Available online at www.sciencedirect.com

ScienceDirect

Geomorphology 98 (2008) 316–339

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Human and climate impact on catchment development during the Holocene — Geul River, the Netherlands

J.J.W. de Moor [a,*], C. Kasse [a], R. van Balen [a], J. Vandenberghe [a], J. Wallinga [b]

[a] *Department of Paleoclimatology and Geomorphology, Faculty of Earth and Life Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*

[b] *Netherlands Centre for Luminescence dating (NCL), Delft University of Technology, Faculty of Applied Sciences, Mekelweg 15, 2629 JB Delft, The Netherlands*

Received in revised form 5 June 2006; accepted 27 December 2006

Available online 21 May 2007

Abstract

Interest in the Holocene development of small to medium-sized river catchments in Western and Central Europe in relation to changes in land use and climate has increased over the past years. In this study we reconstruct the Holocene landscape development and fluvial dynamics of the Geul River (The Netherlands) and the main forcing mechanisms of environmental change. Field studies were carried out and we used OSL and ^{14}C dating methods to reconstruct the Holocene valley development. Our study shows that 2 periods of deforestation (during the Roman Period and the High Middle Ages) led to severe soil erosion and increased floodplain sedimentation in the catchment of the Geul River, possibly combined with periods of increased wetness during the High Middle Ages. Alluvial fans have been active since the Roman deforestation phase. Our results show that the Geul catchment is highly sensitive to changes in land use.

Keywords: Floodplain sedimentation; Alluvial fan sedimentation; Land-use change; Climate change; Geul River

1. Introduction

Small and medium-scale river catchments in Western and Central Europe have important functions as ecological environments, local drinking water reservoirs and as flood retention areas during major floods of rivers they drain into (like the Rhine or Maas rivers). However, during the last few centuries many of these river systems have lost their natural character and have been straightened (Brookes, 1988; Wolfert, 2001). Interest in the Holocene development of small to medium-sized river catchments in Western and Central Europe has increased in the past years. Especially the forcing mechanisms for the development of these catchments have been thoroughly investigated. Important questions hereby are: (1) how are Holocene fluvial dynamics coupled to human impact and changes in climate and; (2) what is the sensitivity of Holocene fluvial systems to environmental change?

Rivers, floodplains and valley environments in the western and central European loess zone (for example Belgium, Germany and Poland) have changed strongly since the Last Glacial Maximum and have been affected by human activities for about 5000 yr (e.g. Houben, 1997, 2002; Klimek, 2002; Starkel, 2002; Kukulak, 2003; Lang et al., 2003; Mäckel et al., 2003; Zolitschka et al., 2003; Raab and Völkel, 2005; Rommens et al.,

---

* Corresponding author.
E-mail address: j.de.moor@orange.nl (J.J.W. de Moor).

0169-555X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.12.033

2006). Many of these catchments had a long cultivation history and are therefore very suitable to study the effect of land-use changes on fluvial dynamics and catchment development. Human activities (for example ore mining and deforestation associated with the development of agriculture) have led to drastic changes in the discharge regimes and floodplain dynamics, and soil erosion has increased. Periods of increased wetness during the Holocene have been reflected in increased floodplain sedimentation rates during the Holocene in Poland (Starkel et al., 2006) and Great Britain (Macklin et al., 2006).

Since most rivers have been embanked or canalized, nearly undisturbed fluvial systems are very hard to find. The Geul River, a small tributary of the Maas in the southern Netherlands (Fig. 1), although it has been influenced by human activities over the last thousands of years, is a nearly undisturbed system. While the Holocene Rhine–Meuse delta in the Netherlands has been thoroughly studied (e.g. Berendsen and Stouthamer, 2001), knowledge of the Holocene development of smaller catchments in the Netherlands is lacking. This study intends to improve our knowledge about human and climate impact on a small river catchment in the fertile and densely populated loess area. Moreover, this study will contribute to the regional picture of Holocene valley development and the forcing mechanisms responsible. This paper focuses on the Holocene landscape development and fluvial dynamics of the Geul River catchment. We make a reconstruction of the river dynamics and sedimentation characteristics during different phases of the Holocene and determine the main factors influencing catchment development and river dynamics. A detailed sedimentological record with numerous radiocarbon dates and some additional OSL dates is used to investigate historical changes in sedimentation and we compare the fluvial record with local and regional vegetation data. We characterize the alluvial architecture of the Holocene Geul River and discuss the forcing mechanisms responsible for its development.

1.1. The Geul River catchment

The Geul River catchment is situated in the southernmost part (South-Limburg) of the Netherlands and adjacent Belgium (Fig. 1). It originates in eastern Belgium near the German border and flows into the Maas River a few kilometres north of Maastricht. Its length is 56 km and the catchment area is about 380 km^2. The altitude of the catchment varies from 50 m above sea level at the confluence with the Maas River to 400 m above sea level in the source area. The average discharge of the Geul River near its confluence with the Maas River is 3.4 m^3 s^{-1} (data from Waterboard Roer and Overmaas). Occasional peak discharges of more than 40 m^3 s^{-1} can cause local floods. The discharge mainly depends on the amount of rainfall. Heavy rainfall can result in overland flow on loess-covered slopes and rapid discharge into the river. The discharge of the Geul River can change very rapidly, for example during heavy thunderstorms (De Laat and Agor, 2003). Small-scale, local floods occur almost every year (mainly during the winter), but they do not cause much damage as only some grasslands along the river become inundated.

An important steering factor in the long-term landscape development of the Geul basin during the Quaternary has been the River Maas. At the end of the Tertiary and the beginning of the Quaternary, the Maas had an easterly flow direction, thereby crossing the present-day Geul catchment. Due to tectonic uplift of the Ardennes and South-Limburg, the river started to shift towards its current south-north position, thereby creating a number of terraces (Van den Berg, 1996). These terrace levels can clearly be recognized at high altitude in the landscape today as large, flat plains (cf. Zonneveld, 1974). Fluvial gravels are often present at the surface of these river terraces. Following the downcutting of the Maas, tributaries like the Geul incised as well. In the Belgian part of the catchment and the southernmost tip in the Netherlands, the Geul River is incised into Palaeozoic rocks (Devonian and Carboniferous sandstones, shales and limestones containing Pb–Zn mineralizations). In the Dutch part of the catchment, the river is incised mainly into Cretaceous lime- and sandstones. Almost the complete catchment has been covered with a blanket of loess, deposited during the Saalian and Weichselian glacial periods.

The present-day landscape of the Geul River catchment is characterized by large, flat plateaus and deeply incised, asymmetrical river valleys (Fig. 2a). The floodplain of the Geul River is in general flat, but several alluvial fans coming from tributary valleys cover the floodplain (Fig. 2b–f).

1.2. Land use, vegetation change and human activity

The Late Glacial and Holocene vegetation cover and land-use history of South-Limburg (Fig. 1) has previously been studied by Bunnik (1999), Havinga and Van den Berg van Saparoea (1980) and Renes (1988). Bunnik (1999) has constructed several detailed pollen diagrams for South-Limburg and adjacent

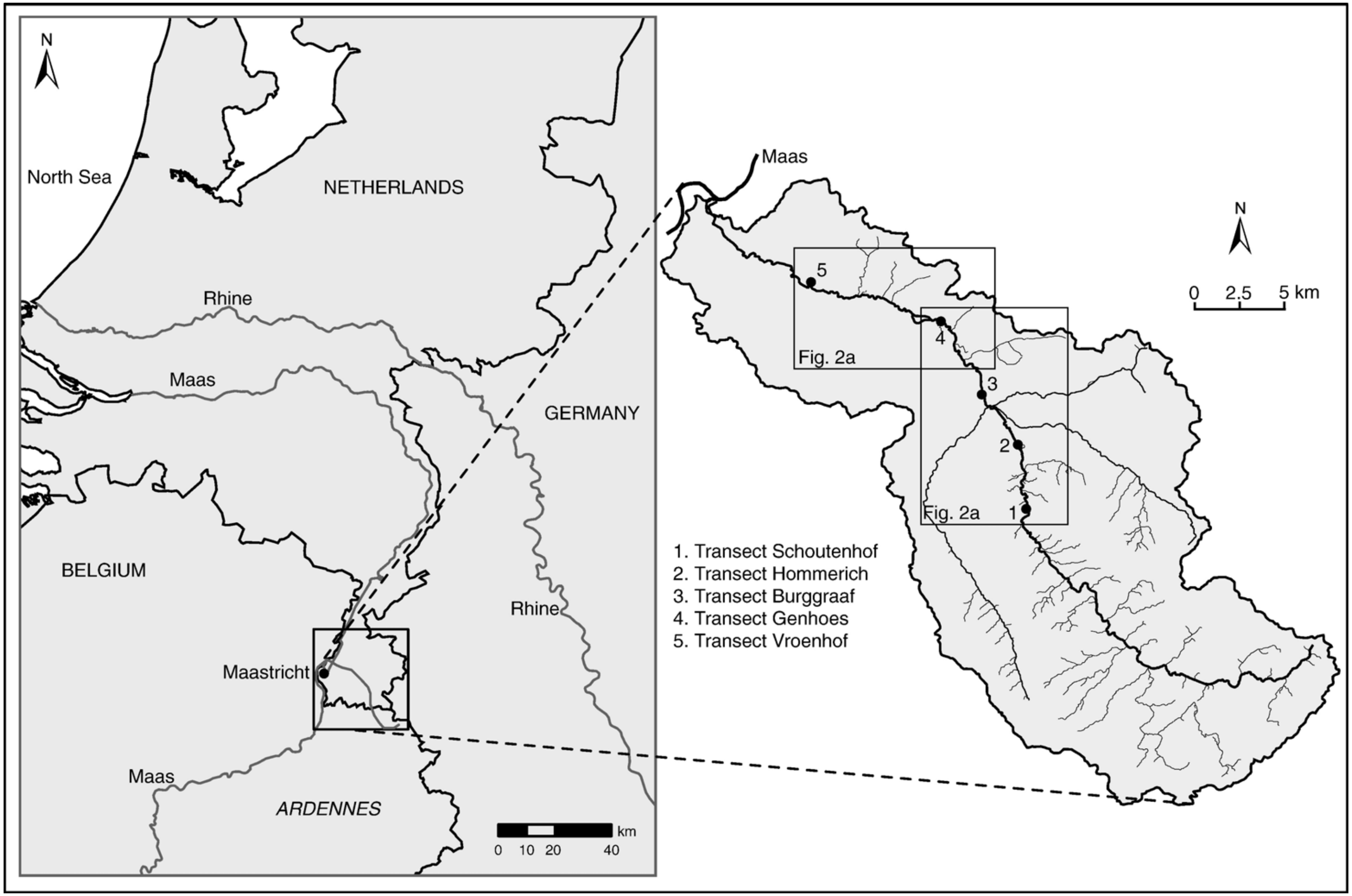


Fig. 1. Location of the Geul River catchment and the study sites in South-Limburg.

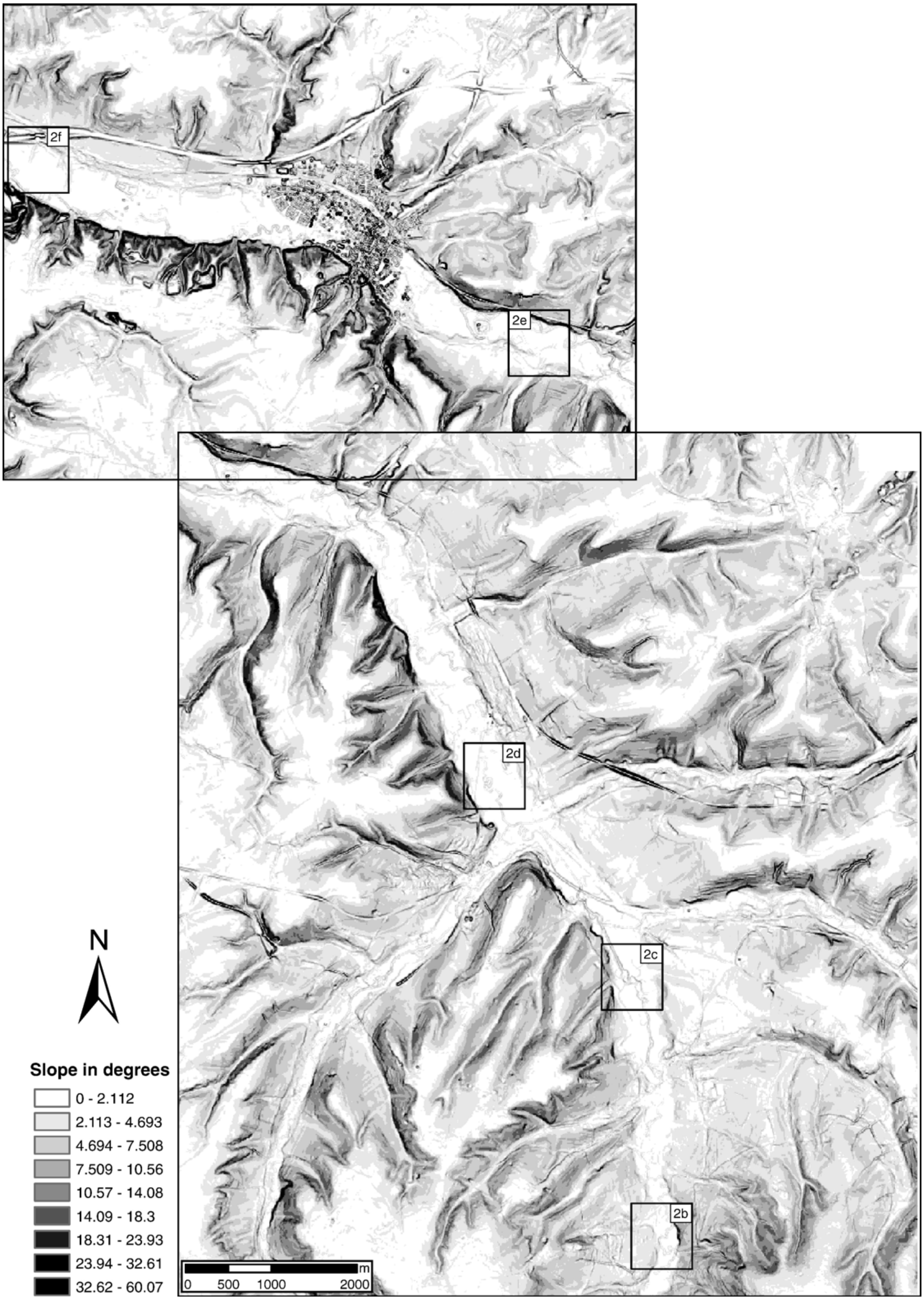


Fig. 2. a. Slope map of the study area. b. Topographic and geomorphologic map with the location of transect Schoutenhof. c. Topographic and geomorphologic map with the location of transect Hommerich. d. Topographic and geomorphologic map with the location of transects Burggraaf West and East. e. Topographic and geomorphologic map with the location of transect Genhoes. f. Topographic and geomorphologic map with the location of transect Vroenhof.

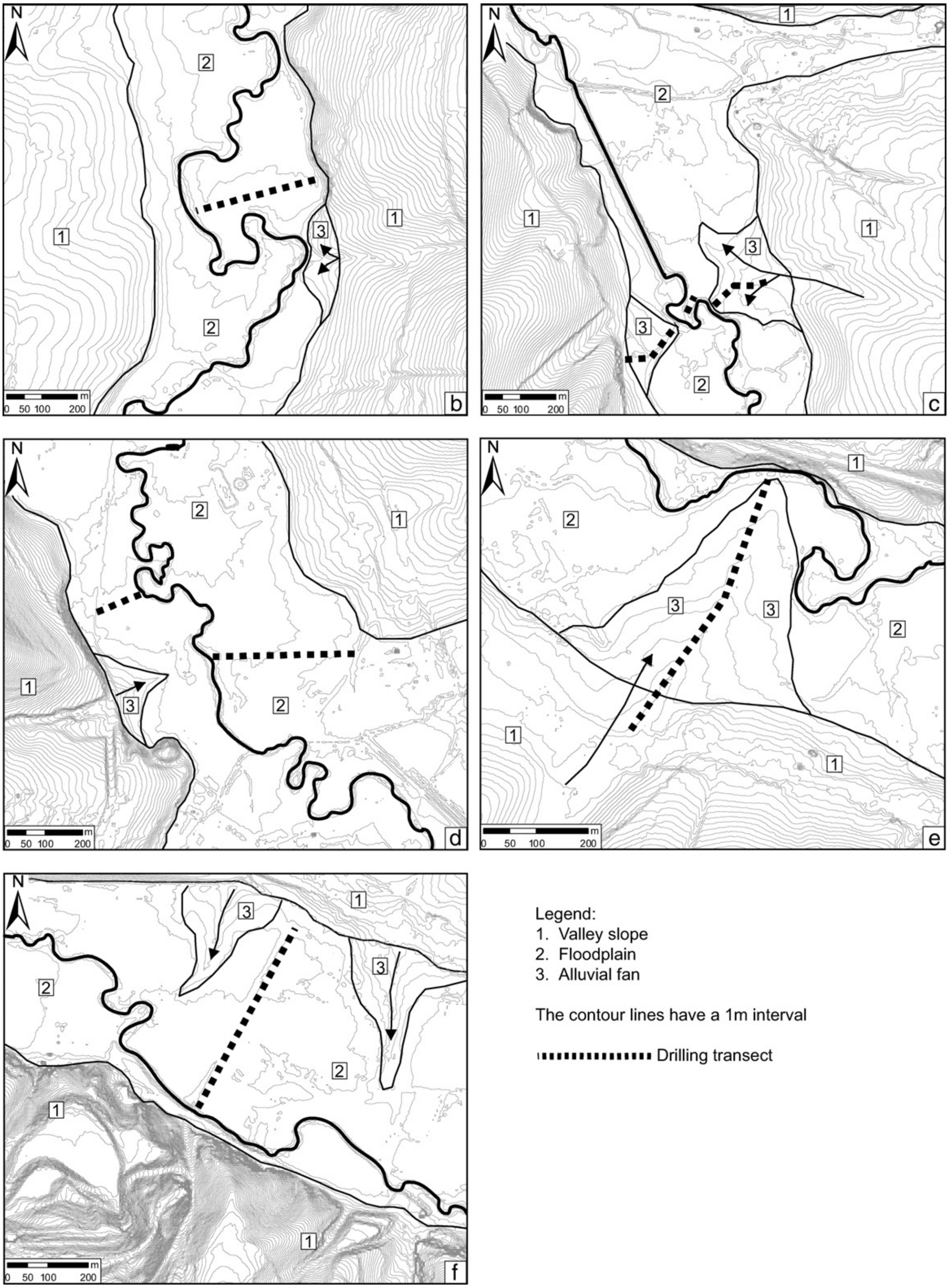


Fig. 2 (*continued*).

Germany, while Havinga and Van den Berg van Saparoea (1980) have constructed pollen diagrams for two locations in the Geul River valley.

The Late Glacial vegetation pattern was characterized by an open vegetation type with birch and pine trees. This changed during the Preboreal when the area was gradually covered by a dense forest with wet vegetation types in the river valleys. Prior to significant human activity, the vegetation reconstructions demonstrate that valley sides with loess soils were covered with mixed deciduous forest (oak and lime), while the river valley floors were covered by alder, willow and poplar (Bunnik, 1999). During the Boreal and Atlantic not much changed in the vegetation cover: dense forest dominated although there were some changes in the tree species composition.

Parts of South-Limburg have been inhabited for the last 7000 yr. Archaeological findings just north of the Geul River catchment indicate the presence of these first settlers (farmers of the Bandkeramik culture, 4500 BC) on the loess plateaus (Renes, 1988). No settlements of the Neolithic Bandkeramik culture have been found in the Geul River catchment (Van de Westeringh, 1980). The Early and Middle Bronze Age (1950–1000 BC) were characterized by an almost complete forest cover in the area (Bunnik, 1999). During the Late Bronze Age (1000–700 BC) the first farming took place in addition with local deforestation. Evidence of presence of man in the area during the Late Bronze Age is supported by the presence of several burial mounds close to the Geul River catchment and by the presence of heath and agricultural indicators (cereals) in the pollen record (Bunnik, 1999). Local deforestation continued during the Iron Age (700–53 BC). In this period the forest in the river valleys was replaced by grassland (Bunnik, 1999). Deforestation on the valley slopes led to the first significant soil erosion and formation of colluvium in the valleys.

A widespread deforestation phase in South-Limburg took place during the first half of the Roman Age (53 BC–415 AD). A population expansion took place resulting in the growth of several cities. Forest areas were transformed into arable land and on the large plateaus so-called Villae Rusticae (a Roman villa associated with a large farm) were founded (Van de Westeringh, 1980; Renes, 1988). The Roman agricultural activities are expressed in pollen diagrams by the presence of high pollen counts for cereals, sweet chestnut and walnut pollen (Havinga and Van den Berg van Saparoea, 1980; Bunnik, 1999; Bazelmans et al., 2004). The deforestation led to severe soil erosion in the catchment of the Geul River. During the second half of the third century, the Roman Empire collapsed and many Roman Villas fell into disrepair, resulting in a population decline (Renes, 1988; Bazelmans et al., 2004). The forest on the plateaus and valley slopes regenerated. During this period (called the dark ages or migration period, 220–500 AD), South-Limburg was not very populated and only a few small settlements were situated in the river valleys (Renes, 1988).

The first signs of the recovery of the arable lands date from the Early Middle Ages (500–1000 AD), although the rapid population expansion during the High Middle Ages (1000–1500 AD) resulted in an almost complete deforestation of the area (Renes, 1988; Bunnik, 1999). Only the steepest slopes and poorest soils remained covered with forest and the river valleys were in use as grassland. The Medieval deforestation phase also marks the second phase of massive soil erosion in the area (Van de Westeringh, 1980). Soil erosion mainly took place on the plateaus and valley slopes and sediment accumulated in river valleys. Due to this soil erosion on the slopes, measures were taken by local farmers to protect their land of further being eroded. Erosion barriers or lynchets were constructed. It is, however, not clear when the first lynchets were constructed. During the last centuries, large parts of arable land were converted into grassland as farming innovations led to higher crop yields (Renes, 1988). During the last 50 yr the scale and intensity of agriculture has increased, while the removal of lynchets and the change of plough direction from parallel to perpendicular to the slope have increased soil erosion. The arable land is exposed now for longer periods during the year and this also increases the vulnerability to erosion (Stam, 2002).

The Geul catchment had a long history of lead and zinc mining, dating back to the Middle Ages with maximum extraction between the middle and the end of the 19th century (Stam, 2002). These mining activities have contaminated floodplain sediments of the Geul and, in turn, may be used as chemical markers to reconstruct valley sedimentation, depositional rates and fluvial dynamics. Leenaers (1989), Swennen et al. (1994) and Stam (1999, 2002) have thoroughly studied the presence, amounts and dispersal of the contaminated sediments. Stam (2002) used the contaminated sediment to reconstruct floodplain sedimentation rates over the last 200 yr in relation to changes in climate and land use.

2. Methods

We cored several detailed cross-sectional profiles across the valley floor at different locations in the Geul catchment (Fig. 2a–f), using an Edelman hand-auger. Occasionally we used a 6 cm diameter gouge to obtain peat and organic samples. Two cut-bank sections were also studied. Sediments were described every 10 cm and classified using the USDA texture triangle (USDA, 2005). Samples from the Edelman cores were taken for radiocarbon dating and grain size analysis. Samples for

Optical Stimulated Luminescence dating (OSL) were taken from the cut-bank exposures by hammering opaque steel tubes into the wall. Grain sizes were analyzed using a Fritsch laser particle sizer A22, with the 8 µm as the upper limit of the clay fraction (Konert and Vandenberghe, 1997).

OSL dating determines the time since deposition and burial of mineral grains; the OSL age is obtained by dividing the absorbed radiation dose received by mineral grains since burial (equivalent dose) by the dose received by the grains per year (dose rate). OSL dating for this research was carried out at the Netherlands Centre for Luminescence Dating at Delft University of Technology. Quartz grains in the fraction 63–90 µm were used for equivalent dose estimation. The samples were sieved and then treated with HCl and H_2O_2 to remove carbonates and organic material. Subsequently the samples were treated with concentrated HF to dissolve feldspars and etch the outer α-exposed skin of the quartz grains. Then the samples were sieved again to remove grains that were severely damaged by the HF treatment. The SAR protocol of Murray and Wintle (2000, 2003) was used for measurement of the equivalent dose (see Table 1); aliquots showing rogue luminescence behaviour were discarded (see Table 2 for rejection criteria). Based on investigations of the dependence of equivalent dose on preheat temperature a 10 s preheat at 225 °C was applied before measurement of the natural and regenerative dose OSL responses, and heating to 200 °C was applied before measurement of the test dose OSL responses. Dose recovery tests (Roberts et al., 1999) confirmed that the adopted procedure could accurately recover a laboratory dose (average dose-recovery ratio 1.02±0.02). Given the fluvial nature of the samples, incomplete resetting of the OSL signal of some grains prior to deposition and burial is likely (e.g. Wallinga, 2002). To avoid bias of results due to this heterogeneous bleaching, single-aliquot equivalent doses of more than 2 standard deviations from the sample mean were removed in an iterative procedure. The dose rate was estimated using high-resolution gamma-ray spectroscopy (Murray et al., 1987). Water contents as measured on the samples (ranging from 20–26% by weight) were used to estimate attenuation of the effective dose rate by water; we included a large uncertainty of 5% to allow for changes in water content during geological burial.

Table 1
The SAR procedure (modified from Murray and Wintle, 2000, 2003)

Step	Action	Measured
1	Regenerative beta dose [a]	
2	10 s Preheat at 225 °C [b]	
3	40 s Blue stimulation at 125 °C	L_n, L_i [c]
4	Fixed test beta dose [d]	
5	Cutheat to 200 °C	
6	40 s Blue stimulation at 125 °C	T_n, T_i [e]
7	40 s Blue bleaching at 245 °C [f]	
8	Repeat step 1–7 for number of regenerative doses	
Extra 1	Fixed test beta dose	
Extra 2	Cutheat to 200 °C	
Extra 3	40 s IR stimulation at 50 °C [g]	IR_e
Extra 4	40 s Blue stimulation at 125 °C	T_e

[a] No beta dose is administered for measurement of the natural OSL signal in the first cycle of the procedure L_n.

[b] The preheat temperature is selected based on the preheat-plateau test and dose-recovery test.

[c] The signal used for analysis is the signal measured during the first 0.32 s of stimulation minus the average background signal determined over the last 4 s of stimulation.

[d] The test dose is chosen to be approximately 25% of the equivalent dose.

[e] Response to the fixed test dose is used to monitor sensitivity changes of the material during the measurement routine.

[f] The preheat temperature plus 20 °C is used as an added bleaching step before the sample is dosed (step 1).

[g] After completion of the standard SAR routine, we use IR stimulation to check whether the sample is contaminated by feldspar.

Table 2
Applied thresholds for accepting data for analysis

Test	Ideal case	Accepted if *
1 — Recycling test	$(L_5/T_5)/(L_1/T_1)=1$	$0.9<(L_5/T_5)/(L_1/T_1)<1.1$
2 — Recuperation test	$(L_4/T_4)/(L_1/T_1)=0$	$(L_4/T_4)/(L_1/T_1)<0.1$
3 — Feldspar test	$IR_e/T_e=0$, $T_e/T_5=1$	$IR_e/T_e<0.2$ or $T_e/T_5>0.9$

For radiocarbon dating, peat and sediments containing organic material (like twigs, leaves, seeds and other macroscopic plant remains) were sieved and suitable material (seeds, charcoal and leaves) was selected for ^{14}C AMS dating at the Centre for Isotope Research at the University of Groningen. Seeds were identified prior to submission for ^{14}C dating. One bulk sample was dated using the conventional method. The 27 ^{14}C dates were calibrated with the CALIB radiocarbon calibration program (Stuiver and Reimer, 1993 (version 5.0)), using the calibration dataset from Reimer et al. (2004).

2.1. General sedimentation pattern and dating results

In this paper we present 5 different cross-valley transects from the middle and downstream sections of the Geul River (Figs. 3–7). In these cross-sections, 11 different lithogenetical units have been identified, based on differences in grain size, lithology and morphology. Table 3 provides a general overview of the sedimentary

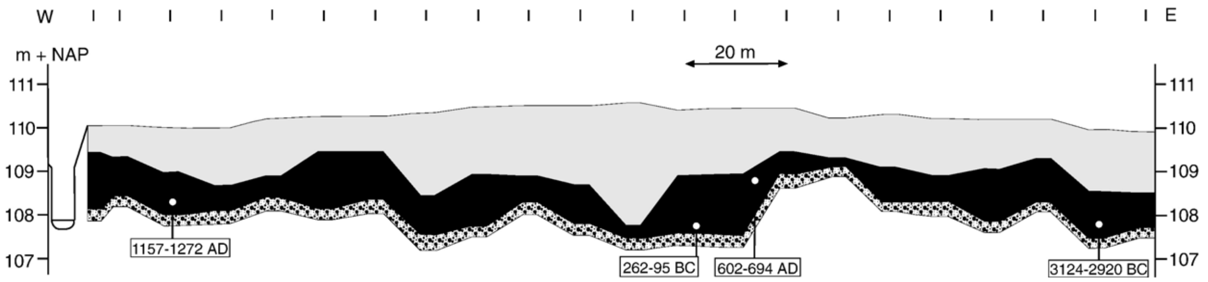


Fig. 3. Coring transect Schoutenhof.

characteristics and environments of the lithogenetical units. Fig. 8a–g show the typical grain-size distributions for several units; the percentages of clay, silt and sand of these units are based on several samples. The units have been dated using ^{14}C and OSL dating techniques (dates are shown in Figs. 3–7 and Table 4/5). All the ^{14}C dates have been accepted and considered reliable, within the context of alluvial systems. The radiocarbon samples all consisted of carefully selected macroscopic (terrestrial) plant remains (seeds) and the material was "fresh" (not rounded by transportation). The dates are consistent with stratigraphy with the younger dates close to the present-day river. OSL ages at both the Partij and Hommerich sites (Fig. 4) are in the correct stratigraphic order. However, single-aliquot equivalent doses for samples Partij 1, and Hommerich 5 and 6 showed large scatter (equivalent dose histograms provided in Fig. 9). The scatter is likely due to incorporation of grains for which the OSL signal was not completely reset upon burial. Bias due to these outliers was largely removed by excluding outliers in an iterative procedure as described in the previous section, but we consider it likely that the OSL ages for these samples slightly overestimate the true burial ages. This is confirmed by the slight reversal between OSL and radiocarbon ages at the Hommerich section. Equivalent dose histograms for samples Partij 3 and 4 show no indication of heterogeneous resetting (Fig. 9); OSL ages on these samples are expected to be accurate estimates of the burial age.

2.1.1. Unit 1

The base of the Holocene valley fill is denoted by a gravel layer. The top of this layer is often mixed with fine to coarse sand and detritus. The gravel is poorly sorted, ranging in size from a few centimetres to more than 15 cm in diameter. The gravel is of local origin, as it is dominated by sub-angular flint, which originates from the surrounding limestones. The depth (from the surface) of the top of this gravel layer varies in all transects. Differences of up to two meters occur (e.g. Figs. 3, 7) and the upper surface of the gravel layer is very irregular. This might be due to the buried (pre-Holocene) topography of a braided floodplain with channels. Another option is that the differences are the result of the lateral migration and the formation of gravel bars of the Holocene river, like those in the present-day Geul River.

The gravel has been deposited as a channel deposit and on channel bars. Since the gravel is often found at the base of a fining-up sequence, it is probable that the top of the gravel unit has been reworked by a meandering system. However, the major body of the gravel may have been deposited under a different climate (glacial) and fluvial regime (braided) during earlier periods (Van de Westeringh, 1980). We do not have dates to confirm this, but it is very likely that the gravel unit ranges widely in age.

2.1.2. Unit 2

This unit consists of a fining-up sequence from gravel with coarse sand to sand loam and loam. The gravel has a maximum diameter of a few centimetres and the grain size of the sand varies between 63 µm and 841 µm with a mode of 250 µm (Fig. 8a). No sedimentary structures have been found in the corings, but in fresh cutbanks cross-stratification is often visible. The lower parts of this unit often contain organic detritus like small twigs, leaves and other macroscopic plant remains. Deposition of such detritus also takes place in the present-day river during the flood stage on the lower parts of the point bar. The unit basically consists of two dominating lithologies: the coarse fraction (gravel and coarse sand) represents the lower point bar, while the finer fraction (fine sand) represents the middle point bar. This fining-up sequence is typical for point-bars. Unit 2 is present across almost the whole valley and it forms part of the lateral accreting floodplain (cf. Wolman and Leopold, 1957; Nanson and Croke, 1992). Unit 2 is especially well developed in the relatively young parts of the floodplain where active lateral migration takes place.

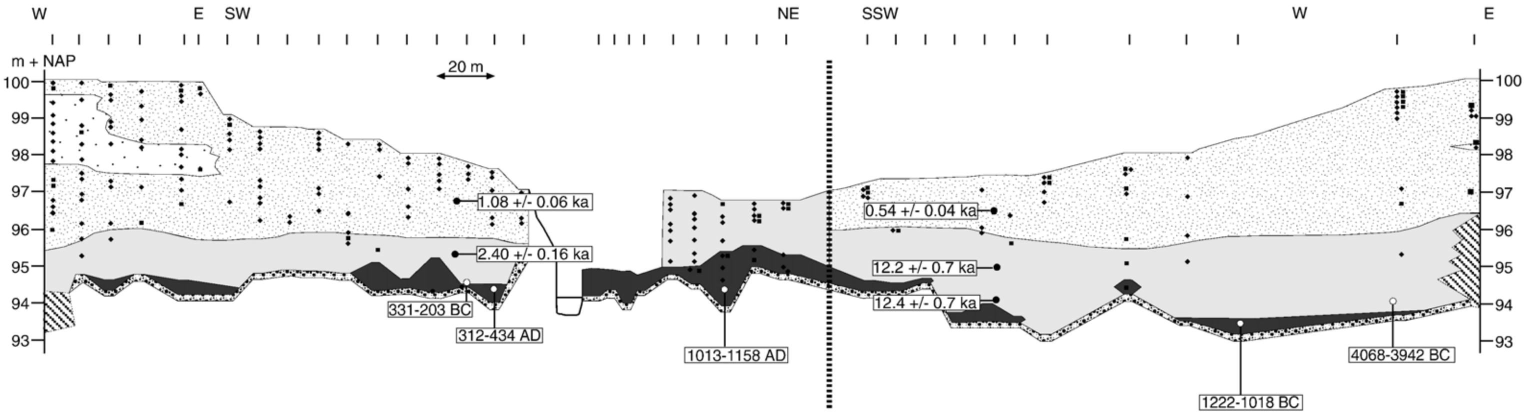


Fig. 4. Coring transect Hommerich.

Most dates of this unit are from the base, near the contact with the gravel of unit 1 (Figs. 3–7), thereby giving a maximum age estimate for this unit. The dates show a wide range of ages for unit 2. The oldest (Late Glacial) parts of this unit have been found in transects Burggraaf (10188–9809 BC, Fig. 5), Genhoes (11134-10926 BC, Fig. 6) and Vroenhof (11635-11330 BC, Fig. 7). In all transects, the youngest dates occur close to the present-day channel. The majority of dates in unit 2 have a Late Holocene age, indicating the young character of this unit (see Figs. 3–7 and Table 4). As most of the dates in this unit have been obtained just above the top of unit 1, it also gives a minimum age estimate for unit 1.

2.1.3. Units 3 and 4

The most widespread and in general thickest units are 3 and 4. These units have a nearly identical texture of silt loam and are very homogeneous and often bioturbated. The modal grain size for both units is 31–37 μm. Unit 3 contains 11.5–15% clay, 65–72% silt and 9–17% sand (Fig. 8b). Unit 4 contains 12–13.5% clay, 64–76% silt and 6.5–17% sand (Fig. 8c). No sedimentary structures are visible in the sediment. The lower part of unit 3 probably represents the upper part of a point bar succession. This silt loam of the upper point bar represents the transition zone between lateral and vertical accreting sediments. The upper part of unit 3 is interpreted as a floodplain unit, formed by vertical accretion of overbank sediments. In the cores it is impossible to distinguish the upper point bar from the overbank floodplain sediments. That is why in all transects (Figs. 3–7) we combined these sediments into one unit (unit 3). In transects Burggraaf West, Burggraaf East and Vroenhof (Figs. 5, 7) the silt loam is deposited purely as vertical accreting floodplain sediment, because it overlies a silty clay loam or peat and is therefore not part of a point bar fining-up sequence. This is unit 4. The grain size distribution of both units strongly resembles loess. The low sand content (Fig. 8b/c) indicates fluvial reworking of the loess (cf. Vandenberghe et al., 1993). Units 3 and 4 have the largest thickness in most transects (Figs. 3, 5, 7) and therefore the vertical accreting floodplain is an important sedimentary environment in the Geul catchment. Together with the lateral accreting point-bar, the vertical accreting overbank sediments form the main components of the floodplain (cf. Nanson and Croke, 1992).

We only have OSL dates from these units; ^{14}C dates were not obtained as these units hardly contain any organic material. Two OSL samples (Table 5) from a cut-bank exposure near transect Hommerich (Fig. 4) returned Late Glacial ages (12.2 ± 0.7 and 12.4 ± 0.7 ka for Partij 3 and 4, respectively). Sample Hommerich 5, taken near the same location but on the other side of the river (Fig. 4) yielded a Late Holocene age (2.40 ± 0.16 ka). Based on the dates from unit 2, we can get a maximum age for these units (see Figs. 3–7 and Table 4). We suggest that most of the sediments in units 3 and 4 have been deposited since Medieval times, although locally much older deposits are preserved as is indicated by the Late Glacial OSL ages obtained on the Partij samples.

2.1.4. Unit 5

This unit has been found in transects Burggraaf, Genhoes and Vroenhof (Figs. 5–7) and consists of (humic) silty clay loam. No sedimentary structures have been observed. The sediments are very compact. The fine-grained character (14.5–28.5% clay; 69–80% silt; 0.5–5% sand; mode 13–26 μm, Fig. 8d) points to a low energy depositional environment, relatively far away from the active channel. Compared to unit 4, the conditions were quieter with less sediment available. No dates have been obtained for these sediments, age determination can only be made using dates from other units.

The lower 20–30 cm of this unit in transect Genhoes (Fig. 6) are more humic and have a darker colour. The

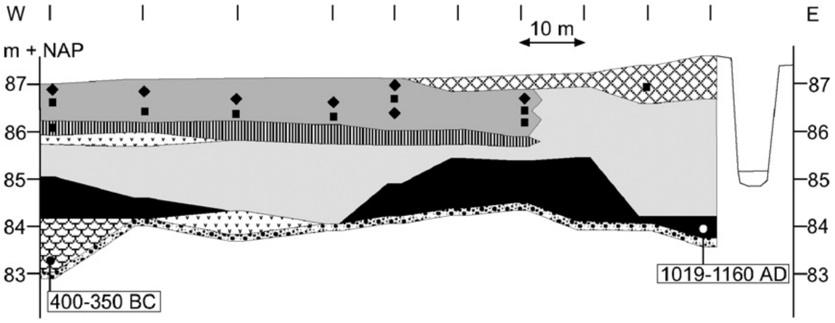


Fig. 5. a. Coring transect Burggraaf West. b. Coring transect Burggraaf East.

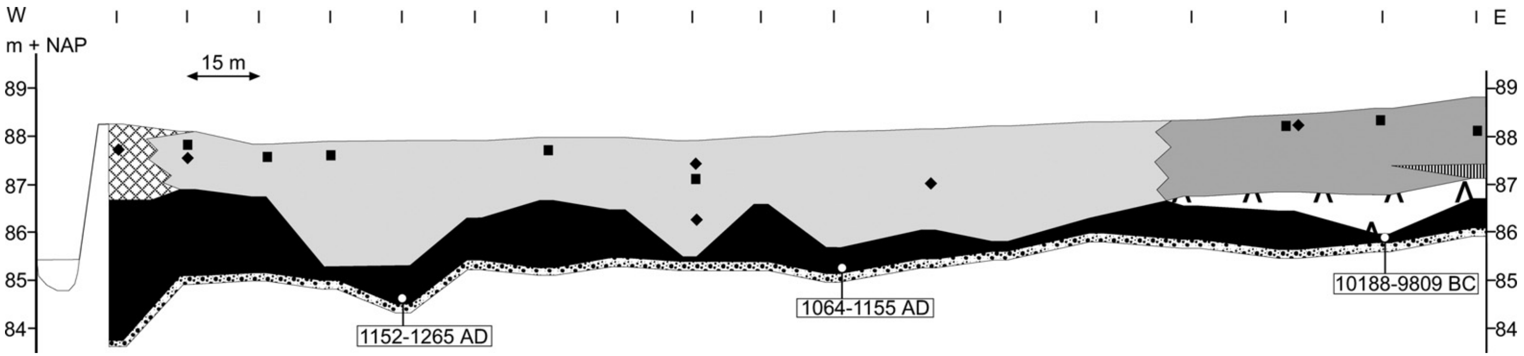


Fig. 5 (*continued*).

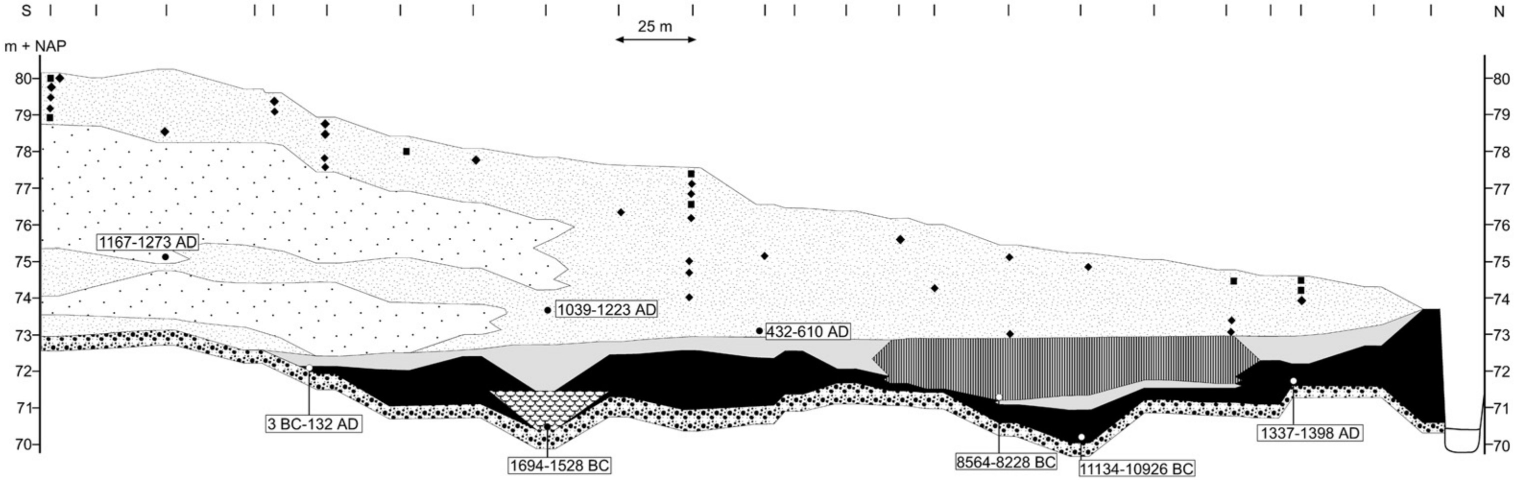


Fig. 6. Coring transect Genhoes.

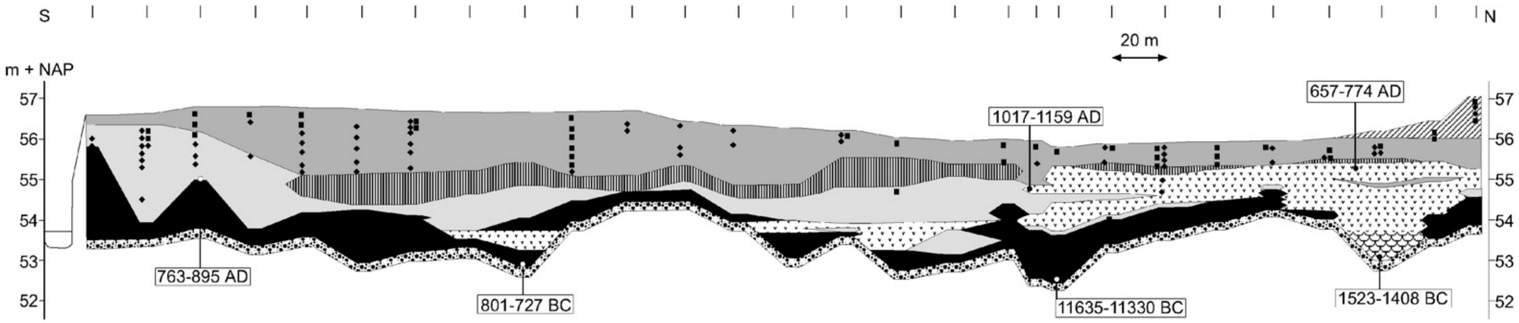


Fig. 7. Coring transect Vroenhof. General legend for Figs. 3–7.

Table 3
Characteristics of river deposits and sedimentary environments for the Geul River catchment (modified after Schumm, 1977; Knighton, 1998)

Place of deposition	Name	Characteristics	Lithology and sedimentary structures	Unit	Transect
Channel	Lag deposit/ channel bars	Consist of the coarsest material transported during floods	Gravel (2–15 cm)	1	All
	Channel fill	Accumulation of predominantly fine-grained sediments and peat in abandoned channel reaches and scour holes	Loam and silt loam, peat and humic silt loam Mainly horizontally layered	6	Genhoes, Burggraaf, Vroenhof
Channel margin	Lateral accretion deposits	Point-bars formed by lateral accretion on the convex bank of meanders. Preserved through channel shifting (lateral migration) and added to the floodplain by vertical accretion deposits at the top	Fining-up sequence from gravel to sand loam and loam to silt loam (unit 3)	2,3	All
Floodplain	Vertical accretion deposits	Fine-grained sediment deposited from suspended load of overbank floodwater;	In general horizontally layered		
		Natural levee	Sand loam and loam	7	Burggraaf
		Floodplain	Silt loam	3,4	All
		Distal floodplain	(humic) silty clay loam	5	Burggraaf, Genhoes, Vroenhof
		Backswamp	Peat, humic silty clay loam	8	Burggraaf, Vroenhof
Valley margin	Colluvium	Deposits derived mainly from unconcentrated slope wash and soil creep on adjacent valley sides	Predominantly silt loam with fragments of brick, tile, coal and charcoal	10	Vroenhof
	Alluvial fan	Formed by ephemeral streams emerging from steeply dissected terrain on to a river valley; sediments rapidly decrease in grain size with distance from the fan apex although grainsize in Geul catchment is rather uniform	Loam and silt loam with fragments of limestone, gravel, brick, tile, coal and charcoal	9a/b	Hommerich, Genhoes

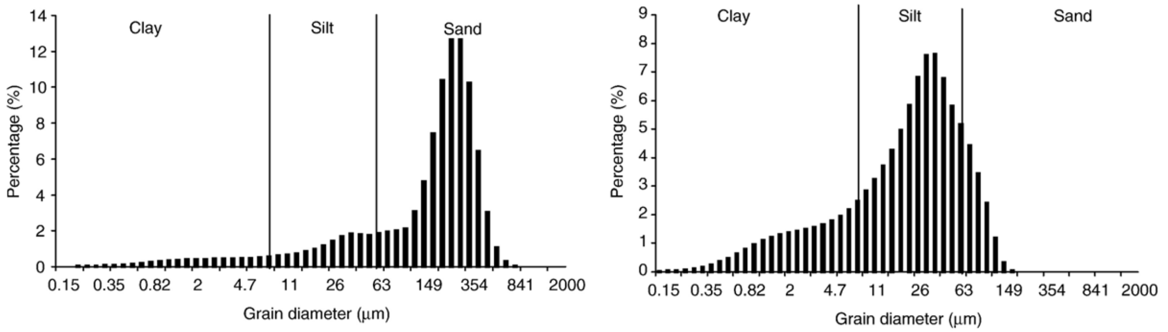
humic character is caused by partial decomposition of vegetation growing on relatively wet parts of the floodplain. Similar humic clays have been found in numerous river valleys in Germany and have been called “Black Floodplain Soil” or “Black Meadow Soil” (Lang and Nolte, 1999; Rittweger, 2000; Dambeck and Thiemeyer, 2002; Houben, 2003; Heine and Niller, 2003; Kalis et al., 2003). Similar dark brown organic clays of Preboreal age have been found by Pastre et al. (2001) in several river catchments in the Paris Basin, France. One date in transect Genhoes (Fig. 6) has been obtained from this unit, revealing a Preboreal age (8564–8228 BC).

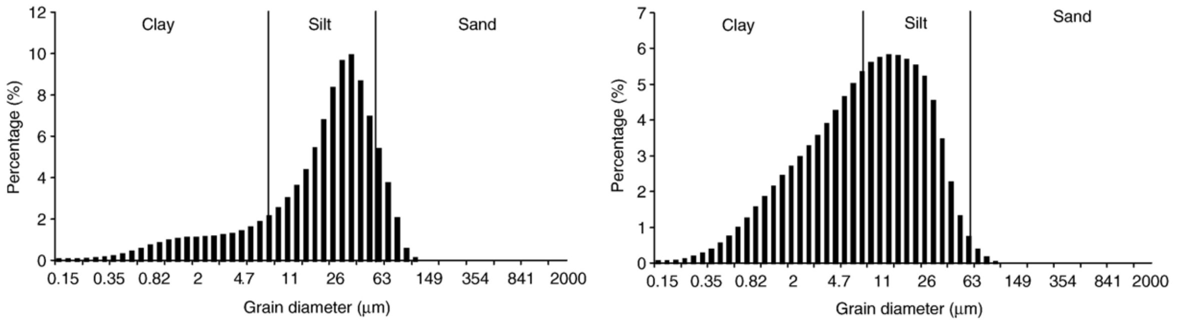
2.1.5. Unit 6

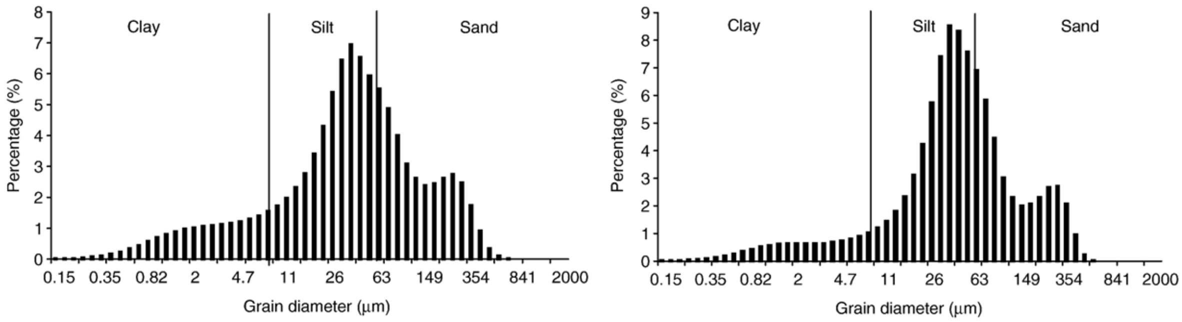
This unit has been found in transect Burggraaf (Fig. 5), transect Genhoes (Fig. 6) and transect Vroenhof (Fig. 7). In transect Burggraaf (Fig. 5), this unit consists predominantly of humic silt loam with some alternating thin layers of silt loam. In transect Genhoes (Fig. 6), this unit consists of alternating thin layers of peat (with numerous wood fragments) and humic loam, also with wood fragments. Towards the top of this unit, the sediment becomes more clastic. The maximum thickness of this unit is 1 m. In transect Vroenhof (Fig. 7), this unit consists of a fining-up sequence of loam and (humic) silt loam. Although the lithology differs slightly at these three locations, the sediments were deposited in the same depositional environment. The horizontal bedding and the topographic position in the three locations point towards deposition in an abandoned channel or temporarily inactive parts of the channel. The base of this unit has been dated at all three locations, revealing ages between 1694–1528 BC (transect Genhoes, Fig. 6) and 400–350 BC (transect Burggraaf, Fig. 5b).

2.1.6. Unit 7

This unit was found only in transect Burggraaf (Fig. 5) on both sides of the river. Horizontally layered silt loams and fine sand (105–250 µm) alternate (clay 10–11%; silt 53–55%; sand 29–30%; Fig. 8e). Fig. 8e also shows the bi-modal grain-size distribution for this unit. This implies that the sediment composition may be based on two different sediment sources. The first


(a) Unit 2 (location: cutbank Hommerich)
(b) Unit 3 (location: transect Burggraaf West)


(c) Unit 4 (location: transect Vroenhof)
(d) Unit 5 (location: transect Genhoes)


(e) Unit 7 (location: transect Burggraaf West)
(f) Unit 9a (location: transect Genhoes)

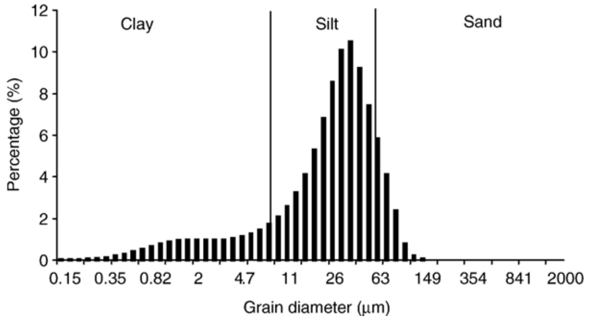

(g) Unit 9b (location: transect Genhoes)

Fig. 8. a–g. Typical grain-size distributions for units 2, 3, 4, 5, 7, 9a and 9b.

source would be reworked loess, eroded from the hillslopes (mode is 37 μm). The second source is likely to be eroded sand from early Cretaceous deposits (mode is 297 μm). On the west bank of the river the sediments become finer and the unit becomes thinner farther away from the present channel.

Table 4
Radiocarbon dating results

Location/sample name	Lab number	Material	Elevation (*m*+NAP)	Depth (m)	Method	Age (^{14}C yr BP)	Cal 2σ
Schoutenhof 3	GrA-26957	Seeds	107.45–107.55	2.4–2.5	AMS	4425±40	3124–2920 BC
Schoutenhof 5	GrA-26960	Seeds/1 beechnut	107.71	2.7	AMS	1370±35	602–694 AD
Schoutenhof 8	GrA-26947	Seeds	107.76–107.86	2.6–2.7	AMS	2160±35	262–95 BC
Schoutenhof 18	GrA-26950	Seeds	108.09–108.26	1.7–1.9	AMS	825±35	1157–1272 AD
Hommerich 5	GrA-26952	Seeds	93.24–93.34	5.0–5.1	AMS	2930±35	1222–1018 BC
Hommerich 15	GrA-26953	Seeds	93.98–94.08	5.6–5.7	AMS	5190±40	4068–3942 BC
Hommerich 21	GrA-26955	Seeds	94.01–94.11	2.6–2.7	AMS	970±35	1013–1158 AD
Hommerich 23	GrA-26956	Seeds	94.08–94.18	3.4–3.5	AMS	1670±35	312–434 AD
Hommerich 46	GrA-27291	Seeds/leaves	93.65–93.75	3.05–3.15	AMS	2230±35	331–203 BC
Burggraaf 39	GrA-26942	Seeds	84.52–84.62	3.3–3.4	AMS	845±35	1152–1265 AD
Burggraaf 43	GrA-26961	Seeds/leaves	85.13–85.28	2.8–2.95	AMS	980±35	1064–1155 AD
Burggraaf 70	GrA-26946	Seeds	85.89–85.99	2.6–2.7	AMS	10230±50	10188–9809 BC
Burggraaf 53	GrA-26943	Seeds	83.75–83.90	3.7–3.85	AMS	955±35	1019–1160 AD
Burggraaf 62	GrA-26945	Charcoal/seeds	83.03–83.13	3.9–4.0	AMS	2275±35	400–350 BC
Genhoes 39	GrA-27289	Seeds	74.94–75.14	5.1–5.3	AMS	810±35	1167–1273 AD
Genhoes 55	GrA-27290	Seeds	72.03–72.23	6.7–6.9	AMS	1935±35	3 BC–132 AD
Genhoes 16	GrA-27285	Seeds	73.93–74.03	3.8–3.9	AMS	880±35	1039–1223 AD
Genhoes 22	GrA-27287	Seeds	70.43–70.63	7.2–7.4	AMS	3345±35	1694–1528 BC
Genhoes 9	GrA-27284	Seeds/charcoal	72.63–72.83	3.7–3.9	AMS	1520±35	432–610 AD
Genhoes 5	GrA-27283	Seeds/wood	70.03–70.43	4.8–5.2	AMS	11040±60	11134–10926 BC
Genhoes 3	GrA-27305	Seeds/wood	71.6–71.8	2.8–3.0	AMS	640±35	1337–1398 AD
Genhoes 7	GrN-29025	Humic silty clay	71.4–71.6	3.9–4.1	Conventional	9130±80	8564–8228 BC
Vroenhof 28	GrA-27296	Seeds	54.29–54.49	2.3–2.5	AMS	1205±35	763–895 AD
Vroenhof V9.4	GrA-27293	Seeds/wood	52.92–53.09	3.54–3.71	AMS	2540±35	800–727 BC
Vroenhof 47	GrA-27307	Seeds	54.75–54.85	1.1–1.2	AMS	960±35	1017–1159 AD
Vroenhof 30	GrA-27308	Seeds/wood	52.63–52.83	3–3.2	AMS	11570±60	11635–11330 BC
Vroenhof V25.1	GrA-27294	Seeds	55.2–55.35	0.85–1	AMS	1305±35	657–774 AD
Vroenhof V25.12	GrA-27295	Seeds/wood	53.41–53.56	2.64–2.79	AMS	3190±35	1523–1408 BC

This unit is interpreted as a natural levee, because of the characteristic topographic position (slightly higher than the rest of the floodplain), the horizontal lamination and the coarser grain size and higher sand content than the surrounding floodplain silt loams (units 3 and 4). During flood stages, the river is capable of transporting medium sized sand and it will deposit the sediments close to the channel as a natural levee. The upper parts of this unit have characteristic dark brown and dark grey colours, pointing to contamination with lead and zinc, giving a clear age indication for this unit (cf. unit 2 from Stam, 2002).

2.1.7. Unit 8

This unit consists almost entirely of peat, humic silt loam and humic silty clay loam and is present at the valley sides in the Burggraaf and Vroenhof transects (Figs. 5, 7). The peat in the Burggraaf transect (Fig. 5) contains large fragments of wood, indicating a waterlogged woodland environment. A few thin (several cm's) clastic layers were found in the Burggraaf transect, indicating (short) periods of increased river activity. The peat in transect Vroenhof (Fig. 7) is predominantly sedge peat containing some wood fragments. In this transect two phases of backswamp development can be distinguished, separated by a

Table 5
Quartz OSL dating results

Sample name	NCL code	Depth	Elevation	Water content	Radionuclide concentration (Bq kg $^{-1}$)			Total Dose rate	Equivalent	Optical
		(m)	(m+NAP)	%	^{238}U	^{232}Th	^{40}K	(Gy ka^{-1})	Dose (Gyr)	age (ka)
Partij 1	6404046	0.85	96.91	20±5	40.1±0.3	39.8±1.0	526±6	2.73±0.12	1.48±0.07	0.54±0.04
Partij 3	6404047	2.40	95.36	21±5	52.5±0.3	45.9±0.9	617±5	3.17±0.14	38.7±1.3	12.2±0.7
Partij 4	6404048	3.00	94.76	26±5	46.1±0.5	46.1±0.5	585±6	2.90±0.12	36.1±1.2	12.4±0.7
Hommerich 6	6504050	1.10	95.70	23±5	37.5±0.4	37.6±0.7	467±4	2.44±0.10	2.63±0.11	1.08±0.06
Hommerich 5	6504049	2.60	94.20	21±5	33.2±0.4	26.0±0.7	326±5	1.89±0.08	4.54±0.22	2.40±0.16

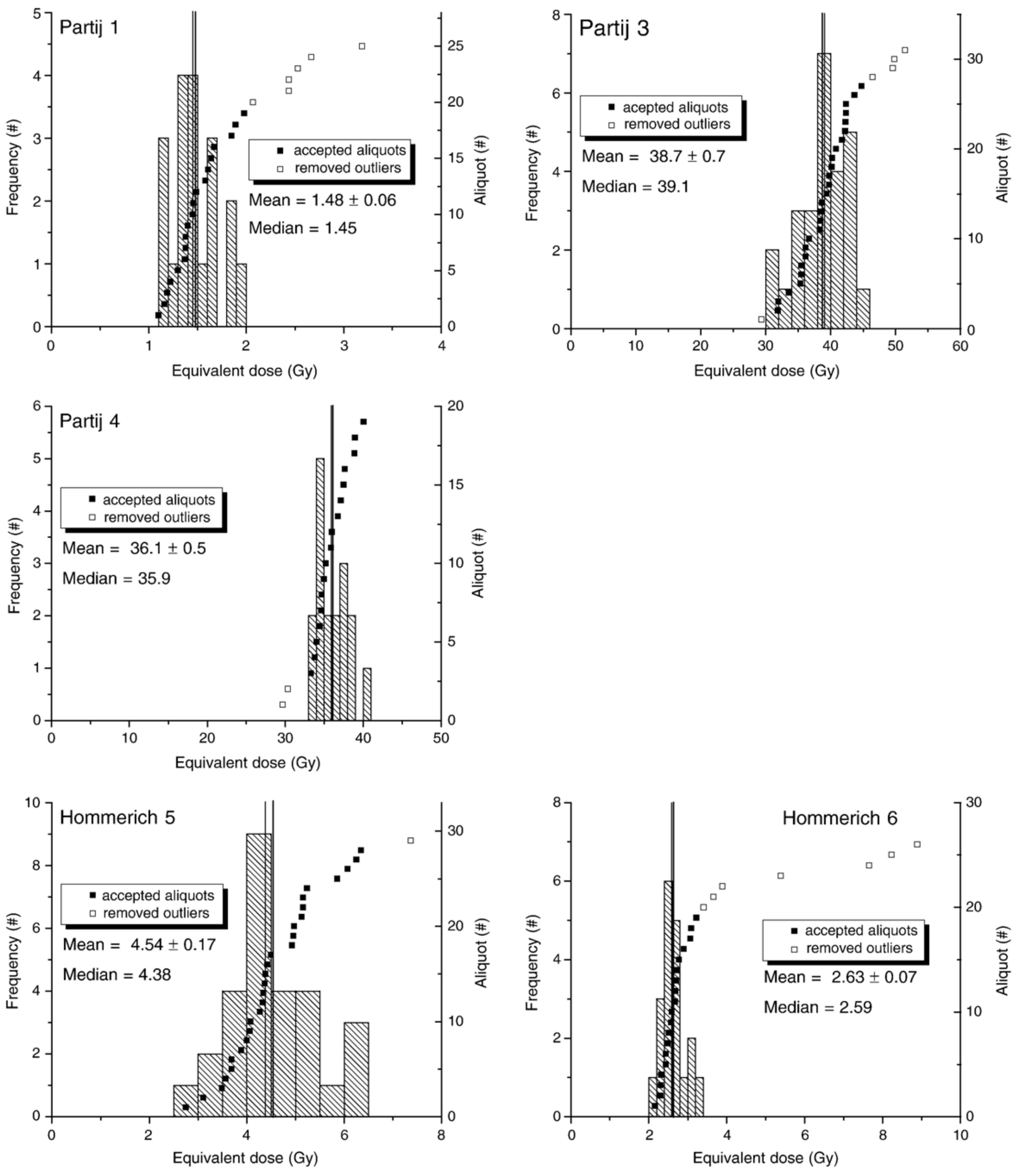


Fig. 9. Histograms of equivalent dose obtained on single aliquots using the single-aliquot regenerative-dose procedure depicted in Table 1. To avoid overestimation of the burial age due to incomplete resetting of the OSL signal in some grains at the time of burial, aliquots returning a value greater than two standard deviations from the sample mean were discarded in an iterative procedure. These points are shown as open circles in the graphs. The sample equivalent dose used for age calculation was obtained on the aliquots remaining after iteration. Note that uncertainties indicated on the graph are only random errors and do not include beta source calibration uncertainties.

thin clastic interval. This silt loam interval is probably related to a period with more river activity. As both units are situated at the edge of the floodplain, it is very likely that they have been formed in a backswamp environment. Wet conditions at these locations were favoured by the occurrence of seepage, especially on the eastern side of the Burggraaf transect (see also Van de Westeringh, 1979). No clear age estimate of this unit in transect Burggraaf is available, only a relative age estimate. The dates in the Vroenhof transect (Fig. 7) indicate that the end of peat formation took place during the Middle Ages (657–774 AD and 1017–1159 AD).

2.1.8. Unit 9 a/b

This unit, which is present in transects Hommerich and Genhoes (Figs. 4, 6), has been divided in a relatively coarse-grained loam (clay 7–9%; silt 55–69%; sand 16–30%; mode 37 µm, Fig. 8f) and a finer-grained silt loam (clay 7.5–14.5%; silt 69–80%; sand 4–9%; mode 31–37 µm, Fig. 8g). Both subunits are characterized by numerous coal, charcoal, brick and tile fragments. Clear sedimentary structures have not been found, but small coarsening-upward sequences occur at the east side of transect Hommerich. The grain size distribution of the finer-grained subunit 9b (see Fig. 8g) is similar to units 3 and 4, which points to a common loess source. However, the depositional environment is completely different. This is also expressed by the morphology (Fig. 2c/e) of this unit and the thickness, which increases towards the valley sides. The sediments have been deposited on an alluvial fan by ephemeral streams from relatively steep dissected terrain. In transect Genhoes (Fig. 6) the sediments rapidly decrease in grain size with distance from the fan apex. However, this is clearly not the case in transect Hommerich (Fig. 4), probably because the catchment area of the alluvial fan is smaller and hence the discharge and transport capacity is lower, leading to less grain-size differentiation on the alluvial fan. We interpret the finer sediments (unit 9b) as the more distal parts and the coarser (loam) sediments (unit 9a) as the proximal part of the alluvial fan. It is difficult to distinguish by grain size the alluvial fan sediments from floodplain sediments (units 3 and 4) in transects Genhoes and Hommerich because of the same loess-derived sediment source. We differentiated the alluvial fan sediments from floodplain sediments by the occurrence of brick, coal and charcoal fragments, the presence of coarsening-up sequences in alluvial fan sediments and the slightly finer grain size of the underlying overbank floodplain sediments.

Dates (OSL) from the Hommerich transect (Fig. 4) indicate that the alluvial fans on both sides of the river were active during and after the Middle Ages (1.08±0.06 ka and 0.54±0.04 ka) and that initial alluvial fan activity probably started before or during the Roman Period (2.40±0.16 ka and 331–203 BC). Activity of the alluvial fan in transect Genhoes (Fig. 6) was probably also initiated during the Roman Period (3 BC–132 AD). This alluvial fan had been very active during and after the High Middle Ages (1167–1273 AD and 1039–1223 AD). The numerous tile, brick and coal fragments in the top of the alluvial fans point to a young age. The presence of charcoal may point to burning activities on the hillsides, either natural of induced by man.

2.1.9. Unit 10

This unit is very similar to unit 9b and has been found at the eastern side of the Vroenhof transect (Fig. 7). The sediments have been deposited by unconcentrated slope wash and soil creep from adjacent valley slopes (colluvium). Such colluvial deposits are very common in the western and central European loess area and are the result of deforestation phases during the last several thousand years (e.g. Brown, 1992; Lang, 2003). No dates have been obtained from this unit, but a date of 657–774 AD in the underlying unit 8 indicates that the sediments of unit 10 must have formed during and after the Middle Ages.

2.1.10. Unit 11

In the western- and easternmost cores in transect Hommerich (Fig. 4) we found a mixture of loam, sand and gravel (predominantly clasts of limestone). As the locations of this unit are very close to the valley edge, it is very likely that these sediments are an infilling of a tributary or are caused by local valley/slope processes. They have probably not been deposited by the Geul River.

2.1.11. Synthesis of sedimentation processes

Based on the lithogenetic units and their volumes we conclude that Geul River sedimentation is dominated by four main processes (Table 3):

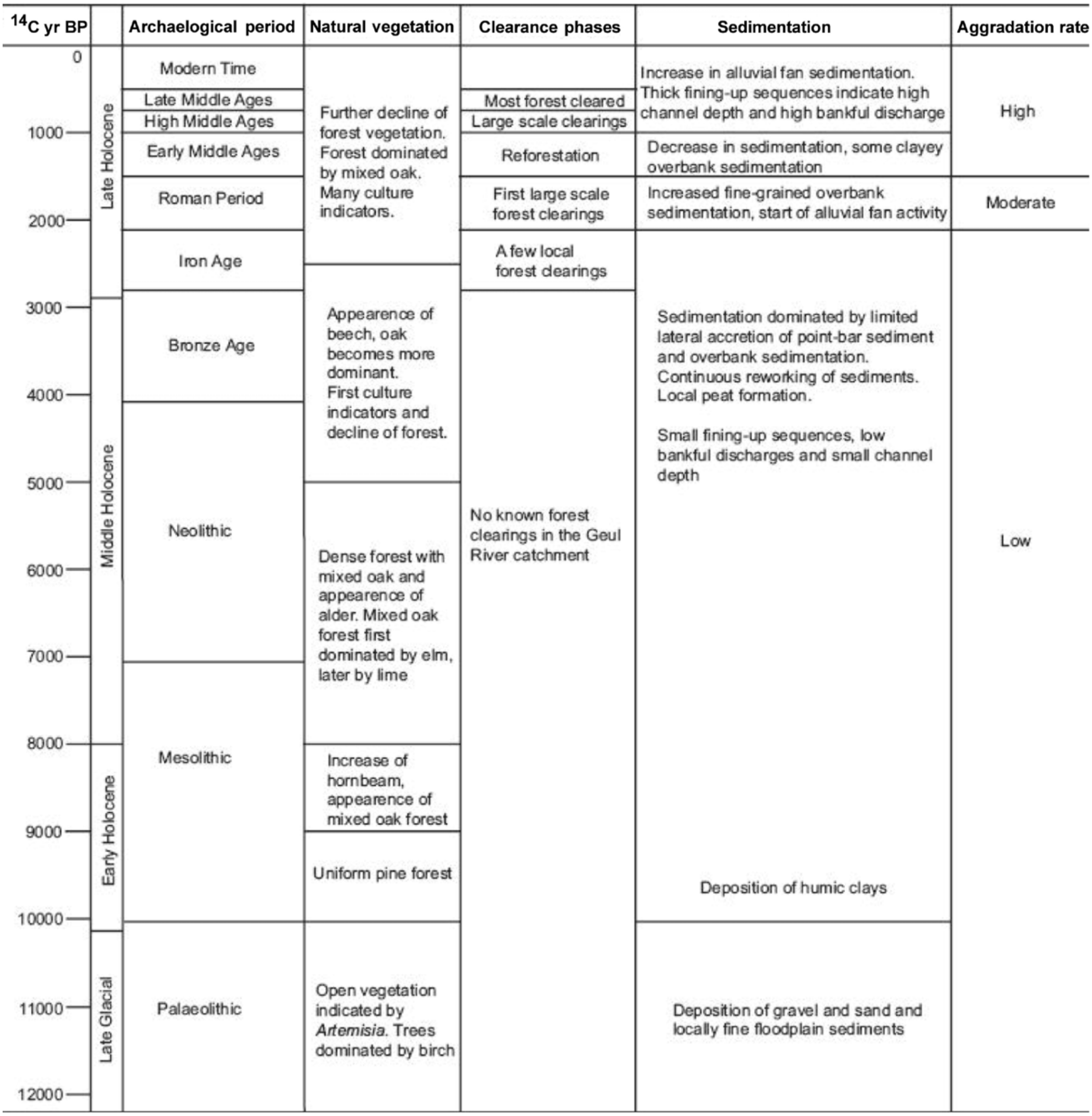
- lateral erosion and channel scour forming a basal gravel unit (unit 1),
- lateral accretion deposits of sand and loam forming point bars across most of the river valley (units 2 and 3),
- vertical accretion forming a thick floodplain consisting of overbank silt loam and silty clay loam (units 4, 5, 7, 8),
- loam and silt loam deposition on alluvial fans with thicknesses up to seven metres (unit 9 a/b).

3. Holocene valley development — alluvial architecture through time

3.1. Overview

Sedimentation in the Geul River catchment throughout the Holocene has been dominated by lateral accretion of point bar sediments and by vertical accretion of overbank silt loam. There are, however, differences between the upstream and downstream areas of the catchment. The thickness of the overbank fines (units 3 and 4) increases in a downstream direction, from about

Table 6
Synthesis diagram of depositional environments, vegetation and land-use history and phases of decreased and increased sedimentation



^{14}C yr BP		Archaeological period	Natural vegetation	Clearance phases	Sedimentation	Aggradation rate
0	Late Holocene	Modern Time	Further decline of forest vegetation. Forest dominated by mixed oak. Many culture indicators.		Increase in alluvial fan sedimentation. Thick fining-up sequences indicate high channel depth and high bankful discharge	High
		Late Middle Ages		Most forest cleared		
1000		High Middle Ages		Large scale clearings		
		Early Middle Ages		Reforestation	Decrease in sedimentation, some clayey overbank sedimentation	
2000		Roman Period		First large scale forest clearings	Increased fine-grained overbank sedimentation, start of alluvial fan activity	Moderate
		Iron Age		A few local forest clearings	Sedimentation dominated by limited lateral accretion of point-bar sediment and overbank sedimentation. Continuous reworking of sediments. Local peat formation. Small fining-up sequences, low bankful discharges and small channel depth	Low
3000 4000	Middle Holocene	Bronze Age	Appearance of beech, oak becomes more dominant. First culture indicators and decline of forest.	No known forest clearings in the Geul River catchment		
5000 6000 7000		Neolithic	Dense forest with mixed oak and appearance of alder. Mixed oak forest first dominated by elm, later by lime			
8000	Early Holocene	Mesolithic	Increase of hornbeam, appearance of mixed oak forest			
9000			Uniform pine forest		Deposition of humic clays	
10000 11000 12000	Late Glacial	Palaeolithic	Open vegetation indicated by *Artemisia*. Trees dominated by birch		Deposition of gravel and sand and locally fine floodplain sediments	

Partly based on data from (Havinga and Van den Berg van Saparoea, 1980; Van de Westeringh, 1980; Renes, 1988; Bunnik, 1999; Bazelmans et al., 2004).

2 m in transect Schoutenhof (Fig. 3) to 2.5 m in transect Burggraaf (Fig. 5) and almost 3 m in transect Vroenhof (Fig. 7). The width of the floodplain increases from 250 m upstream (near the Belgian–Dutch border) to more than 600 m close to the confluence with the Maas River. The gradient decreases downstream from 0.005 m m^{-1} near the Belgian–Dutch border to 0.0015 m m^{-1} near the confluence with the Maas. The wider floodplain (see Fig. 2b–f) and the lower transport capacity resulted in a larger variety of fluvial environments. The occurrence of extensive backswamp deposits in the downstream transect Vroenhof (Fig. 7) is especially striking, compared to transect Schoutenhof (Fig. 3) where only overbank fines and point bar deposits are

present. Apparently due to the narrower floodplain at Schoutenhof (see also Fig. 2a, e) and the more energetic conditions (because of the higher gradient), complete reworking of the sediment across the valley occurred, while in the other transects (with a wider valley) some isolated Late Glacial sediments are still present. In addition, a slight trend of downstream fining of the sediments is visible: in the downstream transects Genhoes and Vroenhof (Figs. 6, 7) thicker units of silty clay loam occur and especially in transect Vroenhof peat and humic sediments are present.

3.2. Fluvial architecture

Late Glacial sedimentation consisted of gravel and sand and local fine-grained (clayey) floodplain formation (e.g. transect Hommerich, Fig. 4). Large parts of the Late Glacial sediments have been eroded and very few Early and Middle Holocene deposits are preserved in the catchment. The only Early Holocene unit still present is the lower part of unit 5 (the “Black Floodplain Soil”) in transect Genhoes (8564–8228 BC, Fig. 6). Limited sediment availability during the Early and Middle Holocene resulted in predominantly low rates of fine-grained overbank sedimentation and local peat formation. During this period, the Geul River was probably a quiet and stable river. Later in the Holocene (the last 2000 yr) more sediment became available and the Geul River changed into a more dynamic system with active lateral migration. The increasing river dynamics clearly had a limiting effect on the preservation potential of older sediments in the floodplain (cf. Lewin and Macklin, 2003), as much of the older sediment has been removed by the laterally migrating river. Sedimentation during the last 2000 yr was dominated by overbank sedimentation and is reflected in the widespread occurrence of units 3 and 4. Numerous radiocarbon dates (Table 4) in all transects (Figs. 3–7) illustrate that the main phase of fine overbank sedimentation (units 3 and 4) took place since High Middle Ages (1000–1500 AD). The fine-grained overbank sediments (unit 5) in transect Burggraaf and Vroenhof (Figs. 5, 7) represent a period with less sediment availability and a less dynamic environment. Bank stabilisation measures during the last few centuries have resulted in local formation of natural levees (unit 7). The Geul River near transect Burggraaf (Fig. 5) has been stable for at least 200 yr (based on analyses of historical maps). The age for the natural levee at this location is supported by the presence of sediment contaminated with lead and zinc, related to 19th century mining (e.g. Stam, 2002). Formation of this unit is probably (partly) induced by the effect of the lead and zinc mining that started at the beginning of the 19th century.

An evaluation of the thickness of the fining-upward sequences in the fluvial deposits shows clear changes in fluvial dynamics through time. During the Early and Middle Holocene, sedimentation was dominated by point bar deposition and limited overbank sedimentation. The fining-up sequences from this period have a maximum thickness of about 1 m (Fig. 7, above the date of 800–727 BC), indicating that the (bankfull) channel depth by that time was also about 1 m. This changed during the Roman Time. Fining-up sequences from this period show a thickness of up to two meters (Fig. 4, above the dates of 2.40 ± 0.16 ka, 331–203 BC and 312–434 AD), giving a bankfull channel depth of about 2 m. Fining-up sequences from the High Middle Ages have a thickness of 2–3 m (for example Fig. 4, above the date of 1013–1158 AD and several dates in transect Burggraaf (Fig. 5)), giving maximum bankfull channel depths of about 3 meters. The increasing thickness of the fining-up sequences could represent an increase in bankfull discharge as a result of deforestation. Our field data indicate that increased discharges have not resulted in incision of the river (the level of the basal gravel (unit 1) is constant through the whole catchment). However, alternative interpretations for an increasing bankfull depth (discharge) can be (1) a multiple channel system as an effect of high vegetation density, cohesive banks and low sediment load, or (2) a higher width-depth ratio of the channel forced by the near surface presence of bedrock (Palaeozoic/Mesozoic basement). According to Nota and Van de Weerd (1978), bedrock is within 1 m below the present-day Gulp River (the main tributary of the Geul River). For these two hypotheses, the bankfull discharge could have been invariable. Unfortunately, we have no data to constrain the paleowidth of the Geul channel.

3.3. Alluvial fan architecture

Transects Genhoes and Hommerich (see Figs. 2c/e and 5/6) largely consist of thick alluvial fan units. The ^{14}C and OSL dates illustrate that several periods of alluvial fan activity can be recognized in the Genhoes transect. The first phase of alluvial fan sedimentation took place during the Roman Period (post 3 BC–132 AD, Fig. 6). After the Roman Period activity of the alluvial fan was limited; locally some organic deposits formed, indicating humid and stable (vegetated) conditions. A second major activation phase of the alluvial fan took place during the High Middle Ages. This second phase is illustrated by two ^{14}C dates in the Genhoes transect (Fig. 6) (1167–1273 AD and 1039–1223 AD). The alluvial fan sediments (units 9 a/b) cover older fluvial sediments (units 3 and 5). The dates in the Hommerich transect (Fig. 4) also confirm the Late Holocene age of the alluvial fans. Small variations in grain size in the alluvial fan deposits represent the proximal and distal parts of the alluvial fan. On the proximal side of the alluvial fan on the east bank of the river (Fig. 4) small coarsening-up sequences are present, indicating the prograding character of the fan during active phases. The alluvial fan sediments in this transect (Fig. 4) also cover older fluvial deposits, consisting of point bar and overbank floodplain sediments (units 2 and 3). The dates (OSL and ^{14}C, see Fig. 4) from the latter deposits indicate that the overlying alluvial fans probably started to form in the Roman Period or later and were active during and after the High Middle Ages. The tile, brick and charcoal fragments in the alluvial fan sediments also indicate the young character of the alluvial fans.

In the alluvial fans a clear difference exists between a coarser-grained unit (9a) and a finer-grained unit (9b), related to the distance to the fan apex and the size of the sub-catchment of the alluvial fan. The thick unit 9a in transect Genhoes points to intensified soil erosion and higher transport rates from the large catchment feeding the Genhoes fan. The fan deposits have a maximum thickness of about 4 m in transect Hommerich and about 7 m at the apex in transect Genhoes. The dates in transect Genhoes clearly show an increase in alluvial fan sedimentation rates during the Roman Period (about 2.5 m of sedimentation) and the High Middle Ages (locally about 5 m of sedimentation).

4. Discussion: human and climate impact on catchment development

The Geul River catchment has experienced considerable changes in fluvial dynamics and sedimentation rates during the Holocene. Knox (1995) identified five major controls on fluvial systems (climate, vegetation, tectonics/eustatic base-level change, human impact and intrinsic factors). Climate has often been regarded as the major control on fluvial systems in Western Europe during glacial and interglacial timescales (Veldkamp and Van den Berg, 1993; Vandenberghe, 1995, 2003). But on shorter timescales, other controls (like human activities) are likely to be of more importance, especially on relatively small river catchments (e.g. Macklin et al., 2005; Starkel, 2005). Although several of these forcing mechanisms can be responsible for the observed changes, it appears that human activities have had the most severe impact in the Geul River catchment. Heine et al. (2005) state that under natural conditions (a fully vegetated area) no significant soil erosion would occur in this type of catchment. According to Starkel (2005), the intensity of sediment load and slope wash is up to 4 orders of magnitude higher in cultivated small catchments (especially in hilly, mountainous regions) than in natural, completely forested situations.

The land-use and vegetation history of the study area (as described earlier in the paper, see also Table 6) is well reflected in the fluvial and alluvial fan sediments. Accelerated rates of overbank sedimentation and alluvial fan sedimentation coincide with two major deforestation phases in the area: the Roman Period (53 yr BC–415 yr AD) and the High Middle Ages (1000–1500 yr AD), although deforestation probably started at a smaller scale during the Iron Age (Bunnik, 1999). Deforestation caused hillslope erosion and sediment (mainly loess) was transported to the river, resulting in a thick floodplain deposit and in the formation of alluvial fans (Table 6). A period of finer-grained sedimentation (unit 5) can be related to a period when forest expansion took place and the population declined (the dark ages, 220–500 AD). The scarcity of older sediments in the Geul catchment can be explained by the pollen and archaeological data (Table 6), which indicate that during the Neolithic and the Bronze Age only on small-scale agriculture was practiced (Renes, 1988; Bunnik, 1999). The effect of these agricultural activities was probably too small to influence landscape development. Stam (2002) shows that high sedimentation rates in the Geul catchment in the nineteenth century were the result of deforestation and mining activities and that only during the second half of the twentieth century increased precipitation has contributed to an increase in sedimentation and channel-change rate.

The central-German loess area reflects similar increased sedimentation patterns during the Roman and Medieval Periods as the Geul River catchment. Heine et al. (2005) describe Medieval alluvial fan activity in southern Germany. Lang and Nolte (1999), Lang (2003) and Zolitschka et al. (2003) found several phases of increased alluvial fan activity (colluvium sedimentation) and floodplain sedimentation related to Roman and Medieval land-use change. Lang (2003) concludes that the periods of increased sedimentation were triggered by changes in land use and that climate change only played a minor role. Lang (2003) and Zolitschka et al. (2003) also report less alluviation and colluviation in the period prior to the Iron Age and during the Migration period. This resembles the pattern in the Geul River catchment. These authors also state that Holocene flooding events are hard to interpret as being the result of (short-term) climate fluctuations or land-use triggered catastrophic events. Zolitschka et al. (2003) found little evidence for a connection between alluviation and climate history during the late Holocene. Heine and Niller (2003) state that climate hardly played a role in the landscape development during the Holocene in Southern Germany and that anthropogenic activities were responsible for accelerated soil erosion, formation of alluvial fans and increased floodplain sedimentation.

Some climatic fluctuations occurred during the Holocene, although not as distinct as during the Weichselian. Some of the most well known climate excursions in the Holocene are the Medieval Warm Period and the Little Ice Age. Several authors report the effects of the Little Ice Age and the Medieval Warm period on fluvial dynamics in Great Britain, Central Europe and Spain (e.g. Rumsby and Macklin, 1996; Brown, 1998; Starkel, 2002; Brown, 2003; Macklin and Lewin, 2003; Thorndycraft and Benito, 2006). This is in most cases expressed by an increase in flood frequency as a result of events of extreme precipitation, an increase in floodplain sedimentation and an increase in channel migration. In transects Burggraaf and Vroenhof (Figs. 5, 7) clastic layers within the peat may indicate phases of increased flooding, however our dating resolution is not sufficient to relate these clastic sediments with a specific period of increased wetness during the Holocene. Our cluster of dates from the High Middle Ages (in alluvial fan and overbank silt loam units) coincides with three episodes (860, 660 and 570 cal. yr BP) of major flooding in Great Britain, Poland and Spain (Macklin et al., 2006). It is, however, very difficult to attribute with any certainty this increased sedimentation to climate-induced, increased flooding. It is possible that a combination of large-scale deforestation and increased wetness during the High Middle Ages resulted in a dramatic increase in fluvial and alluvial fan sedimentation (cf. Brown, 1998; Macklin et al., 2006).

Although the effect of climate on catchment development during the last few thousands of years is not as clearly documented as the effects of land-use change, climate change could play a role in the future development of the Geul River catchment. As present-day channel and floodplain forming processes (lateral channel migration and point bar formation) predominantly take place during high discharges, it is very likely that a future increase of high-intensity precipitation events (as projected by the IPCC, 2001) will have an impact on the catchment. Due to the short response time of the catchment to high precipitation events, the discharge of the river can rise very rapidly. With increasing high discharge events, lateral migration rates and reworking of sediments would be expected to increase.

5. Conclusions

The results of this study show that several periods of decreased and increased sedimentation can be linked with periods of distinct changes in land use (Table 6). During the Early and Middle Holocene, sedimentation rates were low and deposition was dominated by lateral accretion of point-bar sediments and limited overbank deposition. There was a continuous reworking of the sediments due to the lateral migrating river. Deforestation during the Roman Period and the High Middle Ages resulted in severe soil erosion and consequently in increased overbank floodplain sedimentation and the formation of alluvial fans in the valley of the Geul. Following the massive sediment input in the system, vertical accretion dominated the sedimentation pattern and the Geul was able to build up a floodplain of over 2 m above the present river bed.

This study shows that changes in land use have been the main trigger for this increase in sedimentation, although climate factors, like increased flooding due to extreme precipitation events, cannot be ruled out and might have intensified the erosion and sedimentation processes. Our results indicate that a small river catchment in a loess area is very sensitive to changes in land use. This implies that future changes in land use will have a profound effect on fluvial processes in the Geul River catchment and can, in combination with a future increase in extreme precipitation events, have severe consequences regarding flood risk and ecological value.

Acknowledgements

This study is part of the “Wege des Wassers” project and is partly funded by the European Union Interreg III — A program of the Euregio Maas-Rhine (contract number EMR.INT3 06.02–3.1.28). We thank Esther Bootsma, Florian ten Horn and Boris Webbers for their assistance in the field, and Candice Johns for processing the OSL samples. Martin Konert and Maurice Hooyen are thanked for their assistance with the grain-size analyses. Facilities for grain-size analyses and ^{14}C sample preparation were provided by the Vrije Universiteit Amsterdam. Sjoerd Bohncke is thanked for helping to identify the macroscopic plant remains. Critical and constructive comments on this paper by Andy Howard and Tim van der Schriek have been greatly appreciated. Equipment at the Netherlands Centre for Luminescence dating is partly financed by the Netherlands Organisation for Scientific research through investment grant 834.03.003.

References

Bazelmans, J., Bakels, C., Kocken, M., 2004. De Romeinse wachtpost op de Goudsberg, Valkenburg aan de Geul (Limburg). Historische en Heemkundige Studies in en rond het Geuldal 14, 61–86.

Berendsen, H.J.A., Stouthamer, E., 2001. Palaeogeographic development of the Rhine–Meuse delta. Van Gorcum, Assen.

Brookes, A., 1988. Channelized rivers: Perspectives for environmental management. Wiley, Chichester. 326 pp.

Brown, A.G., 1992. Slope erosion and colluviation at the floodplain edge. In: Bell, M., Boardman, J. (Eds.), Past and Present Soil Erosion, vol. 22. Oxbow books, Oxford, pp. 77–88.

Brown, A.G., 1998. Fluvial evidence of the medieval warm period and the Late Medieval climatic deterioration in Europe. In: Benito, G., Baker, V.R., Gregory, K.J. (Eds.), Palaeohydrology and Environmental Change. Wiley, Chichester, pp. 43–52.

Brown, A.G., 2003. Global environmental change and the palaeohydrology of western Europe: a review. In: Gregory, K.J., Benito, G. (Eds.), Palaeohydrology: Understanding Global Change. Wiley, Chichester, pp. 105–121.

Bunnik, F.P.M., 1999. Vegetationsgeschichte der Lößbörden zwischen Rhein und Maas von der Bronzezeit bis in die frühe Neuzeit. Laboratory of Palaeobotany and Palynology, Utrecht University, Utrecht. 149 pp.

Dambeck, R., Thiemeyer, H., 2002. Fluvial history of the northern Upper Rhine River (southwestern Germany) during the Late glacial and Holocene times. Quaternary International 93–94, 53–63. doi:10.1016/S1040-6182(02)00006-X.

De Laat, P.J.M., Agor, M.L.C., 2003. Geen toename van piekafvoer van de Geul. H2O 36 (9), 25–27.

Havinga, A.J., Van den Berg van Saparoea, R.M., 1980. Former vegetation and sedimentation in the valley of the river Geul. Mededelingen van de Landbouwhogeschool te Wageningen 80, 47–59.

Heine, K., Niller, H.-P., 2003. Human and climate impacts on the Holocene landscape development in Southern Germany. Geographia Polonica 76, 109–122.

Heine, K., Niller, H.-P., Nuber, T., Scheibe, R., 2005. Slope and valley sediments as evidence of deforestation and land-use in prehistoric and historic Eastern Bavaria. Zeitschrift für Geomorphologie N.F. Suppl. 139, 147–171.

Houben, P., 1997. Late-glacial and Holocene fluvial sedimentation in a small upland catchment in Hesse (Germany). Zeitschrift für Geomorphologie 41, 461–478.

Houben, P., 2002. Die räumlich-zeitlich veränderte Reaktion des fluvialen Systems auf jungquartäre Klimaänderungen. Eine Fallstudie aus der Hessischen Senke. Frankfurt am Main, Johann Wolfgang Goethe-Universität. 189 pp.

Houben, P., 2003. Spatio-temporally variable response of fluvial systems to Late Pleistocene climate change: a case study from central Germany. Quaternary Science Reviews 22, 2125–2140. doi:10.1016/S0277-3791(03)00181-1.

IPCC, 2001. Climate Change 2001: The Scientific Basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 881 pp.

Kalis, A.J., Merkt, J., Wunderlich, J., 2003. Environmental changes during the Holocene climatic optimum in central Europe — human impact and natural causes. Quaternary Science Reviews 22, 33–79. doi:10.1016/S0277-3791(02)00181-6.

Klimek, K., 2002. Human-induced overbank sedimentation in the foreland of the Eastern Sudety Mountains. Earth Surface Processes and Landforms 27, 391–402.

Knighton, D., 1998. Fluvial forms and processes — a new perspective. Edward Arnold, London. 383 pp.

Knox, J.C., 1995. Fluvial systems since 20 000 years BP. In: Gregory, K.J., Starkel, L., Baker, V.R. (Eds.), Global Continental Palaeohydrology. Wiley, Chichester, pp. 87–108.

Konert, M., Vandenberghe, J., 1997. Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. Sedimentology 44, 523–535.

Kukulak, J., 2003. Impact of mediaeval agriculture on the alluvium in the San River headwaters (Polish Eastern Carpathians). Catena 51, 255–266. doi:10.1016/S0341-8162(02)00165-0.

Lang, A., 2003. Phases of soil erosion-derived colluviation in the loess hills of South Germany. Catena 51, 209–221. doi:10.1016/S0341-8162(02)00166-2.

Lang, A., Nolte, S., 1999. The chronology of Holocene alluvial sediments from the Wetterau, Germany, provided by optical and ^{14}C dating. The Holocene 9, 207–214.

Lang, A., Bork, H.-R., Mäckel, R., Preston, N., Wunderlich, J., Dikau, R., 2003. Changes in sediment flux and storage within a fluvial system: some examples from the Rhine catchment. Hydrological Processes 17, 3321–3334. doi:10.1002/hyp.1389.

Leenaers, H., 1989. The dispersal of metal mining wastes in the catchment of the river Geul (Belgium–The Netherlands). Netherlands Geographical Studies, vol. 102. Koninklijk Aardkundig Genootschap/Geografisch Instituut Rijksuniversiteit Utrecht, Amsterdam/Utrecht. 200 pp.

Lewin, J., Macklin, M.G., 2003. Preservation potential for Late Quaternary river alluvium. Journal of Quaternary Science 18, 107–120. doi:10.1002/jqs.738.

Mäckel, R., Schneider, R., Seidel, J., 2003. Anthropogenic impact on the landscape of southern Badenia (Germany) during the Holocene — documented by colluvial and alluvial sediments. Archaeometry 45, 487–501.

Macklin, M.G., Lewin, J., 2003. River sediments, great floods and centennial-scale Holocene climate change. Journal of Quaternary Science 18, 101–105. doi:10.1002/jqs.751.

Macklin, M.G., Johnstone, E., Lewin, J., 2005. Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. The Holocene 15, 937–943. doi:10.1191/0959683605hl867ft.

Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Michczyńska, D.J., Soja, R., Starkel, L., Thorndycraft, V.R., 2006. Past hydrological events reflected in the Holocene fluvial record of Europe. Catena 66, 145–154. doi:10.1016/j.catena.2005.07.015.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Murray, A.S., Wintle, A.G., 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. Radiation Measurements 37, 377–381.

Murray, A.S., Marten, R., Johnston, A., Martin, P., 1987. Analysis for naturally occurring radionuclides at environmental concentrations by gamma spectrometry. Journal of Radioanalytical and Nuclear Chemistry 115, 263–288.

Nanson, G.C., Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology 4, 459–486. doi:10.1016/0169-555X(92)90039-Q.

Nota, D.J.G., Van de Weerd, B., 1978. A hydrogeological study in the basin of the Gulp creek — a reconnaissance in a small catchment area. Mededelingen van de Landbouwhogeschool te Wageningen 78, 1–26.

Pastre, J.-F., Limondin-Lozouet, L.N., Gebhardt, A., Leroyer, C., Fontugne, M., Krier, V., 2001. Lateglacial and Holocene fluvial records from the central part of the Paris Basin (France). In: Maddy, D., Macklin, M.G., Woodward, J.C. (Eds.), River basin sediment systems; archives of environmental change. Balkema, Rotterdam, pp. 357–373.

Raab, T., Völkel, J., 2005. Soil geomorphological studies on the Prehistoric to Historic landscape change in the former mining area at the Vils River (Bavaria, Germany). Zeitschrift für Geomorphologie N.F. Suppl. 139, 129–145.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., Van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1029–1058.

Renes, J., 1988. De geschiedenis van het Zuidlimburgse cultuurlandschap. Van Gorkum, Maastricht. 265 pp.

Rittweger, H., 2000. The “Black Floodplain Soil” in the Amoneburger Becken, Germany: a lower Holocene marker horizon and indicator of an upper Atlantic to Subboreal dry period in Central Europe? Catena 41, 143–164. doi:10.1016/S0341-8162(00)00113-2.

Roberts, R.G., Galbraith, R.F., Olley, J.M., Yoshida, H., Laslett, G.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rockshelter, northern Australia: Part II, results and implications. Archaeometry 41, 365–395.

Rommens, T., Verstraeten, G., Bogman, P., Peeters, I., Poesen, J., Govers, G., Van Rompaey, A., Lang, A., 2006. Holocene alluvial sediment storage in a small river catchment in the loess area of central Belgium. Geomorphology 77, 187–201. doi:10.1016/j.geomorph.2006.01.028.

Rumsby, B.T., Macklin, M.G., 1996. River response to the last Neoglacial (the “Little Ice Age”) in Northern, Western and Central Europe. In: Branson, J., Brown, A.G., Gregory, K.G. (Eds.), Global Continental Changes: the Context of Palaeohydrology. . Special Publication, vol. 115. Geological Society, London, pp. 217–233.

Schumm, S.A., 1977. The fluvial system. Wiley, New York. 338 pp.

Stam, M.H., 1999. The dating of fluvial deposits with heavy metals, ^{210}Pb and ^{137}Cs in the Geul catchment (The Netherlands). Physics and Chemistry of the Earth. Part B: Hydrology, Oceans and Atmosphere 24, 155–160.

Stam, M.H., 2002. Effects of land-use and precipitation changes on floodplain sedimentation in the nineteenth and twentieth centuries (Geul River, The Netherlands). Special Publications of the International Association of Sedimentologists, vol. 32, pp. 251–267.

Starkel, L., 2002. Change in the frequency of extreme events as the indicator of climatic change in the Holocene (in fluvial systems). Quaternary International 91, 25–32. doi:10.1016/S1040-6182(01)00099-4.

Starkel, L., 2005. Role of climate and anthropogenic factors accelerating soil erosion and fluvial activity in Central Europe. Studia Quaternaria 22, 27–33.

Starkel, L., Soja, R., Michczyńska, D.J., 2006. Past hydrological events reflected in Holocene history of Polish rivers. Catena 66, 24–33. doi:10.1016/j.catena.2005.07.008.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35, 215–230.

Swennen, R., Vankeer, I., De Vos, W., 1994. Heavy-metal contamination in overbank sediments of the Geul river (East Belgium) — its relation to former Pb–Zn mining activities. Environmental Geology 24, 12–21.

Thorndycraft, V.R., Benito, G., 2006. The Holocene fluvial chronology of Spain: evidence from a newly compiled radiocarbon database. Quaternary Science Reviews 25, 223–234. doi:10.1016/j.quascirev.2005.07.003.

USDA, 2005. National Soil Survey Handbook, title 430-VI. U.S. Department of Agriculture, Natural Resources Conservation Service. http://soils.usda.gov/technical/handbook/.

Van den Berg, M.W., 1996. Fluvial sequences of the Maas, a 10 Ma record of neotectonics and climate change at various timescales. PhD Thesis. Wageningen Agricultural University: 181 pp.

Van de Westeringh, W., 1979. Bodemkundig onderzoek in het dal van de Eyserbeek bij Cartiels. Natuurhistorisch Maandblad 68, 234–239.

Van de Westeringh, W., 1980. Soils and their geology in the Geul Valley. Mededelingen van de Landbouwhogeschool te Wageningen 80, 1–25.

Vandenberghe, J., 1995. Timescales, climate and river development. Quaternary Science Reviews 14, 631–638. doi:10.1016/0277-3791(95)00043-O.

Vandenberghe, J., 2003. Climate forcing of fluvial system development: an evolution of ideas. Quaternary Science Reviews 22, 2053–2060. doi:10.1016/S0277-3791(03)00213-0.

Vandenberghe, J., Mommersteeg, H., Edelman, D., 1993. Lithogenesis and geomorphological processes of the Pleistocene deposits at Maastricht–Belvédère. Mededelingen Rijks Geologische Dienst 47, 7–18.

Veldkamp, A., Van den Berg, M.W., 1993. Three-dimensional modelling of Quaternary fluvial dynamics in a climo-tectonic dependent system. A case study of the Maas record (Maastricht, The Netherlands). Global and Planetary Change 8, 203–218. doi:10.1016/0921-8181(93)90009-D.

Wallinga, J., 2002. Optically stimulated luminescence dating of fluvial deposits: a review. Boreas 31, 303–322.

Wolfert, H.P., 2001. Geomorphological change and river rehabilitation: case studies on lowland fluvial systems in the Netherlands. Alterra Scientific Contributions, vol. 6. Alterra Green World Research, Wageningen (the Netherlands). 200 pp.

Wolman, M.G., Leopold, L.B., 1957. River flood plains: some observations on their formation. U.S. Geological Survey Professional Paper, vol. 282-C. U.S. Government Printing Office, Washington, DC, pp. 87–107.

Zolitschka, B., Behre, K.-E., Scheider, J., 2003. Human and climatic impact on the environment as derived from colluvial, fluvial and lacustrine archives-examples from the Bronze Age to the Migration period, Germany. Quaternary Science Reviews 22, 81–100. doi:10.1016/S0277-3791(02)00182-8.

Zonneveld, J.I.S., 1974. The terraces of the Maas (and the Rhine) downstream of Maastricht. Centenaire de la société géologique de Belgique. L’évolution quaternaire des basins fluviaux de la mer du nord méridionale. Liège, pp. 133–157.