and it was mainly dedicated to crop-livestock farming. Cereal production was only possible in a small part of the catchment because of unfit soil moisture conditions. After the war, agriculture modernization sought to evacuate the water in excess from the soils to allow for intensive cereal farming. The hedges have been progressively removed, and land has been reallocated on three occasions (first in 1935 and then in 1955 and 1992). Woodlands and grasslands are now marginal in the catchment (covering respectively 17 and 7% of the total catchment surface) (I and CLC2000, 2002). Streams have been created or re-sized (Foucher et al., 2015) to facilitate the evacuation of water from the hillslopes. Between 50 and 90% of the catchment surface has been drained. As much as 220 tile drain outlets have been identified across the entire catchment.

The Louroux pond (52 ha) was created in the 10th or 11th century (Fig. 1b). Water and sediment are supplied to the pond by five main tributaries that drain the catchment hillslopes. Overflow of the pond only occurs during high water levels in winter. This situation leads to massive deposition of fine particles in the pond during most of the year. A second pond (i.e. Beaulieu pond (3 ha)) was dug out in the 18th century to the west of the Louroux pond. Both reservoirs are directly connected. Nowadays, the Beaulieu pond is almost entirely filled with sediment (Fig. 1b). The Louroux pond has been drained on two occasions during the last 15 years (i.e. between 2001–2003 and in 2012–2013 for 1 year). An aerial LiDAR survey conducted in early spring of 2013 (i.e. during the last drainage period of the pond), underlines the very shallow character of the Louroux pond, with an average depth of 2 m, and a maximum depth of 4.8 m right in front of the dam (Fig. 2a).

Seismic survey

A high-resolution seismic survey was conducted during summer of 2012 across the Louroux pond. In total, 7.5 km-long high-resolution seismic profiles were collected (Fig. 2c) from an inflatable boat (Limnoraft). These analyses provide an overall picture of the sediment deposits, and allow to quantify the volume of sediment accumulated in the pond (Chapron et al., 2007; Twichell et al., 2005). Seismic profiles were collected with a parametric echo-sounder INNOMAR SES-2000 Compact®. The INNOMAR sonar is adapted to shallow water environments. The maximum theoretical resolution is 6 cm with a wavelength that can vary between 5 and 15 kHz. The wave speed in the water was defined at 1500 m/s. Positions were recorded with a GPS device coupled with the seismic acquisition system. Acoustic facies were correlated with observations made on the sediment cores.

Sediment sampling

Surface sediment

Surface sediment samples were collected during summer 2012. Based on the analyses made on these samples, spatial variation of sediment characteristics derived from surface sediment samples, was extrapolated to the entire pond. The samples were collected using a floating platform (quadriraft) and a short gravitational corer UWITEC of 90 mm Ø. In total, 74 surface samples (top 0–5 cm