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Fluvial architecture of Belgian river systems in contrasting environments: implications for reconstructing the sedimentation history

B. Notebaert[1,3,*], G. Houbrechts[2], G. Verstraeten[1], N. Broothaerts[1], J. Haeckx, M. Reynders, G. Govers[1], F. Petit[2] & J. Poesen[1]

1 Department Earth & Environmental Sciences, KU Leuven, Belgium
2 Hydrology and Fluvial Geomorphology Research Centre, Department of Geography, University of Liège, Belgium
3 Research Foundation Flanders – FWO
* Corresponding author. Email: bastiaan.notebaert@ees.kuleuven.be.

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Abstract

Accurate dating is necessary to get insight in the temporal variations in sediment deposition in floodplains. The interpretation of such dates is however dependent on the fluvial architecture of the floodplain. In this study we discuss the fluvial architecture of three contrasting Belgian catchments (Dijle, Geul and Amblève catchment) and how this influences the dating possibilities of net floodplain sediment storage. Although vertical aggradation occurred in all three floodplains during the last part of the Holocene, they differ in the importance of lateral accretion and vertical aggradation during the entire Holocene. Holocene floodplain aggradation is the dominant process in the Dijle catchment. Lateral reworking of the floodplain sediments by river meandering was limited to a part of the floodplain, resulting in stacked point bar deposits. The fluvial architecture allows identifying vertical aggradation without erosional hiatuses. Results show that trends in vertical floodplain aggradation in the Dijle catchment are mainly related to land use changes. In the other two catchments, lateral reworking was the dominant process, and channel lag and point bar deposits occur over the entire floodplain width. Here, tracers were used to date the sediment dynamics: lead from metal mining in the Geul and iron slag from ironworks in the Amblève catchment. These methods allow the identification of two or three discrete periods, but their spatial extent and variations is identified in a continuous way. The fluvial architecture and the limitation in dating with tracers hampered the identification of dominant environmental changes for sediment dynamics in both catchments. Dating methods which provide only discrete point information, like radiocarbon or OSL dating, are best suited for fluvial systems which contain continuous aggradation profiles. Spatially more continuous dating methods, e.g. through the use of tracers, allow to reconstruct past surfaces and allow to reconstruct reworked parts of the floodplain. As such they allow a better reconstruction of past sedimentation rates in systems with important lateral reworking.

Keywords: Belgium; climate change; dating; fluvial architecture; Holocene; land use change

Introduction

Soil erosion and sediment redistribution are important geomorphologic processes during the Holocene in many West- and Central European catchments. An important component of sediment redistribution is (net) floodplain deposition, which provides a buffer between hillslope soil erosion and downstream sediment delivery at different spatial and temporal scales (e.g. Trimble, 2010). In many catchments floodplain deposition has varied during the Holocene, which is often attributed to changes in (anthropogenic) land use or climate (e.g. Dotterweich, 2008; Trimble, 2009; Verstraeten et al., 2009). When studying such relationships, it is essential that net floodplain sediment accumulation is dated, which requires a good insight in floodplain processes and the resulting sedimentary facies. The large variation in river types and dominant processes is reflected in different sedimentary floodplain structures (e.g. Nanson and Croke, 1992). While some floodplains are dominated by lateral accretion deposits, others are dominated by vertical aggradation deposits. The identification of the past deposition environments of the different facies, based on sedimentologic properties, is often referred to as fluvial architecture (e.g. Miall, 1985). The fluvial architecture will help to identify the nature of the dated deposits and therefore the possibilities and interpretations for dating floodplain processes. Dates of overbank fines may produce totally different results from dates of other fluvial settings like channel beds or abandoned channel infillings. Radiocarbon dates from deposits which result from lateral accretion (e.g. channel bed) show other age distributions than dates from floodplain deposits or dates from floodbasins in the same catchment (e.g. Hoffmann et al., 2008; Macklin et al., 2010).

Interpretation of dating results therefore requires a thorough understanding of the depositional environment of the dated material. For many large river (catchment >1000 km^2), the floodplain type and associated processes (e.g. Nanson & Croke, 1992) can be derived from simple topographic information. For smaller rivers this is often difficult (e.g. Notebaert et al., 2009a), especially when floodplain aggradation occurred over the last few hundred years, like in many catchments in Western Europe. In addition, the extent and importance of processes may have changed through time, and determining the past environments may be necessary to evaluate dating possibilities .The main objective of this paper is to identify the fluvial architecture for three Belgian catchments and the implications the different styles of fluvial architecture have on dating possibilities of floodplain sedimentation. The catchments of the selected rivers, the Dijle, Geul and Amblève, differ in environmental settings. We focus on the different elements of the fluvial architecture, and stress the possibilities and limitations for dating floodplain sediment storage based on these elements.

Study areas

This paper discusses the floodplain of three Belgian catchments: the Dijle, Geul and Amblève catchment (Fig. 1). The Dijle catchment (Fig. 2A) is situated in the central Belgian loess belt, and in this study we consider the part of the catchment upstream the city of Leuven (760 km^2). The topography exists of an undulating plateau in which the rivers are incised. The floodplain width of the main valley varies between 200 and 1800 m, while the tributaries have smaller floodplains. The soils of the catchment are mainly Luvisols which developed in Pleistocene loess deposits. The first palynological traces of agriculture date from the Atlantic Period (7800-5000 cal BP; Mullenders & Gullentops, 1957; Mullenders et al., 1966; De Smedt, 1973), and agricultural land use peaked during the Roman Period and from the Middle Ages on. Despite medieval and contemporary intensive land use, some large areas remained forested since at least the 14th century (e.g. Vanwalleghem et al., 2006). Current land use is dominated by cropland and these historical forests on the plateaus and slopes, and grassland and forests on the floodplains. Large quantities of soil have been eroded and deposited in colluvial and alluvial valleys caused by the intensive land use history (e.g. Notebaert et al., 2009b).

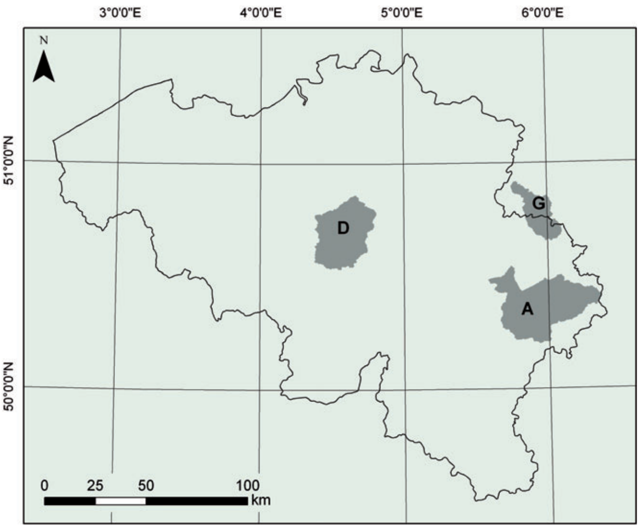
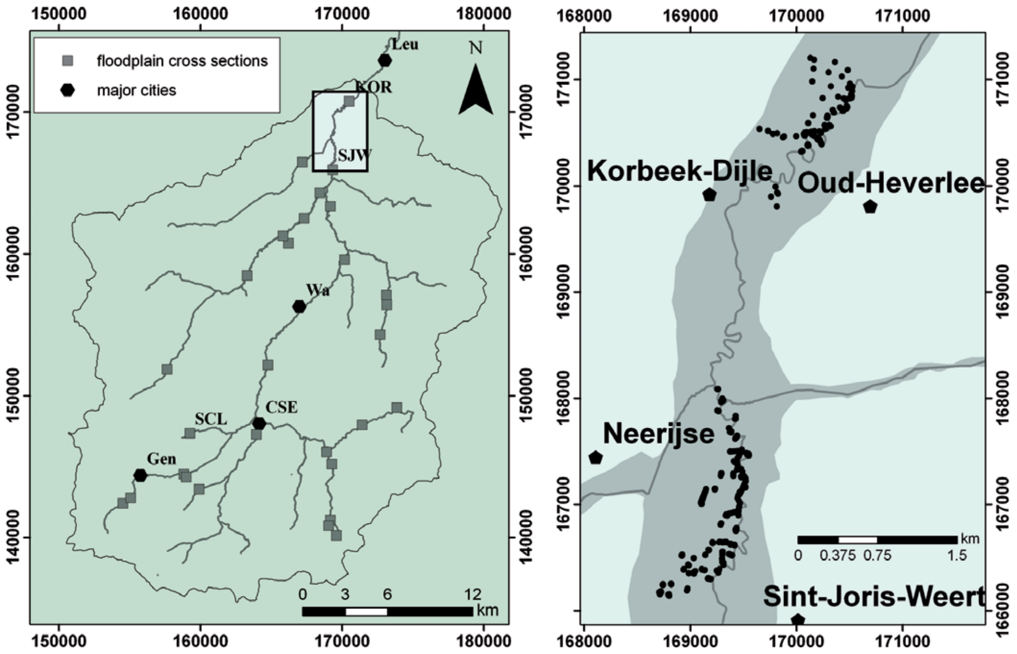


Fig. 1. Location of the study sites in Belgium. A: Amblève; D: Dijle; G: Gulp.

The Geul catchment (350 km^2; Fig. 3) is located in the northeast of Belgium and the southeast of the Netherlands. This study considers the Belgian part of the Geul floodplain (c. 120 km^2 upstream area) and its tributary, the Gulp (c. 47 km^2 upstream area). The topography of the catchment consists of an undulating plateau with deeply incised river valleys. Floodplains are up to 250 m wide. Soils are mainly Luvisols developed in loess, although some sand, gravel and bedrock outcrops occur. The land use history is comparable with that of the Dijle catchment, with the exception of the last few hundred years: a conversion of cropland into grassland started during the 17th century in the south-western part of the catchment, and progressively spread towards the north (Mols, 2004). Hence, current land use is dominated by grassland and forests.

The Amblève catchment (c. 1000 km^2; Fig. 4a) is located in the Belgian Ardennes Hercynian massif. The topography consists of undulating plateaus, deeply incised (up to more than 250 m) by some large river valleys, often with very steep valley slopes (>15%). The floodplains of the upper reaches widen downstream to c. 350 m. The floodplains of the lower, deeper incised reaches are smaller and the width ranges between an almost absent floodplain (~0 m) and 330 m, depending on local geology. The Warche tributary flows through the Malmedy graben, where the floodplain is up to 800 m wide. The upper and lower parts are for most tributaries separated by a reach with a steep gradient (slope >1 m/m), where floodplains are very narrow or absent. The land use history of this catchment is much less intense compared to the other two catchments. The first traces of agriculture in palynological records from the Hautes Fagnes date from the Neolithic period, but the anthropogenic influence remains very low until c. 1200 AD (Damblon, 1969, 1978). Gullentops et al. (1966) report palynological evidence for agriculture in the Lienne catchment from the Subboreal period onwards, while Houbrechts (2005) reports on the local start of



a. b.

Fig. 2. a. Overview of the Dijle catchment. The rectangle displays the extend of Fig. 2b. Main cities: CSE: Court-St-Etienne; Gen: Genappes; Leu: Leuven; Wa: Wavre. Cross sections: KOR: Korbeek-Dijle (Fig. 7); SJW: Sint-Joris-Weert (Fig. 8); SCL: Sclage (Fig. 9); b. Location of surface samples of the floodplain deposits for study of the contemporary texture as function of the depositional environment. Coordinates in this and following figures are in the Belgium Lambert 72 system.

colluvial deposition related to agriculture in a subcatchment at 3195±30 BP (1517-1417 BC; ages are calibrated using Oxcal 4.1 (Bronk Ramsey, 2001, 2009) and the Intcal 04 calibration curve (Reimer et al., 2004), with a 2σ uncertainty; non-calibrated radiocarbon ages are referred years BP, calibrated as years BC/AD). Large deforestations for iron industries occurred from the 14th century on (e.g. Houbrechts & Petit, 2004). Historical maps indicate a far lesser extent of cropland during the 18th century than for the other catchments (e.g. de Ferraris map, 1775), and a conversion from cropland to grassland occurred during the 20th century (Mols, 2004). The contemporary land use is dominated by forests and grassland.

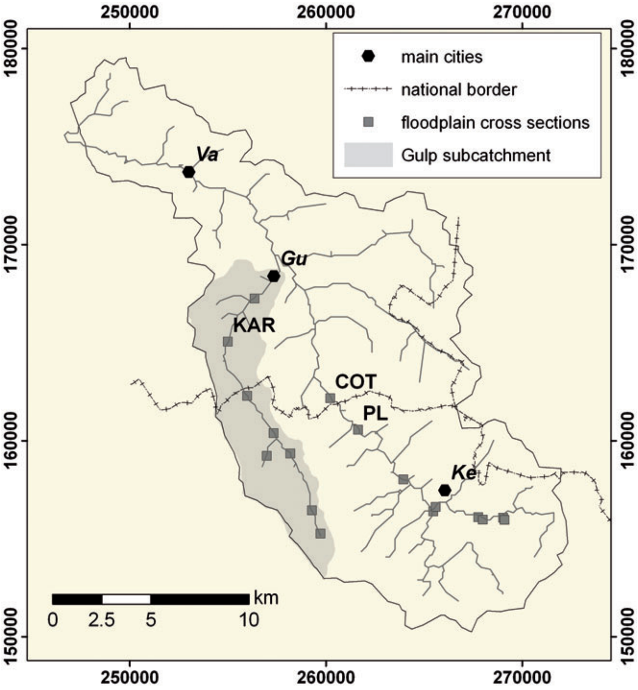


Fig. 3. Overview of the Geul catchment. Main cities: Gu: Gulpen; Ke: Kelmis; Va: Valkenburg. Cross sections: COT: Cotessen; KAR: Karsveld; Pl: Plombières; TEU: Teuven.

Methods

Floodplain characterization

Information on the nature of fluvial deposits is retrieved through an extended coring datasets, complemented with profile pit data. Corings are grouped in floodplain cross sections. For each coring a detailed in field description is made with a vertical resolution of 5 cm, providing information on approximate texture class, colour, quantity, nature and size of gravel, presence of plant material, peat or other inclusions, and soil horizons. Table 1 provides an overview of the number of corings for each catchment. In order to study the complete fluvial architecture of the floodplain, corings should be spaced at a distance that is smaller than the width of the smallest architectural element, which is often the river channel (e.g. Houben, 2007). Achieving

Table 1. Overview of the collected field date for the different catchments.

Catchment	Number of corings	Number of cross sections	Catchment area (km^2)	Total floodplain area (km^2)
Dijle	232	28	780	59.9
Amblève	655	55	1080	37.7
Gulp	72	8	47	2.1
Geul excluding Gulp	90	8	120	-

such a coring density is very time and labour demanding, especially for catchments larger than a few km^2 where multiple cross sections are required to tackle the spatial variability between sites. The coring densities in this study vary between less than 1 time the river channel width in the downstream valley sections of the Amblève catchment to more than 10 times the channel width in the underfit periglacial valleys of the upper reaches of the Amblève. For most cross-sections the distance between two cores is c. 2 times the channel width, which allows identifying most sedimentary units.

In order to evaluate the relationship between the sediment texture and the depositional environments in the contemporary Dijle catchment, detailed textural analysis was performed. Two study sites were selected in the main trunk valley: the floodplain immediately downstream Korbeek-Dijle, and the floodplain near Sint-Joris-Weert (Fig. 2b). Samples were taken from the upper 0.3 m of the deposits, and as such the samples represent the current depositional environment (Table 2). Samples were homogenized, sieved at 500 µm, and the grain size distribution was determined through laser diffraction particle-size analysis, using a Beckham Coulter LS 13 320. For each sample the median, 90%, 95% and 99% percentile of the grain size distribution was determined. A CM pattern (Passega, 1957) is obtained by plotting the 99% percentile (C, from coarsest fraction) on the Y-axis and the median grain size (M, from median fraction) on the X-axis, using a logarithmic scale for both axes. The different depositional processes are reported to form separate groups on these diagrams (e.g. Passega, 1957).

Table 2. Number of samples per depositional environment used for the grain size analysis.

Depositional environment	**Korbeek-Dijle**	**Sint-Joris-Weert**
Backswamps	10	10
Floodplain	12	9
Levee (40m from channel)	10	9
Levee (top; 2-4m from channel)	9	9
Point Bar	9	8
Channel	9	9
Total	**59**	**54**

Dating of floodplain deposits

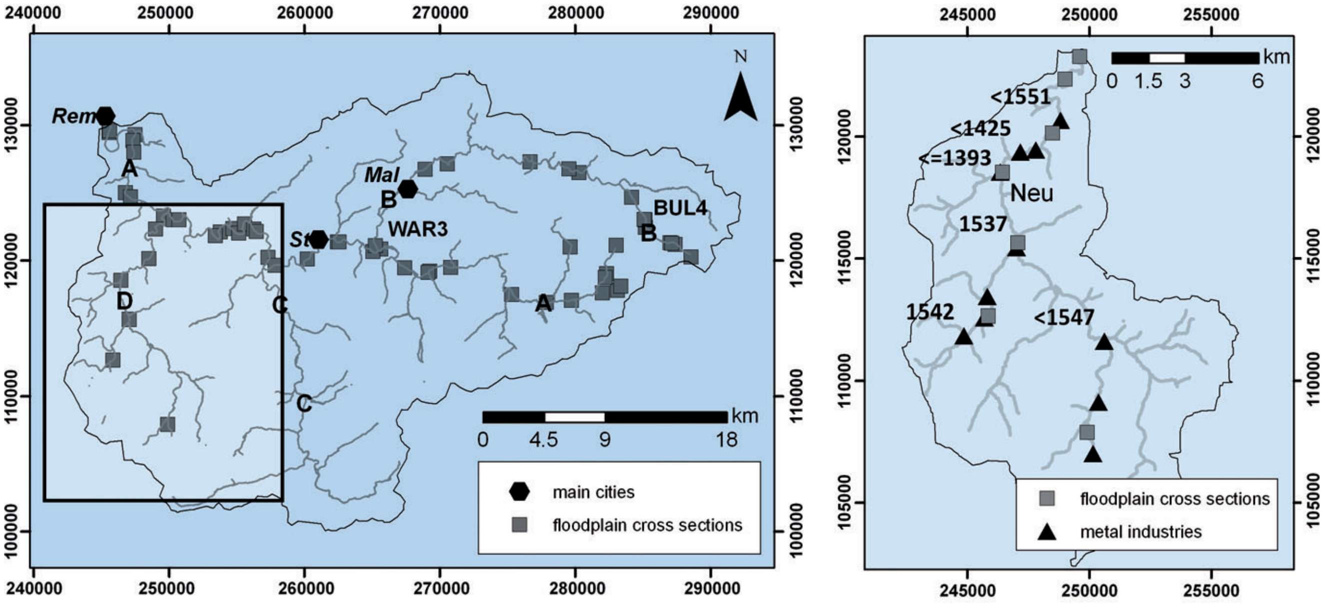
The chosen method for dating floodplain deposition depends on the depositional environment and the resulting nature and availability of datable material. In this study, we focus on the net floodplain aggradation, which requires dates from overbank deposits. Ages from in-channel deposits provide information on the former position of the river channels and the lateral migration. Ages of overbank deposits provide information on net sediment accumulation in the floodplain. Samples for radiocarbon dating were sieved, dried, and manually searched for datable material. Identified terrestrial plant remains were preferred above charcoal. Only a few samples were dated in the Amblève catchment, due to the lack of datable material in overbank deposits. Optical Stimulated Luminescence dating (OSL) was performed in the Dijle catchment and the used methodology and associated problems are discussed by Notebaert et al. (2011a).

Tracers may provide another dating method for floodplain deposits (e.g. Brown et al., 2003): sediments deposited after the introduction of a tracer in a fluvial system will be contaminated with this tracer. Sediments deposited after the removal of the tracer sources may still be contaminated, as reworking of the (contaminated) floodplain sediments by the river may continue to provide a source of the tracer. In this case, the presence of the tracer provides one discrete age control point. Additional age control is derived if the temporal variations in tracer introductions are known, as these can be linked to tracer concentrations in the floodplain deposits (e.g. Stam, 1999, 2002).

At least since the Middle Ages until the end of the 19th century Pb and Zn mining occurred in the Geul catchment (Fig. 5), causing severe contamination of fluvial deposits. Previous studies (Stam, 1999, 2002) have shown that peaks in heavy metal concentrations in fluvial deposits can be linked with peaks in 19th century mining activities. Where previous studies focused on profiles at cutbanks, we sampled within the alluvial plain to get a better spatial distribution of sampling sites over the floodplain.

Samples were taken at two sites: at Plombières (Belgium) and 1700 m downstream at Cottessen (the Netherlands) (Fig. 3). Samples were taking using a percussion drill with a diameter of 5 cm, and samples have depth intervals of 5 to 15 cm. In total 12 percussion drillings were analysed. Samples were dried, sieved at 2 mm and grounded. Pb concentrations were determined after dissolution with concentrated HCl, HNO_3 and HF, using flam atomic absorption spectroscopy (F-AAS). Pb concentrations where plotted as function of sample depth, and these plots were correlated with the historical Pb mining activity intensity. For each coring the start of increased Pb concentrations and the peak was identified, corresponding with c. 1847 and ca 1869 AD respectively.

In the Amblève catchment, contamination of floodplain deposits by slag particles originating from metal industries (blast furnaces and bloomeries) has previously been used to study floodplain histories in the Belgian Ardennes (e.g. Henrottay, 1973; Brown et al., 2003; Houbrechts & Petit, 2003, 2004). Metal industries were set up in the Lienne valley (Fig. 4b), a tributary of the Amblève, starting at the end of the 14th century AD (Houbrechts & Weber, 2007), and large amounts of ironwork waste products were dumped in the river channel and on the alluvial plain. Slag particles dumped in the floodplain are reworked by the river ever since, providing a continuous source of scoria.



a. *b.*

Fig. 4. a. Overview of the Amblève catchment. Main cities: Mal: Malmedy; Rem: Remouchamps; St: Stavelot. Main rivers: A: Amblève; B: Warche; C: Salm; D: Lienne. The rectangle displays the extend of Fig. 4b. Floodplain cross sections: BUL4: Bulingen 4; FDQ: Fond de Quarreux; WAR3: Warche 3; b. Overview of the Lienne subcatchment. Years indicate the year of initiation of metal industry for the given location, if known (Houbrechts and Weber, 2007). Neu: Neucy cross section; Mont: Monty cross section; Rah: Rahier cross section.

Samples with a thickness of 0.05 to 0.15 m were taken at 6 sites (Fig. 4b) using a cleaned Edelman auger. Dry samples were sieved and the coarsest sand fraction was analysed for the presence of metal slag elements. Metal slag concentrations were plotted on the cross sections, which allowed the identification of sediments deposited after the initiation of metal industries. Small contaminations caused by bioturbation and sampling were taken into account: only when the mass percentage of scoria is larger than 2%, the sample is considered as containing such scoria.

Results

Dijle catchment

Sediment grain size

The analysis of the grain size of contemporary deposits shows that the different deposition environments can be differentiated based on the coarsest (C) and median (M) grain size. There is a clear decrease in median grain size when comparing depositional environments in or close to the river channel with those further from the channel (Table 3). The channel lag deposits have a mode of about 200 µm (Fig. 6) and sand is the dominant fraction (Table 3 and 4), although some samples contain larger amounts of silt and clay (up to 35 and 50%). This is possibly caused by sampling a combination of channel lag and underlying fine grained Holocene overbank deposits due to the limited thickness of channel lag deposits. This superposition of channel lag deposits above overbank deposits is the result of floodplain aggradation (e.g. Notebaert et al., 2011a), combined with a recent migration of the meander.

Point bar deposits show typically a bimodal grain size distribution, with peaks around 160-200 µm (sand) and 35-55 µm (silt). The levee deposits still show a bimodal distribution, but because the coarsest peak becomes less important, they are dominated by silts. The histograms of overbank and backswamps deposits are dominated by a peak around 30-50 µm (Korbeek-Dijle) or 15-25 µm (St-Joris-Weert). They are dominated by silt and clay. T-tests show that the depositional facies can best be differentiated using median values combined with 90% or 95% percentiles (Broothaerts, 2008), while the 99% percentile is less fitting. We hypothesise that this is mainly due to the sensitiveness of the 99% percentile, as this percentile relies on a very low amount of grains. Based on the t-tests on the 50% and 95% percentiles, all groups are significantly different. The CM pattern (Fig. 7) of both sites are in agreement with the patterns found by other studies (e.g. Passega, 1957, 1964; Bravard et al., 1989; Bravard & Peiry, 1999). These results confirm that grain size distribution can be used distinguish depositional environments.

Fluvial architecture

Different Holocene fluvial facies units could be distinguished based on texture and other sedimentologic properties like layering patterns and presence and nature of organic material. Figure 8 displays typical cross sections of the floodplains in the Dijle catchment, and the different facies units are listed in Table 5.

Table 3. Grain size properties for the different deposition environments: median texture (μm), average en standard deviation of the percentage clay, silt and sand.

	Korbeek-Dijle				**Sint-Joris-Weert**			
	Median (μm)	**% clay**	**% silt**	**% sand**	**Median (μm)**	**% clay**	**% silt**	**% sand**
Backswamps	17±8	35.6±6.2	54.1±5.0	10.3±2.9	9±5	45.7±9.1	47.8±8.1	6.5±2.9
Floodplain	21±6	25.3± 6.4	57.9±2.9	16.8±5.6	11±3	44.8±8.2	48.0±7.3	7.2±3.5
Levee (~40 m from channel)	27±6	23.9±5.6	55.3±3.2	20.8±5.4	20±2	29.0±3.3	59.6±3.4	11.3±2.5
Levee (top; 2-4 m from channel)	31±13	19.3±7.5	52.0±5.3	28.7±11.7	25±3	24.9±2.5	56.6±2.6	18.5±4.3
Point Bar	55±35	12.9±2.7	40.6±8.6	46.5±11.2	46±54	15.1±4.8	40.6±10.0	44.3±14.3
Channel	169±86	6.9±5.9	20.5±14.8	72.6±20.6	178±111	12.2±12.6	24.7±20.8	63.1±32.6

Table 4. Grain size properties of the different deposition environments: range in percentage clay, sand and silt.

	Korbeek-Dijle			**Sint-Joris-Weert**		
	% clay	**% silt**	**% sand**	**% clay**	**% silt**	**% sand**
Backswamps	27.1-44.6	48-62.4	6.2-13.5	26.6-57.8	37.8-62.2	2.6-12.4
Floodplain	17.3-34.6	52.4-61.6	11.3-26.8	31.6-59.9	36.9-62.2	3.2-11.8
Levee (~40 m from channel)	15.8-32.9	49.9-58.3	13.1-30.5	24.2-33.2	54.4-63.2	7.3-15.3
Levee (top; 2-4m from channel)	8.7-29.9	44.3-58.8	13.8-47.0	21.3-28.1	53.2-60.3	11.6-24.1
Point Bar	8.4-16.3	27.6-50.3	34.3-62.5	7.5-22.4	24.1-48.1	31.1-68.4
Channel	1.2-16.3	3-46.4	37.3-95-8	1.2-34.8	2.5-50.1	19-96.3

Facies unit 1 exists of sandy sediments, deposited at the bottom of the cross sections. Its texture varies between loamy sand and sand with fine gravel (<2 cm), without organic material. This texture indicates a relatively high energy fluvial system. The top of this layer is not horizontal and has indications of shallow channels, which are possibly caused by a post-depositional erosional phase (see also De Smedt, 1973). A single OSL age is available from this layer: 26000±4000 BP (2σ uncertainty; Notebaert et al., 2011a). This unit is interpreted as a Weichselian and Lateglacial braided river deposit.

Facies unit 2 is found in comparable positions as unit 1, and exists of compact silty to loamy sediments. This layer grades horizontally and vertically in unit 1, often with an intermediate texture in between. Because of its position, this unit is considered as a Late Weichselian to Lateglacial deposit. Possibly it was deposited in the braided river plain at a distance from the channels, although it may also be an in-situ loess deposit or a mixture of both.

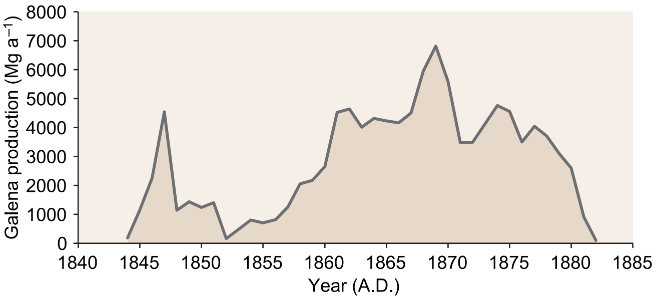


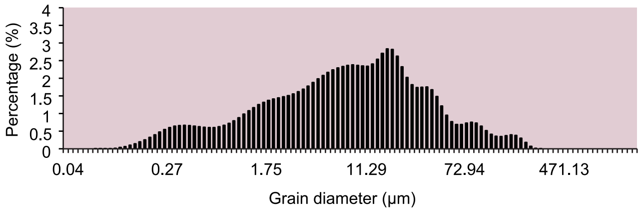
Fig. 5. Yearly production of galena at Plombières (after Dejonghe et al., 1993).

Unit 3a exists of a complex of organic layers. This layer sometimes consists of reed peat or in some cases woody peat. But in most corings it consists of a very organic layer of decomposed peat or a very organic silty to clayey layer with plenty of organic material. Sometimes this layer exists of gyttja, especially the lower parts. This layer often contains small freshwater shells. These different types grade into each other both vertically and horizontally. The organic matter content varies between c. 20 and 80% (Rommens, 2006; Notebaert et al., 2011a).

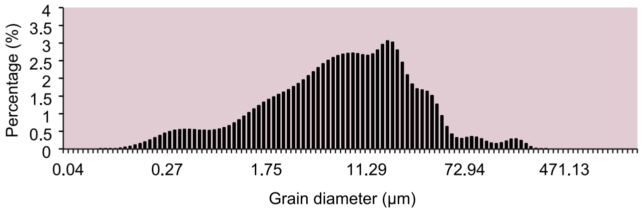
Facies unit 3b exists of a complex of calciumcarbonate rich, often organic, layers. It varies from layers with a high content of calciumcarbonates (nodules, sometimes shells) to deposits of almost pure calciumcarbonate nodules. Like unit 3b, it can consist of gyttja. This unit is located at the same position and grades vertically and horizontally in facies unit 3a. In the Train tributary, this layer exists locally of almost pure calciumcarbonate nodules, with only a few organic layers. Here, this deposit was previously identified as travertine (Geurts, 1976).

Unit 3a and 3b (= unit 3) form a large complex of organic and calciumcarbonate rich deposits and are deposited above units 1 and 2. Dates from the base of unit 3 range from 9500 BC to c. 5100 BCE, ages of the top vary between c. 4600 BC and c. 1500 AD (Notebaert et al., 2011a). The thickness of unit 3 varies, but most often it is 1 to 3 m thick. It is interpreted as an early to middle Holocene organic and calcic vertical floodplain accumulation. The high calciumcarbonate content of unit 3b and the presence of gyttja indicate an environment with stagnant water. Downstream the studied catchment, comparable deposits are formed (De Smedt, 1973). Exposed profiles along the entire floodplain width indicate the absence of a channel facies formed synchronous with unit 3, which is explained by a diffuse water flow (De Smedt, 1973). The formation of this facies unit is related to a period with limited water and sediment discharge, during which floodplains were stable and mineral sediment deposition rates were low.

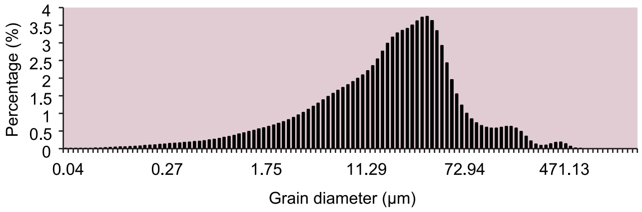
a. Backswamps - SJW 158



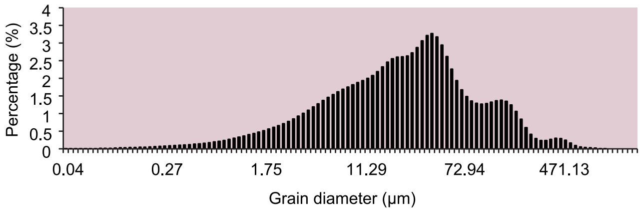
b. Floodplains- SJW 113



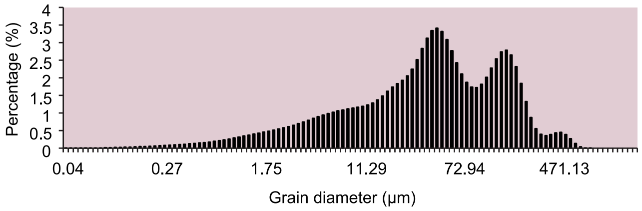
c. Levee (40 m from channel) - SJW 121



d. Levee (top) - SJW 111



e. Point bar - SJW 143



f. Channel - SJW 141

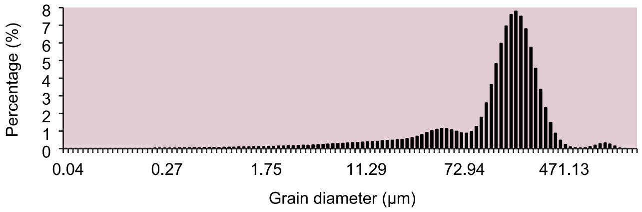
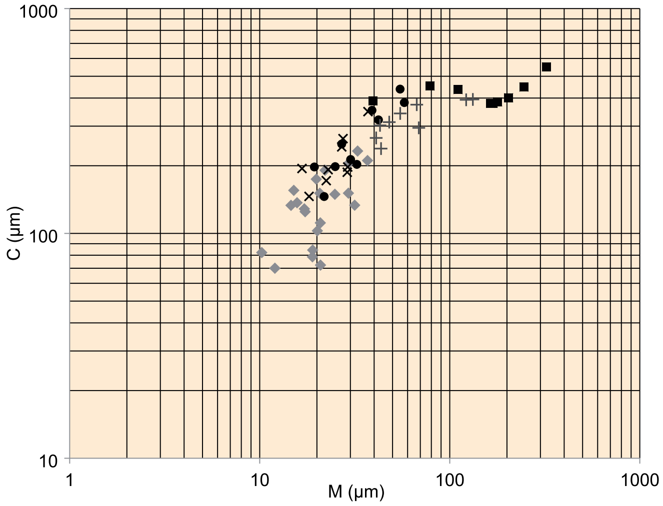


Fig. 6. Typical grain size distributions for the different depositional environments in the contemporary Dijle floodplain.

CM pattern Korbeek-Dijle



CM pattern Sint-Joris-Weert

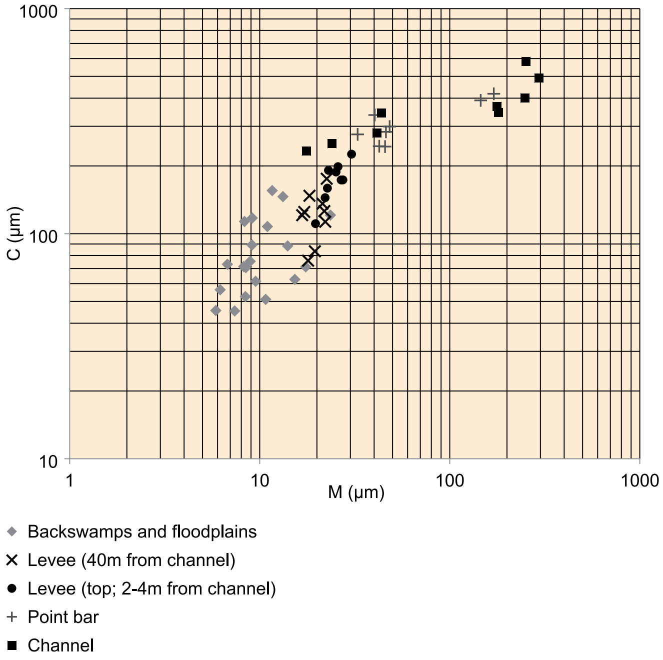


Fig. 7. CM patterns (Passega, 1957) for Korbeek-Dijle and Sint-Joris-Weert.

Unit 4 exists of a silty clay loam and silt loam. There are often small organic layers, sometimes small peat layers, but in general the amount of organic matter is decreasing. The top of this layer is often a well developed organic or peat layer. Unit 4 covers unit 3, and the transition between both units is gradual. Ages from the top peat layer range between c. 700 and 1500 AD (Notebaert et al., 2011a). This unit is interpreted as an overbank sediment, deposited under conditions of increasing sediment load and floodplain deposition, and decreasing importance of aggradation of organics in the floodplain. The texture of the unit varies both laterally and vertically, as a function of the local stream power of the water, varying between the more distal parts of the floodplains and the parts close to the channel. Well developed levees cannot be identified for this unit.

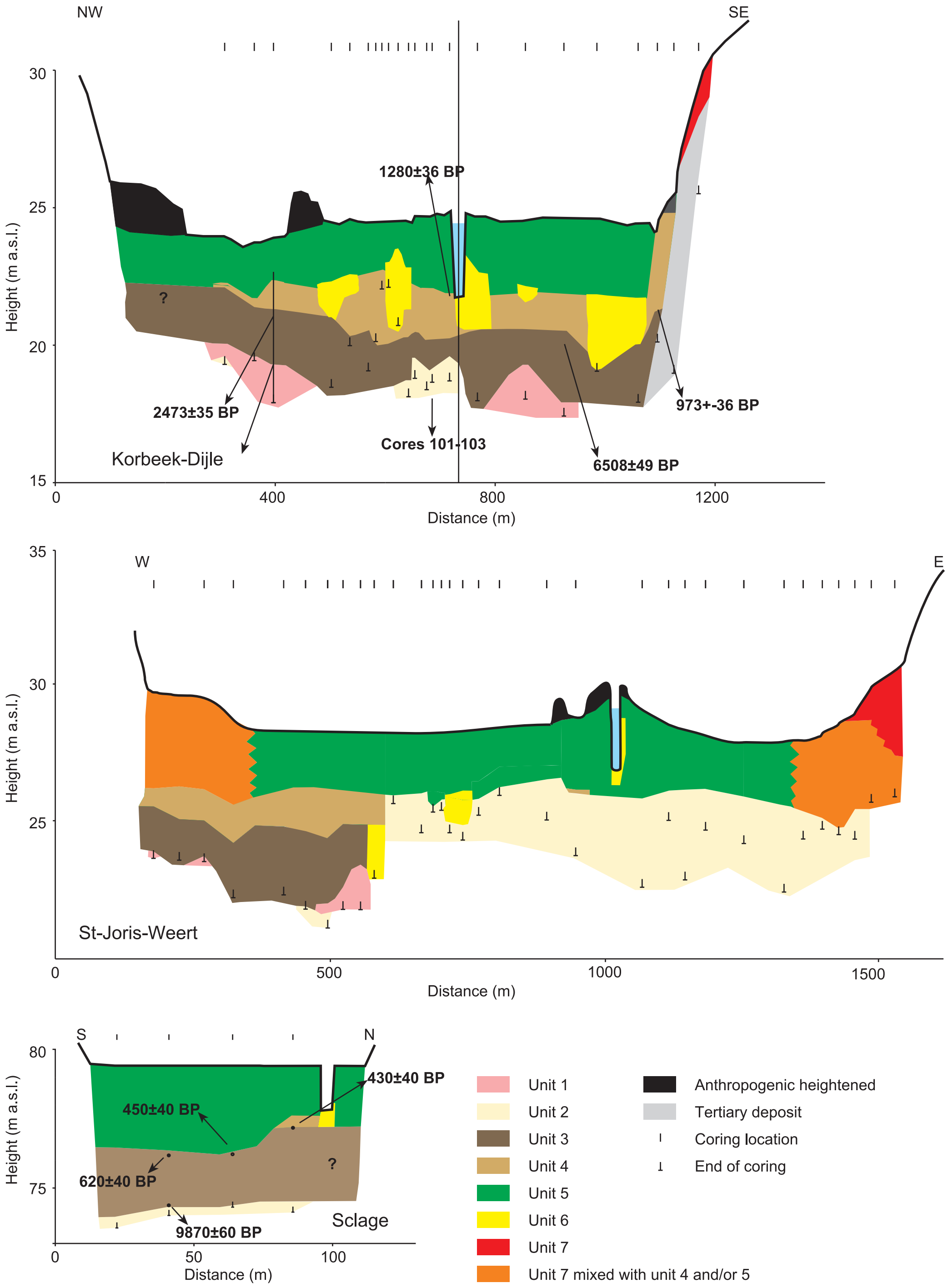


Fig. 8. Floodplain cross section in the Dijle catchment at Korbeek-Dijle (Dijle River), St-Joris-Weert (Dijle River) and Sclage (Cala River). An explanation of the different units can be found in the text and Table 5. Vertical exaggeration 50 times for Korbeek-Dijle and St-Joris-Weert, and 10 times for Sclage. The location of the different cross sections is indicated on Figure 2.

Unit 5 exists of complex of silty clay loam, silt loam and some loam, which are laterally and vertically grading into each other. This unit is located at the top of the floodplain, and contains in general no peat or organic-rich layers, except for the current A-horizon. Unit 5 is often between two and five metres thick, and is interpreted as the overbank deposits of the last 1000 years, which are related to large scale deforestations that triggered severe soil erosion on the loess plateau (Rommens et al., 2006; Notebaert et al., 2009b; Verstraeten et al., 2009). At some locations thin layers (<15 cm) of sandy loam to loam deposits interrupt the silty (clay) loam layers. These deposits are interpreted as being deposited by large floods, probably on crevasse splays. Other heterogeneous sandy and silty deposits which are situated close to a palace channel are interpreted as levees. More clayey deposits can be found at the distal parts of the floodplains (backswamps). This unit was deposited during the last 1000 to 1300 years, and makes up the largest part of the Holocene floodplain deposits of the catchment (Notebaert et al., 2011a).

Unit 6 exists of sandy loam, sands with at some location <20% fine (<5 cm) gravel, and is found at the same absolute height as units 4 and/or 5, sometimes forming a depression in

Table 5. Different facies units of the Dijle catchment.

Unit	Texture	Position	Other properties	Interpreted deposition environment	Age
1	Sands with fine gravels to loamy sand	Bottom of the floodplain deposits	-	Braided river deposits	Pleistocene
2	Compact silty and loamy sediments	Bottom of floodplain deposits; grades laterally and vertically into unit 1	-	Braided river deposit: distal parts of the floodplain?	Pleistocene?
3a	Organic: peat to very organic silt and clay deposits	Above units 1 and 2, covered by unit 4 or unit 5; over the entire floodplain width	-	Organic floodplain infilling	Start: early Holocene End: 4600 BC to 1500 AD, depending on location
3b	Calciumcarbonate rich deposits, often organic		-	Organic and calciumcarbonate rich floodplain infilling with stagnant water	
4	Silty clay loam and silt loam, contains some organic or peat layers	Covering unit 3 and covered by unit 5	Top is often a peat layer	Overbank deposit	Start: depending on location from c. 4600 BC onwards End: c. 1000 AD
5	Silty clay loam to loam	Top of floodplain	-	Overbank deposits	Deposition from c. 1000 AD onwards
6	Sandy loam, sands and sands with some (<20%) fine(<5 cm) gravel	At the same level of units 4 and 5, with an erosive lower boundary; covers <20% of floodplain width; often associated with current or known past channel belts	Contains sometimes brick fragments, twigs, or other organic remains	River channel and point bar deposits	After c. 4600 BC
7	Fine sand to silty clay loam, often arranged in small layers	At location of colluvial fans or footslope deposits; grades laterally into units 4 and 5	Sometimes contains fragments of bricks and charcoal	Colluvial deposit	After c. 4600 BC

unit 3. In some cases a textural fining up can be observed, but generally textural variations are hard to determine. The transition to the underlying unit is sharp, indicating an erosive boundary, while the upper transition to unit 4 or 5 is mostly gradual. Unit 6 often contains small wood fragments. This unit is interpreted as a combination of channel lag and point bar deposits. The differentiation between both facies is not possible in the field. The position of this unit is always confined to a part of the floodplain, and often located in its centre, forming stacked point bar deposits. In most cases less than 20% of the floodplain area in the cross section contains unit 6, but in some exceptional cases (like the Korbeek-Dijle cross section, Fig. 8) the Holocene channel belt crosses the cross-section several times.

The texture of unit 7 contains fine sand to silty clay loam, often arranged in small horizontal layers. This layer sometimes contains fragments of bricks and charcoal and is always positioned along the floodplain edges, and connects to colluvial fans and footslope deposits. It is interpreted as a colluvial deposit or a mixture of colluvial and alluvial deposits (unit 7b). It only occurs in the upper parts of the floodplain deposits, at a higher altitude than unit 3, indicating that it was deposited later than unit 3. Due to the slight differences between units 4, 5 and 7, it is unclear whether unit 7 was deposited contemporary with unit 5 or with unit 5 and unit 4.

In general, the Holocene floodplain deposition in the Dijle catchment can be divided in three phases. During phase 1 the organic and calciumcarbonate deposits of unit 3 were deposited. This phase started in the early Holocene, and the end varies from site to site. During phase 2 units 4 and the lower parts of unit 6 were deposited. This phase is the result of the increase of sediment load in the floodplain, which is related with anthropogenic land use (Notebaert et al., 2011a). During this phase peat growth in the floodplain was replaced by clastic aggradation. Phase 3 consists of unit 5 and the upper part of unit 6, and started approximately at 1000 CE. This is the major floodplain aggradation phase, and is related to an intense anthropogenic land use, causing severe soil erosion and sediment redistribution (Rommens et al., 2006; Verstraeten et al., 2009; Notebaert et al., 2011 a).

This general pattern is not homogenously present in the catchment, and variations occur in the presence and thickness of units 3 to 5. Locally only two units (units 3 and 5) can be differentiated. Locally a deep channel belt incised before the Holocene in the Weichselian deposits (units 1 and 2), and this depression was filled during the earlier parts of the Holocene (units 3 and 4). Only from the moment that this depression was filled up, the entire contemporary floodplain was covered with sediments (phase 3) (e.g. Fig. 8, cross section St-Joris-Weert).

In its upper reaches, the Train River is incised in Early and Middle Holocene floodplain deposits, forming a gorge with steep, up to six meter high, banks, while a contemporary floodplain is absent. The (terraced) floodplain is build up of unit 3b, and the subsequent deposition of units 4 to 6 did not occur here. At a depth of 0.2 m, this terraced floodplain was dated at c. 1400 BCE, providing the only dating control of the start of the incision phase (Notebaert et al., 2011a; location 'Bonlez U'). There are no indications why late Holocene aggradation is absent for this location. Thick Early and Mid Holocene travertine deposits are, however, present here (see also Geurts, 1976), and we hypothesise that breaching of a travertine dam and a subsequent lowering of the base level is responsible for the incision phase.

Geul catchment

Fluvial architecture

In the Geul catchment, the floodplains of the Gulp tributary and of the Belgian part of the Geul itself were studied. De Moor et al. (2008) discuss the different sedimentary units encountered in the Geul floodplain, and these units largely agree with the units encountered in the Gulp catchment. But not all units that are described by De Moor et al. (2008) were encountered in this study, mainly because some units occur only downstream of the studied stretches. A summary of all units is provided in Table 6, while typical floodplain cross sections are provided in Fig. 9. There are also some other differences with the descriptions of De Moor et al. (2008): they make a distinction between units with a silty loam (their units 3 and 4) and a silty clay loam (their unit 5) texture, while this was not possible for most corings in this study, and hence these units are merged (unit 3). But in addition, we were able to make a further distinction within the overbank deposits (unit 3): the upper parts (unit 3b) have characteristic dark brown and dark grey colour, which coincides with high lead concentrations (see below). This unit can only be found in the floodplain of the Geul, downstream of the mining sites near Plombières, and it is interpreted as being deposited since the initiation of large scaled lead mining in the catchment (1842 CE).

In general, the floodplains of the Gulp and Geul show a pattern of a basal gravel layer (unit 1), covered with finer sediments (units 2 to 7) deposited on point bars or as overbank floodplain deposits. The accumulated thickness of these fine deposits increases downstream, for the Geul from c. 0.5 m to more than 3 m near the Belgian-Dutch border, and for the Gulp from c. 0.5 m to c. 2.6 m. The occurrence of point bar deposits over the entire floodplain width (Fig. 9) indicates the importance of lateral migration of the river channel during the Holocene. The thickness of these point bars varies within cross sections, which may be partially due to the fuzzy delineation of this unit, both with respect to units 1 and 3. Locally gravels are deposited on the lower parts of point bars, and as a result the upper parts of unit 1 may have been deposited on such point bars. In addition, the thickness of the point bars may have increased over time, simultaneous with floodplain aggradation (see also De Moor et al., 2008). Dates from the organic material directly on top of unit 1 in the Dutch Geul floodplain indicate that the majority of the floodplain was reworked during the Holocene period (De Moor et al., 2008).

Dating floodplain deposition

Radiocarbon datable material found in the Geul floodplain is always situated in units 1 and 2, and most often at the transition between both units. The resulting ages would provide information on the moment of floodplain reworking (and lateral channel movement) but not on floodplain aggradation. But as point bar deposits mainly consist of reworked material, the value of dating such material is further reduced.

As a result, dating based on Pb as a tracer is used to identify net floodplain sedimentation within the studied section of the Geul catchment. Lead concentrations for sediments deposited before 1842 show large variations between corings for the Plombières site (150 to 700 mg Pb per kg soil) while they are more constant at Cottessen (around 200 mg Pb per kg soil) (Table 7). This can be explained by small scaled and localised mining activities before this period. Peak values reach 6000 mg Pb per kg soil at Plombières and 1600 mg Pb per kg soil at Cottessen, which is a function of downstream dilution of the pollution. Peaks in lead concentration corresponding with ~1842 AD and ~1869 AD are determined for the different corings (Fig. 10).

The results of the sediment deposition per time span (Table 8) show that for both studied sites on average 17% of the total Holocene floodplain deposition occurred after the initiation of the metal mining (~1842 AD). There are some differences between both sites concerning the deposited fractions in the time frames 1842 AD - 1869 AD and 1869 AD - present (Table 8). Results are influenced by the vertical sampling resolution and difficulties in interpreting the peaks in lead concentrations, which hampers a detailed reconstruction of the sedimentation history. Nevertheless, for both sites the sedimentation rate is higher for time frame 1842 AD - 1869 AD.

Amblève catchment

Fluvial architecture

The floodplains of the Amblève catchment can be distinguished into three reaches: the upper reaches (e.g. cross section Bullingen 4, Fig. 11), the lower reaches (e.g. cross section Warche 4,

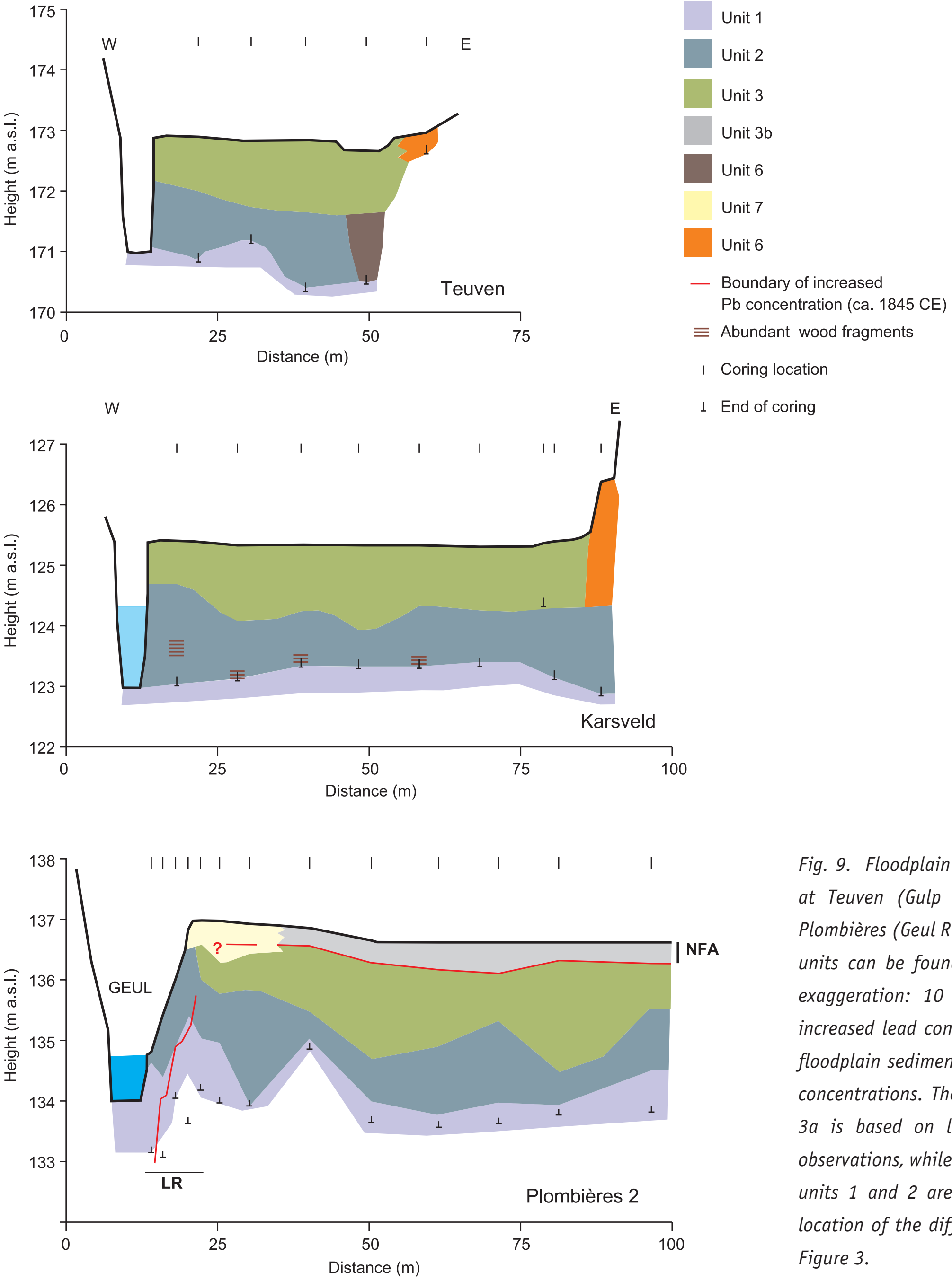


Fig. 9. Floodplain cross section in the Geul catchment at Teuven (Gulp River), Karsveld (Gulp River) and Plombières (Geul River). An explanation of the different units can be found in the text and Table 6. Vertical exaggeration: 10 times. LR: lateral reworked since increased lead concentrations (c. 1845 AD). NFA: net floodplain sediment accumulation since increased lead concentrations. The boundary between unit 3 and unit 3a is based on laboratory measurements and field observations, while the increased lead concentrations in units 1 and 2 are based on laboratory analysis. The location of the different cross sections is indicated on Figure 3.

Fig. 11), both having relatively gentle slopes, separated by reaches with steeper gradients which are associated with a river long profile knickpoint. Also the lower reaches contain one steeper reach (Fonds de Quarreux; cross section depicted in Fig. 11), which has a comparable valley morphology and fluvial architecture as the other steep reaches. The upper reaches often have broad floodplains along a meandering river. Here, the river has a low width/depth ratio (<10). The width of the floodplain of the lower reaches is highly variable, depending on local geology, and the rivers have a straight pattern within their inherited meandering valleys. The width/depth ratio of these lower reaches is high (>10, most often >20). Steep reaches occur just downstream the knickpoints which separate these upper and lower reaches, and at a lithological knickpoint at Fonds de Quarreux. Here floodplains are almost absent. The fluvial architecture between upper and lower reaches differs only slightly, except for the steep reaches.

Unit 1 consists of a poor sorted basal gravel layer, sometimes mixed with some sands or organic material. The depth of the top of this gravel layer varies between and within cross sections. In the lower reaches, abandoned river channels are still visible in the floodplains as depressions, and form often also depressions in the top of this gravel layer (Notebaert et al., 2009a). This gravel layer was most probably deposited during the Weichselian, and is currently being reworked in the river channel and deposited as channel lag deposit or on bars. A

Table 6 Different facies units of the Geul and Gulp catchments.

Unit	Unit De Moor et al. (2008)	Texture	Position	Other properties	Interpreted deposition environment	Age
1	1	Poor sorted gravel, mixed with some sand	Base of Holocene fluvial deposits,underlying the entire valley width	Contains sometimes organic material (twigs, nuts)	Channel lag and lower bar deposits; reworked Pleistocene material	Weichselian and reworked Holocene
2	2	Fining up sequence of sand and sandy loam to silt loam or silty clay loam	Above unit 1 and covered by unit 3, over the entire valley width	Lower part may contain organic material like twigs and nuts	Point bar	Holocene
3	3, 4 and 5	Silt loam and silty clay loam	On top of unit 2, at the surface or covered by unit 4 or 7	-	Overbank fines; lower part	Holocene
3b	-	Silt loam and silty clay loam	Downstream the mining sites in the mean Geul valley, at the surface	Distinctive grey color	Overbank deposit	Since c. 1845 AD
6	6	Silty or loamy organic deposits, often containing decomposed peat	In the floodplain, with a limited width	-	Organic infilling of cut off channel	Holocene
7	7	Heterogeneous mixture of silty clay loam to sand; at cutbanks it shows a structure of small layers with differing texture	(contemporary) levees	Often a distinctive grey color similar to unit 4	Levee deposit	Holocene
9	9	Heterogenous silty clay loam to loam	Footslopes; grades laterally into unit3	Contains sometimes bricks and charcoals	Colluvial deposit	Holocene

profile pit in the Lienne catchment shows that this unit is locally at least three meter thick, while locally surfacing bedrock in the river bed indicates that it can also be just a few cm thick.

Unit 2 is situated directly on top of this gravel layer, and consists of a textural fining up from sandy deposits to silty clay loam. The thickness varies, and it grades into the overlying unit 3 from which it can be hardly separated. It contains often organic material like twigs, wood or nuts and also some rounded gravels, with a diameter varying between 2 and 20 cm. This unit is interpreted as deposited on bars. The limited thickness of these point bars is explained by the limited depth of the river channel and the sheet like nature of point bars. The plan view position of contemporary deposits of this unit, in the meander inner bends, provides additional indications for its genesis.

Table 7. Average depth of different marker horizons (m), standard deviation (m) and number of used corings (n) for the two study sites in the Geul catchment.

	Plombières	Cottessen
Bottom of Holocene deposition (m)	2.36±0.43 (n = 8)	2.70±0.25 (n = 4)
Bottom of increased Pb pollution (~1842 AD) (m)	0.41±0.09 (n = 6)	0.45±0.09 (n = 3)
Peak in Pb pollution (~1869 AD) (m)	0.24±0.13 (n = 5)	0.18±0.05 (n = 4)

Unit 3, situated on top of unit 2, consist of rather homogenous silty loam to silty clay loam. It contains sometimes charcoals and a few gravels with a diameter of 2 to 20 cm. At most locations, the combination of units 2 and 3 cover unit 1 over the entire floodplain. This unit is interpreted as overbank fines, but the lower part is probably deposited on bars like unit 2.

Unit 4 consists of small (often <15 cm thick) layers of sands, sandy loams and gravels, and can sometimes be found within units 2 or 3. These deposits are interpreted as flood deposits.

Unit 5 consist of poor sorted sands, sometimes mixed with gravels. This unit occurs in the steep reaches and makes up the entire non-gravel fraction of the floodplain sediments. This unit is interpreted as a bank deposit. The combined thickness of units 2 to 5 (the fine deposits) ranges from c. 0.2 m to more than 1.5 m, and is between 0.6 and 1.2 m for most locations.

Unit 6a consists of peat and silty deposits with a high organic matter content and decomposed plant remains. This unit occurs in distal parts of the floodplain at a few locations in the upper reaches, covering unit 1 or a layer of unit 2, and is covered by some centimetres of unit 3. The thickness of this unit ranges from some centimetres to c. 0.4 m. Given its position and nature, it is being interpreted as a back swamp facies of the distal part of the floodplain. Unit 6b consists, like unit 6a, of

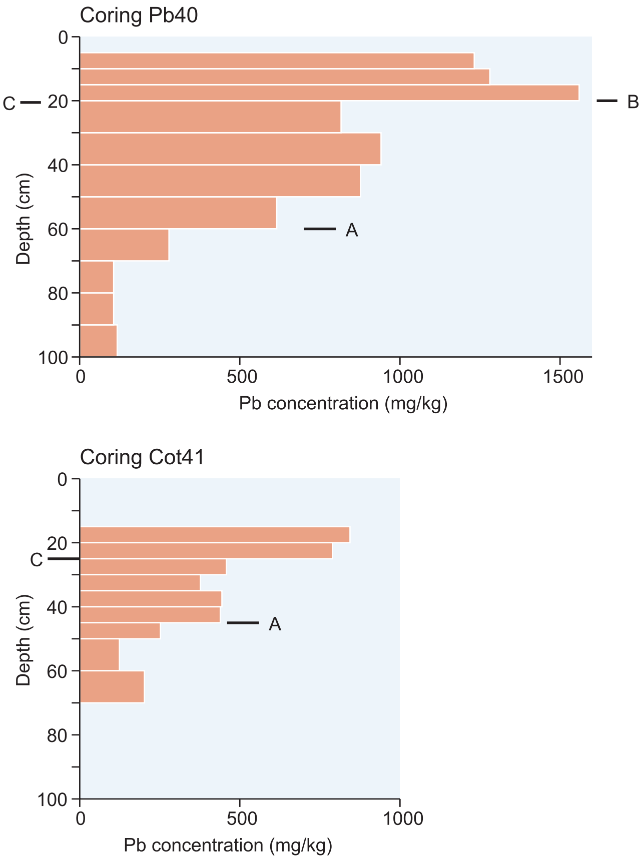


Fig. 10. Pb concentrations in function of depth for coring Pb04 at Plombières and cot41 at Cottessen (Geul catchment). The interpreted depths of the deposits of ~1842AD (A) and ~1869AD (B) are indicated, as well as the in field observed lower border of the dark-grey upper layer (C). Both corings are located in the floodplain, not on levees.

Table 8. Average fraction of sediments deposited during different time periods compared to the total Holocene deposition and sedimentation rate for the two study sites in the Geul catchment. For the sedimentation rate prior to 1842 AD, different sedimentation periods (with a start varying between 9000 BC and 6000 BC) are used, in order to incorporate the uncertainty on the start of the deposition.

	Fraction (%) of Holocene deposits		Sedimentation rate (mm/a)	
Time period	**Plombières**	**Cottessen**	**Plombières**	**Cottessen**
9000 BC - 1842 AD	83	83	0.18	0.21
8 000 BC - 1842 AD	83	83	0.20	0.23
7000 BC - 1842 AD	83	83	0.22	0.25
6000 BC 1842 AD	83	83	0.25	0.29
1842 AD - 1869 AD	7	10	6.3	10.0
1869 AD - present	10	7	1.7	1.3

peaty deposits and silty deposits with a high organic matter content, but has a different position. This unit is only encountered at a few locations, and is found in the middle of the floodplain, surrounded by places where units 2 and 3 make up the entire thickness of the Holocene deposits. In the lower reaches this unit is always associated with depressions related with former channels (Notebaert et al., 2009b). This unit is positioned above unit 1 or 2 and is covered by unit 3, and has a limited lateral extend (maximal about the width of the current channel). Given its texture and position in the floodplain, unit 6b is interpreted as an organic infilling of abandoned (cut off) channels.

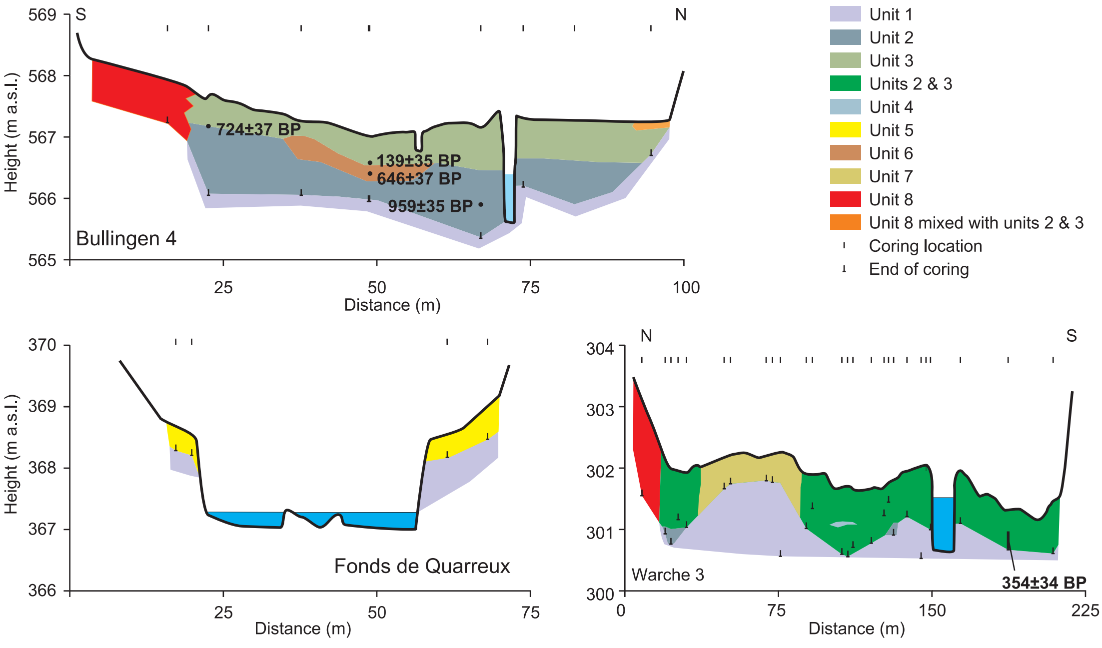


Fig. 11. Floodplain cross section in the Amblève catchment at Bullingen (cross section Bullingen 4; Warche River), Fonds de Quarreux (Amblève River) and the village Warche (cross section Warche 3; Amblève River). Vertical exaggeration 10 times for the cross sections at Bullingen and Fonds de Quarreux, and 30 times for the cross section at Warche. An explanation of the different units can be found in the text and Table 9. The location of the different cross sections is indicated on Figure 4.

Table 9. Different facies units of the Amblève catchment.

Unit	Texture	Position	Interpreted deposition environment	Age
1	Poor sorted gravel	Base of floodplain deposits, in the channel and on the bars; over the entire width of the valley	Channel and bar deposits; reworked Pleistocene material	Pleistocene and Holocene
2	Textural fining up from sands to silty clay loam. Bottom sometimes contains twigs, wood and nuts.	On top of unit 1; often over the entire width of the valley	(Point) bar	Holocene
3	Loam to silty clay loam	Floodplain surface, on top of unit 2; often over the entire width of the valley	Overbank fines; lower part possibly on point bars	Holocene
4	Small layers of sand or fine gravel	Floodplain, within units 2 and/or 3	Flood deposits	Holocene
5	Poor sorted sands, sometimes with gravels	Floodplain of the steep reaches	River banks and overbank	Holocene
6a	Silt with high organic matter content and peat	Distal parts of the floodplains of the upper reaches; covers unit 1 or 2 and is covered by unit 3	Distal parts of the floodplain with peatland	Holocene
6b		In the middle of the floodplain of the lower and upper reaches, often associated with former channels; above unit 2, covered by unit 3	Organic cut-off channel infilling	Holocene
7	Silty clay loam to loamy sand with >5% gravel	Lower terrace level in the lower reaches	Terrace deposit?	?
8	Silt to loam, >10% gravel	Colluvial footslope; grades laterally into units 2 and 3	Colluvial deposits	Holocene

Unit 7 consist of heterogeneous silty clay loam to loamy sand, with a domination of silty clay loam, and contains >10%, but often >30%, large, well rounded gravels (longest side >3 cm). This unit is positioned above unit 1 at a lower terrace level of unknown age in the lower reaches (see Fig. 11, Warche 3 cross section). The upper part of this unit is more fine grained, and sometimes a thin (<0.4 m) cover of unit 3 can be distinguished. The thickness of unit 7 varies from 0.1 m to 0.6 m. The terrace level is situated 0.2 to 0.8 m above the rest of the floodplain, while the top of unit 1 is here also elevated distinctively higher (0.2 to 1 m) than in the surrounding floodplain. Due to the low elevation of this terrace, it is still flooded occasionally and recent floodplain sediments (unit 3) are still being deposited. This unit was deposited before the formation of the current floodplain, but given the contemporary flooding, the upper parts may be deposited more recently.

Unit 8 has a silty to loamy texture, and contains often >10% often angular stone fragments and also often some charcoals. It is always encountered at the footslope, and is interpreted as a colluvial deposit. It grades often in the fine floodplain deposits of units 2 and 3.

Dating results

Radiocarbon datable material within this catchment was mainly found at the contact of the basal gravel layer and the finer deposits, or within the sandy deposits just above the gravels, indicating that these wood and plant remains were deposited on a point bar. Dating these deposits provides information on past positions and lateral movement of the channel, if it is assumed that the remains were not reworked.

The presence of iron slag proved to be the most useful dating method to yield net sediment accumulation rates. This technique was applied in the Lienne subcatchment (Table 10). In total 6 sites were examined and sampled, while data from a site on the Chavanne tributary are available from Houbrechts & Petit (2004; pers. comm.). Metal slag concentrations in the coarsest sand textural class were plotted for the different cross sections (Fig. 12). A slag concentration of 2% was used to differentiate the sediments that were deposited before or after the initiation of metal industries, in this way taking into account bioturbations and minor contaminations during coring.

Results show that a disproportional part of net floodplain accumulation occurred during the last 500-600 years. In the Chavanne floodplain (Fig. 4), which is located in the upper reaches, about 50% of net sediment accumulation occurred after 1537 (Houbrechts & Petit, 2004, pers. comm.). One site was sampled on a small tributary near Monty, and here only the upper samples contain slag. Due to the thickness (0.2 m) of these upper samples, only a maximum estimate can be made: 40% or less of the net sediment accumulation occurred since 1600. In the lower Lienne floodplain, 5 sites were studied (Fig. 4). The coring site near Rahier (Fig. 4) is situated at a former scoria dumping site associated with a local blast furnace, and is considered to be not representative for natural floodplain accumulation. The other studied sites show a net floodplain

Table 10. Results for the different cross sections in the Lienne catchment. The Rahier site is located at a historical scoria dump site and is not included in further analysis. Data from the Chavanne come from Houbrechts and Petit (2004).

Coring site	**Initiation of metal industry upstream the site (year AD)**	**Mean thickness of floodplain fines (m)**	**Net floodplain accumulation since initiation of metal industries**		**Part of the floodplain reworked since initiation of metal industries**
			(m)	**(%)**	**(%)**
Targnon	1421	0.79	0.43	54	29
Chession	1421	0.96	0.16	17	14
Rahier	1421	0.88	0.61	69	39
Neucy	1421	1.03	0.38	33	50
Trou de Bra	1537	0.78	0.24	31	18
Monty	~1600	0.5	≤0.20	≤40	18
Chavanne	1537			50	

accumulation of 17 to 51% during the last 500-600 years, a period comprising ~5% of the total Holocene period. Results also show the importance of lateral reworking of the floodplain by the river: between 14% and 50% of the floodplain has been reworked in the last 500-600 years, as indicated by the presence of iron slag in point bar deposits.

Discussion

Dijle catchment

The fluvial architecture of the Dijle catchment demonstrates that vertical floodplain aggradation is the main Holocene floodplain process in this catchment, while lateral reworking of the floodplain by the river affects only a limited part of the floodplain. Dating of the parts of the floodplain not affected by such lateral reworking provides a tool for getting insight in the Holocene sediment dynamics and especially in the net sediment accumulation in the floodplains. The high synchronicity between cultural phases and floodplain aggradation indicate that these sediment dynamics were, during the Holocene, mainly driven by land use changes (Notebaert et al., 2011a).

The fluvial architecture of the Dijle catchment indicates several changes in the fluvial system, both before and during the Holocene. First, a braided system occurred during the Weichselian, although the end of this phase is not well dated. Downstream of Leuven, incision of large meanders is reported from the Younger Dryas (De Smedt, 1973), and although such incision also occurred upstream Leuven, they are not yet well dated. During the early Holocene, vertical organic and calcium-rich accumulation dominated the floodplain. Water discharge was probably diffuse (De Smedt, 1973). This system changed radically with the introduction of agriculture, and silty to clayey floodplain deposition started, combined with the formation of river channels which formed sandy facies. Deposition of these clastic sediments occurred during two phases: between

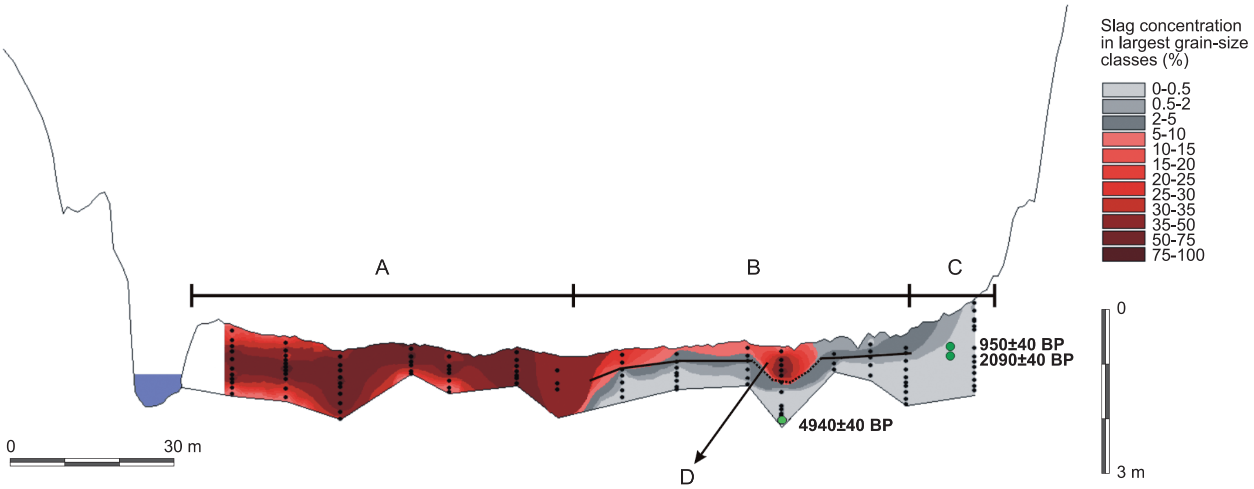


Fig. 12. Cross section of the Lienne floodplain at Neucy with indication of the metal slag concentrations. The metal industry upstream this cross section were probably started in 1421 AD or slightly earlier. A – part of the floodplain that was laterally reworked since 1421 AD. Several depressions which are remnants of former river channels are still present; B – part of the floodplain with net sediment accumulation (20-30% of total net Holocene (non-gravel) deposition) since 1421 AD; C – part of the floodplain with colluvial deposition above overbank deposits which lack scoria. D – former river channel, partially infilled before and partially infilled after 1421 AD. The radiocarbon age of the bottom of the channel does not necessarily correspond with the latest occupation of this channel.

c. 4600 BC and 1000 AD deposition rates were relatively low, but under increasing land use pressure these rates increased after 1000 AD, resulting in an important deposition phase. The first formation of textural clearly identifiable levees occurs during this last phase, and also downstream levees are reported to start forming during this period (De Smedt, 1973). This implies the change from a flat floodplain type to a convex floodplain, resulting from the availability of sand outside the river channel. This is related to an increase in flood discharge and/or an increase in sediment supply, two processes which can be related to an increased anthropogenic land use.

Geul catchment

The fluvial architecture of the Geul catchment indicates the importance of lateral reworking of the floodplain by the river. The presence of bed and bar deposits over the full width of the floodplain indicates that the entire floodplain was reworked at least once over the course of the Holocene. This is confirmed by dates from these bar deposits (De Moor et al., 2008). Modelling results from a meander model suggest a floodplain reworking time of a couple hundred years (De Moor, 2006). As a consequence, only the upper parts of the Holocene deposits, the overbank fines, are suited for dating the sedimentation history of the catchment. In addition, information from the early Holocene will be missing, as they are eroded during the lateral reworking.

The fluvial architecture of the Geul catchment demonstrates only one distinct change in the fluvial style of this river system, from a Pleistocene braided river to a straight or meandering river in the Holocene with a river channel and a floodplain. It can however not be excluded that channel contraction occurred during the Holocene and that a multiple channel system was transformed to a single channel system (see also De Moor et al., 2008). Due to lateral reworking of the floodplain by the meandering river, information on the past fluvial styles is not well preserved.

In this study, the interpretation of the floodplain sedimentation history of the Geul catchment suffers from an averaging effect over time: the use of lead as a tracer allows the reconstruction of sedimentation rates of three different timeframes with contrasting lengths: early Holocene to c. 1842 AD, 1842 AD to 1869 AD and 1869 AD to 2008 AD. It is clear that a disproportional part of sedimentation (~17%) took place after 1842 AD, which equals c. 1.5% of the total Holocene timeframe. The presence of a dark grey upper soil layer was observed during sampling, and lab analysis proved that this layer coincides with the peak lead contamination situated after c. 1860 AD. Because of the coarse temporal resolution, it cannot be excluded that phases with a comparable high sedimentation rate also occurred earlier during the Holocene, as only an average value of a very long time interval is available.

The results of this study are comparable with results of exposed cut banks of the Geul River dated with lead contamination and cosmogenic tracers (Stam 1999, 2002), which also indicate an increased sedimentation during the mining period, followed by a sharp decline in sedimentation and again higher sedimentation in the 20th century. The higher sedimentation rates in the 19th century can partially be explained by the mining activities, because large amounts of soil and rocks originating from mining were deposited in the alluvial plain. Information is also provided from the height of point bars, which is reported to increase over the Holocene, associated with an aggrading floodplain which related to land use changes (De Moor et al., 2008). In addition, the sedimentation history of alluvial fans indicates the causal relationship between land use changes and alluvial fan sedimentation (De Moor et al., 2008). These different observations suggest the important influence of land use changes on the sedimentation history, while the influence of the climate remains unclear, because of the limited temporal resolution of the records (Notebaert et al., 2011a, 2011b).

Amblève catchment

Comparable to the Geul catchment, the fluvial architecture of the Amblève catchment indicates that at most sites the entire width of the floodplain was reworked by the river during the Holocene, and a sequence that spans the full Holocene is missing. The methodology used in this study provides a solution, as it allows the identification of zones which are affected by lateral reworking and the identification of the net sediment accumulation over the last c. 600 years.

The fluvial architecture of the Amblève catchment demonstrates one important change in fluvial style: from a braided river system in the Pleistocene to a single thread meandering or straight channel in the Holocene, in the lower reaches sometimes with islands. For the lower reaches depressions can be observed at many locations, which are linked to former cut off channels. For most locations of these lower reaches, at least one former cut off channel is present, often near one valley edge while the river is located at the other one. Locally, several former cut off channels resemble a braided pattern (e.g. fig. 10 in Notebaert et al., 2009a). There are however no dates available to prove the co-existence of several channels.

The averaging of sedimentation rates over timeframes with totally different lengths form a major problem in calculating the sedimentation rates for the Amblève catchment. These time frames are, however, less contrasting than for the Geul catchment, and provide therefore a better interpretation framework. Reported incision rates for rivers in the Ardennes during the Late Pleistocene and Holocene are in the order of 20-30 m/Ma (e.g. Van Balen et al., 2000), which corresponds with c. 0.2-0.3 m for the entire Holocene. As a consequence, the c. 0.2 to 1 m high 'lower' terrace, formed by units 1 and 7, dates most likely from before the Holocene. There are no indications for the studied catchment, nor reports for other catchments in the Ardennes, of Holocene floodplain incision and terrace formation. We hypothesize that the sediments found in the contemporary floodplain combined with a thin layer of fine sediments deposited above these lower terraces (unit 7), represent the total Holocene floodplain sediment deposit.

The dating results show that a disproportional large part of the total net floodplain sediment accumulation (17-69%, c. 40% on average) was deposited during the last 400 to 600 year, a period which equals c. 5% of the entire Holocene. The limitations of the applied dating methodology put some constraints on the identification of the environmental parameters which influence the sediment dynamics. The increased sedimentation rate of the last 400 to 600 a can be explained by the first major deforestation and anthropogenic land use which occurred for the first time during this period. But climatic events, like the little ice age, can also have influenced sedimentation rates through changes in precipitation patterns. The dating resolution does not allow identifying the influence of such climatic events or the interplay between climate and anthropogenic factors. The large difference in the relative importance of recent sedimentation between sites (17-69%) can only be explained by the importance of local factors controlling local sediment deposition. Possibly the position of anthropogenic (hydro)engineering structures (e.g. mills, milldams, bridges, ...) in the floodplain has an influence, while also topographic variations in the floodplain may have an influence.

Fluvial architecture and dating methods

The fluvial architecture of the three studied catchments shows great differences, with a dominance of vertical aggradation in the Dijle catchment and a dominance of lateral reworking in the Amblève and Geul catchments. These differences have important implication for the use of dating techniques to identify the dynamics of sediment accumulation on the floodplains. The used dating methods fall apart in two main categories, based on the spatial information they provide: discrete dating methods like radiocarbon and OSL dating, and continuous dating methods based on the presence of a tracer. Where discrete dating methods provide an age control for discrete points in a core, continuous dating methods allow the reconstruction of palaeosurfaces and provide information on preservation of past deposits.

When continuous vertical aggradation profiles are present, like in the Dijle catchment, reliable sedimentation rates can be expected on any core which does not contain point bar or river bed deposits, or other indications for a hiatus or incision phase. Discrete dating methods like AMS radiocarbon dating and OSL dating provide age information on individual cores and allow reconstructing a site specific sedimentation history (see Notebaert et al., 2011a). When it is assumed that the dated core(s) are representative for the entire floodplain, such discrete dates provide information on floodplain aggradation. In this case, the fluvial architecture of the floodplain makes an important contribution as it allows identifying cores where the fluvial archive has not been influenced by erosion phases.

When the fluvial architecture is dominated by lateral accretion and the river valley was (almost) entirely reworked by the river channel during the Holocene, other dating methods are required, as for example in the Geul and Amblève catchment. As the transition between the lower point bar deposits and the upper floodplain deposits is often hard to identify, the interpretation of discrete dates is difficult, as it remains unclear which process is dated. As a result it is often uncertain whether the dating results provides information on lateral accretion or vertical aggradation, and such discrete data rather provide core specific information than data on overall floodplain aggradation. Core specific data may be influenced by local point bar formation. Using a spatially continuous tracer, like metal slag or the presence of lead pollution, allows the reconstruction of past surfaces. As such, two sedimentary bodies are identified, those deposited before and after introduction of the tracer. The combination of the dating information with the fluvial architecture allows identifying which parts of the floodplain are laterally reworked since the introduction of the tracer. For the parts which are not laterally reworked, the vertical aggradation can be assessed.

Using tracers as a dating method provides more or less continues information over space, but only a limited number of periods, two and three respectively in the studied catchments, can be differentiated. Using radiocarbon or optical dating can result in different ages for the same coring and, depending on the availability of data, in more or less continuous data over time. In order to reconstruct past surfaces like with continuous dating methods, discrete data from more or less the same age should be available for each coring. This would require a much extended dataset or is even impossible due to the limited availability of datable material. Therefore it is important to get insight in the fluvial architecture to optimise the use of dating techniques. The value of sedimentary archives to study the influence of environmental changes on the (fluvial) sediment dynamics depends largely on the fluvial architecture of the catchment. With a continuous aggrading system where lateral reworking is limited to parts of the floodplain, a sedimentation history can be constructed and linked to past land use and climatic changes. When the fluvial architecture is dominated by lateral reworking, like in the Geul and Amblève catchments, parts of the fluvial archive are missing due to erosion, and there is a low preservation potential (Lewin & Macklin, 2003). The floodplain sedimentation history can only be studied for the overbank deposits that are present and make up the upper part of the floodplain, creating a potential bias towards the most recent sedimentation period. The results of the Dijle catchment allow a more detailed correlation with the past environmental changes than the results of the Amblève and Geul catchment which are less detailed and have a larger uncertainty in the correlation with environmental changes. When dating floodplain deposition in a lateral reworking river system without understanding the fluvial architecture, incorrect temporal variations of the sedimentation rate will be concluded.

For any single core or spatial point in the floodplain, the point bar deposits are deposited during a short time period, leading to an overestimation of the sedimentation rates for this period. Figure 13 provides a conceptual model for a floodplain where lateral movement of the channel is dominant, based on the Neucy site of the Lienne River (Fig. 12) but applicable on any studied site in the Geul and Amblève catchments. When dating radiocarbon datable material originating from the point bar deposits, and not taking into account the fluvial architecture (Fig. 13B), the sedimentation rate for the period after the deposition of the dated material is overestimated, while the rate for the preceding period is underestimated. Additional problems arise due to the increased possibility for datable material in point bars to have an age which does not correspond with the sedimentation moment, due to the accumulation of fluvial transported material on pointbars. When the fluvial architecture is taken into account when dating (Fig. 13C), the average sedimentation rate of the period after introduction of the tracer is well established. But the sedimentation rate before the introduction is suffering from an unknown start of the sedimentation. This paper it is supposed that the sedimentation started at the beginning of the Holocene. In addition, as the tracers are introduced rather late in the Holocene, the calculated sedimentation rate represents an average value for a very long period. It is possible that over such a long timescale, comparable sedimentation rates as the post tracer introduction rate occurred.

The influence of environmental changes

The dating results of three studied catchments show that periods with increased floodplain sedimentation coincide with periods with increased land use changes, which suggests a relationship between both. The dating results do not allow identifying an influence of climatic events.

Due to synchronous variations in land use and climate the individual effect of both parameters is often difficult to assess, also because of the possible occurrence of a lag time between variations in environmental setting and the fluvial response (e.g. Vandenberghe, 1995). The construction of a sediment budget incorporating the different sinks and sources of sediment in a catchment may allow to further establish the link between environmental changes and sedimentary response (e.g. Trimble, 1999; Notebaert et al., 2009b, 2011a). Modelling results from the Dijle catchment show indeed the important influence of land use changes on soil erosion and colluviale and alluvial sediment deposition (Notebaert et al., 2011b). The same model results show that the influence of climatic variations during the Holocene is very low compared to land use changes.

When comparing the total masses of Holocene sediment deposition between the three studied catchments, largest area specific quantities are present in the Dijle catchment (0.40 Tg km^{-2} = 0.40 1015 g km^{-2}), followed by the Gulp catchment (0.10 Tg km^{-2}) and the Amblève catchment (0.03 Tg km^{-2}) (Notebaert et al., 2010). The values for the Gulp catchment are in accordance with previously published data for the entire Geul catchment (c. 0.11 Tg km^{-2}) (De Moor & Verstraeten, 2008). The differences between the three catchments can be explained

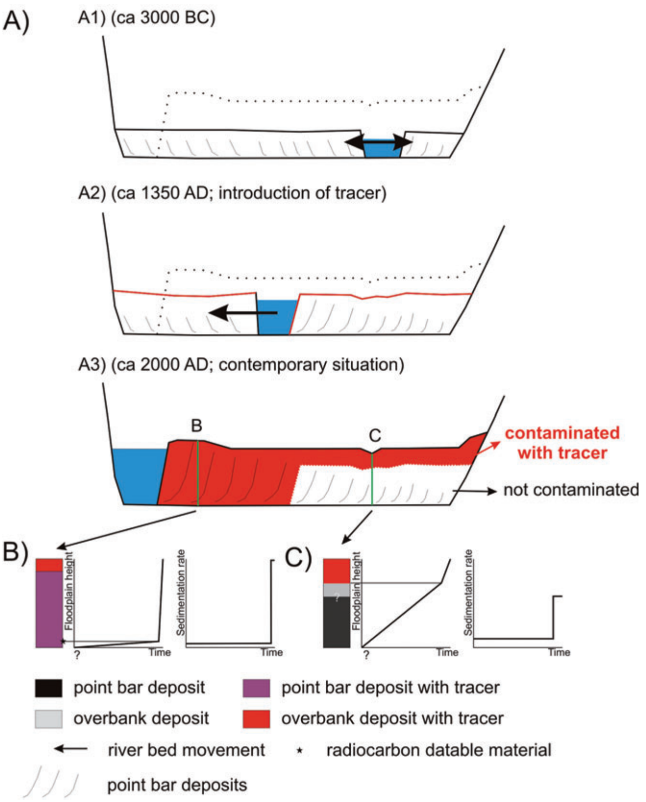


Fig. 13. Conceptual model of the importance of fluvial architecture for dating floodplain aggradation. This conceptual model is based on the Neucy site (Fig. 12) but is applicable for the studied sites in the Amblève and Geul floodplains. A – temporal development of the floodplain through the Holocene, with three time frames: A1 – hypothetical surface before the introduction of the tracer; A2 – surface at the time of the introduction of the tracer; A3 – contemporary surface with indication of the sediment containing the tracer (red). B and C – hypothetical corings in the floodplain, with an indication of the different architectural units. For each coring a depth/age and a time/sedimentation rate curve are plotted. Coring B is dated using a radiocarbon age from the lower parts of the floodplain deposits, and the resulting sedimentation rates are not in accordance with net floodplain aggradation. Coring C is dated using the tracer horizon and taking into account the fluvial architecture. The resulting sedimentation rate after the introduction of the tracer provides an average floodplain aggradation rate, while the rate for the period before the introduction is influenced by the unknown start of the sedimentation.

by differences in land use history and connectivity between slopes and floodplains (Notebaert et al., 2010), but the fluvial architecture may possibly also have influenced floodplain storage. The floodplain processes which become clear from the fluvial architecture may influence the possibility for a floodplain to store sediment, especially when aggradation rates differ between the different depositional environments. In the Dijle river, the river bed and the floodplain have aggraded, although no data are available to estimate the evolution of the channel depth over a long timescale. For the Geul and Amblève river, there are no traces of a change of the absolute height of the river bed over the Holocene. With an aggrading floodplain and a constant absolute river bed height, the river channel increases in absolute depth, greater flows will remain restricted to the channel and stream power increases (see e.g. Trimble, 2009). As a result floodplain sedimentation slows down as only larger events will cause overbank flooding. Similar processes in the UK are described by Brown & Keough (1992) as the stable-bed aggrading-banks model (SBAB). This may particularly be true for the Geul catchment, as river banks in the Amblève catchment still have a limited height.

Conclusions

In this study the fluvial architecture was studied for three catchments in Belgium, the Dijle, Geul and Amblève catchment, and this was combined with different dating methods in order to derive the Holocene fluvial sedimentation history. The fluvial architecture of the Dijle catchment is dominated by vertical aggradation, which allows dating aggradation profiles of the entire Holocene using radiocarbon or optical dating. In the Amblève and Geul catchment, lateral reworking dominates, and vertical aggradation deposits from the early Holocene are eroded. The upper parts of the floodplain contain vertical aggradation overbank deposits, which were dated using tracers. In the Geul catchment Pb contamination resulting from 19th century mining activities was used, while in the Amblève catchment contamination with metal slag from medieval metal industries was used. These dating methods allow the identification of post-contamination vertical aggradation and of post-contamination lateral reworking deposits. As such, only two (or three) discrete periods can be identified, but the spatial variation is more easily identified.

Linking environmental changes with variations in floodplain deposition is most straightforward for the Dijle catchment, due to a denser temporal resolution. Establishing such links is hampered by the limited temporal resolution for the other two catchments. Nevertheless, the sedimentation history of all three catchments indicates a major influence of anthropogenic land use changes, which caused an increase in floodplain deposition.

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