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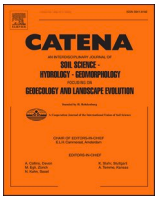

Holocene sediment budget for the Thue and the Mue catchments (NW France): European comparison and methodological issues

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ABSTRACT

To contribute to the understanding of Holocene sediment dynamics in Western Europe, a Holocene sediment budget is proposed for the Thue and Mue catchments (52 and 97 km^2 respectively) located in NW France. In this budget, soil erosion as well as colluvial sediment storage is estimated from soil profiles analysis for a representative catchment and extrapolated to the entire catchments. Alluvial sediment storage, including a chronology of the alluvial fills, has been quantified by augerings cores distributed on several transects located along the floodplain of the two rivers. The proposed sediment budget highlights significant sediment storage in the catchment: 12.3 Mt (32.5 %) is stored as colluvium and 15.5 Mt as alluvium (40.8 %), i.e. more than 70 % of eroded sediments on the slopes. The remaining eroded sediments (10.2 Mt) are considered to have been exported out of the catchments. The timing of slope erosion and colluvial storages indicates the initiation of soil erosion from the Neolithic period and an acceleration over the last 3 millennia. However, a long gap is observed between forest clearance, soil erosion and the acceleration of alluvial filling underlying a progressive improvement of the connectivity induced by a progressive transformation of the running water circulation within the catchment. The results thus highlight the complexity of Holocene sediment dynamics across spatial and temporal scales and emphasize the necessity to integrate the question of the efficiency of the sediment cascade particularly induced by the landscape structure and drainage density.

1. Introduction

Spatial patterns of sediment deposition within a catchment and sediment export out of a catchment is often variable over timescales of centuries to millennia and more (Hinderer, 2012). This relates to variations in sediment production through erosion processes and sediment removal from storages influenced by (i) internal controlling factors of the hydrosystem such as slopes, geological setting or the catchment morphology and (ii) external controlling factors such as climate and land use. It also relates to changing sediment pathways as a result of changes in connectivity within the catchment (Trimble, 2009). Understanding these variations is important to understand the functioning of the catchment under changing land use and climate conditions and to predict the future sediment transfers under those conditions. Moreover, quantifying the redistribution of sediment is crucial to assess the significance of soil erosion and to compare erosion rate and pattern from catchments to others (Dotterweich, 2008; Notebaert and Verstraeten, 2010).

Research on sediment dynamics during the Holocene has often focused on the role played by climate and land use. Holocene climate variability has been clearly demonstrated (Mayewski et al., 2004; Wanner et al., 2008; 2011) and, until 7000–7500 cal. BP, sediments dynamics evolution is principally explained by climatic changes in Northwestern Europe (Notebaert and Verstraeten, 2010). During the Middle to Late Holocene, long-standing research has shown that luvisols developed on chalky plateaus and brown soils on slopes were subjected to severe erosion during the Bronze Age in relation to agricultural intensification (Pastre et al., 1997; Bell, 1992; Allen, 1992; Macphail, 1992; Macaire et al., 2002; 2006; Notebaert and Verstraeten, 2010; Houben, 2012; Lespez et al., 2015). For French (2003), this degradation

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would locally occur earlier, as early as the Neolithic (4th millennium BC, c. 6000–5500 cal. BP) and studies of soils under megalithic monuments have also demonstrated early erosion of soil profiles. It has had locally irreversible consequences by favoring the extension of thin soils as rankosoils (French, 2003; French and Lewis, 2005). These findings have been linked to an increase of overbank silt deposition in the floodplain from the Iron Age (Brown et al., 1994; Foulds and Macklin, 2006), rarely sooner (Brown et al., 2013), and mostly later in relation with the intensification and extension of farming activities (Brown, 2009; Chiverrell et al., 2009; Brown et al., 2013). More generally, with the introduction of agriculture during the Neolithic period (7500–6000 cal. BP), the role of climate become less clear as sediment dynamics within catchments get increasingly influenced by anthropogenic deforestation and agricultural practices (e.g. Dotterweich, 2008; Notebaert and Verstraeten, 2010; Houben, 2012; Lespez et al., 2015; Verstraeten et al., 2017; Brown et al., 2018). Thus, there is a general consensus on the overwhelming role of anthropogenic land use changes on the evolution of sediment dynamics, however, it remains difficult to measure the role of agricultural development on widespread silting up of the valley bottoms.

This difficulty is primarily due to the diversity of internal and external controlling factors of the hydrosystem that influence sediment production, transport and redistribution in the catchment and the diversity of temporalities, thresholds and spatial and temporal scales at which these controlling factors operate (Amoros and Petts, 1993). Climate and land use characteristics may also combine with slopes, geological context or the morphology of the catchment to define a degree of sediment connectivity inducing a more or less efficient sediment cascade. As a consequence, human impact on sediment systems is non-linear in space and time and specific trajectories can be observed in similar climatic, geologic or land use context (Verstraeten et al., 2017). Hence, case-studies from different environmental settings are required to compare and to increase our understanding of the sediment cascade under human impact.

The difficulty is also due to the multiplicity of data required to clearly quantify slope erosion and sediment redistribution into the catchment. The construction of the sediment budget (Reid and Dunne, 2003; Trimble, 2009), developed to quantify sediment inputs, transport, sinks and export, appears as the most efficient way to understand the Holocene sediment dynamics within a catchment (Houben et al. 2009; Notebaert et al., 2009; Notebaert and Verstraeten, 2010). However, studies quantifying all components of the sediment budget remain limited. In Northwestern Europe, several studies have estimated minimal past erosion rates from the quantification of the alluvial storage (Rommens et al., 2006; Hoffmann et al., 2007; Stolz, 2011b). However, these studies do not consider the intermediate sediment sinks which are often more important than alluvial deposits (Hoffmann, 2013). Few studies have attempted to quantify the rates of erosion on the slopes and colluvial and alluvial deposition at the scale of medium size fluvial catchment (>50 km^2) for a time period from centuries to millennia (Notebaert et al., 2009; Houben, 2012). Several studies have demonstrated the large volume of sediment stored on slopes leading to a high underestimation of Holocene soil erosion rates (Notebaert et al., 2009; Houben, 2012; Hoffmann et al., 2013). Thus, the quantification of sediment sinks in the catchment is of high importance to better estimate soil erosion rates and appreciate the complexity of sediment dynamics during the Holocene.

With this study, we aim at contributing to the understanding of Holocene sediment dynamics in Northwestern Europe and contribute to the discussion on the role of the anthropogenic changes in the triggering of sediment erosion, transport and deposition. Our objective is to construct a detailed Holocene sediment budget for two loess catchments located in western France, a region which has until now received little attention, by combining alluvial and colluvial storage quantification and erosion estimates. The alluvial filling and the chronostratigraphy of the two rivers are already well known (Lespez et al. 2008; 2015) and this study adds estimation of erosion processes on slopes and colluvial deposition. The results will complement the existing sediment budget studies in France (e.g. Orth et al., 2004; Macaire et al., 2002; Macaire et al., 2006; Notebaert et al., 2014), the Benelux (e.g. Rommens et al., 2006; De Moor and Verstraeten, 2008; Verstraeten et al., 2009; Notebaert et al., 2009; Notebaert et al., 2011) and Germany (e.g. Förster and Wunderlich, 2009; Stolz, 2011a; Stolz, 2011b; Houben, 2012) to get more insights in the regional variations in Holocene sediment dynamics. Finally, we would also discuss difficulties of accurate comparison of several sediment budgets realized in Northwestern Europe and the role of connectivity, in addition to alluvial and colluvial sedimentation rates, to interpret erosion processes and their evolution under human impact in a catchment.

2. Study area

2.1. A typical feature of low energy water system in the Paris Basin

The Thue and Mue are two small catchments (52 and 97 km^2 respectively) located in Normandy, western France (Fig. 1). They are downstream tributaries of the Seulles river, a small coastal river situated west of the Caen conurbation. The region has a temperate humid climate with a mean annual rainfall of 740 mm (1990–2020), well distributed over the year. The watersheds have a similar geological setting. The valleys incise the Bathonian and Bajocian limestones and Bathonian marls of Port-en-Bessin and plateaus are mostly covered by late Pleistocene loess (Lautridou, 1985). The topography is characterized by flat plateaus at an altitude between 50 and 80 m a.s.l. with generally low gradient slopes (less than 5 %), in which the dry valleys and rivers are 15 to 40 m incised. However, slope gradient can reach more than 25 % in the downstream part of the catchments, where valleys are more deeply incised to reach the base level of the Seulles estuary. Floodplains are often between 70 and 220 m wide. Both rivers at a general level show a sinuous to meandering pattern, 8 to 11 m wide, although long stretches have been straightened and channelized during at least two millennia (Lespez et al., 2008; 2015). The Mue is 24 km long, the Thue 15 km, and they are 4th Strahler order rivers. They have a specific water discharge of 5.5 $l.s^{-1}$ km^{-2}. These are typical features of low energy river systems with longitudinal slopes falling below 3 ‰ and weak specific stream power (<10 $W.m^{-2}$). Sediments exported from the catchment are almost entirely composed of suspended load (Viel, 2012; Viel et al., 2014b). On the plateaus, luvisols have developed from the loess deposits which are truncated shallow especially in steeper sloping areas. The luvisols are mostly used for intensive cropland agriculture (wheat, barley, rape, beet, corn, etc.) while the steeper slopes are mostly covered by grassland, fallow land and forest. Floodplains constitute of cohesive loamy deposits. Wet fallow land, meadows and associated grounds are typical landscapes on valley bottoms.

The Seulles catchment (254 km^2 upstream of the Thue confluence) offers a good geographical and scientific context to discuss results obtained in the Thue and Mue catchments. The Seulles river is 70 km long and has a mean monthly discharge of 2.5 $m^3.s^{-1}$ (9.7 $l.s^{-1}.km^{-2}$) at the outlet. The source (286 m a.s.l) is located in the Armorican massif and characterized by a bocage landscape. Upstream, the crystalline substrate (schists, sandstones and conglomerates) favors a higher drainage density than those observed in the lower valley and the Thue and Mue catchments and steeper slopes are observed. The river has a single fairly straight channel, 5 m wide, with bed slope between 5 and 10 ‰ and specific stream power is in a range from 35 to 85 W m^{-2} in the Armorican bloc (see Lespez et al., 2015 for more details). The current hydrological and sedimentary dynamics of the Seulles catchment are also well-known. Continuous monitoring (2009–2024) of suspended sediments and water discharge are recorded at four points of the catchment from the bocage area to the downstream after the confluence with the Thue and Mue rivers at a time step of 6 min (Viel, 2012; Viel et al., 2013; 2014a).

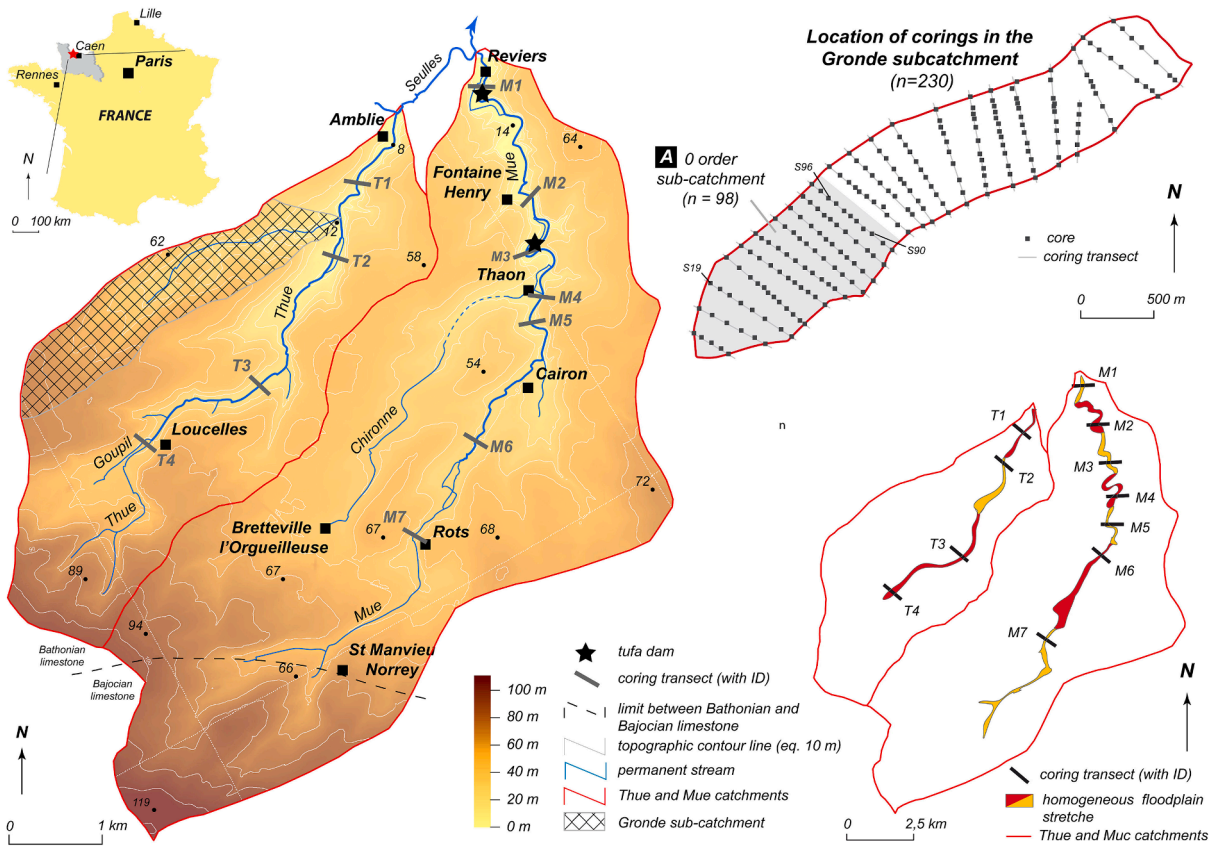

Fig. 1. Location and geomorphological characteristics of the study area. Location of homogenous stretches, coring transects (M1 – M7; T1 – T4) and cores on the Gronde subcatchment.

2.2. Previous work on the Thue and Mue alluvial and colluvial sedimentation

Geomorphological research on the long-term changes of the environment and, particularly, investigations on the anthropogenic impact on the fluvial system were operated in the Thue and Mue catchment. Based on palaeoenvironmental analyses, studies of the Holocene alluvial filling give information about the chronology of the alluvial silting on the valley bottom (Lespez et al, 2008) while, the study of the pedosediments of the Plain of Caen, according to micromorphological analyses, give precious indications of the chronology and process of the soil erosion from the Neolithic period (Germain-Vallée and Lespez, 2011).

For the Thue and Mue catchments (Fig. 2), available radiocarbon dates (Lespez et al., 2008) indicate that the onset of floodplain sedimentation is during the Early Holocene period: before 10 550–10 237 cal. BP at Thaon (Old Church) and before 9181–8 779 cal. BP at Cairon. After a period of incision, silts (0.3–1.0 m thick) are deposited during the Boreal period (around 10 000–9 000 cal. BP). Next, the sedimentation is mainly characterized by calcium-carbonates deposited in the upper floodplains (Fig. 1, M6, M7, T3, T4), including numerous tufa deposits. From *c.* 7450 cal. BP to 2750 cal. BP, the sedimentation is strongly controlled by the formation of the tufa dams across the valley bottom at Thaon and Cairon (M1, M3, T1), providing an autogenic control on upstream sedimentation (M2, M4, M5, T2). Tufa deposition then slows down from around 6 000 cal. BP while organic or silty organic sedimentation (4 m to 7 m thick) spread throughout the valley bottom until 2 800 cal. BP, during the Subboreal period. Finally, these organic deposits are covered by very homogenous silty overbank deposits, with a thickness varying between 1 m for the upstream floodplains to 2 m for downstream floodplain. Although few intercalated thin layers of detritic sedimentation have been observed, particularly during the Middle Bronze Age (*c.* 3 500/3 200 cal. BP), radiocarbons dating on the last organic remains date the beginning of the silting of the valley bottom from 2 800 cal. BP at the beginning of the early Iron Age.

3. Methodology

Soil profile development of the luvisols includes A, E and BT horizons, superposed on a C horizon or, if loess thickness is insufficient, on a bedrock substrate. Soil erosion and sediment deposition has altered these typical luvisols profile, resulting in truncated and/or buried soil profiles. Following other studies (Rommens et al., 2005; Notebaert et al., 2009; Houben, 2012) we hypothesize that the depth of the different soil horizons is constant for the study area in the absence of erosion or burial. Such a constant soil horizon depth, independent from environmental variables like slope direction, was demonstrated for luvisols on uneroded sites in the Belgian loess belt (Vanwalleghem et al., 2010). In this study, this assumption was also tested for the depth of the upper and the lower border of the clay illuviation-horizon (Bt) at plateau sites (16 cores). According to the 'soil profile truncation method' discussed in detail by Rommens et al. (2005), observed soil horizon depths can then be compared to these estimated uneroded depths to estimate the total net erosion and deposition thickness. In total, 230 corings were made on a representative small tributary of the Thue river (Gronde catchment, 10 km^2, Fig. 1), and the soil profile horizons were described in detail. In the upstream part of the Gronde river, 98 corings are located on luvisols in a zero-order subcatchment (Fig. 1, A), while 132 corings, located on steeper slopes along the main valley bottom are truncated soil profiles beyond the Bt horizon. The erosion and/or deposition thickness was determined for each of the 230 corings based on this soil profile truncation method. In a next step, topographical classes were used to extrapolate the coring data to the entire catchment. This 'average per

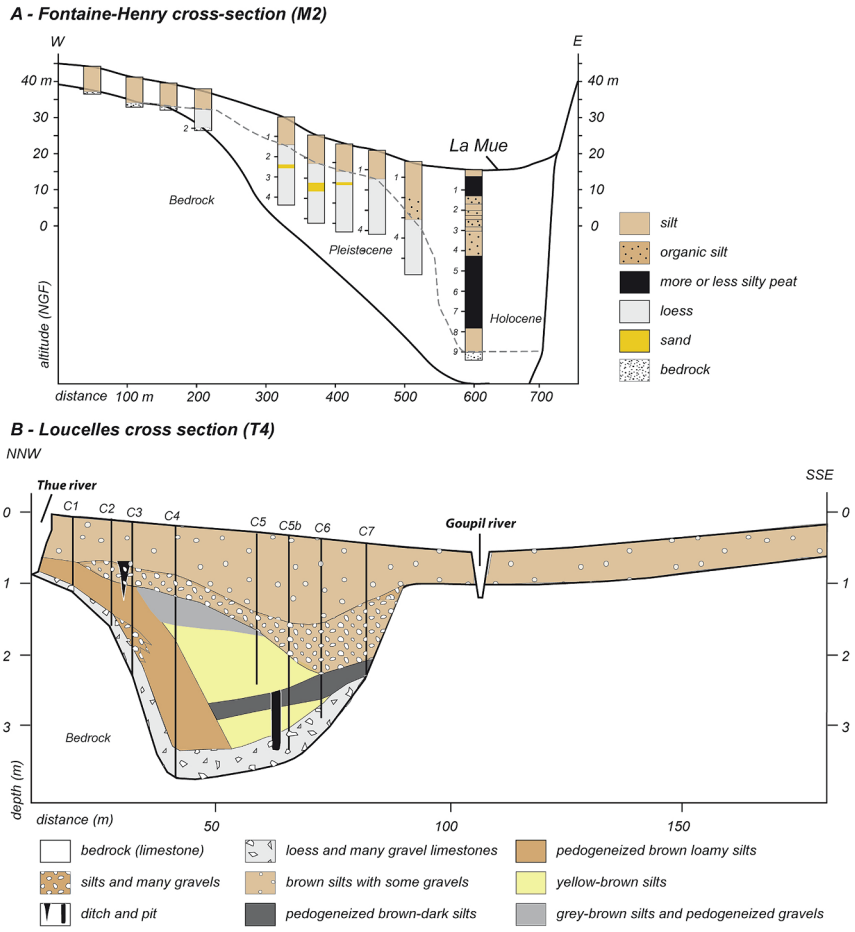

Fig. 2. Cross section of the alluvial filling on the Mue and Thue river: cross-sections of Fontaine-Henry (M2) and Loucelles (T4) (modified from Lespez, 2009).

unit' (APU) method was previously used by other studies (for an overview see Rommens et al., 2005). Slope classes for the catchment were derived from a 20 m resolution DTM, and slopes were calculated using ArcGIS 10.1. The boundaries of the dry valleys were delimited based on 1: 25,000 topographical maps, aerial photographs, and were validated with field observations and an accurate mapping of the superficial deposits of the downstream Gronde study site. Consequently, we assume an error on the area of less than 10 %. Based on the coring dataset, average erosion and deposition values were calculated for each class, and then combined with the surface area of each class to get total volumes. To convert volumes to masses, the dry bulk density value was estimated from 22 topsoil samples taken using Kopecky rings (100 cm^3) at depths between 5 and 20 cm, randomly taken from the studied soil profiles.

Then, the quantification of Holocene floodplain sediment deposition is based on 11 cross sections, totaling 84 hand corings and 5 cores drilled using a percussion drilling machine in key areas and several sections. For each coring, a detailed description was made with a 0.05 m vertical resolution according to texture, grain size, color, vegetal remains and macrofossil content (Lespez et al., 2008). We applied the fluvial architecture concepts (Miall, 1985) to identify the different Holocene sediment units. The cross sectional area was determined for each cross section to calculate an average sediment thickness over the entire floodplain width. Floodplains were manually delineated based on a DTM (20 m resolution) and field observations. Floodplain were divided in homogenous stretches based on their long profile, floodplain width, the structure of the hydrographical network and floodplain geomorphology following Seidel and Mackel (2007) and Notebaert et al. (2009). Conversion of floodplain sediment volumes to masses takes into account the organic content and dry bulk density. Organic matter content was determined using the combustion method (Bisutti et al., 2004) for 13 samples of peaty floodplain sediments, and 61 samples of non-peaty sediments. For non-peaty sediments we used the average organic matter content, the mineral dry bulk density obtained from 15 samples and the formula proposed by Verstraeten and Poesen (2001). For peaty deposits, we also considered the average organic matter content and the sediment cover on top of the peat layers (varying between 0 and 3 m) to estimate values before and after compaction, based on Van Asselen et al. (2010). In addition 12 bulk density measurements of these peaty deposits were performed for 3 cores coming from alluvial settings, using a cylinder sampler.

Locally, large amounts of calcium-carbonates are deposited in the floodplain. Authigenic deposits entirely composed of dissolved carbonate constituents as tufa dams (Lespez et al., 2008; Fig. 1) were excluded from the sediment budget. Calcium-carbonated-rich silts have been found in the alluvial filling throughout the catchment. Some of these carbonates are of detrital origin, from decarbonate soils or from erosion of tufa dams deposits whereas others are authigenic. It was not possible to differentiate authigenic carbonates from those of detrital origin, all calcium-carbonated-rich silts were therefore included in the sediment budget.

As proposed by Rommens (2006), errors on sedimentological analysis (dry bulk density, thickness of augering cores and upper or lower border of the Bt horizon) used to apply the 'soil profile truncation method' can be considered independent. Thus, we used the Gaussian error propagation to estimate the precision of the calculation of eroded and deposited sediment mass.

Floodplains deposits were dated using 18 radiocarbon dates obtained from cores samples (Lespez et al., 2008; Table 1). Datable material was handpicked and dated using standard methods. Radiocarbon dates are

Table 1
Results of radiocarbon dating of floodplain sediments in the Mue valley bottom. Dates were calibrated using oxcal 4.1 (Bronk Ramsey, 2008) and the Intcal 13 curve (Reimer et al., 2020).

Location	*Transect*	*Lab. Code*	*Depth (m)*	*Materials*	*Methods*	*Date 14C BP (1 σ)*	*Calibrated age AD-BC (2 σ)*
Revier	M1	Erl-6608	11,24–11,30	organic silt	AMS	7715+/-66	6652–6436 BCE
Revier	M1	Erl-6607	8,45–8,53	organic silt	AMS	5989+/-50	5001–4726 BCE
Revier	M1	Erl-6606	6,75–6,80	coal	AMS	5315+/-45	4319–3996 BCE
Fontaine-Henry	M2	Gif-11175	2,47–2,65	organic silt	conventional	7740+/-80	6774–6426 BCE
Fontaine-Henry	M2	Gif-11711	2,40–2,50	organic silt	conventional	3245+/-40	1612–1433 BCE
Fontaine-Henry	M2	Gif-11713	3,90–3,00	organic silt	conventional	5030+/-65	3960–3655 BCE
Fontaine-Henry	M2	Gif-11864	7,71–7,75	peat	conventional	4475+/-40	3347–3024 BCE
Fontaine-Henry	M2	Gif-11868	5,05–5,10	peat	conventional	3150+/-45	1507–1296 BCE
Fontaine-Henry	M2	Gif-11867	3,96–4,01	peat	conventional	2420+/-40	751–400 BCE
Fontaine-Henry	M2	Gif-11865	1,45–1,52	peat	conventional	1500+/-45	435–649 CE
Thaon (Vielle-Eglise)	M3	Erl-6604	7,20–7,30	sediments	AMS	9214+/-68	8615–8291 BCE
Thaon (Vielle-Eglise)	M3	Erl-6605	1,79–1,89	sediments	AMS	5220+/-69	4246–3810 BCE
Thaon (Colonie de Vacances)	M4	Gif-11716	3,17–3,28	organic silt	conventional	4535+/-60	3494–3025 BCE
Thaon (Colonie de Vacances)	M4S	Gif-11756	4,00–3,98	organic silt	conventional	3805+/-40	2452–2465 BCE
Thaon (Colonie de Vacances)	M4	Gif-11714	1,90–1,98	organic silt	conventional	3300+/-40	1686–1460 BCE
Cairon	M6	Erl-6790	1,98–202	organic silt	AMS	8102+/-58	7322–6827 BCE
Cairon	M6	Erl-6789	1,78–1,81	peat	AMS	6695+/-49	5633–5480 BCE
Cairon	M6	Erl-6788	1,56–1,59	peat	AMS	6242+/-49	5316–5050 BCE
Cairon	M6	Erl-6787	0,78–0,82	peat	AMS	5108+/-47	4037–3787 BCE

Lespez et al, 2008.
Radiocarbon ages were calibrated using OxCal v4.4 software (Bronk Ramsey, 2017) based on the IntCal20 atmospheric curve (Reimer et al., 2020).

calibrated using Oxcal 4.4 version software (Bronk Ramsey, 2017) and calibration curve of Reimer et al. (2020). We established the chronostratigraphical framework of the floodplains using these dates. For three dated coring we constructed age-depth relations as proposed by Notebaert et al. (2011), these relations were also normalized using the total Holocene sediment thickness and also the varying sediment dry bulk density was taken into account. The resulting curves depict the relative and accumulative Holocene net floodplain aggradation as a function of time.

4. Results

4.1. Soil description and dry bulk densities estimation

An average thickness of 1.02 ± 0.11 m is observed for the 16 profiles of luvisols on uneroded sites. They are developed on loess material and are characterized on the top of the profile by a thin brown silty plough layer (horizon A; 0.2 ± 0.08 m). The E horizon is constituted of homogeneous brown and yellowish silt loam covering a more massive Bt horizon made up of clayey brown silt loam. Texture analysis confirm for each profile an increase of the clay content moving from 11-16 % in the eluvial horizon to 36–44 % in the illuvial horizon. In the studied area, the depth of the lower border of the Bt horizon is estimated at 0.95 ± 0.07 m and the depth of the upper border of the Bt horizon for these non-eroded soils is in a range from 0.50 to 0.63 m. A mean value of 0.57 ± 0.05 m for the top of the Bt horizon were used to estimate erosion and deposition on the Gronde catchment. A dry bulk density of 1.48 ± 0.1 Mg m^{-3} was obtained from the 22 samples collected in studied soil profiles and used to convert volumes to masses. This dry bulk density value is significantly close to values used by Rommens et al. (2005) and Notebaert et al. (2009) in a similar pedosedimentary context.

To convert floodplain sediment volumes to masses, an average organic matter content of 1.79 % was obtained for non-peaty sediments and the formula proposed by Verstraeten and Poesen (2001) and yields a value of 1.34 Mg m^{-3}. For peaty deposits, the average organic matter content is estimated at 51.05 %. Resulting values for mineral dry bulk density are 0.19 to 0.23 Mg.m^{-3} for uncompacted peaty deposits, and 0.38 to 0.46 Mg.m^{-3} when taking compaction into account. In addition, an average value of 0.21 Mg.m^{-3} have been obtained for the 3 cores coming from alluvial settings. Considering this range in dry bulk density values, we used a value of 0.33 Mg.m^{-3} for the budget calculations, while a range of 0.19 to 0.46 Mg.m^{-3} was used for a sensitivity analysis.

4.2. Erosion and deposition on the hillslopes

Soil profile analysis carried out on the Gronde catchment highlights opposition between slopes where the erosion processes dominate and dry valleys in which sediment storage is observed (Table 2). As expected, erosion and deposition rates are correlated to the slope gradient. A slight truncation of the soil profiles located on the weakest slopes (<1%) is observed for which erosion is between 3 and 17 cm. Deposition rates are in between 9 and 13 cm. For slopes ranging from 1 to 5 %, according to the increase of the slope gradient, soil profile truncation reaches higher values, in between 10 and 28 cm. Sediment deposits can, however, be locally observed but remain very low (less than 3 cm). Beyond a slope of 5 %, only erosion processes are observed in all the Gronde catchment (from 19 to 33 cm). Finally, sediment storage dominated for all profiles operated in dry valleys (from 56 to 108 cm). Average erosion and deposition rates are then calculated for different slope classes (Table 2). Erosion processes intensity was found for all slope gradient classes excepted for dry valleys. These vary from 0.145 m to 0.284 m according to the slope gradient. Sediment deposition was also found for dry valleys and slopes gradient less than 5 %. These vary from 0.019 m to 0.877 m, also according to the slope gradient. Those values are then extrapolated, following the APU method, to the entire catchments, yielding total soil erosion of 37.97 Mt, and a total sediment deposition of 12.34 Mt (Table 3). The uncertainty on the mineral dry bulk density, thickness of the soil horizons obtained through coring, reference depth of Bt horizon and the floodplain extent, leads to an uncertainty on calculated erosion and sediment volumes of 12 and 44 %, respectively. Hence total erosion ranges between 33.74 Mt and 42.55 Mt, and total sediment deposition between 8.1 Mt and 17.85 Mt.

4.3. Floodplain deposition

In the Thue and Mue catchments, the thickness of alluvial deposits varies between 1 and 7.8 m (Fig. 3; Table 4). In the floodplains, alluvial sediment storage increases gradually from 1 t.m^{-1} in the upstream part to 3 t.m^{-1} at the outlet of the catchment. Total Holocene floodplain storage amounts to 3.69 Mt, i.e. 0.07 Mt.km^{-2} for the Thue catchment. Alluvial storage is also thin in the upper Mue floodplains (M7, M6; *c.* 1.5 t.m^{-1}). It increases downstream (from M5 to M1) from 2 to 5 t.m^{-1}. For the Mue catchment total deposition is 11.79 Mt, which equals 0.12 Mt.km^{-2} catchment area. This area specific value is almost 1.7 time higher than for the Thue catchment. The sensitivity analysis on the uncertainty

Table 2
Erosion and deposition rates measured in the Gronde zero-order subcatchment.

			Gronde catchment					
			Number of augerings	***Mean (m)***	***Standard deviation (m)***	***median (m)***	**min *(m)***	**max *(m)***
Dry valleys		*Deposition (m)*	34	0.877	0.21	0.903	0.5	1.1
		Erosion (m)	0	0	0.00	0	0	0
Slopes	***0–1 %***	*Deposition (m)*	8	0.095	0.02	0.09	0.08	0.13
		Erosion (m)	31	0.145	0.04	0.16	0.03	0.17
	1–3 %	*Deposition (m)*	15	0.014	0.01	0.01	0	0.03
		Erosion (m)	53	0.196	0.04	0.21	0.10	0.27
	3–5 %	*Deposition (m)*	13	0.019	0.01	0.02	0	0.03
		Erosion (m)	49	0.204	0.04	0.22	0.13	0.28
	5–10 %	*Deposition (m)*	0	0	0.00	0	0	0
		Erosion (m)	21	0.263	0.04	0.27	0.19	0.31
	> 10 %	*Deposition (m)*	0	0	0.00	0	0	0
		Erosion (m)	6	0.284	0.05	0.27	0.20	0.33

Table 3
Erosion and deposition values obtained for the entire Thue and Mue sub-catchments calculated using the APU method (Rommens et al., 2005).

		Gronde catchment		*Thue and Mue catchment*						
		Erosion (m)	***Deposition (m)***	***Surface (10^6 m^2)***	***Eroded volume (10^6 m^3)***	***Deposited volume (10^6 m^3)***	***Eroded sediment mass (10^6 t)***		***Deposited sediment mass (10^6 t)***	
							Estimation	**uncertainty (Gauss)**	***Estimation***	**uncertainty (Gauss)**
	Dry valleys	0	0.877	7.55	0.00	6.62	0.00	0	9.80	8,1–11,66
Slopes	***0–1 %***	0.145	0.0095	53.09	7.70	0.50	11.39	9,79–13,31	0.75	0–2,3
	1–3 %	0.196	0.014	28.51	5.59	0.40	8.27	7,46–9,09	0.59	0–1,35
	3–5 %	0.204	0.019	42.81	8.73	0.81	12.93	11,69–14,17	1.20	0–2,54
	5–10 %	0.263	0	10.63	2.80	0.00	4.14	3,74–4,54	0.00	0.00
	> 10 %	0.284	0	2.96	0.84	0.00	1.25	1,06–1,44	0.00	0.00
				Total	25.66	8.34	37.97	33,74–42,55	12.34	8,1–17,85

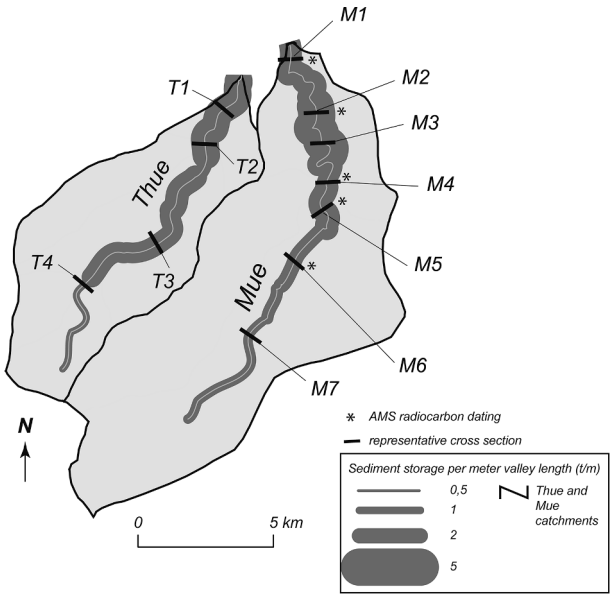

Fig. 3. Alluvial sediment storage for the Thue and Mue catchments.

of the mineral dry bulk density of silts and peat deposits, combined with the uncertainty of the delineation of the flood plain results in an error of ± 0.8 Mt in alluvial sediment storage for the Mue and Thue, which is about ± 5.2 %. Therefore, we calculate that the total alluvial storage for the combined Thue and Mue catchments ranges between 14.29 and 16.24 Mt.

4.4. Sediment budget

The combination of the quantified hillslope soil erosion and sediment deposition with the floodplain deposition result in a Holocene sediment budget for the Mue and Thue (Fig. 4). During the Holocene, 37.97 Mt of sediments have been eroded in the Thue and Mue catchments. This erosion essentially occurs on slight slopes (<5%) which despite lower erosion rates than those observed on steeper slopes are dominant in the studied area.

More than 70 % (27.82 Mt) of eroded sediments on slopes remain stored into the catchments as alluvial (15,48 Mt) or colluvial storage (12.34 Mt), essentially on dry valleys and has not been exported to the sea. The remaining eroded sediments (10.15 Mt) have been considered to be exported to the Seulles river, 4 km above the outlet of the Seulles catchment.

4.5. Chronology of alluvial sediment deposition

Radiocarbon dating on the alluvial filling also gives information to discuss the chronology of sediment transport and the intensity of sediment fluxes through time in the catchment (Fig. 5). The quantification of the alluvial sedimentation, combined with available radiocarbon dating on the alluvial filling of the Mue floodplain (transects M2, M3 and M4; Lespez et al., 2008) underline an important increase in sedimentation rates during the Holocene (Fig. 5). From 9000 to 6000 cal. BP, mineral sedimentation in the Mue valley bottom is very low. Specific sedimentation rate is around 3.5 $t.km^{-2}.yr^{-1}$ representing an average aggradation of 0.1 $mm.yr^{-1}$ in the Mue valley. From c. 6 000 to 2 800 cal. BP, the organic sedimentation spread throughout the valley bottom induces an increase in specific sedimentation rates but remains very low, increasing in the Mue valley from 3.5 to 5.1 $t.km^{-2}.yr^{-1}$ (aggradation rate of 0.3 $mm.yr^{-1}$). Finally, radiocarbon dating on the last organic remains, on the beginning of the silting of the valley bottom, indicate a clear increase

Table 4
Homogenous floodplain stretches and their representative coring transects, floodplain area, average sediment thickness, total sediment volume and mass stored in the valley bottoms.

	Homogenous floodplain stretches	*Coring transect*	*Area (10^6 m^2)*	*Average thickness (m)*	*Volume (10^6 m^3)*	*Mass (10^6 t)*	
						Estimation	uncertainty (Gauss)
Mue	Reviers	M1	0.14	4.18	0.60	0.70	0,65–0,73
	Fontaine-Henry	M2	0.78	4.76	3.86	4.32	3,93–4,53
	Thaon Vieille Eglise	M3	0.14	7.8	1.06	1.41	1,30–1,48
	Thaon Colonie de Vacances	M4	0.19	6.86	1.25	0.91	0,71–1,01
	Cairon	M5	0.23	4.62	0.92	1.06	0,98–1,13
	Rots	M6	0.28	2.75	0.79	0.82	0,77–0,89
	Vauculay	M7	0.95	2.31	1.95	2.57	2,48–2,66
Thue	Pierrepont	T1	0.12	3.09	0.33	0.44	0,42–0,46
	Lantheuil	T2	0.27	2.29	0.71	0.51	0,39–0,53
	Secqueville	T3	0.79	1.25	1.75	2.30	2,26–2,35
	Loucelles	T4	0.20	0.88	0.33	0.44	0,40–0,47

Total 15.48 14,29–16,24.

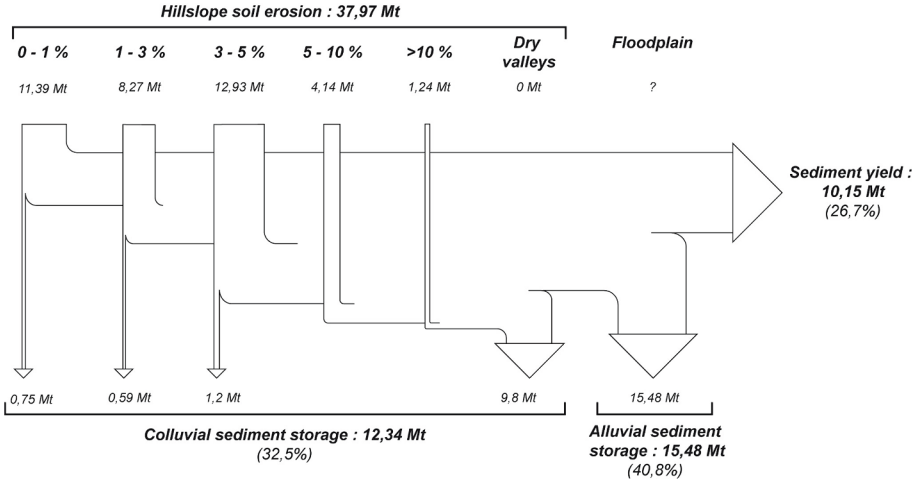

Fig. 4. Holocene sediment budget for the Thue and Mue catchments.

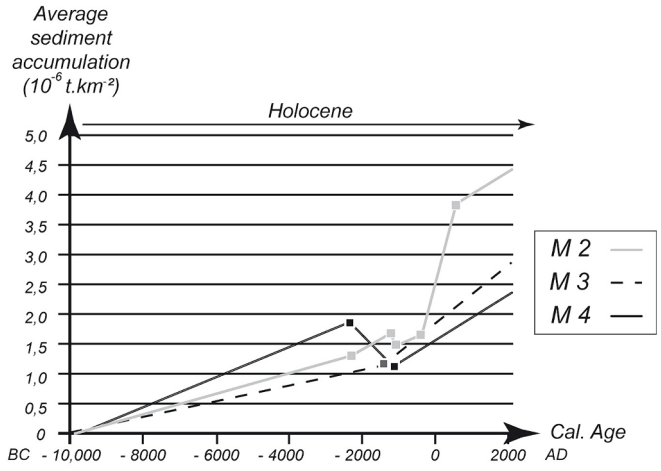

Fig. 5. Relative and accumulative Holocene net floodplain aggradation as a function of time (M2, M3, M4).

in specific sedimentation rates in each cross section of the Mue catchment. For the last 3000 years we estimated average specific sedimentation rates at around 22.1 t.km^{-2}.yr^{-1} (aggradation rate of 0.7 mm. yr^{-1}).

5. Discussion

5.1. Soil erosion and sedimentary cascade activation in the Plain of Caen

Despite the lack of chronology of soil erosion and colluvial sink on the studied river basins, the relation between soil erosion and floodplain deposition can be discussed thanks to several accurate observations of soils profiles and colluvial stratigraphy's obtained within the catchment and more generally in the Plain of Caen. Numerous sections studied during archeological excavations give access to the soil profile below and above the settlement were established, and give information on the timing of soil erosion. Although localized and limited erosive processes may have occurred since the beginning of the Holocene, all the available data obtained on the plateau of the Plain of Caen point to an onset of soil erosion during the Neolithic period. At Fontenay-le-Marmion, 15 km to the South of the Mue Catchment, Germain-Vallée and Lespez (2011) show that luvisols were truncated after the development of an Early Neolithic Settlement (6850–6650 cal. BP). After the abandonment of the site, a new phase of pedogenesis is observed resulting in a new luvisol dated before the Middle Bronze age. This is confirmed by other observations of the soil under the Iron Age settlements of the Plain of Caen which most of the time show a well preserved luvisol. During the Neolithic, the Plain of Caen and the two studied subcatchments are characterized by an extensive development of farming activities, mainly cereal cultivation (wheat and barley) and secondly pulses, and breeding activities (mainly cattle). Palynological data show that farming activities have created glades open into the regional forest in the studied

catchments (Lemer et al., 2020). They favor the development of soil erosion but the regular displacement of the cultivated areas and settlements allowed the return of the mixed oak forest and prevent the sediment transfer to the main rivers (Lespez et al., 2005; Lespez and Germain-Vallée, 2009; Lespez, 2012).

The specific erosion rate estimated on the basis of the alluvial deposits was quadrupled during the Late Holocene and more precisely during the last 3 millennia (Lespez et al., 2015). And, all the soil profile examine under Antiquity and Middle Ages archaeological sites show the erosion of the top horizons (A and E) of the luvisol. This testifies a widespread expansion of the soil erosion during the Iron Age on the plateau of the Plain of Caen (Germain-Vallée and Lespez, 2011; Lespez and Germain, 2011). The observations made at Thaon, within the Mue catchment, confirm this soil erosion pattern. An excavation of an Iron Age and Gallo-Roman site in the Mue valley reveals several pits dug into the luvisol. The erosion of luvisols caused a first generation of colluviation which have been attributed to the Iron Age, and a second phase is observed during the Middle Age and Modern Periods (Germain-Vallée and Lespez, 2011). A similar observation has been made at Creully, at the western edge of the Thue catchment, where the first phase of the erosion of the luvisol is dated to the second part of the Iron Age and relates to the development of agriculture on the plateau. Indeed, the very abundant archaeological data indicate a rural landscape organized in farming land of several hundred hectares managed by groups of farms located on the plateau (Lepaumier et al., 2010). Increasing soil erosion result from the activation of the sedimentary cascade from the cultivated plots to small order valleys and then to the main valleys. It is possible that the more humid oscillation of the beginning of the Iron Age (Barber et al., 2003; Magny, 2004) played a role in triggering this process, although no reversal in this trend is seen and the long-lasting sedimentation undeniably indicates a human cause for the change of the morphogenic system. Thus, the extension of the cultivated areas combined with the development of agricultural techniques (animal-drawn) and the reduction of fallow-land duration explain the development of the connectivity (small order stream, ditch, dirt road). It is contemporary with landscape opens of the valley bottom where the alluvial forest mainly composed by alder was cleared and substituted by meadows mainly during the Iron Age (Lespez et al., 2015) generating direct connectivity between agricultural plots and the rivers. This observation imply a long period of transition from the Neolithic to the Late Bronze Age which correspond to an improvement of the connectivity linked to the progressive transformation of the running water circulation within the catchment.

5.2. Soil erosion and rate of deposition in NW Europe

The comparison of the results obtained with those of other studies that have been subjected to numerical analysis (Table 5) offer the opportunity to discuss of the rate and magnitude of the soil erosion and alluvial aggradation. These studies are still few in number, but the comparison highlights a general trend already revealed by the comparison of qualitative observations (Notebaert, Verstraeten, 2010; Brown et al., 2018), but also underlines the weight of the specificity of the spaces studied in the results obtained.

The results obtained in Normandy are quite similar to those observed in Northwestern France. On the Paris Basin, the beginning of the Holocene is often marked by a long period of stability of the fluvial system. It is generally characterized by authigenic organic or organo-tuffaceous sedimentation (Pastre et al., 2002; Lespez et al., 2005; Chaussée et al., 2008). The allogeneic sedimentation peaks in the alluvial plains were generally recorded from the period 4000–3300 cal. BP (Pastre et al., 2002), even if silting up of the valley bottoms was sometimes observed from 5500 cal. BP on the Oise and Beuvronne catchments and attributed to a first anthropogenic impact on the fluvial systems (Pastre et al., 2006). Even if there is no quantification of the sediment aggradation before this period, the increase of the silting of the valley floor is clear (up 40 to 62 $t.km^{-2}.yr^{-1}$) and correspond to an increase of soil erosion from the Iron Age (Orth et al., 2004). In the Negron catchments, a tributary of the Loire river, silty sedimentation is continuously observed from the middle of the Neolithic, except from the period 1500–700 cal. BP when the sedimentation is organic again (Macaire et al., 2002; Macaire et al., 2006). The sedimentation increases during the thousand

Table 5
Evolution of sedimentation rates in the alluvial plain of some Western European rivers.

Country	Catchment	Catchment area	Start of the Colluvium	Alluvial storage	Storage within the watershed (alluvial + colluvial)	% of alluvial deposits	Agradation rates of the alluvial sedimentation (**in bold silty detrital sedimentation**)		References
		km^2	cal BP	10^6 t			cal BP	$t.km^{-2}.yr^{-1}$	
France	Thue et Mue	150	4,000	15.5	73.3 %	40.80 %	11 700–6 000	3.5	This study
							6 000–2 800	5.1	
							post 2 800	**22**	
	Seulles	430	4,000	35	?	?	9 000–500	0.5	Viel, 2012; Lespez et al, 2015
							500–1 200	23.6	
							post 1200	**77.2**	
	Négron	162	> 1 000	1.4	88 %	37 %	**post 1 000**	**8.6**	Macaire et al, 2002, 2006
	Beuvronne	170	4,500	?	?	?	2 800–680	42	Orth, 2004
							post 680	**61**	
Belgium	Nethen	55	3 100–2 800	14	61 %	23 %	2 500–1 000	24	Verstraeten et al, 2009
							post 1 000	**126**	
	Djile	758	6 160–2 600	351	78 %	18 %	4 000–1 000	24	Notebaert et al, 2011
							post 1 000	**277**	
Netherlands	Geul	380	2 053–2 415	34.2	80 %	12.70 %	**1 500–1 000**	**60–90**	De Moor and Verstraeten, 2008
Germany	Lieser	402	1,000	35.1	67 %	9 %	ante 1 000	2	Stloz et al, 2011b
							1 000–680	**49**	
							post 680	**89**	
	Schwarzbach	1151	?	52.5	?	?	post 3 500	13	Stloz et al, 2011a

years and correspond to the silting of the valley floor. Alluvial sedimentation rates in this watershed are in between 0.4 and 0.8 mm.yr^{-1}. They substantially similar to those observed in the Mue, however, the specific degradation rate (8.6 t.km^{-2}.yr^{-1}) is lower than for the Thue and Mue catchments.

Investigations conducted in other western European catchments highlight a similar trend. For the Dijle catchment (Belgium), a long phase of stability of the fluvial system, characterized by the development of an organic sedimentation which begins during the Preboreal and which continues until the Subatlantic. A silty sedimentation in the floodplain is observed from the second half of the Atlantic and began more important during the Subboreal, around 4 000 cal. BP and an amplification of sedimentation rates is observed going from 24 t.km^{-2}.yr^{-1} over the period 4000–1000 cal. BP to 277 t.km^{-2}.yr^{-1} from 1,000 CE (Notebaert et al, 2009). Similar observations are made for the Nethen catchment where sedimentation rates go from 8 t.km^{-2}.yr^{-1} before 2500 cal. BP to 24 t.km^{-2}.yr^{-1} between 2500 and 1000 cal. BP then to 126 t.km^{-2}.yr^{-1} from 1000 cal. BP (Verstraeten et al, 2009). In the Geul catchment (The Netherlands) higher alluvial sedimentation rates are observed between 1 500 and 1000 cal. BP corresponding to an acceleration of the silty sedimentation in the valley floor (60 and 90 t.km^{-2}.yr^{-1}, De Moor et Verstraeten, 2008). The increase of soil erosion and valley floor sedimention is due to intensification of land use that has also been accelerated from the Iron Age in Belgium and Netherlands (Broothers et al., 2014).

In Germany, extensive work on old colluviums shows an erosion of soil from the early Neolithic period (7 450–6 250 cal. BP) and then an increase during the transition between the Final Neolithic and the Bronze Age (c. 5000–4500 cal. BP) (Dreibrodt et al., 2010; Fuchs et al., 2011; Dreibrodt et al., 2013). The data available on the Lieser catchment show a spectacular acceleration of sedimentation in the valley bottoms, similar to that observed in Normandy. The 25-fold increase in the minimum specific erosion rate during the Middle Ages (from 2 to 49 t.km^{-2}.yr^{-1}) is the result of the transformation of the watershed by agricultural practices which continues to increase in the late Middle Ages and in modern times (89 t.km^{-2}.yr^{-1}). This result agrees with most of the qualitative research that the highest sedimentation rates are only reached from 1000 cal. BP when agricultural practices and land use became more intense. (Bork, 1983; Houben, 2007; Dotterweich, 2008; Dreibrodt et al., 2010; Fuchs et al., 2011; Houben et al., 2013; Larsen et al., 2016. A further acceleration of alluvial filling is related to an intensification of land use along with an increase in the intense rainfall episodes during the Little Ice Age (Bork et al., 1998, Dotterweich, 2008, Dreibrodt et al., 2010, Notebaert et al., 2011).

The magnitude of the acceleration of alluvial sedimentation is always very significant, reaching factors from 5 to 100 and is explain by land use changes in Northwestern Europe (Notebaert and Verstraeten., 2010). But there is in general a long gap between the initial forest clearance, soil erosion and the acceleration of alluvial filling which is generally later from the Iron Age to Medieval period. During the transitional phases corresponding to the end of protohistory, from the Bronze Age to the Early Middle Ages, the available numerical data show that the multiplication of alluvial aggradation are in the order of 1.5 to 10. More generally, this transition period is often observed in the catchments where specific rates of erosion based on alluvial sedimentation have been calculated (Macklin et al., 1991; Lang and Hönscheidt, 1999; Taylor et al., 2000; Lang, 2003; Notebaert and Verstraeten, 2010; Verstraeten et al., 2009).

5.3. *Human impact on sediment dynamics: The sediment connectivity issue*

Even if soil erosion and alluvial sedimentation have similar timings in Western Europe during the Holocene, the chronology usually differs from one region to another one and sometimes from one catchment to another one in the same area (Brown et al., 2013). Likewise observations made in the Thue and the Mue catchments differ from those made for the main stream, the Seulles River. They indicate clearly sooner alluviation than along the Seulles river where thick silty deposits have been deposited during the last two millennia and mainly from the Middle Ages (Viel, 2012). The sediment yield jumped from 0.5 t.km^{-2}.yr^{-1} for the period 9 000–2 800 cal BP to 25 t.km^{-2}.yr^{-1} for 2 800–800 cal. BP and then to 77.2 t.km^{-2}.yr^{-1} after 800 cal BP (Table 3; Lespez et al., 2015). These results are not linked to the size of the catchment because it is consistent from upstream to downstream (Viel, 2012; Lespez et al., 2015; Beauchamp et al., 2017). The late increase of the rate of alluvial filling in the Seulles valley raises the question of the different chronology of the land use changes in these two areas but also of the differences in sediment connectivity between the Paris Basin and the Armorican block.

In the Paris Basin, soil erosion seems to have been sooner and higher than in the Armorican block where the intensity of agricultural practices and soil crusting sensibility promote runoff processes at plot scale. However, the morphostructural and hydrological patterns, with numerous dry valleys, imply an important distance between runoff producing areas and the river (Viel et al, 2014a). The low drainage density promotes sediment deposition on dry valleys. Slope erosion has to be generalized and a long time is needed to generate sedimentation in the main valley bottoms, probably amplified by the significant longitudinal discontinuities induced by tufa dams downstream of the Mue catchment. Despite greater and earlier susceptibility to soil erosion, the morphostructural context of the Thue and Mue catchments favored a large internal storage (71 %) of a large part of the eroded sediments in the watershed. This should be compared with the results obtained for the percentage of Holocene sediment stored in the catchments of Northwest Europe for which a sediment budget has been calculated. The rate of sediment trapping within catchments is still very high, ranging from 61 % to 88 % for catchments between 55 and 758 km^2 in size confirming previous observation (Hoffmann et al., 2013). In fact, most of these catchments are located in a similar morphostructural and pedoclimatic context and are characterized by Pleistocene loess formations, which at the beginning of the Holocene favored the development of brown, more or less leached soils.

However, despite a similar geological context, significant differences are recorded in the repartition between sediment stored in dry valley and floodplains (Table 5). If the redistribution of sediments observed in the Thue and Mue catchments is quite similar to those observed in the Nethen catchment (Verstraeten et al., 2009), in the Geul catchment, a higher storage is observed on dry valleys (67 % of eroded sediments remain) whereas only 13 % as alluvial sediment storage. The origin of this variability remains poorly documented but demonstrates the need to better consider the spatial organization of the morphology of the catchment which can define different slope systems and spatial organization of (dry) valleys for a similar geological, pedologic and climatic context. In combination with the landscape structure (runoff producing areas and landscape linear networks), this may induce different sediment redistribution (patterns and rates) for apparently similar catchments.

In the Armorican block, the timing of slope cultivation development is less precisely known. However, high drainage density significantly reduces the distance between runoff erosion area and the river and make the sediment cascade more efficient to transport sediment from erosion areas to the main valley bottom or to export sediments to the outlet. Research conducted on the current sediment dynamics of the Seulles catchment (Viel, 2012; Viel et al., 2014b) underline that ditches and roads networks can then complete the initial hydrographic network. Their spatial organization thus modifies not only the location of surfaces connected, but also the thresholds and frequencies of sediment connection to the river, facilitating sediment transfers to the downstream part of the catchment. The hydrogeological context, combine with the landscape structure organization thus made the catchment more sensitive to landscape and climatic changes. The sediment budget

proposed to describe the contemporary dynamics of the Seulles (Viel, 2012) shows that almost half of the sediment exported comes from the erosion of sediments accumulated in the alluvial plains during the Holocene. The sedimentary cascade is therefore still active, but with a multi-millennial rhythm for sediment exchanges between the alluvial plain and the Channel.

As suggested or observed by several authors (e.g. Verstraeten et al, 2009; Hoffmann et al, 2010; Fuchs et al, 2011; Houben et al, 2013; Verstraeten et al, 2017), this study confirms that data from valley bottoms must be interpreted with caution if we are to reconstruct the long-term erosion history of watersheds. The origin of the variability in the timing of sediment deposition on the valley bottoms should be further investigated, but it appears that the rate of sedimentation in alluvial floodplains is more an indicator of changes in the efficiency of connectivity within the catchment rather an indirect indicator of soil erosion within the catchment. These observations show the necessity of reconstructing precisely the landscape history before generalizing local observation on soil erosion and sediment transfer. It also highlights the importance to integrate the question of the efficiency of the sediment cascade, in particular induced by the spatial organization of landscape structure, drainage density and catchment morphology that can constitute as important explanatory factors as climatic, geological or pedological context. The spatial organization of linear structures such as hedges, embankments and ditches, which are often less well documented than land use, needs to be studied over time. It is therefore necessary not only to establish a sediment budget to evaluate the significance of soil erosion but also to have an accurate knowledge of the land use pattern changes to understand thresholds and tipping point in the sedimentary cascade operation before to evoke the role of the climate changes in the studied areas. This highlights the need for further work on Holocene colluvium rates.

5.4. *Toward an improvement of the sediment budget method*

Calculations used to propose this Holocene sediment budget induce uncertainties described in the methodological framework. Methods used to define and quantify all variables of the Holocene sediment budget can significantly vary from one study to another and make sometime difficult the comparison between obtained results. The first step of the sediment budget calculation is to estimate sediment storage into the catchment. The geometry of sediment storages is generally obtained from sediment thickness extrapolated to the area deposited sediments. The impact of cores densities on sediment storages evaluation has been evaluated. Notebaert et al. (2010) demonstrate that a much smaller coring density than the one used in this study is sufficient to get a representative dataset, although errors remain around 10–20 %. However, the delineation of alluvial and colluvial sediment storages can induce important errors. This delineation is generally easy in floodplain area. However, there is not widely agreed method used to precisely identify colluvial deposits stored in dry valleys where the limits with slopes areas is less clear. Given sedimentation rates allocated to these areas, accuracy delineation is essential to estimate colluvial storage. The generalisation of high resolution DEM as Lidar should in the future help to limit these errors.

The mass conversion can also induce difficulties in comparing sediment budgets. For similar sedimentary units, the dry bulk density (DBD) significantly varies from a study to another. For example, Verstraeten and Poesen (2001) estimate slits DBD from 1.04 $Mg.m^{-3}$ and 1.31 Mg.m-3, Rommens et al. (2006), 1.42 $Mg.m^{-3}$ and Macaire et al. (2002), 2 $Mg.m^{-3}$. These differences can reflect regional variations, however, the differences for similar grain sizes are sometimes significant. It could therefore be interesting to usually indicate results in mass and volume to limit errors linked to DBD estimation uncertainties.

Finally, sediment budgets opened the way to a quantitative approach to long-term erosion at different time and space scales. After a wave of development at the beginning of the century, they were gradually abandoned, while quantitative studies continued to develop, from the plot scale to the elementary catchment scale and qualitative studies on the modalities and rhythms of Holocene erosion in the European lowlands continued to develop (e.g. Verstraeten et al. 2017). The reason for this is undoubtedly the sheer volume of data required to complete sediment budget calculations, and the uncertainty associated with the various estimates and generalizations of spatial information involved. Nevertheless, research in North America (e.g. Trimble, 2009) and Australia (e.g. Brierley and Fryirs, 1998; Fryirs and Brierley, 2001) demonstrates the importance of such research in understanding erosion rates, the impact of the development of agricultural practices at different spatial and temporal scales and the role of connectivity changes in lowland areas. This is also the only way to propose long-term models of hydrosedimentary dynamics and to test the changes of connectivity efficiency (Tangi et al., 2022). As emphasized by Houben, 2007, 2012, to this end, it would be important to work towards a better understanding of Holocene sediment dynamics in watersheds whose complexity is often greatly simplified in Holocene sediment budgets. As a consequence, temporal changes in rates of erosion and deposition are inevitably hidden. Many studies highlight several phases of erosion and sedimentation took place during the Holocene. For example Germain Vallée and Lespez (2011) demonstrated for the Seulles catchment the existence of different successive phases of erosion, colluviation and stability favourable to pedological processes since the early Holocene. A better understanding of Holocene sediment dynamics allow by (i) the combination between sedimentological, pedological and geoarcheological data, (ii) the realization of dating carried out at different spatial scales and (iii) taking into account the role of sedimentary connectivity on the efficiency of the sedimentary cascade would precise erosion processes intensity on slopes and estimate storage rates to better evaluate the role of interconnected scales in spatial and temporal sediment dynamics into a catchment. These elements would also allow discussing the catchment size effect and would make easier the comparison of Holocene sediment budgets achieved in Northwestern Europe. More generally, additional numerical results are needed to initiate a comparison that would allow us to accurately discuss the various factors explaining local variations in the volume and distribution of sediment storage in alluvial or colluvial zones and enable a history of connectivity over the long term (Wohl et al., 2019).

6. Conclusion

The Holocene sediment budget carried out for the Thue and Mue catchment provides new information on Holocene sedimentary dynamics observed in northwestern France, and more generally in northwestern Europe. The results firstly confirm the importance of sediment storage within the catchment (about 70 %). The chronology of the alluvial deposits established for the Thue and Mue catchments is comparable to those observed in northern and western France and Northwestern Europe. They indicate a start of soil erosion during the Neolithic and acceleration during the last 3 millennia. Results also confirm the importance of analyzing colluvial deposits (i) to limit the underestimation of erosion processes, as colluvial storage is similar to alluvial storage; and (ii) to date with more accuracy erosion processes that were initiated much earlier than the timing given by the alluvial archives. It therefore seems important to multiply the observations through the spatial scales to appreciate more finely the temporality of soil erosion and to understand how the sediments are redistributed in the catchment area. It is also crucial to examine the agrarian structure and networks which can strongly influence the effectiveness of connectivities in catchments and the efficiency of the sediment cascade (Viel et al., 2014b; Boardman et al., 2019). This can considerably modify alluvial and colluvial sediment rates in response to changes in land use or climatic conditions and make it difficult to compare erosion rates in different catchments according to alluvial sedimentation rates. This knowledge is crucial for current soil resource management and to

measure the role of inherited agrarian structures for integrated management of the river basin in a context of land use change driven by economic and climatic controls.

CRediT authorship contribution statement

Vincent Viel: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Laurent Lespez:** Writing – original draft. **Daniel Delahaye:** Investigation. **Bastiaan Notebaert:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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