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Differentiated fluvial and environmental responses of trunk and tributary systems to Lateglacial and Holocene climate change

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Abstract

The geomorphic development of major rivers and smaller tributaries in response to climatic and environmental changes has been studied intensively in the past. However, impacts on confluence regions, with tributaries, have rarely been investigated. We aim to explore the similarities and differences in fluvial development over the last glacial to interglacial transition in the confluence area of the Meuse and the Loobeek in the southern Netherlands. We established five coring transects to investigate the fluvial architecture and sedimentary environments of the systems. Pollen analyses and radiocarbon dating enabled to establish the regional and local vegetation and the palaeogeographic evolution. The fluvial responses of the large Meuse and small Loobeek are strongly different and depend on differences in discharge, sediment supply and vegetation development. The fluvial response to the early Lateglacial warming is rapid in the small tributary and more delayed in the large-scale system. Smaller or shorter climate changes (during the Younger Dryas) are not registered in the channel pattern of the small-scale system. An anastomosing or diffuse drainage pattern and peat formation characterise the brook system during most of the Holocene, in contrast to the meandering Meuse system.

Introduction

The geomorphological and sedimentary response of rivers to climatic changes has been extensively studied over the past decades (Berendsen et al., 1995; Rose, 1995; Vandenberghe, 1995; Antoine et al., 2000; Blum & Törnqvist, 2000; Busschers et al., 2007; Bridgland & Westaway, 2008; Janssens et al., 2012; Starkel et al., 2015). The Meuse River in the Netherlands was particularly well studied (Pons & Schelling, 1951; Pons, 1954; Van den Broek & Maarleveld, 1963; Kasse et al., 1995; Huisink, 1997; Tebbens et al., 1999; Rensink et al., 2015; Hoek et al., 2017; Isarin et al., 2017; Wooldерink et al., 2018; Van den Berg, 1996; Zonneveld, 1974). A general conclusion from these studies is that the development of the youngest river terraces of the Meuse (younger than approximately 20,000 years) is a result of climate-driven variations in river discharge, sediment budget and vegetation cover. However, the fluvial response to climate change is also dependent on catchment size, geomorphology, gradient, discharge characteristics (Erkens et al., 2011), and sediment propagation (Van Balen et al., 2010; Tofelde et al., 2021). For example, the Rhine and Meuse systems show a channel pattern change from meandering to braided during the Younger Dryas stadial, while this change did not occur in the Warta, Tisza and Niers-Rhine systems (Vandenberghe et al., 1984; Bohncke et al., 1993; Kasse et al., 2005, 2010).

Over the past decades, small river systems are more and more subjected to river restoration practices to increase water storage capacity and biodiversity, to reduce peak discharges and flooding, or, more generally, to adapt to the effects of climate change (Wohl et al., 2015; Makaske et al., 2020). This is also the case for small river systems in the southern part of the Netherlands. However, the 'natural' (pre-agricultural) state and responses of smaller river systems to climatic changes in the southern Netherlands are relatively poorly studied up till now (Vandenberghe et al., 1984; Van Huissteden et al., 1986; Vandenberghe et al., 1987; Broothaerts et al., 2013; Candel et al., 2020).

The previously performed studies on the geomorphological and sedimentological evolution of lowland (tributary) systems in the southern Netherlands showed a phase of incision during the Early and Middle Pleniglacial period (~73–28 ka BP), leading to relatively wide and shallow river valleys. These valleys were subsequently filled with relatively coarse sediments by a braided river system during the Late Pleniglacial period (Geys, 1976; Vandenberghe & De Smedt, 1979; Diriken, 1982; Vandenberghe et al., 1984; Van Huissteden, 1986). The coarse-grained fluvial deposits are generally covered by relatively fine and well-sorted sands. These are characterised as fluvio-aeolian deposits, i.e. (aeolian) sediments that are (re-) deposited by low-energy shallow streams or by periglacial (slope) processes (Van Huissteden et al., 1986). During the early onset of the Lateglacial period (14.7–11.7 ka cal BP), a phase of incision by a (meandering) river channel is often recognised, followed by gyttja deposition in palaeochannels and peat formation in the floodplains (Vandenberghe et al., 1984; Van Huissteden et al., 1986; Broothaerts et al., 2013; Makaske & Maas, 2023). During the Holocene, fluvial activity was limited in the upstream parts (first order streams) of small catchments and peat formation occurred on a large scale, at least until large-scale human intervention in the landscape during the late Holocene (Vandenberghe et al., 1984; Broothaerts et al., 2014; Candel et al., 2020). Thus, these studies show that lowland tributary systems responded with a geomorphological adjustment to Lateglacial and Holocene climate change, which differs from the larger Meuse (and Rhine) rivers. However, a detailed comparison of the morphological and morphodynamic changes of the lowland tributary systems and those of a main trunk channel (i.e. Meuse River) to combined climate and environmental changes since the Lateglacial is still lacking. Such a detailed comparison is needed to explain the observed differences and disentangle the forcing factors of lowland tributary and trunk river systems to Lateglacial and Holocene climate change.

The Loobeek valley and its confluence area in the Meuse valley (i.e. Smakterbroek) provide the case study to investigate the effects of Lateglacial and Holocene climate change on tributary landscape dynamics and compare them to changes in the trunk channel systems. Hence, the aims of this study are to (1) reconstruct landscape dynamics of the Loobeek valley tributary resulting from climate and vegetation change, (2) compare the tributary responses to climate changes with those of the main river, and (3) investigate the interaction between the main river and its tributary (i.e. the impact of incision by the main river on the evolution of the tributary).

Setting

The Loobeek is a small lowland tributary system of the Meuse (Figure 1). The Loobeek rises near Ysselsteyn and subsequently flows to the east, to Venray (Figure 1). At the village of Smakt, the Loobeek alters its course to the northeast as it occupies the course of a palaeomeander of the Meuse, to debouche into the Meuse at Vierlingsbeek (Figure 1). The catchment size of the Loobeek is approximately 77 km^2 and it has a length of 15 kilometres. The current mean summer and winter discharge are respectively 0.60 m^3/s and ~1.5 m^3/s, while the bankfull discharge is ~5.40 m^3/s.

The Meuse River is a 900 km long rain-fed river that rises in northeastern France, flows along the eastern margin of the Paris Basin and crosses the Ardennes Massif before it enters the Netherlands near Eijsden. The catchment size of the Meuse river system is 33,000 km^2; it has a mean annual discharge of ~250 m^3/s and the bankfull discharge is 1500 m^3/s.

Tectonic and geological setting

The study area is situated in the Roer Valley Rift System (RVRS), which is part of the larger Lower Rhine Graben. The RVRS covers the southeastern part of the Netherlands, northeastern Belgium and a part of western Germany. As a result, the subsurface of the southeastern Netherlands is characterised by various tectonic blocks and fault zones (Ahorner, 1962; Klostermann, 1983; Van Balen et al., 2005; Westerhoff et al., 2008). The most upstream part of the Loobeek valley lies on the uplifting Peel Block. The majority of the study area is positioned on the subsiding Venlo Block to the east, which is separated from the Peel Block by the Tegelen fault zone (Van Balen et al., 2005; Woolderink et al., 2018, 2021). Faults of the Tegelen fault zone lie within the upstream part of the Loobeek valley. However, based on geological coring and subsurface models, these faults do not show any offset in the upper part of the stratigraphy (Geologische Dienst Nederland, n.d.). It is, therefore, assumed that faulting did not (directly) influence the Lateglacial and Holocene development of the Loobeek.

Climatic changes and landscape dynamics of the lower Meuse Valley

Vegetation is an important controlling factor on river activity and morphology, as it influences riverbank and floodplain stability and cohesion, sediment load and river discharge (Kasse et al., 1995; Hoek, 1997; Vandenberghe, 2003). In addition, vegetation cover influences the availability of (aeolian) sediments on a regional and local scale. Regional biostratigraphy can be used for vegetation reconstruction and for (relative) dating.

The regional vegetation history of the Meuse valley since the Late Pleniglacial is briefly presented in Figure 2, which supports the interpretation of the local pollen diagrams presented in this study and provides a chronostratigraphic framework for river terrace formation. The regional vegetation history of the Lateglacial and early Holocene is based on Hoek (1997) and Hoek et al. (2017). The biostratigraphy of the Holocene is based on a representative pollen diagram from the Meuse valley near Well-Aijen (Figure 1; Bos & Zuidhoff, 2015).

Methods

Geomorphological map

Geomorphological units were based on a LIDAR digital elevation model with a resolution of 0.5 × 0.5 metres (Actueel Hoogtebestand Nederland [AHN], 2024), the previously published geomorphological map (1:50,000; Wageningen Environmental Research, 2022a) and terrace maps of this part of the Meuse valley (Kasse et al., 1995; Huisink, 1997; Tebbens et al., 1999; Woolderink et al., 2018). Additionally, subsurface borehole data (Geologische Dienst Nederland, n.d.) and the soil map (1:50,000) (Wageningen Environmental Research, 2022b) were used. Urban areas were identified using open source aerial photographs with a 0.25 m resolution (Kadaster, 2023). The geomorphological map was made in ArcGIS at a 1:10,000 scale (Van der Kuijl, 2020).

Coring transects and sediment cores

Coring transects were planned based on the LiDAR imagery (elevation), the constructed geomorphological map (valleys and floodplains) and the soil map (peat occurrences). The cross sections cover both the Loobeek valley (Loobeekdal, Merselo) and

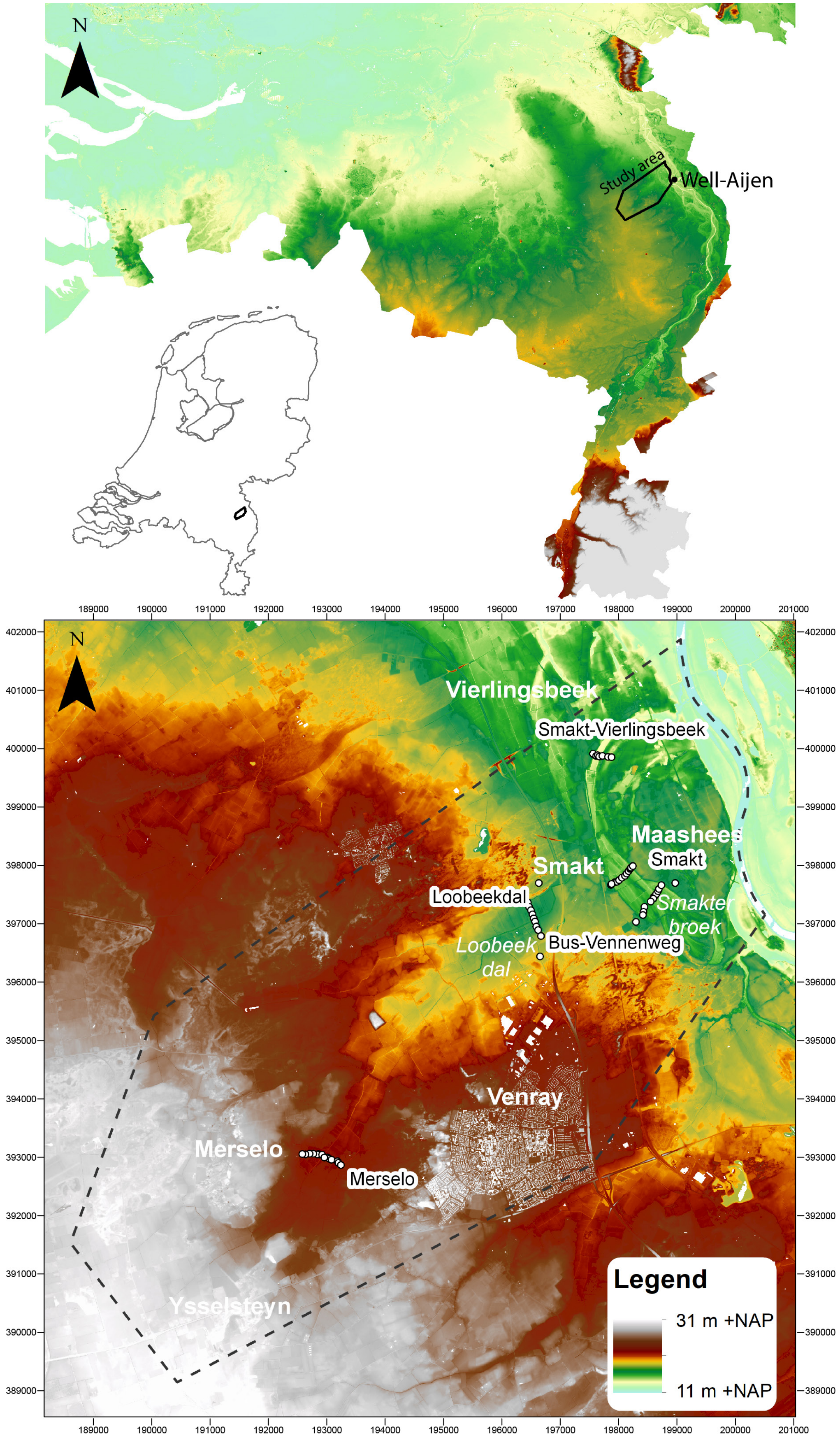

Figure 1. Overview of the study area; Loobeek Valley and Smakt area are indicated. Top panel shows the location of the study area in the Netherlands (solid line). Bottom panel shows the elevation of the study area (dashed line) and the cored transects (white dots).

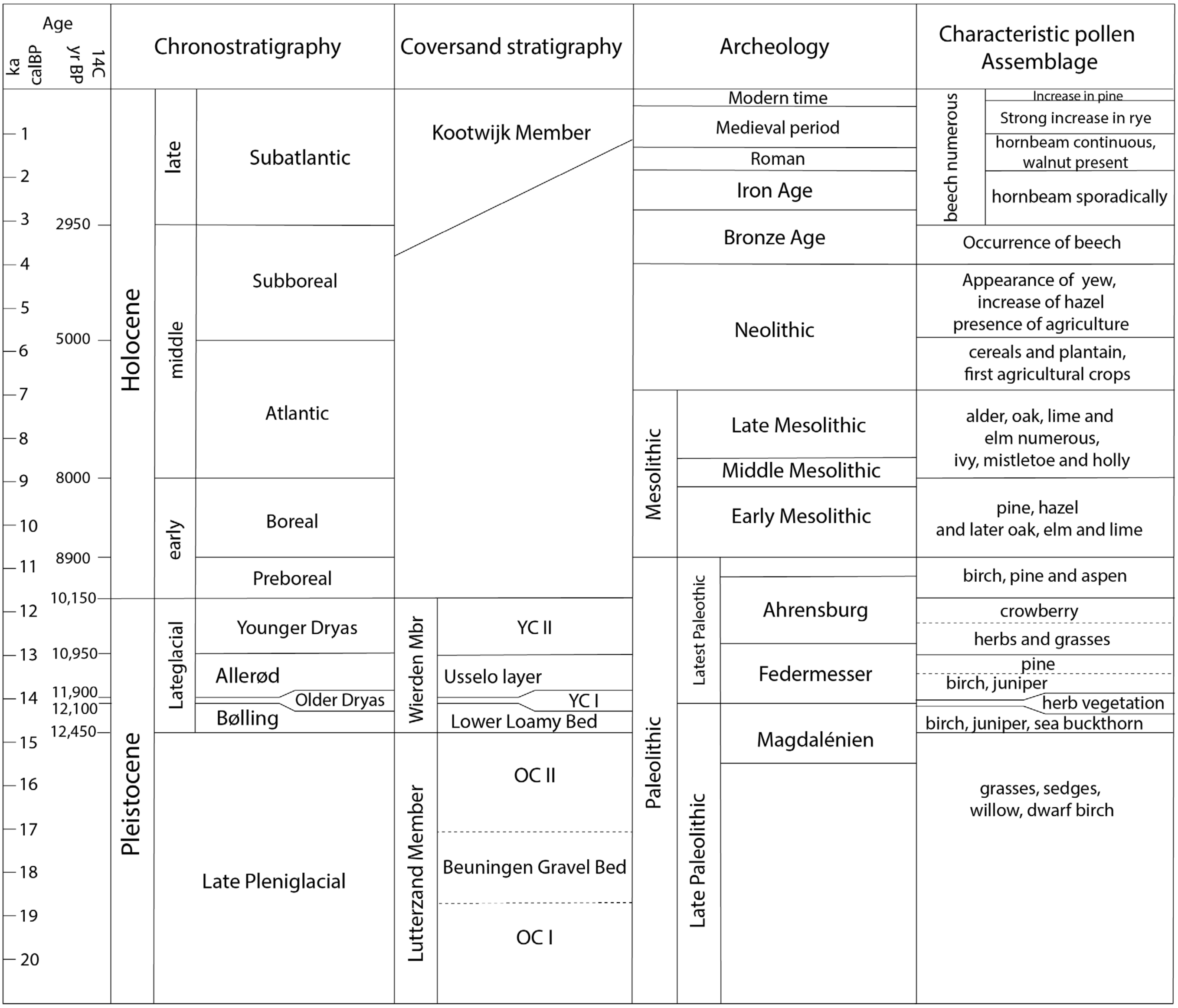

Figure 2. Overview of the chronostratigraphy, coversand stratigraphy, most important archaeological periods and characteristic pollen assemblages for the larger regional setting.

Meuse valley (Vierlingsbeek, Smakt, Bus-Vennenweg) (Figure 1). Cross sections are mostly located where peat deposits are present, based on existing geomorphological and soil maps, to enable biostratigraphic interpretations, vegetation reconstruction and radiocarbon dating. Reconnaissance coring was done with an Edelman soil auger above the ground-water table, and a gouge (diameter 3 cm) below it. Sediments were described in the field for lithology, grain size, sedimentary bedding, carbonate content, colour and presence of plant remains following NEN 5104 (1989). Cores for laboratory analyses were taken with a 60-mm diameter gouge at locations with the thickest fine-grained and organic fill in residual channels or floodplains. The retrieved cores were stored in a cool room at Vrije Universiteit Amsterdam. In the laboratory, the cores were split in two halves and lithology was described in detail. Subsequently, subsamples were taken for grain-size measurements, thermogravimetric analysis, pollen analyses and radiocarbon dating.

Sediment analysis

Subsamples were taken for grain size and thermogravimetric analysis. The subsamples were taken from the core at variable resolutions, based on visual observations of changes in lithology, colour or organic matter content. The grain size samples were pre-treated for analysis using the method by Konert and Vandenberghe (1997) in which organic matter and calcium carbonates are removed from the samples. Subsequently, the grain-size distribution was measured using a Sympatec HELOS KR laser-diffraction particle sizer at the Vrije Universiteit Amsterdam. To assess the loss-on-ignition (LOI_{330} and LOI_{550} [Heiri et al., 2001]) and total calcium carbonate content (LOI_{950}), the loss of mass under a stepwise heating process from room temperature up to 1000 ˚C was measured using a Leco 701 Thermogravimetric analyser at the Vrije Universiteit Amsterdam.

Palynology

The subsamples for palynology were taken at variable resolutions, following visual observations of changes in lithology, colour or organic matter content. Subsamples for pollen analyses were treated following the standard method by Fægri and Iversen (1989). The pollens were mounted in glycerine jelly and identified using Beug (2015) and Moore et al. (1994). Pollen diagrams were created using the Tilia software (Grimm, 1992). The pollen sum of the diagrams includes trees, shrubs, upland herbs, heathers and Poaceae. Differentiation into Local Pollen Assemblage Zones (LPAZ) was performed based on changes in the main pollen taxa. The LPAZs were correlated to the regional Pollen Assemblage Zones (PAZ) as defined by Hoek (1997), Hoek et al. (2017) and Bos and Zuidhoff (2015).

Radiocarbon dating

Samples for radiocarbon dating were taken mostly from the base of organic channel fills in order to date channel abandonment and the start of peat formation. Since the channel fills are mostly fine grained and organic sediment, reworking of older organic material is limited. The samples were treated with diluted potassium hydroxide to disperse organic compounds before they were sieved over a 200 μm mesh. Thereafter, terrestrial macro remains from the organic deposits were targeted for dating. Samples Smakt 203A and Smakt 411A did not contain sufficient terrestrial macro remains. Therefore, bulk organic material was dated from which aquatic seeds and root fragments were removed as much as possible, based on visual inspection with a binocular microscope. The samples were sent to the Beta Analytic laboratory (Miami, Florida) where they were pre-treated following a standard triple A method prior to AMS dating. Table 1 shows the sample depth, lithology, selected material for dating and dating results. The radiocarbon dates were calibrated using IntCal20 (Reimer et al., 2020).

Results

Geomorphological map

Three major landscape units are distinguished on the geomorphological map (Figure 3). The northeastern part is dominated by terraces of the Meuse river (T1–4, RC, Fp), previously attributed to the Lateglacial (Kasse et al., 1995; Huisink, 1997; Woolderink et al., 2018). Terrace fragments T4/3 are situated at 17–18 m above NAP (Dutch Ordnance Datum) and are characterised by straight terrace scarps and residual channels (Figure 3). Terrace T2 at 15.5–16.5 m elevation is characterised by well-developed scroll-bar morphology and a residual meandering channel (RC). Terrace T1 at a height of 13.5–14.5 m is a small fragment of a more extensive terrace with straight channels further southeast (Figure 3). The Holocene floodplain (Fp) at 12–13 m is found on the inner bend of the present-day Meuse channel.

The second unit, in the central and southwestern part of the map, is characterised by aeolian morphology of last glacial coversands (Cs) at an elevation of circa 21–24 m, and Holocene drift sands (DuH, DuL, FCsDu) at a height of 25–30 m (Figure 3). The southwest – northeast oriented Loobeek valley is the third major landscape unit. It is characterised by aeolian and fluvially reworked aeolian deposits (BvA and Bv). In the mid and downstream reaches wider valley segments with peat (BvP) alternate with narrower valley segments with clastic deposits (Bv). The gradients of the segments are shown in Figure 3.

Lithogenetic cross sections

Five coring transects were made in the study area. Two are located over the Loobeek valley (Figures 1 & 3). The other three are located in the Meuse terrace area near Smakterbroek (Figures 1 & 3). The lithology of the cores has been interpreted genetically, resulting in lithogenetic units.

Loobeek valley (Loobeekdal and Merselo)

Six lithogenetic units were distinguished in the coring transects over the Loobeek valley (Figure 4: Loobeekdal, Merselo) (Table 2).

In cross section Loobeekdal, unit A consists of coarse and poorly sorted sands that locally show a fining upward trend. It is interpreted as coarse Meuse river deposits of late Saalian age (Beegden Formation). In cross section Merselo, unit A consists of sandy loam and fine sands which are interpreted as lacustro-aeolian and shallow fluvial deposits of Weichselian Pleniglacial age ('Brabant leem').

Unit B is characterised by moderately fine to very coarse, moderately to poorly sorted sands with loamy laminea (Table 2). The unit locally contains small gravel and the top is often penetrated by roots. Based on these characteristics, unit B is interpreted as fluvio-periglacial deposits. Fluvio-periglacial deposits are deposited by low-energy shallow streams or by periglacial slope- and aeolian processes. The aeolian sediments can have been reworked by superficial runoff and deposited on the flanks and on the broad valley floor.

Unit C consists of (very) fine, moderately to well sorted, homogeneous sands. Based on the sediment characteristics and the morphology along the valley edge, unit C is interpreted as aeolian coversand deposits.

Table 1. Radiocarbon samples and dates for the Smakt study site

Sample name	Sample lab name	x	y	Depth (cm below surface)	Material	Age 14C (BP)	Age cal yr BP (95.4% probability, Intcal20)
Smakt 203 A	Beta-586763	196,533	397,198	71–74	Bulk fragmented organic material	4880 ± 30	5660–5579
Smakt 308A	Beta-586764	193,053	392,974	280–285	Seeds	12,070 ± 40	14,053–13,808
Smakt 411A	Beta-586765	198,448	397,121	220–230	Bulk fragmented organic material	10,440 ± 30	12,607–12,537
Smakt 401AB	Beta-586766	198,657	397,449	120–130	Seeds	10,000 ± 40	11,648–11,273

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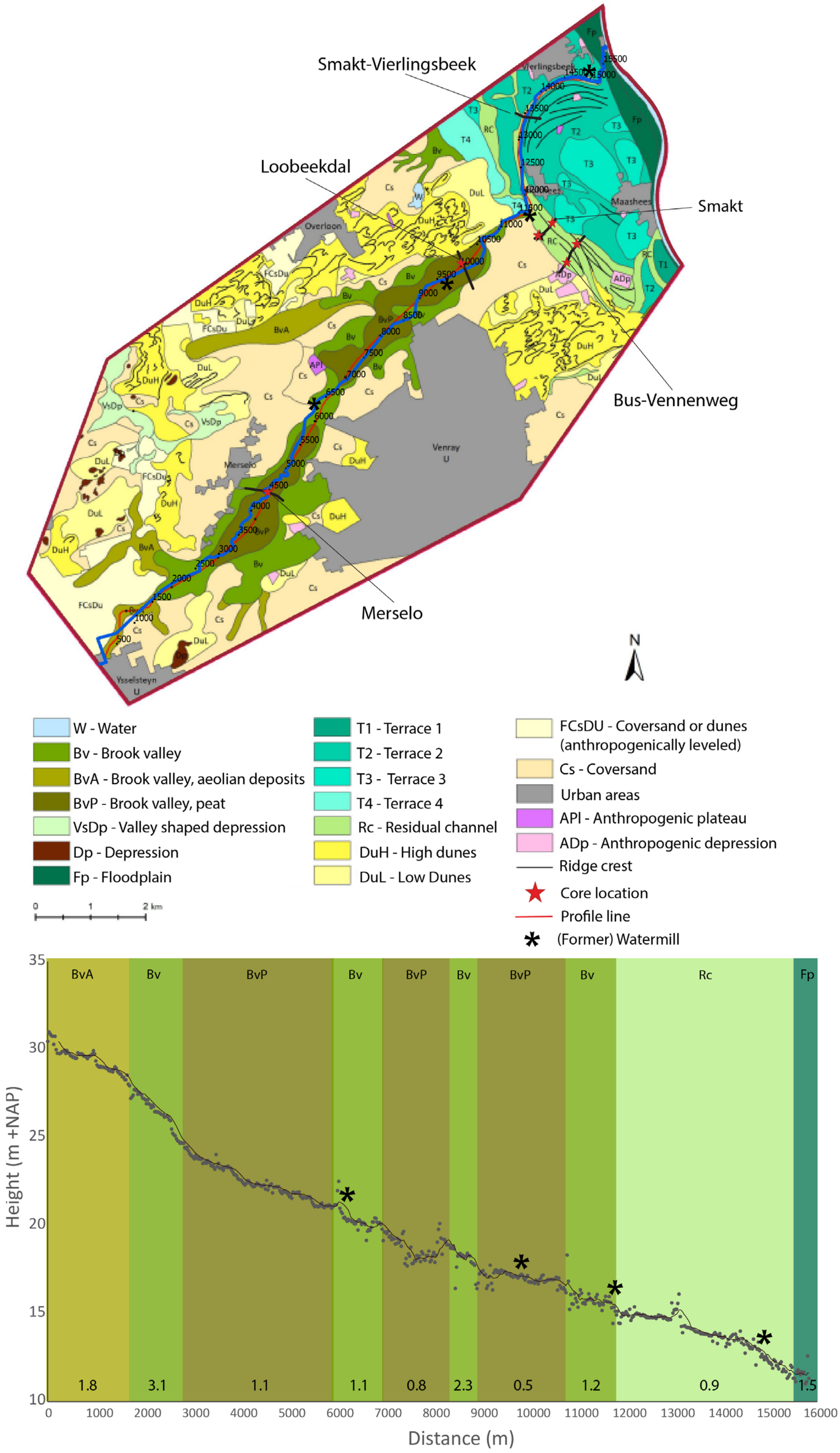


Figure 3. Top panel shows the geomorphological map of the Smakterbroek area. Locations of the lithogenetic cross sections are annotated. Bottom panel shows the elevation profile of the Loobeek from upstream to where it debouches into the Meuse River. Gradients are presented in the bottom of each segment. Note the irregularities in the valley gradient related to aeolian deposition (Bv) and knickpoint formation by incision of the Meuse. The asterix show the location of (former) watermills in the Loobeek valley.

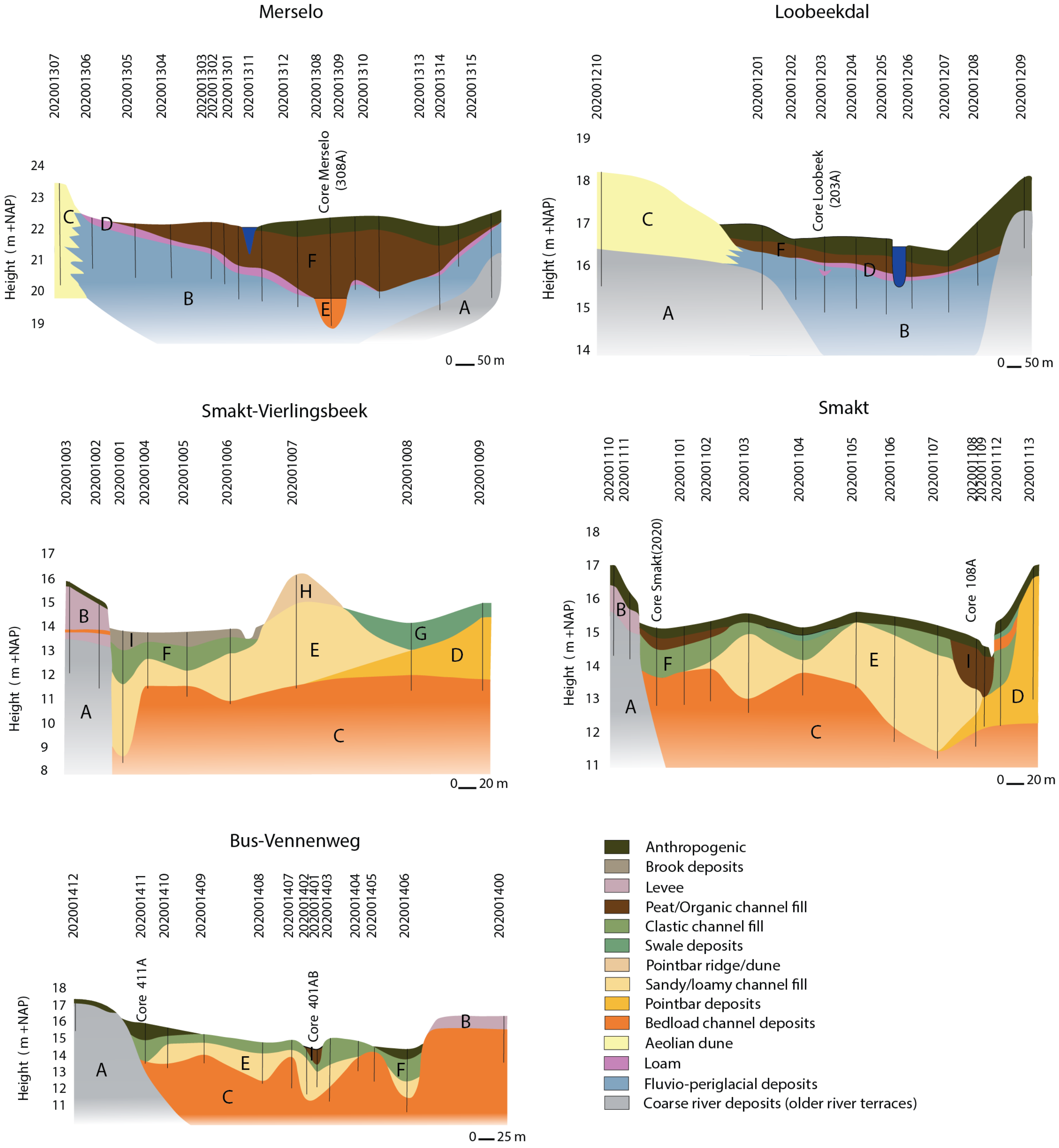


Figure 4. Lithogenetic cross sections of the study area. For locations, see Figure 1 or Figure 3. Description of the lithogenetic units can be found in Table 2 and Table 3.

The sediments of unit D are characterised by sandy loams and loamy sands (Table 2), which are slightly humic and contain plant remains, mostly roots. Since unit D overlies unit B in a fining-upward sequence, unit D is interpreted as floodplain sediments deposited in the final stage of fluvio-periglacial deposition (unit B). The elevation difference of unit D might indicate diachronous deposition.

Unit E is only found in the Merselo profile and consists of very to extremely coarse sands and (coarse) organic detritus in a fining upward trend. The base of unit E has incised into units B and D. Therefore, unit E is considered an incised channel fill (Table 2 & Figure 4).

Unit F consists of peat that contains wood remains at the valley margin. In the more central part of the valley, the peat consists of sedges and mosses with local seeds of *Menyanthes*.

Table 2. Description of the lithogenetic units in the Loobeek area, including their main lithology, sorting characteristics, and sedimentary structures

Lithogenetic units	Unit in profile	Lithology/Grain size	Sorting	Sedimentary structures	Additional characteristics
Peat swamp (Unit F)	Loobeekdal	Peat	-	-	Wood
	Merselo	Peat	-	-	wood at valley margin (core 311, 313); sedge, moss and *Menyanthes* seeds in central part (core 308, 309, 310, 312); *Menyanthes* seeds in the deepest part (core 308, 309, 312)
Incised channel fill (Unit E)	Merselo	Medium coarse to coarse sand (210–600 μm)	Poor	Fining upward sequence	Organic detritus
Floodplain loam (Unit D)	Loobeekdal	Sandy loam	-	-	Slightly humic, plant remains (roots)
	Merselo	Loamy sand (105–210 μm)	-	-	Slightly humic, roots
Coversand (Unit C)	Loobeekdal	Very fine to fine sand (105–210 μm)	Good	-	-
	Merselo	Fine sand (150–210 μm)	Good to moderate	-	Thin gravel bed (core 307, 230 cm; Beuningen Gravel Bed)
Fluvio-periglacial deposits (Unit B)	Loobeekdal	Medium coarse sand (210–300/420 μm)	Moderate to poor	Loamy laminae (core 201); top fining up	Compact, top rooted, some gravel (core 202)
	Merselo	Medium fine to medium coarse sand (150–300 μm)	Moderate	Loamy laminae (core 304)	Top rooted
Older fluvial Meuse deposits / *Brabantse leem* (Unit A)	Loobeekdal	Coarse sand (210/600–850 μm)	Poor	Fining upward sequence	-
	Merselo	Sandy loam and fine sand (150–210 μm)	-	-	-

Unit F is interpreted as a peat swamp filling in and flattening the valley morphology (Table 2).

Smakterbroek (Smakt-Vierlingsbeek, Smakt, Bus-Vennenweg)

The cross sections Smakt-Vierlingsbeek, Smakt and Bus-Vennenweg (Figures 1, 3 and 4) contain nine lithogenetic units (Table 3).

Unit A consists of poorly sorted, coarse sands and gravels. The grain size of the sand is between 210 and 850 μm (Table 3). Therefore, unit A is interpreted as fluvial deposits of the Meuse river (late Saalian Beegden Formation), probably deposited by a braiding river system.

Unit B consists of homogeneous sandy loams, loamy sands and silty sands (Table 3). The sediment characteristics and the position next to former channels lead to the interpretation of this unit as floodplain and levee deposits.

Unit C is characterised by moderately to extremely coarse, poorly sorted sands that locally contain gravel and some organic detritus (Table 3). The sediments of unit C are very compact and hard to drill with a hand-auger. The sediment characteristics point to channel and bar deposits based on these characteristics.

Unit D consists of moderately coarse, well-sorted sands that are loosely packed and locally contain loamy laminae. The fining-upward trend in unit D indicates pointbar deposits (Table 3).

The sediments of unit E are characterised by laminated, (very) fine to moderately coarse sands, silty sands and loam. The sediments are well to moderately sorted. The sediment characteristics and succession on top of channel bed deposits are interpreted as an initial sandy channel fill.

Unit F and G consist mainly of sandy loams and silty and sandy clays (Table 3). The sediments locally show laminae, are slightly humic and contain plant remains (Table 3). Unit F is interpreted as a fine-grained channel fill. Unit G is only found in the Smakt-Vierlingsbeek cross section (Table 3 and Figure 4) in the topographic depression in the eastern part of the profile and is interpreted as a swale infill.

Unit H consists of well-sorted and well-rounded fine sands (150–210 μm). The grain size, in combination with the morphological position, points to scrollbar deposition, possibly overlain by a thin aeolian sand cover (low dune).

Unit I consists of mottled humic sandy loams, with occasional organic layers and leaf remnants in the Smakt-Vierlingsbeek profile. Therefore, these deposits are interpreted as brook deposits. In the Smakt and Bus-Venneweg cross sections, unit I mainly consists of clayey peat and peat (Table 3) with wood remains of alder. Sand and clay lenses occur in the peat. Unit I is interpreted as peat swamp deposits with local influxes of clastic material by local brooks (Table 3).

Palynology

Six cores have been recovered from the Loobeek valley and from the confluence zone where the Loobeek enters the Meuse terraces area (Figures 3 & 4). The regional and local vegetation development, and the biochronostratigraphic framework, supplemented by radiocarbon dating, are based on core samples. LPAZs are correlated with the regional PAZ according to Hoek (1997) and Bos and Zuidhoff (2015).

Merselo (core 308A)

Core Merselo (Figures 3 & 4: profile Merselo core 308A) is located in the upstream part of the Loobeek valley, near the village of Merselo. The results of pollen analyses can be grouped into six LPAZs (Figure 5).

Table 3. Description of the lithogenetic units in the Smakt area, including their main lithology, sorting characteristics, and sedimentary structures

Lithogenetic units	Unit in profile	Lithology/Grain size	Sorting	Sedimentary structures	Additional characteristics
Brook deposits; peat swamp (Unit I)	Smakt-Vierl.	Humic sandy loam	-	Sand & clay beds	Organic beds
	Smakt	Peat and peaty clay	-	-	Wood
	Bus-Vweg	Clayey peat	-	-	-
Aeolian dune (Unit H)	Smakt-Vierl.	Fine sand (150–210 μm)	Good	-	-
Swale fill (Unit G)	Smakt-Vierl.	Silty-sandy clay	-	-	-
Clayey channel fill (Unit F)	Smakt-Vierl.	Sandy loam	-	Laminated	Plant remains
	Smakt	Sandy clay	-	-	-
	Bus-Vweg	Silty & sandy clay	-	Massive	Slightly humic
Initial sandy channel fill (Unit E)	Smakt-Vierl.	Very fine & fine sand (105–210/300 μm)	Good to moderate	Loamy laminae/beds	Organic detritus in cores 004 & 007 (base)
	Smakt	Silty sand and loam (150–210 μm)	Good	Laminated	-
	Bus-Vweg	Fine to medium coarse sand (150–300 μm)	Good	Loamy laminae/beds	-
Pointbar (Unit D)	Smakt-Vierl.	Fine to medium coarse sand (150–210/300 μm)	Good	Fining up	Loose
	Smakt	Medium coarse sand (210–300 μm)	Good	Loamy laminae	-
Channel and bars (Unit C)	Smakt-Vierl.	Medium coarse sand (210–300 μm) some gravel	Moderate	-	Compact
	Smakt	Medium coarse to coarse gravelly sand (300–850 μm)	Poor	-	Compact; organic detritus in core 106 (top)
	Bus-Vweg	Coarse sand (210/420–600/850 μm) & some gravel	Poor	-	-
Levee (Unit B)	Smakt-Vierl.	Sandy loam	-	-	-
	Smakt	Sandy loam & silty sand (150–300 μm)	-	-	-
	Bus-Vweg	Loamy sand	-	-	-
Fluvial terrace (Unit A)	Smakt-Vierl.	Coarse sand (420–600 μm)	Poor	-	-
	Smakt	Coarse sand & gravel (210–850 μm)	-	-	-
	Bus-Vweg	Sandy gravel	-	-	-

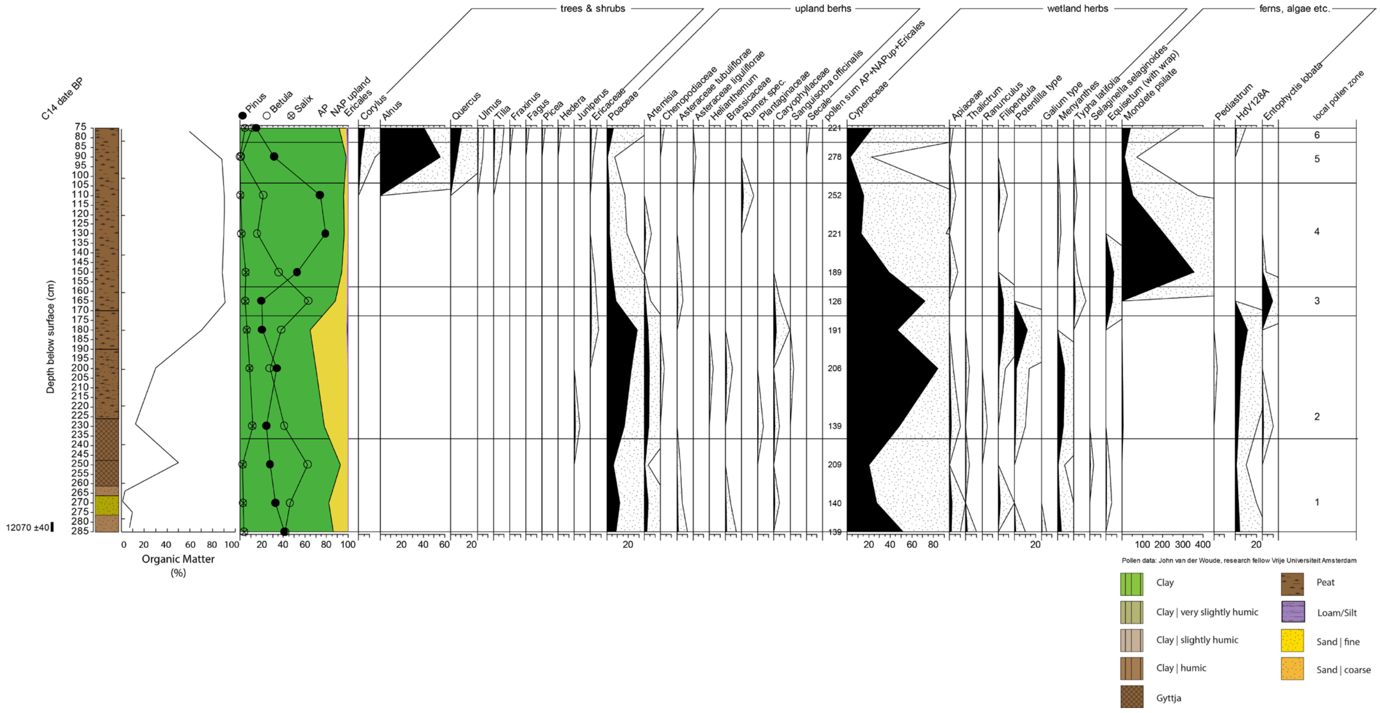


Figure 5. Pollen diagram Merselo (Core 308A).

LPAZ 1 (285–235 cm; medium fine sand with detritus, coarse detritus gyttja, unit E)

This LPAZ is characterised by a high percentage (~60%) of *Betula* (Birch). Besides birch, only *Pinus* (pine) is present as tree pollen. Furthermore, the regional vegetation consists of grasses (Poaceae) and upland herbs (Figure 5). The regional vegetation points to a birch-pine woodland. The presence of *Menyanthes* and sedges (Cyperaceae) indicates shallow water conditions in accordance with the lithological characteristics of this interval (sandy gyttja). Based on the high *Betula* value, the presence of *Pinus* and the lack of thermophilous tree taxa, LPAZ 1 is considered to belong to the Allerød (13.9–12.85 ka cal BP) (Hoek, 1997, PAZ 2). The ^{14}C dating of 12,070 ± 40 yr BP (13,922 cal yr BP) agrees reasonably well with the biochronostratigraphic interpretation.

LPAZ 2 (235–170 cm; detritus gyttja, peat with occasional sand grains, unit F)

LPAZ 2 shows a decrease in *Betula* to about 30%, while *Pinus* remains relatively stable. A small peak of *Juniperus* (juniper) and Ericaceae (heather) is visible in the lower and upper part of LPAZ 2 respectively. Poaceae, *Salix* and upland herbs (especially *Artemisia*) increase considerably (Figure 5) indicating that the landscape became more open. *Menyanthes* reaches maximum values and Cyperaceae counts show a strong increase, pointing to shallow water and sedge march conditions. *Menyanthes*, in particular points to seepage water from the valley flanks. *Potentilla* and *Filipendula* count values increase in the upper part, indicating a hydroseral succession, as is also demonstrated by the lithological change from gyttja to peat and an increasing organic matter content (LOI). *Potentilla* is presently especially known in cut-off meander channels. Given the above characteristics, LPAZ 2 is considered to represent the Younger Dryas (12.85–11.7 ka cal BP) (Hoek, 1997, PAZ 3).

LPAZ 3 (170–157 cm; peat, unit F)

This LPAZ shows a strong increase in *Betula*, while the upland herbs and Poaceae decrease (Figure 5). The local vegetation is dominated by Cyperaceae, *Equisetum* and *Entophyctis*, indicating sedge marsh conditions. Based on especially the *Betula* peak, this zone is interpreted as the first part of the Preboreal (11.7–10.8 ka cal BP) (Hoek, 1997, PAZ 4). The presence of *Typha latifolia* indicates higher summer temperatures (Isarin & Bohncke, 1999).

LPAZ 4 (157–104 cm; peat, unit F)

This zone shows that *Pinus* strongly prevails over *Betula*, while upland herb values are low, indicating pine forest development (Figure 5). Monolete psilate spores show a strong increase indicating that ferns are important in the marsh vegetation. The strong increase of *Pinus* is characteristic of the second/late part of the Preboreal (Hoek, 1997, PAZ 4).

LPAZ 5 (104–82 cm; peat, unit F)

LPAZ 5 is characterised by a strong decline of *Pinus* and a dominance of *Alnus* (alder) (Figure 5). Thermophilous tree taxa such as *Corylus* (hazel), *Quercus* (oak), *Ulmus* and *Tilia* are also present in the pollen assemblage. The wetland species show a strong decrease, probably due to the local presence of *Alnus* (alder) on the valley floor. The combination of these pollen taxa places LPAZ 5 in the Atlantic (8.9–5.8 ka cal BP). This means that the Boreal pollen zone is missing or has not been encountered due to the large sampling interval.

LPAZ 6 (82–75 cm; peat, unit F)

This zone shows a diverse pollen assemblage with a variety of tree taxa (Figure 5). Present are *Corylus*, *Alnus*, *Quercus*, *Ulmus*, *Tilia*, *Fraxinus* and *Fagus*, while *Pinus* strongly decreases. This points to a further diversification of the woodland in and beyond the valley. Although the tree taxa are dominant, the percentages of grasses and heather (Ericaceae) increase compared to the previous pollen zone, indicating a slight opening of the vegetation cover. In combination with the occurrence of *Secale*, this can be explained by human activity (deforestation and agriculture). Based on these characteristics, LPAZ 6 is correlated with the Subatlantic and Medieval periods (Bos & Zuidhoff, 2015). The transition of zone 5 (Atlantic) to zone 6 (Medieval) indicates a hiatus and a condensed upper part of the sequence, probably related to a hydroseral succession and decreasing accommodation space.

Loobeekdal (core 203A)

The pollen diagram of core Loobeekdal (Figures 3 & 4: profile Loobeekdal core 203A) is located in the downstream part of the Loobeek valley. The pollen diagram is divided into four LPAZs (Figure 6).

LPAZ 1 (80–78 cm; loamy fine sand, unit B)

LPAZ 1 is dominated by the presence of *Pinus* which reaches a value of approximately 60% (Figure 6). Furthermore, *Betula* is present with more than 20%, indicating the presence of a pine-birch woodland surrounding the valley. The presence of *Sphagnum* (peat moss), *Pediastrum* (green algae), *Cyperaceae* (sedges) and *Filipendula* shows that the local environment was characterised by open water fringed by sedges and peatland. The presence of *Alnus* and *Picea* indicates some reworking of older material which is supported by the sandy character of the fluvial sediments (see cross section). Based on the dominance of *Pinus* and the absence of thermophile deciduous trees, LPAZ 1 is attributed to the *Pinus* phase of the Allerød (13.9–12.85 ka cal BP) (Hoek, 1997; PAZ 2b).

LPAZ 2 (78–55 cm; slightly humic sandy clay, fine sand, laminated humic loamy sand, unit D)

LPAZ 2 shows a decrease in pine and a strong increase in grasses (Poaceae), *Artemisia* and other upland herbs pointing to forest decline and opening of the regional vegetation (Figure 6). Furthermore, the presence of *Juniperus* and *Empetrum* (crowberry) in the pollen assemblage is important. These features are characteristic of the Younger Dryas stadial (12.85–11.7 ka cal BP) (Hoek, 1997, PAZ 3). The local vegetation is dominated by *Cyperaceae* that formed a dense fringe around a pond given the high values of the aquatic submerged *Myriophyllum* and aquatic Pediastrum algae. This low-energy environment is supported by the fine-grained character of the sediment at the top of the fluvial sequence (final stage of fluvial deposition) (Figure 4).

The date of 4880 ± 30 ^{14}C yr BP (5605 cal yr BP) does not support the biochronostratigraphic interpretation of this interval. Due to a lack of sufficient terrestrial macro remains, the bulk organic material was dated. Presumably this resulted in the incorporation of younger root fragments. Due to the characteristic

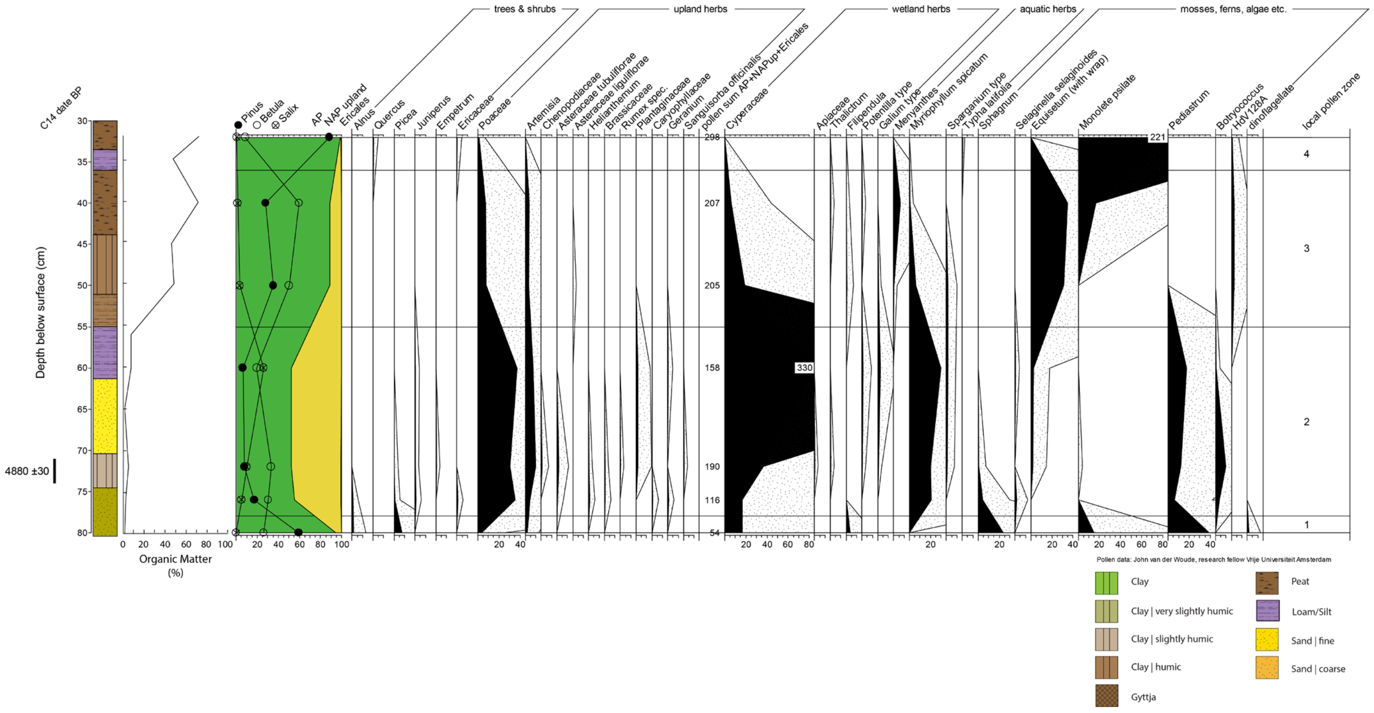


Figure 6. Pollen diagram Loobeekdal (Core Smakt 203A).

vegetation elements of the Younger Dryas, in combination with the lack of thermophile trees (which should be present if the radiocarbon date was correct), the biochronostratigraphic Younger Dryas age is considered most likely.

LPAZ 3 (55–36 cm; humic loam, clayey peat, (wood) peat, unit F)

This zone is characterised by a strong increase in *Betula* to approximately 60% (Figure 6). *Pinus* also shows an increase to a maximum of 30%. The rise of birches and pines in the landscape is at the expense of grasses and upland herbs (Figure 6). The peak of *Betula* and the simultaneous emergence of pine place LPAZ 3 in the (early) part of the Preboreal (11.7–10.8 ka cal BP) (Hoek, 1997; PAZ 4). In the local vegetation, the aquatic herbs (*Myriophyllum)* decrease and are replaced by wetland herbs (*Menyanthes*), pointing to decreasing water depth. It coincides with a lithological change towards organic deposition.

LPAZ 4 (36–33 cm; humic loam and oxidised peat, unit F)

LPAZ 4 shows that *Pinus* exceeds *Betula* in the pollen assemblage (Figure 6). Upland herbs show a decrease related to the establishment of a pine forest close to the valley. This transition is characteristic of the second/late part of the Preboreal (Hoek, 1997; PAZ 5). Wetland herbs show a strong decline indicating a further decrease of open water conditions on the valley floor. The high values of fern spores (monolete psilate) indicate local fern growth at the moist border of the pine forest.

Smakt (Core Smakt 2020)

Core Smakt 2020 is taken in the residual channel of the Meuse at the most western part of profile Smakt (Figures 3 & 4). The pollen diagram is divided into five LPAZs (Figure 4). The site was previously investigated by Tebbens et al. (1999).

LPAZ 1 (300–205 cm; alternations of sandy loams, coarse and fine sands, unit C)

This zone shows a dominance of *Betula* up to 60% (Figure 7). *Pinus* and *Salix* occur in relatively low percentages. The presence of *Juniperus* and *Hippophaë* in this zone and relatively high Poaceae (grasses) values indicates a rather open scrubland vegetation. Based on the high percentage of *Betula* and the absence of thermophile tree taxa, LPAZ 1 is attributed to the *Betula* phase of the Allerød (Hoek, 1997, PAZ 2a). Tebbens et al. (1999) dated this interval at 11,170 ± 230 years BP (13,080 cal yr BP), which corresponds with the Allerød period. The lithology of zone 1 suggests alternating inundations and slack water periods during the final stage of channel activity of the Meuse.

LPAZ 2 (205–152 cm; fine sand, sandy loam, unit F)

This LPAZ is characterised by a decrease of *Betula*, while *Pinus* increases (Figure 7). Upland herbaceous taxa such as Asteraceae increase in this LPAZ showing a relatively open landscape. Thermophile tree taxa such as *Alnus*, *Corylus*, *Tilia*, *Fagus* and *Carpinus* are present in low values (Figure 7). The stratigraphic position and radiocarbon age (see below) suggest that the latter are reworked from older interglacial deposits, possibly from the Eemian interglacial (Zagwijn, 1960). The *Pinus* values are relatively high, and this easily floating pollen can have been washed in as well. A ^{14}C date from a nearby core yielded a ^{14}C age of 10,350 ± 130 years BP (Tebbens et al., 1999). Therefore, LPAZ 2 is attributed to the Younger Dryas, a period of increased upland erosion and high discharge of the Meuse River (Kasse et al., 1995). The local habitat was characterised by open water (*Sparganium* type, *Pediastrum*) bordered by extensive sedge vegetation (Cyperaceae). The fine-grained loamy lithology indicates waning flow conditions (fining-upward sequence) in the abandoned Meuse channel. *Salix* has its highest percentages here, as a pioneer in this open dynamic wetland (Figure 7).

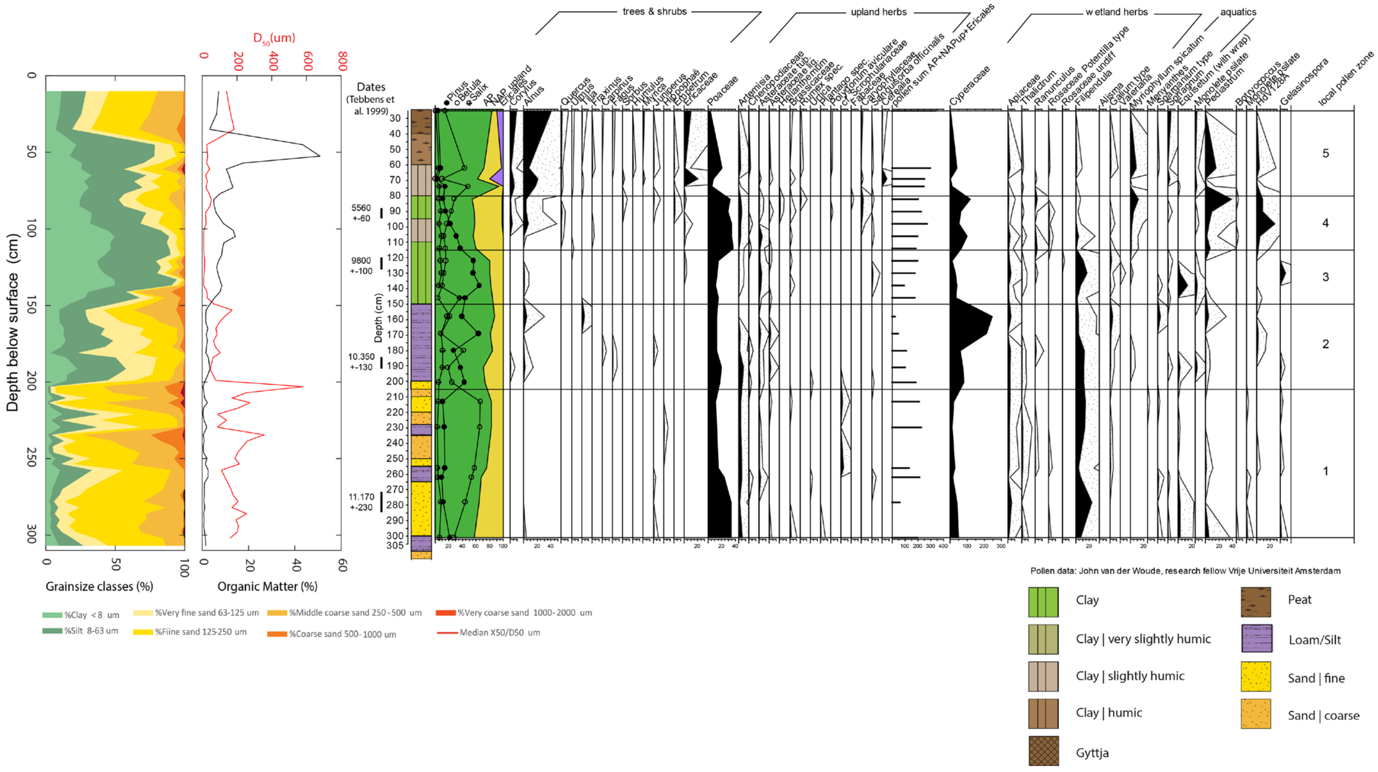


Figure 7. Pollen diagram and grain sizes of the Smakt 2020 core. The radiocarbon dates in the diagram were transposed from a core by Tebbens et al. (1999) at approximately 5 metres distance from the Smakt2020 core.

LPAZ 3 (152–118 cm; clay, unit F)

LPAZ 3 shows a peak of *Pinus* with values up to 60% (Figure 7). Upland herbs (mainly Asteraceae) are found and thermophile tree taxa are not present. This peak in *Pinus* can be assigned to the expansion of pine during the end of the Preboreal (Hoek, 1997, PAZ 5). This interpretation is supported by a radiocarbon dating of 9800 ± 100 ^{14}C years BP (11,221 cal yr BP) (Tebbens et al., 1999). The local wetland vegetation was comparable to the foregoing zone. The clayey lithology indicates low-energy (distal) inundations of the abandoned meander by the Meuse river.

LPAZ 4 (118–80 cm; clay, slightly humic, unit F)

This zone is characterised by low values of *Betula* and *Pinus* and the first occurrence of thermophile tree taxa such as *Corylus*, *Alnus* and *Quercus* (Figure 7). Poaceae (grasses) and upland herbs are important. *Helianthemum*, a heliophytic pioneer species normally found in the Late Glacial, may indicate local open vegetation conditions on the channel bank west of the core site or in the abandoned floodplain (Figure 4). It may, however, also indicate some reworking of sediments. There is no indication of cultivated grasses (Cerealia) in this zone pointing to a Late Holocene. Therefore, LPAZ 4 is correlated with the late Boreal to (early) Atlantic (Bos & Zuidhoff, 2015). This is supported by a radiocarbon date in a nearby core of 5560 ± 60 ^{14}C years BP (6363 cal yr BP) (Tebbens et al., 1999). Towards the end of this zone, the habitat was characterised by standing open water (humic clay deposition) with *Pediastrum* and *Myriophyllum*.

LPAZ 5 (80–25 cm; humic clay, clayey peat and loamy sand, unit I)

LPAZ 5 is dominated by *Alnus* and *Corylus* but also shows the occurrence of *Quercus*, *Tilia*, *Fagus* and *Carpinus* (Figure 7). Furthermore, the percentage of Ericaceae is relatively high. The occurrence of Cerealia points to cultivation of arable fields, and the presence of *Juniperus* indicates more open vegetation conditions, probably on the higher former channel bank west of the site. The upland herbs (like Brassicaceae and Asteraceae) can be interpreted as field weeds. LPAZ 5 is considered to belong to the Subatlantic.

't Buske (Core 411A)

Core 411A is located in the residual channel of the Meuse River in front of the terrace scarp in profile Buss-Vennenweg (Figures 3 & 4). The pollen diagram of core 411A is subdivided into six LPAZs (Figure 8).

LPAZ 1 (231–217 cm; clayey gyttja, unit F)

This first LPAZ is characterised by *Betula* (birch) percentages up to approximately 65%. There are also relatively high percentages of grasses (Poaceae) and upland herbs. The vegetation cover is probably an open birch woodland with some *Juniperus*. This assemblage is characteristic of the *Betula* phase of the Allerød (Hoek, 1997, PAZ 2a). The lithology and pollen zones above this interval clearly indicate a late Allerød and Younger Dryas age. However, the radiocarbon date of 10,440 ± 30 BP (12,319 cal yr BP) is not in agreement with the biostratigraphic interpretation. Since not enough terrestrial macro-remains were present in the gyttja, organic detritus was dated as a bulk sample. Possibly root fragments were present in the bulk material, resulting in a younger age. The local wetland vegetation was dominated by *Filipendula* and Cyperaceae fringing the abandoned channel. Some *Salix* is present that may have been a pioneer tree species growing on the bare sediment surface shortly after channel abandonment.

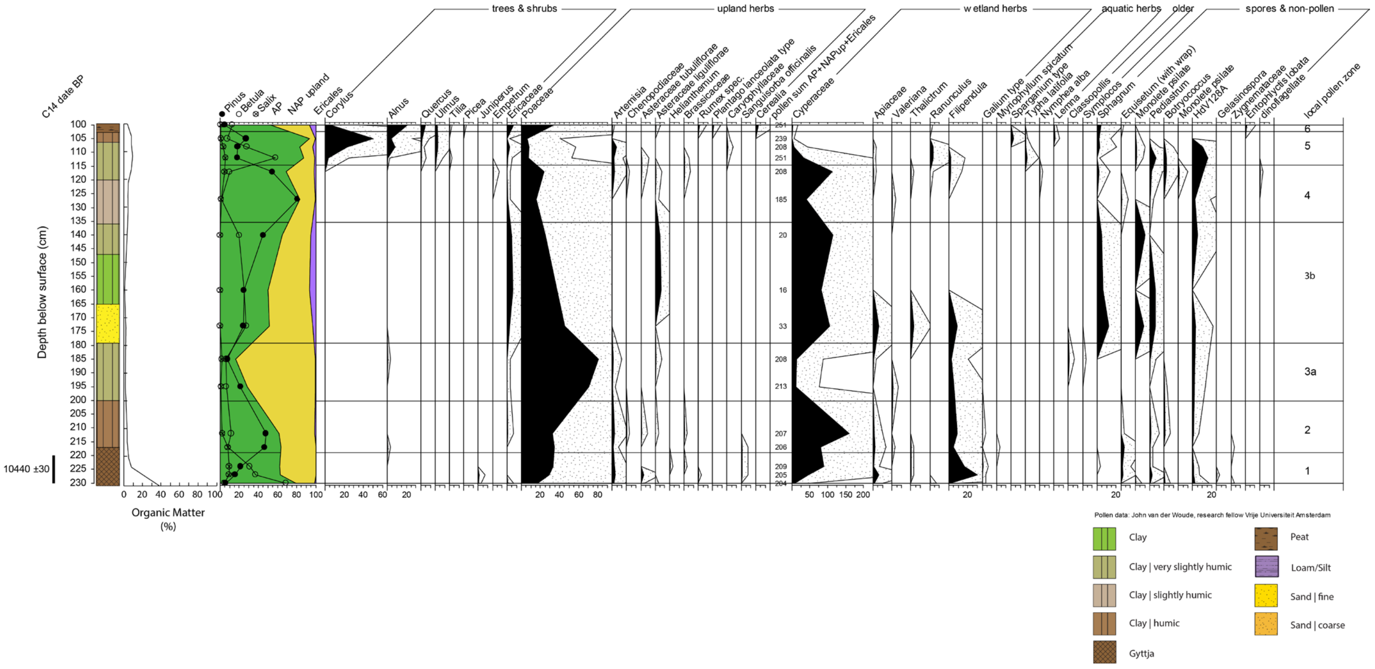


Figure 8. Pollen diagram 't Buske (Core 411).

LPAZ 2 (217–200 cm; slightly humic silty clay, unit F)

LPAZ 2 shows a strong increase in *Pinus* (pine) with a simultaneous decrease in *Betula* (Figure 8). Grasses (Poaceae) and *Artemisia* are important, indicating a rather open pine woodland. The emergence of pine in the landscape is characteristic of the *Pinus* phase of the Allerød (Hoek, 1997, PAZ 2b). The local wetland vegetation was dominated by Cyperaceae.

LPAZ 3 (200–135 cm; very lightly humic silty clay, sand, sandy clay, unit F)

In this zone, *Pinus* (pine) strongly decreases and grasses (Poaceae) and upland herbs (Asteraceae) increase (Figure 8). Especially, striking is the increase in Ericaceae (heather) in LPAZ 3b. LPAZ 3 shows an opening of the vegetation cover, after the *Pinus* phase of the Allerød, probably related to climate cooling at the onset of the Younger Dryas stadial (12.85–11.7 ka cal BP). Zone 3b can be correlated with the 2nd phase of the Younger Dryas. The local vegetation shows higher values of *Sphagnum* and fern spores (*Monolete psilate*), indicating more open vegetation and acidification of the landscape. What is remarkable is the presence of pre-Quaternary pollen (*Classopollis*, *Symplocos*) in the upper part of zone 3a. These pollen types were probably eroded from the upstream Meuse catchment and deposited in the abandoned meander during Younger Dryas peak flood events (cf. Bohncke et al., 1993; Kasse et al., 1995). The lithological transition from organic deposits in zone 1 and 2 to clastic deposits in zone 3 supports the increased energetic conditions, related to higher Meuse discharges, more intense flooding and more open water conditions (presence of *Pediastrum*) in the abandoned meander.

LPAZ 4 (135–115 cm; slightly humic sandy clay, unit F)

LPAZ 4 is characterised by a strong increase in *Pinus* to approximately 80% and decrease of upland herbs (Figure 8) indicating the establishment of a pine forest. Thermophile trees are absent and therefore LPAZ 4 is attributed to the last phase of the Preboreal (Hoek, 1997, PAZ 5). The *Betula* phase of the Preboreal seems to be lacking, possibly because of the large sampling interval. The local vegetation is dominated by Cyperaceae, indicating the presence of a sedge marsh in the abandoned meander.

LPAZ 5 (115–102 cm; humic silty clay, charcoal, unit F)

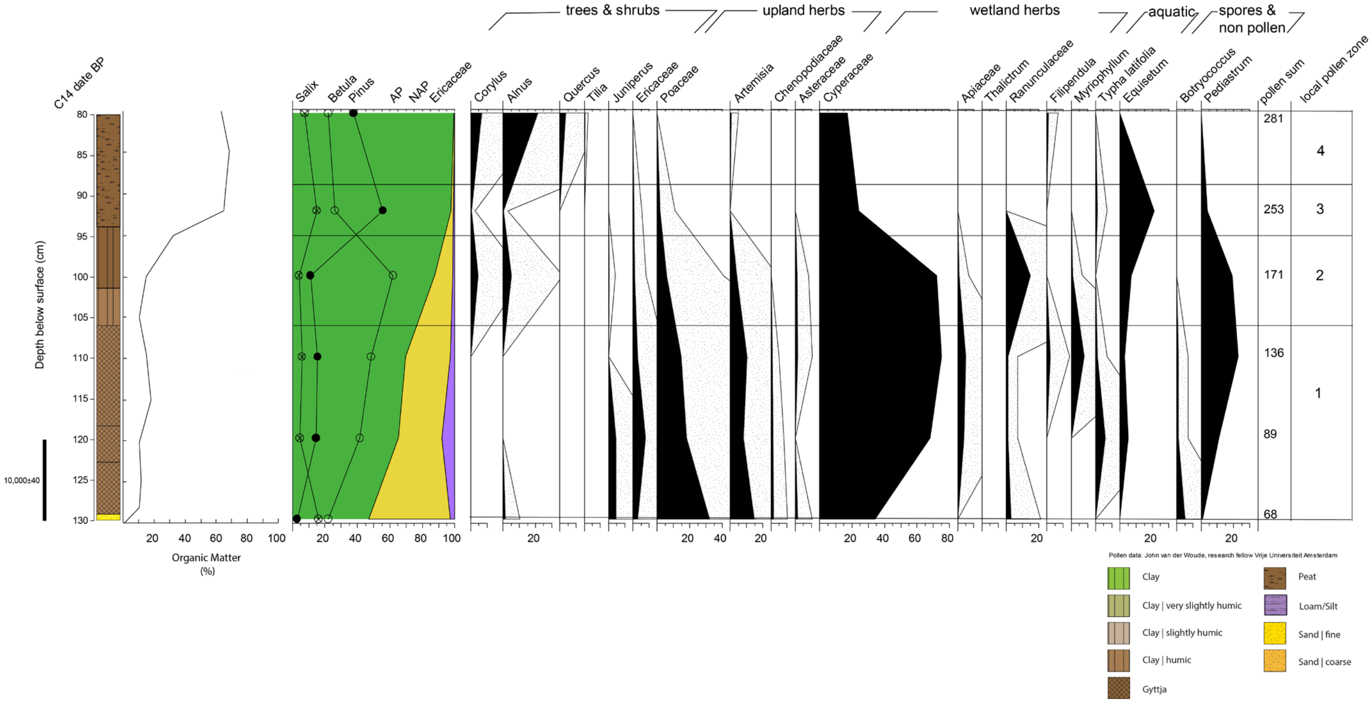
LPAZ 5 shows a strong decline and low values of *Pinus* and presence of deciduous forest taxa such as *Corylus* (hazel), *Alnus* (alder), *Quercus* (oak) and *Ulmus* (elm) (Figure 8). The upland herb values are low. The dominance of *Corylus* and the first appearance of *Quercus* and *Ulmus* at the base of the zone point to the Boreal period (Bos & Zuidhoff, 2015). The weak presence of *Alnus*, however, might indicate deposition during the Atlantic. *Typha latifolia* and *Sparganium* type indicate wetter conditions, and the former also warmer conditions.

LPAZ 6 (102–100 cm; peat (oxidised), unit I)

This LPAZ shows a decrease in the tree taxa and an increase of grasses and heather (Figure 8). The pollen assemblage is characterised by the presence of Cerealia (grains) and arable field weeds such as *Rumex* and *Plantago lanceolata*. Based on these characteristics, LPAZ 6 is correlated with the (late part of the) Subatlantic (3.1–0 ka cal BP). This implies a long hiatus between zones 5 and 6. The absence of the (Atlantic and) Subboreal periods is probably due to peat extraction (peat excavation pits were observed near the sampling site in the abandoned meander).

Vennenweg (Core 401A)

Core 401A is located in the lowest depression of the abandoned Meuse channel in the middle of cross section Buss-Vennenweg (Figures 3 & 4). The pollen diagram is subdivided into four LPAZs (Figure 9).



Pollen data: John van der Woude, research fellow Vrije Universiteit Amsterdam

Figure 9. Pollen diagram Vennenweg (Core 401A).

LPAZ 1 (129–106 cm; clayey (laminated) gyttja, unit F)

This LPAZ is characterised by increasing values of *Betula* (birch), which rise to approximately 50%. *Pinus* (pine) is present up to a maximum percentage of 20%. Heathers (Ericaceae), grasses (Poaceae), *Artemisia* and *Juniperus* (juniper) are important, indicating an open vegetation cover. LPAZ 1 is correlated to the late Younger Dryas and early part of the Preboreal (Hoek, 1997, PAZ 4a). The presence of *Typha latifolia*, indicating higher summer temperatures, supports a final Younger Dryas to the early Holocene age (Isarin & Bohncke, 1999). The ^{14}C date of 10,000 ± 40 ^{14}C years BP (11,478 cal yr BP) (Figure 8) is in good agreement with the biostratigraphic interpretation. In the local vegetation, *Typha latifolia*, *Pediastrum* and *Myriophyllum* are present indicating open water conditions in the abandoned channel, fringed by sedges (Cyperaceae).

LPAZ 2 (106–94 cm; (slightly) humic sandy clay, unit F)

This zone shows high *Betula* values (60%) and a decrease of Poaceae and upland herbs. *Corylus* (hazel) and *Alnus* (alder) are present; however, the pollens are mostly corroded and are therefore considered as reworked pollen from older deposits. Alternatively, these pollens may be displaced by roots that were found in this zone. The high *Betula* values and the relatively strong presence of Poaceae point to the early part of the Preboreal.

LPAZ 3 (94–88 cm; peat, unit I)

LPAZ 3 is characterised by a decrease in *Betula* and a strong increase in *Pinus* (Figure 9). Poaceae and other upland herbs decrease sharply in this zone (Figure 9). Based on these features, LPAZ 3 is correlated with the *Pinus*-phase at the end of the Preboreal, previously dated at 9,500 ^{14}C BP (Hoek, 1997). The local aquatic and wetland vegetation (except for *Equisetum*) shows a strong decrease, probably indicating a hydroseral succession in the abandoned channel, which is also reflected by the lithological change from humic clay (zone 2) to peat (zone 3).

LPAZ 4 (88–80 cm; peat, unit I)

LPAZ 4 (one spectrum only) shows a decrease in *Pinus* to approximately 35% (Figure 9). Furthermore, several thermophile tree taxa are present, such as *Corylus* (hazel), *Alnus* (alder) and *Quercus* (oak) indicating nearby mixed pine and deciduous forest conditions. The presence of Poaceae and heathers is minimal. Based on the pollen assemblage in which *Alnus* plays an important role, LPAZ 4 is correlated with the Atlantic. The Boreal period is missing or has not been sampled given the large sampling interval.

Smakt (core 108A)

Core Smakt 108A is located in the lowest part of a residual channel of the Meuse River (Figures 3 & 4). The pollen diagram is divided into four LPAZs (Figure 10).

LPAZ 1 (137–133 cm; laminated clayey peat, unit I)

LPAZ 1 is dominated by *Pinus* (pine) with values up to approximately 45% (Figure 10). In addition, *Corylus* (hazel), Quercus and *Ulmus* (elm) are present. Therefore, LPAZ1 is correlated with the Boreal (10.8–8.9 ka) (Bos & Zuidhoff, 2015). The presence of *Typha latifolia* indicates some open water during the first stage of infilling of the abandoned channel. The small pond was bordered by Cyperaceae (sedges) and *Salix* (willow).

LPAZ 2 (133–95 cm; clayey peat, sedges, wood remains, unit I)

This zone is dominated by *Alnus* (alder), but also shows relatively high values of *Quercus* (Figure 10). Furthermore,

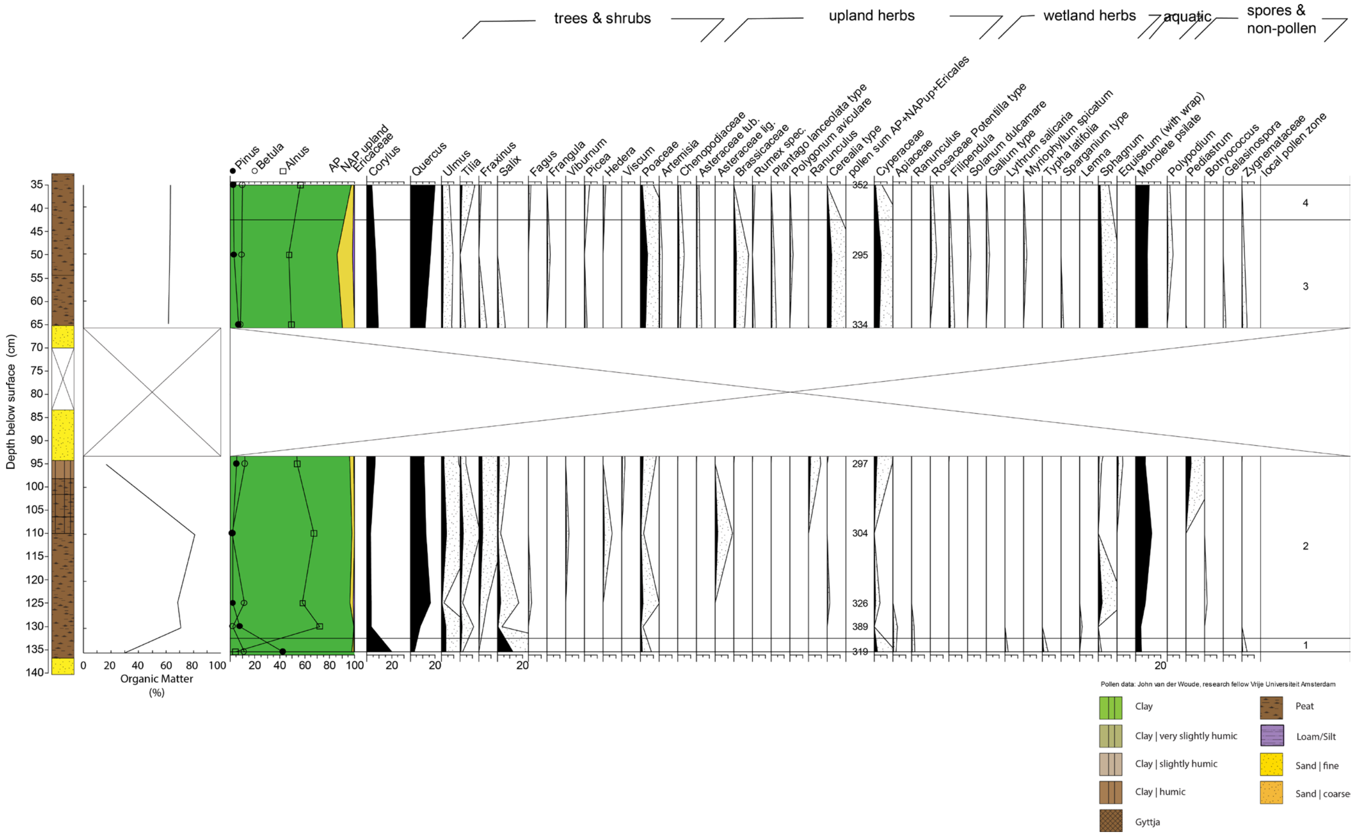


Figure 10. Pollen diagram Smakt (Core 108A).

Ulmus, *Tilia* (lime) and *Fraxinus* (ash) are present. This pollen assemblage of a mixed deciduous forest with locally (wet) alder forest can be correlated with the Atlantic period (8.9–5.8 ka BP). However, the presence of *Fagus* (one grain only) and Cerealia type (one grain) might point to a Subboreal age as well. The local vegetation with *Pediastrum* (green algae) and *Equisetum* (horsetail) shows that some open water occurred in the later phase of LPAZ 2.

LPAZ 3 (65–43 cm; peat, partly oxidised, unit I)

Alder is dominant and oak pollen is also well represented (Figure 10). The percentage of trees is decreasing and grasses and upland herbs are increasing indicating that the regional vegetation became more open. The solid occurrence of Cerealia together with an assemblage of herbs indicating cultivated soil (Chenopodiaceae [Amaranthaceae], *Artemisia*, Asteraceae, Brassicaceae, *Plantago lanceolata*, *Polygonum aviculare*) indicate opening of the vegetation cover by agriculture. LPAZ 3 is therefore attributed to the Subatlantic period (3.1–0 ka BP) (Bos & Zuidhoff, 2015).

LPAZ 4 (43–35 cm; peat, partly oxidised, unit I)

Quercus and *Tilia* show an increase in this zone (1 spectrum only) (Figure 10). Grasses, Cerealia and herbs indicating cultivated soil are decreasing. The dominant taxon is *Alnus* with values up to approximately 50%, indicating the local presence of a wetland forest. LPAZ 4 is assigned to the Subatlantic, but possibly represents a phase of reforestation between the Roman period and the Middle Ages.

Discussion

Evolution and landscape dynamics of the Loobeek and Meuse in relation to climate and vegetation change

Late Pleniglacial (28–14.7 ka cal BP)

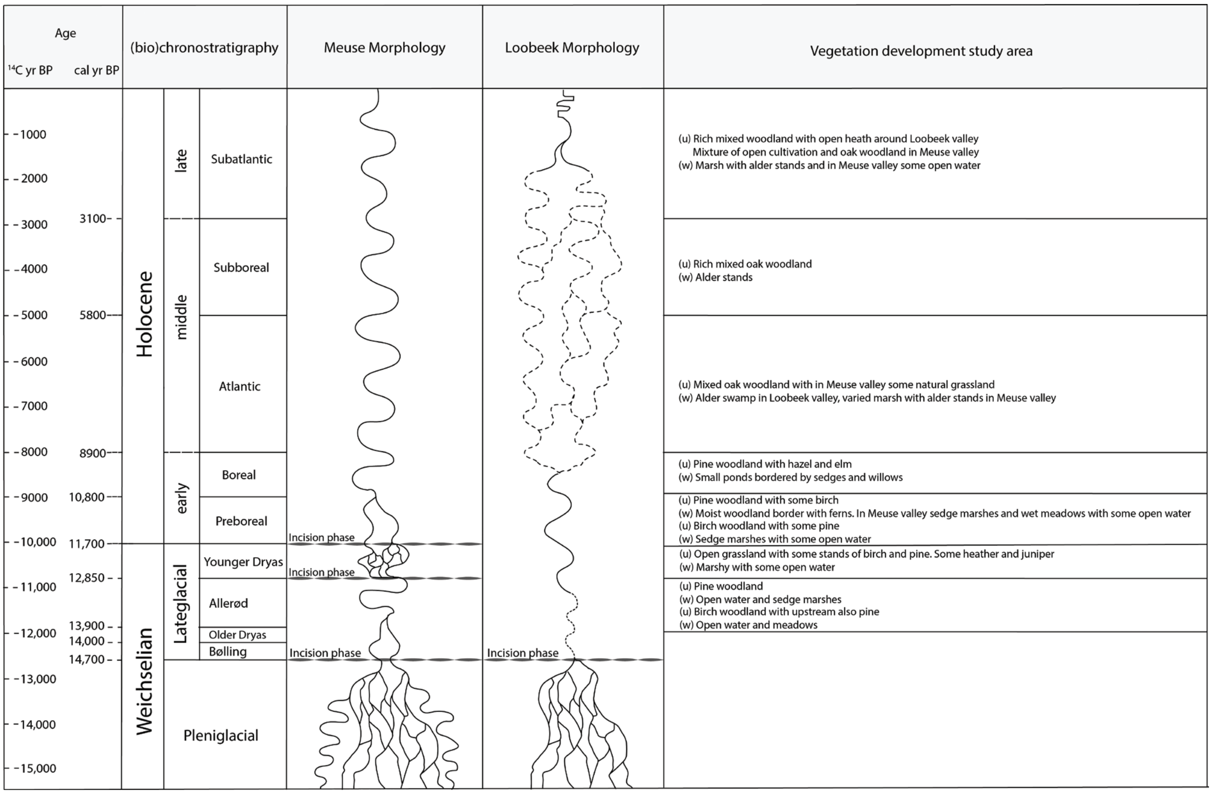
During the Late Pleniglacial, the Meuse was a braided river system with many relatively shallow channels separated by sand and gravel bars (Kasse et al., 1995; Huisink, 1997; Tebbens et al., 1999; Woolderink et al., 2018). The tributary valley of the Loobeek was relatively wide and shallow (Figure 4; cross sections Merselo, Loobeekdal, unit B), had a braided morphology and debouched into the broad river plain of the Meuse River (Figure 3). The vegetation cover was limited and consisted mainly of herbs and (a few) shrubs, according to Hoek (1997) and Hoek et al. (2017). According to Vandenberghe et al. (1994) and Kasse (2002), the cold and dry climate of the Late Pleniglacial, the scarcity of vegetation and the large amount of available sediment resulted in the widespread deposition of coversands in the study area (Older Coversands I & II). In the Loobeek valley, these coversands have often been reworked by fluvial activity and runoff, resulting in the deposition of fluvio-periglacial sediments (Profile Loobeekdal: unit B, and Merselo: unit B). Similar deposits were found in other Pleistocene brook valleys in the southern and eastern Netherlands (Vandenberghe et al., 1984; Van Huissteden et al., 1986).

Bølling-Allerød (14.7–13.0 ka cal BP)

The Bølling (14.7–14.0 ka cal BP) is characterised by a rapid increase in temperature and precipitation (Renssen & Isarin, 2001). As a result, the vegetation cover increased, although it remained a relatively open landscape that was dominated by a herbaceous vegetation with shrubs (*Betula*, *Juniperus*) and a few birch trees (Hoek, 1997; Hoek et al., 2017). The development of this pioneer vegetation had an important impact on river dynamics, as was previously indicated for the Meuse River (Woolderink et al., 2018 and references herein). The vegetation cover partly stabilised the sand and gravel bars of the Pleniglacial river plains and reduced sediment supply from the hinterland and the valley sides. The pioneer vegetation on the floodplain also captured and retained fine, loamy sediments during flooding. As a result, the discharge of the river systems concentrated in a reduced number of channels, forming the transition from a braided to a meandering system in the Meuse valley (Vandenberghe et al., 1994; Kasse et al., 1995; Huisink, 1997; Woolderink et al., 2018). However, the absence of Late Pleniglacial and Bølling age sediments and organic material in the study area (Figure 11 & Table 4) demonstrates that the fluvial dynamics (lateral migration and incision) of the Meuse river was still large during this transitional phase. Still, the concentration of the discharge in fewer channels, in combination with the decrease in sediment supply due to an increased vegetation cover, allowed the rivers to incise (Vandenberghe et al., 1994) (Figure 11). For the Meuse River, this resulted in a river pattern of several incised channels with low sinuosity (T3 in Figure 3 [Kasse et al., 1995; Woolderink et al., 2018]). However, the river pattern of the Loobeek most likely was a single (possibly meandering) channel during the Bølling (Figure 11). Coring transect Merselo (Figure 4; cross section Merselo) shows only one incised channel in the middle of the valley. The infill of this channel started at 12,070 ± 40 ^{14}C years BP (13,922 cal yr BP) which indicates that the incision must have taken place prior to this date, i.e. during the Bølling. A similar early phase of incision has also been observed for the Mark valley in the southern Netherlands (and Belgium) (Vandenberghe et al., 1984).

According to Vandenberghe et al. (1984), periodic aeolian sedimentation in and around the Mark brook valley caused local obstruction of the drainage of the river system during the Lateglacial (~14.7–11.7 ka BP). A similar phenomenon was observed for the Loobeek valley in this study (Figures 3 & 4: cross sections Merselo, Loobeekdal: unit C). Aeolian coversand deposition created low barriers in the brook valley (Figure 3, code Bv) that changed the valley gradient and partly restricted the flow at several locations in the headwaters of the valley. As a result, the valley of the Loobeek is characterised by several relatively wide low-gradient basins (Figure 3, code BvP), characterised by open water and later peat formation (see cross sections Merselo, Loobeekdal: unit F), which are divided by narrow reaches at the location of the aeolian barriers (Figure 3, code Bv & Figure 12). Van den Toorn (1967) indicated that these barriers are relatively common in the upstream parts of brook valleys in the southern Netherlands. This was supported by studies of the northern Belgium Mark valley (Vandenberghe et al., 1984) and Dijle-Demer catchment (De Smedt, 1973).

Although locally a large influx of aeolian coversands in the Maas has been established (Verhoeven et al., 2015), aeolian sedimentation did not cause blockages of the trunk channel of the Meuse River, most likely due to the higher discharge and larger sediment transport capacity of the Meuse in comparison to the Loobeek system.



(u) Rich mixed woodland with open heath around Loobeek valley
Mixture of open cultivation and oak woodland in Meuse valley
(w) Marsh with alder stands and in Meuse valley some open water

(u) Rich mixed oak woodland
(w) Alder stands

(u) Mixed oak woodland with in Meuse valley some natural grassland
(w) Alder swamp in Loobeek valley, varied marsh with alder stands in Meuse valley

(u) Pine woodland with hazel and elm
(w) Small ponds bordered by sedges and willows

(u) Pine woodland with some birch
(w) Moist woodland border with ferns. In Meuse valley sedge marshes and wet meadows with some open water
(u) Birch woodland with some pine
(w) Sedge marshes with some open water

(u) Open grassland with some stands of birch and pine. Some heather and juniper
(w) Marshy with some open water

(u) Pine woodland
(w) Open water and sedge marshes
(u) Birch woodland with upstream also pine
(w) Open water and meadows

Figure 11. Overview of the morphological changes of the Meuse river and Loobeek since the Pleniglacial. The dotted lines in the sketch of the Loobeek indicate that these are most likely (flow-through) marsh channels that are not actively meandering but have sinuosity due to peat formation in the valley.

Table 4. Main characteristics of the vegetation cover in the study area for the biostratigraphic periods based on the pollen diagrams

Biostratigraphy	Merselo 308A	Loobeek 203A	Venneweg 401A	Buske 411A	Smakt 108A	Smakt 2020	overall trends in study area
Subatlantic	Zone 6 (Subboreal or Subatlantic) *u.* rich mixed woodland with open heath patches *w.* sedge marsh with alder stands.			Zone 6 *u.* mixture of open grass-land, arable fields, oak woodland, heather *w.* alder swamp patches.	Zone 3–4 *u.* open cultivated areas amidst oak woodland *w.* alder stands	Zone 5 *u.* open cultivated areas with some mixed oak woodland and heather *w.* small marshland with open water	*Upland* – Rich mixed woodland with open heath around side valley. Mixture of open cultivation and oak woodland in Meuse valley. *Local wetland* – Marsh with alder stands and in Meuse valley some open water.
Subboreal					Zone 2 *u.* rich mixed oak woodland w. alder stands.		*Upland* – Rich mixed oak woodland. *Local wetland* – Alder stands.
Atlantic	Zone 5 *u.* mixed oak woodland *w.* alder swamp.		Zone 3 *u.* mixed woodland *w.* alder swamp with sedges.	Zone 5 *u.* mixed oak woodland *w.* varied marsh with alder stands.	Zone 2 *u.* rich mixed oak woodland *w.* alder stands.	Zone 4 (late Boreal, early Atlantic) *u.* mixed oak woodland with natural grasslands, *w.* increasingly wetter habitat, with open water; possibly open levee vegetation.	*Upland* – Mixed oak woodland, some natural grassland in Meuse valley. *Local wetland* – Alder swamp in tributary valley, varied marsh with alder stands in Meuse valley.
Boreal			Zone 3 *u.* mixed woodland *w.* alder swamp with sedges.	Zone 5 *u.* mixed oak woodland *w.* varied marsh with alder stands.	Zone 1 *u.* pine woodland with hazel and elm *w.* small ponds bordered by sedges and willows.		*Upland* – Pine woodland with hazel and elm *Local wetland* – small ponds bordered by sedges and willows.
Preboreal *Pinus*-phase	Zone 4 *u.* pine-birch woodland, *w.* moist woodland border with ferns.	Zone 4 *u.* pine woodland *w.* moist woodland border with ferns.	Zone 2 *u.* pine woodland with birch *w.* sedge marsh with some open water.	Zone 4 *u.* pine woodland *w.* sedge marsh.		Zone 3 *u.* pine woodland and some open terrain *w.* moist tall herb meadow without open water.	*Upland* – Pine woodland with some birch. *Local wetland* – Sedge marshes and wet meadows with some open water. In tributary valley just a moist woodland border with ferns.
Preboreal *Betula*-phase	Zone 3 *u.* birch woodland *w.* sedge marsh with ponds and moist tall herb meadows.	Zone 3 *u.* birch woodland with pines *w.* shallow open water with marshy borders.	Zone 1 *u.* open birch woodland with some pine and juniper *w.* sedge marsh with open water, increasingly wetter.				*Upland* – Birch woodland with some pine. *Local wetland* – Sedge marshes with some open water.

(*Continued*)

Table 4 (Continued). Main characteristics of the vegetation cover in the study area for the biostratigraphic periods based on the pollen diagrams

Biostratigraphy	Merselo 308A	Loobeek 203A	Venneweg 401A	Buske 411A	Smakt 108A	Smakt 2020	overall trends in study area
Younger Dryas	Zone 2 *u.* open vegetation *w.* shallow open water, hydrosere.	Zone 2 *u.* sparse birch stands with grassland, juniper, shrub willows and heath *w.* sedge marsh with open water.		Zone 3a *u.* open grassland *w.* some moist tall herb meadows. Zone 3b. *u.* grassland and heather, and some pine-birch woodland, *w.* varied peaty wetland with some open water.		Zone 2 *u.* open herbaceous terrain between distant pine-birch woodland *w.* dynamic wetland with willow, increasingly wet.	*Upland* – Open grassland with some stands of birch and pine, and some heather and juniper. *Local wetland* – Marshy with some open water.
Allerød *Pinus*-phase		Zone 1 *u.* pine woodland *w.* mixed peaty wetland with open water.		Zone 2 *u.* pine woodland *w.* sedge marsh.			*Upland* – Pine woodland. *Local wetland* – Sedge marshes and in tributary valley some open water.
Allerød *Betula*-phase	Zone 1 *u.* birch-pine woodland *w.* shallow open water.			Zone 1 *u.* open birch bush *w.* moist tall herb meadows		Zone 1 *u.* birch woodland (with still some juniper) and grasslands *w.* moist tall herb meadows with some open water.	*Upland* – Birch woodland with upstream also pine. *Local wetland* – In tributary valley some open water, Meuse valley more meadows.

u: upland; w: local wetland.

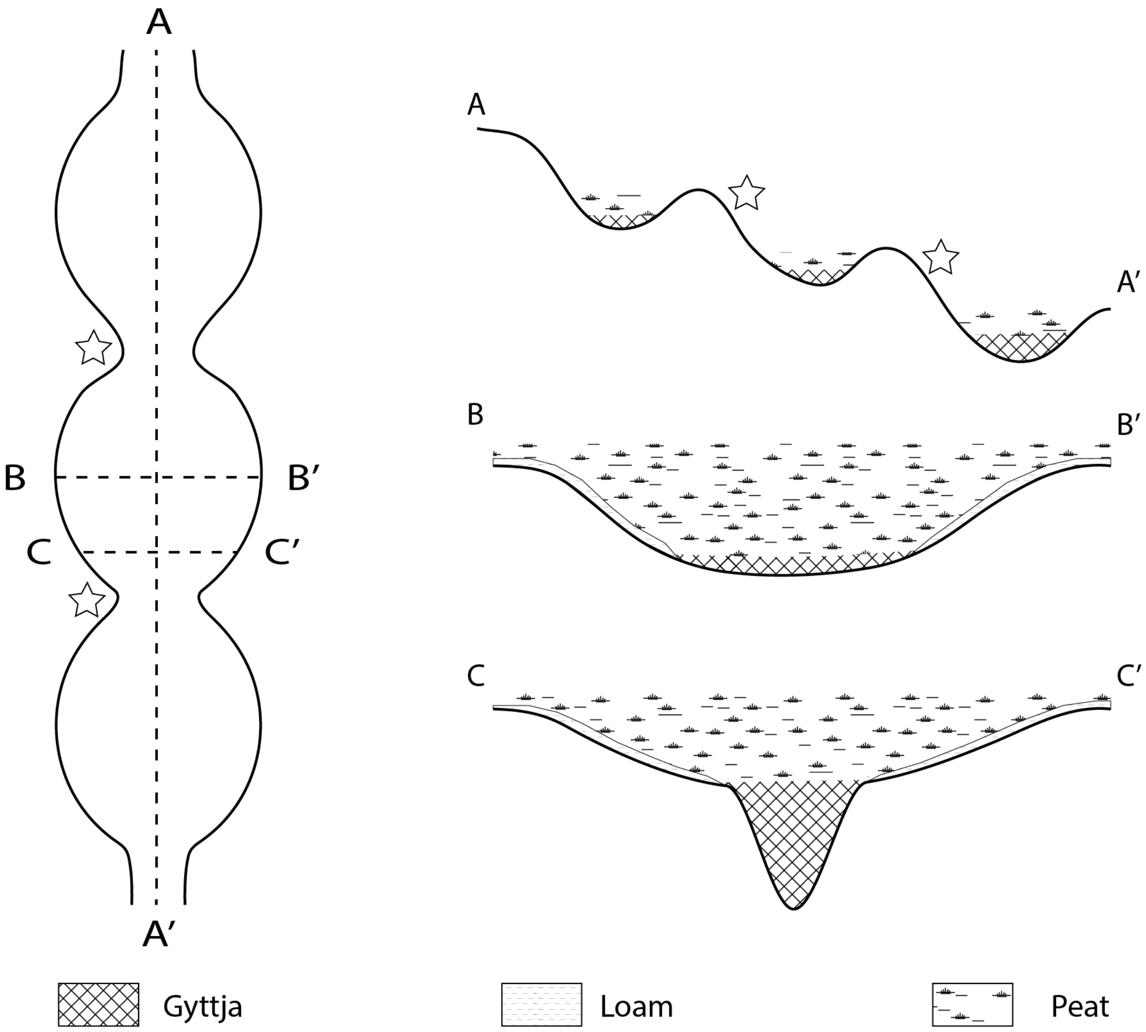


Figure 12. Overview of the 'pearl necklace' structure of the Loobeek valley. In the broad valley sections, peat formation occurred due to the partial damming by aeolian deposits so that the gradient in the valley decreased leading to wet conditions. At the locations where the valley was partially dammed by the aeolian deposits, the gradient was relatively high and possibly meandering channels formed at these locations (indicated by a star in the figure). It is at some of these locations in the valley that watermills were built, due to the higher gradient and flow velocities.

As a consequence of the local aeolian accumulations in the Loobeek valley, the gradient of the valley is relatively low (0.2–1.1 m/km) in the basins in between the blockades (Figure 3). As a result, the flow velocity and transport capacity of the Loobeek decreased and overbank flow was common, leading to (periodically) wet floodplains with loam deposition and peat formation (Figure 4: cross sections Merselo: unit D, E; cross section Loobeekdal: unit D). This is also reflected in the vegetation assemblage as can be derived from the pollen analyses results of the Loobeekdal and Merselo cores. These show a presence of the wetland taxa Cyperaceae, *Equisetum*, *Menyanthes trifoliata*, and also *Pediastrum*, and *Filipendula*.

Previous studies showed that in the course of the Lateglacial, a more regular discharge regime and an increase in vegetation cover and soil formation changed the river pattern of the Meuse River (Kasse et al., 1995; Makaske & Nap; 1995; Huisink, 1997; Woolderink et al., 2018). Decreasing aeolian activity and increasing landscape stability during the Allerød are demonstrated in pollen diagrams 't Buske (Figure 8: zones 1 and 2) and Smakt 2020 (Figure 7: zone 1) by the change from a birch to a pine-dominated vegetation. The Bølling low-sinuous, multi-channel system gradually changed to a single channel meandering system with a high sinuosity during the Allerød. This meandering channel incised into the landscape, forming a new floodplain near Smakterbroek (level T2 in Figures 3 & 13). The Loobeek debouched into the meandering Meuse River near Smakt (Figure 1). The incision of the Meuse during the Allerød probably had an effect on the gradient of the Loobeek near this confluence. Here, the gradient of the Loobeek increased (Figure 3), causing the flow velocity and erosive potential of the Loobeek to increase for a distance in upstream direction. This created a knickpoint in the longitudinal profile of the Loobeek valley (Figure 3), which may explain the location of the historic water mill at Smakt.

The river pattern of the Loobeek during the Allerød could not be reconstructed (Figure 11) because the fluvial landscape is buried under Holocene sediments. This is in contrast to the main Meuse valley, where incision phases during the Bølling-Allerød, start of the Younger Dryas and Holocene, created several morphological terraces. However, it is likely that the Loobeek flowed in the incised channel that was formed during the Bølling, as no evidence was found for other channels and incision phases in the brook valley during the Lateglacial (Figure 4; cross section Merselo: base of unit E; Figure 5). This demonstrates a different response to climate and vegetation change of the main river in comparison to the tributary during the early Lateglacial. While the Meuse was characterised by incision, the Loobeek was dominated by aggradation in a low-energy environment. The different behaviour may be related to different catchment areas, discharge, transport capacity and sediment input (see below).

Younger Dryas (12.85–11.7 ka cal BP)

The cooling of the climate at the beginning of the Younger Dryas caused a change in vegetation cover (Hoek, 1997; Hoek et al., 2017; Bazelmans et al., 2021). This is also reflected in the various pollen diagrams from the study area. Cores Smakt2020 (Figure 7), Loobeekdal (203A) (Figure 6), Merselo (308A) (Figure 5) and 't Buske (411A) (Figure 8) show a decrease in tree pollen (especially pine) and an increase in grasses and herbs, which represents an opening of the regional vegetation cover (Table 4). The presence of Poaceae and *Artemisia* can be interpreted as an open grassland with sagebrush on the higher ruderal soils next to the brook and river valleys. Further towards the upland, the presence of patches of heather and juniper and (remaining) stands of pine and birch is likely. Coinciding with this opening of the vegetation cover, the amount of (fine) sand also increases in some cores during the Younger Dryas (Merselo 308A; Loobeekdal 203A; 't Buske 411A). In the abandoned (Allerød) Meuse meander (Figure 3; T2) and the downstream part of the Loobeek valley, this sand is probably supplied by both aeolian (see Figure 13, with dunes migrating in the abandoned channel) and fluvial transport, while it is possible that the sand in the upstream part of the Loobeek valley (Merselo diagram [Figure 5]) is of aeolian origin as these sand grains are found in a matrix of peat. Increased aeolian activity, due to the increase of bare surfaces, and increased fluvial dynamics, due to higher peak discharges, have been reported previously (Kasse et al., 1995; Hoek et al., 2017; Woolderink et al., 2018). For the Loobeek valley, the river pattern during the Younger Dryas could not be reconstructed based on morphology or boreholes. However, the Lateglacial loam deposits in the Loobeek valley (Unit D in profiles Loobeek valley (Figure 4)) have been attributed partly to the Younger Dryas period (pollen diagram Loobeekdal, zone 2 [Figure 6]). They are found continuously in the boreholes and are covered with peat, which makes both extensive lateral reworking and accumulation by a braided system unlikely. Therefore, we assume that the brook channel remained in a single channel (meandering) planform (Figure 11), as was observed for the Niers (Kasse et al., 2005), Roer (Kasse et al., 2017), Warta (Vandenberghe et al., 1994) and Tisza rivers (Kasse et al., 2010). However, a reduced soil infiltration capacity due to deep seasonal frost, and a possible re-establishment of permafrost (Bohncke et al., 1993; Kasse, 1995), may also have led to the start of paludification in the Loobeek valley in which a more diffuse discharge pattern developed.

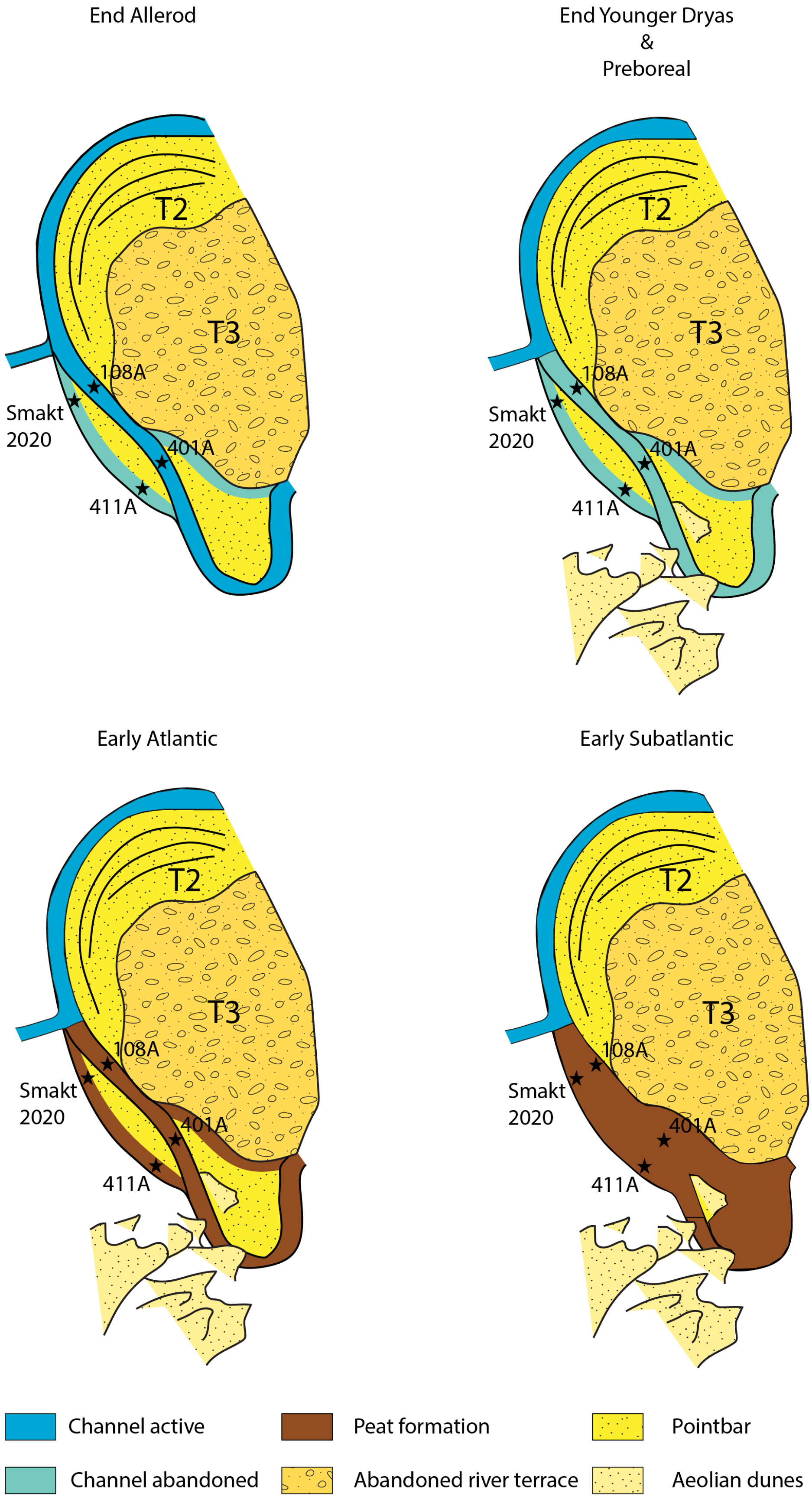
In the Meuse valley, during the Younger Dryas, despite the change in vegetation cover, the increase in peak discharges and transport capacity led to a phase of incision and simultaneous change in river pattern from meandering to wandering/braiding (Figure 3: level T1 and Figure 11 [Kasse et al., 1995; Tebbens et al., 1999; Hoek et al., 2017; Woolderink et al., 2018]). Due to chute-cutoff and straightening of the river channel (Kasse, 1995), the Allerød meander at Smakt was abandoned as demonstrated by the abrupt transition of sand to loam in Smakt 2020 (Figure 7: boundary between zones 1 and 2). The main Younger Dryas braid channels of the Meuse developed east of the Smakt area (Figure 3: level T1). However, a smaller secondary channel remained active in the previous Allerød meander during peak discharges of the Meuse as demonstrated by its abandonment date at the Younger Dryas to Holocene transition (Figure 3: unit RC; Figure 13 core 401A; Figure 9, base zone 1 [Woolderink et al., 2018]). The sandy deposits found in the residual channel fills of the Allerød Meuse meander (T2) in the 't Buske core (Figures 3 & 8 core 411A) are most likely deposited during high discharges of the Meuse. The presence of pre-Quaternary pollen (*Classopollis*, *Symplocos*) in diagram 't Buske (Figure 8; zone 3a), probably eroded from the upstream Meuse catchment, indicates deposition in the abandoned meander during Younger Dryas peak flood events (cf. Bohncke et al., 1993; Kasse et al., 1995).

During the second drier phase of the Younger Dryas, the Meuse further incised (Woolderink et al., 2018), thereby lowering the groundwater table, which caused renewed aeolian activity in the Meuse valley (Kasse et al., 1995; Hoek et al., 2017). As a result, the secondary flood channel in the study area was partly blocked by aeolian sediments (Figures 1, 3 and 13). Consequently, the Smakterbroek area became disconnected from the Meuse and fine-grained and organic deposition became dominant (diagrams Smakt 2020; 't Buske; Vennenweg). However, flood (back flow) water from the Meuse could still inundate the abandoned (Allerød) meander (Figure 3: T2) from the north along the downstream Loobeek course near Vierlingsbeek (Figure 13). Since the Meuse had shifted to the east, the confluence of the Loobeek and the Meuse also moved towards the north-east, to Vierlingsbeek (Figures 1 and 3). From this moment on, a differentiation occurred between the northern (between Smakt and Vierlingsbeek) and southern (between Maashees and Smakt) parts of the abandoned Allerød Meuse meander (T2) (Figure 13). The northern part became occupied by the Loobeek, while the southern part was fully abandoned, and peat started to grow in the residual channels (diagram Smakt 2020 [Figure 7]; 't Buske [Figure 8]; Vennenweg [Figure 9]).

Early Holocene (Preboreal and Boreal; 11,7–8,9 ka cal BP)

The transition from the Younger Dryas to the Holocene is characterised by a rapid and strong increase in temperature and precipitation (Hoek & Bohncke, 2001). Consequently, vegetation cover and soil formation increased and the discharge of the rivers became more evenly distributed. As a result, the discharge of the Meuse River concentrated in a smaller number of channels. This caused the river to incise, leaving the braid plain of the Younger Dryas as a terrace in the landscape (Figure 3: T1 & Figure 11 [Kasse et al., 1995; Huisink, 1997; Tebbens et al., 1999; Hoek et al., 2017; Woolderink et al., 2018]). During the latter part of the early Holocene, the multi-channel Meuse River changed into a single channel meandering river (Figure 11 [Kasse et al., 1995; Huisink, 1997; Tebbens et al., 1999; Woolderink et al., 2018]).

The incision of the Meuse River in the Early Holocene lowered the groundwater level in the older river terraces. The impact of climate change is clearly visible in the vegetation of the Smakt2020 and 't Buske cores (Smakt 2020: transition zones 2–3 [Figure 7] and 't Buske: transition zones 3b–4 [Figure 8]).



End Allerod

End Younger Dryas & Preboreal

Early Atlantic

Early Subatlantic

Figure 13. Palaeogeographic development of the Smakterbroek region. During the Allerød, a meandering Meuse channel existed with high sinuosity (Terrace T2 on Geomorphological map Figure 3; pollen diagram Buske, core 411A, Betula and Pine phase present). This channel was abandoned during the transition to the Younger Dryas (pollen diagram Smakt 2020). However, a flood channel remained active in the Smakterbroek during the Younger Dryas. This high-water channel was abandoned by the Meuse during the transition to the Holocene (pollen diagram Vennenweg, core 401A). As a consequence, a division of the Smakterbroek area occurred. Towards the south of the confluence with the Loobeek, a peat/marsh area developed (pollen diagram Smakt 108), while the northern part of Smakterbroek had less peat formation due to the presence of the Loobeek (cross section Vierlingsbeek).

The pollen diagrams show an expansion of trees, in particular the prominent peak of pine at the end of the Preboreal and subsequent Boreal. In addition, indications of soil formation (including charcoal) have been found in core 't Buske indicating a lower ground water level. The transition from Younger Dryas to early Holocene is also visible in the grain size and organic matter content of cores Smakt2020, 't Buske and Vennenweg. Core Smakt2020 shows an increase in the fine fractions (silt and clay) and organic matter content (Figure 7: 150 cm below surface). Core Vennenweg shows an abrupt transition from sand to gyttja (Figure 9: base zone 1) indicating the sudden abandonment of the channel. These grain-size and organic matter changes are related to the incision of the Meuse at the Younger Dryas to Holocene transition in the study area. Only during extreme high water events of the Meuse during the Preboreal sedimentation of clayey sediments occurred in the residual Vennenweg channel (Figure 9: zone 2, 100–105 cm).

In the downstream part of the Loobeek, the transition from Younger Dryas to early Holocene is reflected in the sediments as a transition from mostly sandy and silty deposits to humic loam and clayey peat (Figure 6: diagram Loobeekdal 203A, transition zone 2–3). The pollen diagram shows the transition to the early Holocene by an increase in mainly birch followed by pine (Figure 6: zones 3 and 4). A similar increase in birch and pine is present in the more upstream core at Merselo, where a clear division is present between the birch and pine phases of the early Holocene (Figure 5: zones 3 and 4). The upstream location consists of peat, in contrast to the more clastic sediments in the downstream part of the Loobeek valley. This can probably be attributed to the more limited supply of clastic material and stream power in this upstream setting. Reconstruction of the river pattern in the Loobeek valley in the early Holocene is not straightforward (Figure 11). Sandy channel deposits have not been found, indicating limited discharge and transport capacity of the Loobeek, and widespread peat formation started in the early Holocene. Therefore, a diffuse drainage network in a marshy floodplain may have been initiated in this period, related to increased precipitation, and vegetation growth, a low valley gradient and limited sediment supply (e.g. Roymans & Sprengers, 2012; Ruijters et al., 2015). This is supported by the presence of aquatic and wetland species like *Menyanthes* and *Typha* in the pollen diagram (Figure 5: Merselo zones 3–4; Figure 6: Loobeekdal zones 3–4), pointing to some open water amidst sedge marshes. Similar natural peat and swamp floodplain situations were described for the Dijle catchment (Belgium) and other small river catchments in northwest Europe as well (Rittweger, 2000; Houben, 2007; Notebaert & Verstraeten, 2010; Broothaerts et al., 2013, 2014).

Middle Holocene (Atlantic and Subboreal; 8,9–3,1 ka cal BP)

Groundwater levels in the river valleys and adjacent areas rose during the middle Holocene (Stouthamer et al., 2015), causing stagnating drainage and extensive peat formation. This is also visible in profiles Loobeek valley and Merselo (Figure 4: unit F) with a widespread peat layer in the brook valley. Also, in the low-lying channels and depressions of the Meuse terraces (Smakterbroek area), peat was formed (cross sections Smakt 108, 't Buske, Vennenweg) (Figure 4 & 13). Sandy channel deposits (channel belts) have not been found in these peat deposits, except for core 108A (Figure 10), and the valley environment can be characterised as a flow-through swamp (Figure 11) (Kurstjens et al., 2012). However, this does not necessarily mean that channels were totally absent in the swamps, but they were probably small (diffuse or anastomosing drainage network) and transported little or no clastic sediment and are, therefore, not traceable in the peat deposits (De Smedt, 1973; Vandenberghe et al., 1984; Broothaerts et al., 2013, 2014).

Peat has been not found in the Smakt-Vierlingbeek profile (Figure 4: unit I), possibly due to peat excavation, or the location was not favourable for peat formation. The latter can be explained by the Lateglacial and early Holocene incision of the Meuse River, which lowered the groundwater level in the abandoned Allerød meander (RC in Figure 3, T2). Moreover, humic loamy brook sediments were found in the topmost unit I of this profile, pointing to some channel dynamics by the Loobeek in this part of the abandoned Meuse channel. Also, during high water levels of the Meuse, stagnation and backflow of Meuse water into the Loobeek may have added to this loamy sedimentation, whether or not in combination with high discharge of the Loobeek.

The relatively low gradient (0.2–1.1 m/km) in combination with a limited catchment size and discharge resulted in low transport capacity in most of the Loobeek valley (Figure 3). Therefore, actively meandering channels were not present in the peat swamp during the middle Holocene. In addition, peat provides relatively erosion-resistant banks due to the intertwining of the plant remains. This hampers active meandering (i.e. lateral displacement of the brook channel(s) due to erosion in the outer bend and sedimentation in the inner bend) despite their sinuous planform (Kleinhans & Van den Berg, 2011, Candel et al., 2021). At specific locations where the gradient of the channel was locally steeper, meandering may have occurred, e.g. where the channel cuts through the Late Pleniglacial aeolian deposits that partially block the valley or where the Loobeek steps down a terrace scarp of the Meuse (Figure 3 near Smakt).

The pollen diagrams of the cores in the Loobeek valley and the Smakterbroek area show that the vegetation during the middle Holocene mainly consisted of deciduous forest on the higher grounds (oak, elm, lime, hazel) and riparian woodland in the lower parts of the landscape (alder and willow dominated). In the channels of the Smakterbroek, the peat consists largely of alder wood peat. In the upstream part of the Loobeek valley, the peat is dominated by sedges, although (alder) wood is also frequently found in the peat. This vegetation pattern of the Loobeek valley and Smakterbroek area corresponds well with the regional vegetation development of the Meuse Valley (Bos & Zuidhoff, 2015; Hoek et al., 2017).

Late Holocene (<3.1 ka cal BP)

In the pollen diagrams, the transition from middle to late Holocene can be recognised by a slight decline in tree pollen and the emergence of grasses, herbs, heather and cereals. These changes are caused by deforestation and the introduction of agriculture. The increase in herbs can largely be explained by the presence of arable field weeds. There was still a lot of rich mixed woodlands and the emergence of the cultivated crops in the study area only took place on a large scale during the latter part of the late Holocene (Bos & Zuidhoff, 2015).

During the late Holocene, the discharge and sediment load of the Meuse River increased, resulting in the deposition of a relatively thick layer of levee and floodplain sediments

(Woolderink et al., 2018; Peng et al., 2019, 2020). However, this was not observed in the study area due to its location on the higher river terraces which are (largely) outside the reach of the late Holocene Meuse floods. The landscape of the study area has clearly been influenced by human activity, especially since the Middle Ages (Van den Munckhof, 1981). According to the first topographic maps in the 19th century (Van der Linden, 1973), the channel pattern of the Loobeek changed from a diffuse or anastomosing network during the peat-forming phase in the middle Holocene to a sinuous (meandering) system. The exact timing of the channel pattern change is unknown. The change in river style may be related to ongoing deforestation, peat excavation, increased discharge, drainage of brook meadows and channel-bank stabilisation (Candel et al., 2020).

Tributary versus trunk systems

Response to early Lateglacial climate change

A difference between the tributary Loobeek valley and the trunk Meuse river is possibly present for the transition between the Late Pleniglacial and the Lateglacial, although data for the Loobeek valley is limited (Figure 11). Although the climatic changes were the same for both systems, their responses in river dynamics and planform seem to have been different (Figure 11). The Meuse system transitioned gradually from a braiding river during the Late Pleniglacial via a multi-channel, low-sinuosity system during the Bølling to an incised single high-sinuosity meandering channel in the Allerød (Kasse, 1995; Woolderink et al., 2018). The Loobeek possibly changed its planform more rapidly from a fluvio-periglacial (braided) aggrading system to an incised single-channel planform prior to the Allerød, since fine-grained organic infilling of the incised channel already started at the onset of the Allerød. A transitional phase was not encountered in the cross sections over the Loobeek valley. In addition, the Meuse was characterised by stepwise incision during the Lateglacial while the Loobeek brook, following the Bølling-Older Dryas incision, was characterised by an (limited) aggrading (possibly meandering) low-energy system in both the Allerød and Younger Dryas (Vandenberghe et al., 1984; Broothaerts et al., 2013). This difference in planform change and incision versus aggradation, despite the common climatic forcing, is most likely the result of different thresholds in transport capacity of both systems (e.g. Schumm, 1973). The response of the Loobeek shows that this small tributary system was, most likely, already at a critical geomorphic state at the end of the Late Pleniglacial. At the start of the Lateglacial, vegetation spread rapidly over the southern Netherlands (Hoek et al., 2017). These climatic and vegetational changes during the onset of the Lateglacial resulted in a rapid reduction in sediment supply, increase in bank stability and concentration of flow in the brook valley (Van Oorschot et al., 2016; Kleinhans et al., 2018). Hence, the brook system responded rapidly by incision and adapting a meandering planform.

The changes in vegetation cover, discharge and transport capacity and sediment supply were different in the larger Meuse catchment. Especially in the upstream Ardennes region of the Meuse, the vegetation development will have been delayed due to a cooler climate, resulting in a more gradual response of the river system (Vandenberghe & Pissart, 1993; Pissart, 2003). The changes in sediment balance (determined by transport capacity and sediment supply) of the Meuse system is the sum of the changes in its tributary systems, which may lead to a more buffered or gradual change before its geomorphic threshold is achieved. This larger buffering capacity with increasing catchment size was observed for the impact of anthropogenic disturbances on geomorphic responses (e.g. Dearing & Jones, 2003; Vanmaercke et al., 2015; Verstraeten et al., 2017). A similar gradual geomorphic response to the last glacial-interglacial transition was observed for the Rhine River by Erkens et al. (2011). They state that the geomorphic response is delayed to the allogenic climatic forcing depending on reach-specific conditions of a river system (e.g. valley gradient, bed material, position within the catchment).

Impact of the Younger Dryas cooling

The Younger Dryas cooling had a strong impact on the Meuse valley. The presence of pre-Quaternary pollen (Classopollis, Symplocos) in flood sediments (Figure 8: zone 3a) indicates deposition during Younger Dryas peak flood events (cf. Bohncke et al., 1993; Kasse et al., 1995). Higher peak discharge (due to more snow melt in the Ardennes) and transport capacity pushed the Meuse system over the meandering to braiding state (Kasse et al., 1995; Hoek et al., 2017; Woolderink et al., 2018). Such a response to cooling is not concluded for the Loobeek system. The tributary channel persisted in a single-channel meandering or anastomosing planform, as was also inferred for the Niers- (Kasse et al., 2005) and Roer rivers (Kasse et al., 2017). Apparently, the transport capacity increase of the local systems was limited and the threshold to braiding was not crossed. This could also explain the (albeit sparse) vegetation cover of grasses, heather and some stands of trees in the area during the Younger Dryas.

Fluvial architecture and lithology

Differences in lithology of fluvial deposits between the main valley and the tributary can be related to differences in discharge, sediment supply and vegetation cover. The Lateglacial Meuse is characterised by clastic deposition of sand and loam by a meandering (Bølling-Allerød) and braided (Younger Dryas) system. During the Holocene, the Meuse River was a laterally migrating meandering system (Woolderink et al., 2018), with increased fine-grained loam deposition in the later part of the Holocene (Peng et al., 2019, 2020). In the first-order Loobeek system mostly organic deposition, peat formation and continuous aggradation occurred in swamps with a diffuse or anastomosing drainage pattern during the Lateglacial and most of the Holocene. These first-order streams were probably active during Pleniglacial cold conditions due to permafrost and deep seasonal frost (Kasse, 1997). This reduced the infiltration capacity and resulted in overland flow and river discharge forming the valleys. During the onset of the Late Glacial interstadials permafrost melted, infiltration increased and the groundwater system was restored. This limited the surface runoff, and river discharge, if any, was low and dominated by groundwater seepage. Valleys with deep groundwater levels changed into dry valleys, while valleys with a more shallow ground water level changed into wetlands (De Smedt, 1973; Vandenberghe et al., 1984; Notebaert & Verstraeten, 2010; Broothaerts et al., 2013, 2014). Wetter climatic conditions in the Lateglacial and Holocene led to elevated groundwater levels promoting peat formation and accumulation in the valleys.

Impact of the trunk system on the tributary

The geomorphic development of the tributary Loobeek valley during the Lateglacial and Holocene differed significantly from the trunk channel system of the Meuse (see paragraph 5.2.1). However, the fluvial development of the Meuse had a profound influence on the downstream reaches of the Loobeek system. The eastward displacement of the Meuse during the Younger Dryas and early Holocene influenced the longitudinal profile of the Loobeek, which was extended by circa 3.5 km following the abandoned Meuse meander (Figure 3). In addition, the incision of the Meuse lowered the base-level of the tributary system with circa 3 metres. As a result, ground-water level was lowered which explains the absence of extensive peat layers in the downstream reach of the Loobeek (see Figure 4: cross section Vierlingsbeek), and the emergence of grasslands and heather in the study area. The steepening (higher gradient) of the river profile of the tributary system, by the incision of the trunk channel, also led to a geomorphic response in the tributary system. In the Loobeek valley, the stepwise incision of the Meuse during the Bølling-Allerød and the Younger Dryas-Holocene transition caused the formation of knickpoints. These knickpoints may explain the location of the water mills in the Loobeek near Smakt and Vierlingsbeek as these need a high gradient for increased flow and hence force to turn the mill wheel (Figure 3 [Molens in Nederland, n.d.]). Apparently, the stream power of the Loobeek was too small to remove the knickpoints by headward erosion. In contrast, the Roer river (southern Netherlands and adjacent Germany) with higher stream power showed an increase in channel sinuosity in response to early Holocene incision of the Meuse River (Woolderink et al., 2019). The difference in response is caused by the differences in catchment size and stream power of the Loobeek and Roer river. This emphasises that similar changes in the trunk system, such as incision, can result in varying fluvial morphodynamic responses in tributary systems depending on their regional characteristics.

Conclusions

This study on the fluvial evolution of the Meuse and Loobeek confluence area in the southern Netherlands from the Late Pleniglacial to the late Holocene reveals a differentiated response of trunk river and tributary system to climate and vegetation changes.

During the Late Pleniglacial, both the Meuse and Loobeek were characterised by braided systems, complemented by aeolian sedimentation in the Loobeek Valley and Smakterbroek area. The Bølling-Allerød transition resulted in a gradual transformation from a braided to an incised meandering river for the Meuse. The Loobeek incised into the wide Pleniglacial valley and adopted a single-channel course already during the Bølling, while a transition in planform could not be established with certainty. This different development was probably caused by differences in transport capacity and sediment supply. The onset of the cold Younger Dryas resulted in contrasting responses. The Meuse River returned to a braided/wandering system, abandoning its active meanders, while the Loobeek, due to differences in size, discharge, vegetation, and sediment supply, remained unaffected, maintaining its meandering morphology. The increase in temperature and precipitation at the beginning of the Holocene resulted in an increase of the vegetation cover, and less sediment supply. The Meuse incised and changed from a braiding river system to several incised channels with a low sinuosity. Due to the incision of the Meuse, the residual channel of the Allerød terrace was fully abandoned, and the Smakterbroek area at the confluence of the Loobeek to the Meuse was not influenced anymore by the Meuse River. High groundwater levels during the Holocene caused extensive peat formation in both the Loobeek valley and the Smakterbroek area. The river pattern of the Loobeek was a diffuse drainage pattern in a sedge and alder swamp (flow-through swamp or swamp stream). These channels mainly carried water and little sediment and were not actively meandering channels. During the late Holocene, human influence on the landscape strongly increased due to the rise of agriculture and associated deforestation. Peat drainage and excavation in the upstream catchment may have enhanced the discharge. A meandering stream established in the Loobeek valley, probably due to increased discharge, drainage of brook meadows and channel-bank stabilisation.

Overall, our study emphasises the dominating role of catchment size and vegetation cover in shaping the morphodynamic responses of river systems to climatic fluctuations. The smaller Loobeek tributary exhibited rapid adaptations driven by changes in vegetation, contrasting with the buffered, slower responses observed in the larger Meuse River trunk channel. These findings underscore the critical influence of catchment dimensions in shaping fluvial landscapes during environmental perturbations.

Data availability statement. The underlying measurement sequences, measurement bin files, spectrometer data and code to run the analysis are published on the Dutch 4TU research data repository under DOI: 10.4121/03543625-cc1b-4650-aea3-5992f077f417.v1

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