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Human-induced lowland floodplain transformation from peat- to clastic-dominated during the early modern period

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Abstract

Many stream valleys in Northwestern Europe were once peat-filled during the Holocene. Nonetheless, they are often not considered as peat valleys in restoration projects, as they are now covered by thick clastic deposits. This sediment influx is often attributed to past deforestation and intensification of agriculture on adjacent hill slopes. However, this explanation fails in lowlands such as the Netherlands. How the clastic material formed in those stream valleys is still unclear. This study aims to determine the origin of thick humic sand covers in formerly peat-rich stream valleys. Two stream valleys in the sandy southern Netherlands were studied, the Keersop and the Kleine Dommel. The formation of the humic sand covers was studied by mapping the soils and subsurface lithology, luminescence dating and a review of archaeological and historical information. Our interdisciplinary research design has revealed direct human controls on historical floodplain transformations from peat-dominated to clastic-dominated in both valleys. The results show that the humic sand covers display many similarities with other Plaggic Anthrosols in the region, which developed after fertilisation of arable lands since the Middle Ages. Both contain humic sand, traces of charcoal and ceramics, and both can contain light-coloured sand inclusions. Our datings show the soils in the Kleine Dommel valley were anthropogenically raised during the late 17th or early 18th centuries. We argue that artificial raising of stream valleys with sands was a common practice in the southern Netherlands, intended to support agriculture on the existing peaty soils by improving their bearing capacity and drainage. This identified human-induced lowland floodplain transformation from peat-dominated to clastic-dominated underlines that these past human alterations should be considered when restoring stream valley ecosystems.

Introduction

Stream restoration has become a multi-billion euro industry worldwide (Kondolf & Yang, 2008; Szałkiewicz et al., 2018). The main aim of stream restoration is to restore the biodiversity, water quality and water retention of stream valleys (Carvalho et al., 2019; Palmer et al., 2014). Given today's policies, there is the ambition to restore hundreds of thousands of additional kilometers before 2030, in order to create healthy stream and river systems globally (Carvalho et al., 2019; Doyle & Douglas Shields, 2012; Feeney et al., 2023; Feio et al., 2021). Examples of such policies within Europe are the Nature Rehabilitation Law (Paulus & Sprackett, 2021) and Water Framework Directive (Hering et al., 2010).

Wohl et al. (2021) argued that the key to successful restoration is the ability to regenerate the stream-wetland connectivity: the floodplain should be seen as a wetland where water, biota, sediments and nutrients are being exchanged with the stream channel. Many wetlands in Northwestern Europe were strongly connected to low-energy streams and rivers during the Middle Holocene (Brown et al., 2018; Notebaert & Verstraeten, 2010). The floodplains were dominated by peaty or organic-dominated wetlands (Broothaerts et al., 2013; Wohl et al., 2021). Most valleys are believed to have lacked a clear main channel and to have consisted of many smaller channels (Brown et al., 2018; Notebaert & Verstraeten, 2010), though clear evidence of this alternative channel type is still missing (Candel, 2020; Storme et al., 2019). Peaty wetlands provide many ecosystem services; they retain and purify water, enhance biodiversity and are very effective long-term carbon sinks (Lamers et al., 2015; Wohl et al., 2017).

Currently, many Northwestern European stream valley floodplains are dominated by clastic deposits (Brown et al., 2018; Candel et al., 2020). The once common peaty wetlands have largely disappeared due to increased drainage (Andersen et al., 2017; Verhoeven, 2014), or largely got buried underneath thick sediment deposits (Notebaert & Verstraeten, 2010). At a smaller scale, peat was excavated from stream valleys where

oligotrophic to mesotrophic conditions existed, generally far away from the stream influence (Leenders, 2013). Peat is therefore obscured in the landscape or on maps that are being used to provide a landscape context in restoration work (Brown *et al.*, 2018).

Middle to Late Holocene floodplain transformations in lowland catchments without steep hills are still underexposed in research (Candel *et al.*, 2018; Hoevers *et al.*, 2024). Many studies described the transition from peat-dominated to clastic-dominated floodplains in hilly and mountainous catchments with loamy soils. Deforestation and agriculture on the adjacent hillslopes were identified as key causal factors for increased sediment input in stream valleys during the Late Holocene, burying the peat (Kirchner *et al.*, 2022; Lespez *et al.*, 2008; Notebaert *et al.*, 2009; Rommens *et al.*, 2006; Tinapp *et al.*, 2019; Von Suchodoletz *et al.*, 2024). However, the input of clastic sediments in lowlands such as The Netherlands is less likely to be explained by deforestation and consequent hillslope erosion, due to far smaller elevation differences and lower erodibility of sand.

Nevertheless, thick humic sand covers are widespread in stream valleys in the southern Dutch sand area today,

despite the flat topography (Figure 1). They are indicated as *lage enkeerdgronden* on Dutch soil maps (De Vries *et al.*, 2003), which translates to low-lying Plaggic Anthrosols following the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2022). The name *lage enkeerdgronden* suggests that the soils were raised with a brought-up mixture of sods and sands enriched with manure, a practice common on the well-drained sandy soils in the Netherlands (De Bakker & Schelling, 1989). However, fertilisation of the grasslands with plaggic material is debated, with some authors (Vervloet & Leenders, 1986; Weterings & Taat, 1987) stating that meadows in the valleys were rarely fertilised, while others claim that this practice was common (Burny, 1999; StiBoKa, 1968; Van Diepen, 1951).

Humic sand covers are scarcely found in the valleys of the other sandy regions of the Netherlands, which are rich in Plaggic Anthrosols (*hoge enkeerdgronden* in Dutch) on the valley flanks (De Vries *et al.*, 2003). They do appear in the adjacent part of the Campine region of northern Belgium (Databank Ondergrond Vlaanderen, 2015; Hoevers *et al.*, 2024) which has a similar landscape character as southern Netherlands. Spek (2004, pp. 746–753) indicates that the

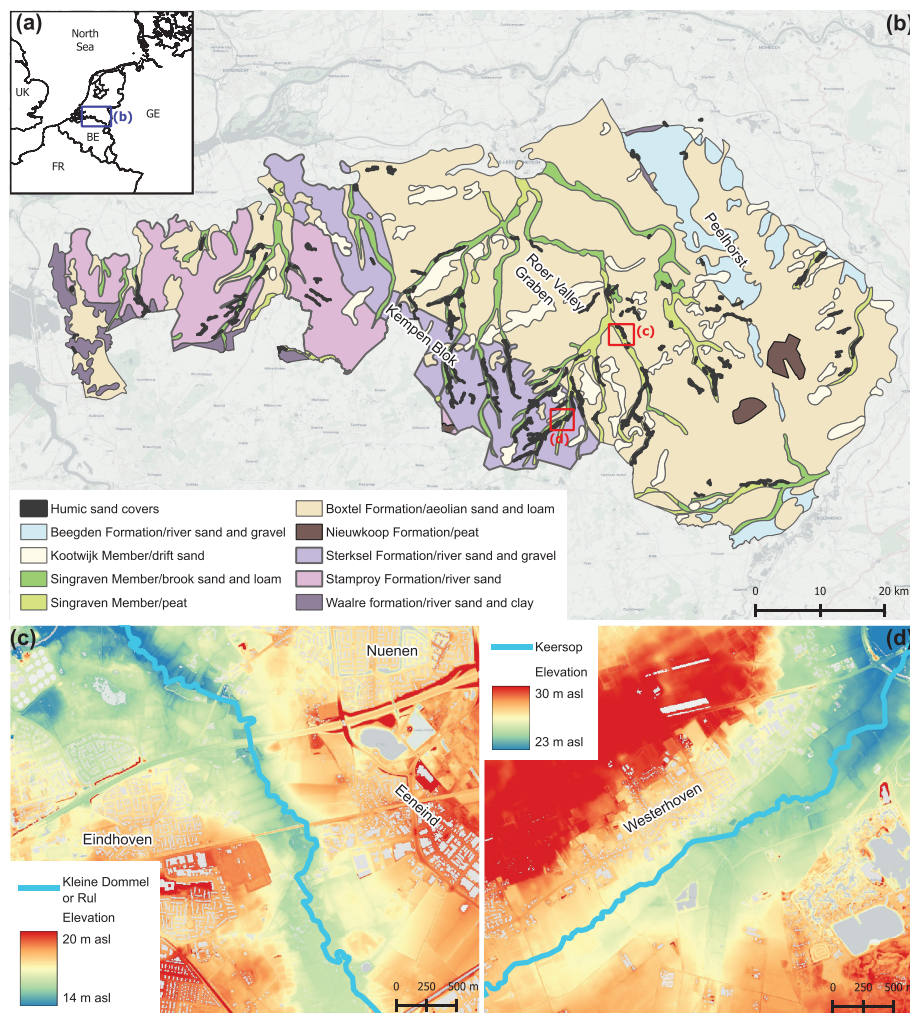


Figure 1. (a) The location of the study area within Northwestern Europe. (b) The distribution of the humic sand covers (in Dutch: *Lage enkeerdgronden*) and the geology of the Southern Dutch Sand landscape (data derived from De Mulder *et al.*, 2003; De Vries *et al.*, 2003; TNO-GDN, 2021). The pilot areas are indicated with red rectangles. (c) The valley of the Kleine Dommel or Rul near Nuenen on an elevation map (AHN 4, 2020). (d) The valley of the Keersop near Westerhoven on an elevation map (AHN 4, 2020).

southern Dutch coversand landscape and adjacent parts of Belgium are remarkably rich in Plaggic Anthrosols compared to other regions, and have been underexposed in research so far. According to him, the humic sand covers were probably brought-up by farmers in single actions in historical times using material from higher parts of adjacent arable fields (Spek, 2004, p. 748). However, this hypothesis requires testing by means of detailed field observations.

Here we aim to improve the understanding of the genesis of these thick humic sand covers in the southern Dutch stream valleys. We have formulated the following research questions to achieve this aim:

- What is the composition and age of the humic sand covers?
- Where are the humic sand covers located within the stream valleys in the southern Dutch sandy landscape?
- What are important cultural-historic developments in the stream valley landscape, and do they relate to the formation of humic sand covers?

To answer these questions, we will combine field observations of the humic sand covers, optically stimulated luminescence (OSL) dating and a review of historic and archaeological literature.

Study area

This study focuses on two stream valleys in the southern Netherlands, where humic sand covers are most common (Figure 1). These are The Kleine Dommel near Nuenen and the Keersop near Westerhoven. Elevation differences in the study area are generally smaller than 10 m (Koomen & Maas, 2004), and stream gradients in the area vary between 0.03 m/km (Candel et al., 2020) and 0.007 m/km (Wolfert, 2001). The two study areas differ in geology and historic development and cover most of the variation found in the stream valleys with humic sand covers in southern Netherlands.

Geological background

The southern Netherlands is characterised by the Roer Valley Graben. The current extension phase of the graben started at the Palaeogene – Neogene transition (Van Balen et al., 2000, 2005), and got filled with Rhine and Meuse deposits during the Pleistocene until approximately 400 ka, after which it filled with aeolian and regional stream deposits (Kasse et al., 2017; Schokker et al., 2005). Hence, the shallow subsoil of the Roer Valley Graben is dominated by aeolian sand and thin layers of loam from the Middle to Late Pleistocene. Those are part of the Bortel Formation and can reach thicknesses of over 30 meters (Schokker et al., 2007; TNO-GDN, 2021). The surface is often covered by over one meter of the so-called coversand, well-sorted sand with a median grain size of 105–210 μm (Wierden member; Koster, 2009).

The Peelhorst region is situated in the northeast of the Roer Valley Graben, while the Kempen Plateau is situated to the southwest. On the Kempen Plateau, the Bortel Formation is only a few meters thick, or when absent with the Sterksel Formation exposed at the surface (Figure 1) (Bisschops et al., 1985; TNO-GDN, 2021). The Sterksel formation is composed of coarse sand and gravel deposited by the Meuse, Rhine and

their tributaries during the Pleistocene (Bisschops et al., 1985; Westerhoff et al., 2008).

The stream valleys formed during the Early and Late Pleniglacial (Isotope stage 4 and 2; Kasse et al., 2003; VandenBerghe, 1993; VandenBerghe et al. 1984). Initially, meltwater channels formed on the permanently frozen soils. They incised and formed valleys that partly filled in with locally reworked fluvial-aeolian sediments (Bisschops et al., 1985; VandenBerghe, 2008; VandenBerghe et al. 1987). During the Holocene, peat formed in most stream valleys due to sea-level rise and regionally rising groundwater levels (Bisschops, 1973; Makaske & Maas, 2023). The peat deposits can be intersected by thin clastic layers (Kijm, 2018; van der Linden, 2010; Verbruggen & Kooistra, 2012). Peat has been dated in different stream segments of the Dommel River, with results ranging from 11 to 1.4 kya (Candel et al., 2020; Janssen, 1972; van der Linden, 2010; Van der Linden et al., 2011; Verbruggen & Kooistra, 2012). However, caution is needed for the youngest peat dates, as they do not necessarily represent the moment that peat has stopped forming. The tops of the peats may have been lost due to excavation or oxidation due to drainage.

The Keersop originates at the Kempen Plateau, where the coarse sand and gravel of the Sterksel formation lies close to the surface (Figure 1) and drains into the Dommel in the Roer Valley Graben. The mean annual discharge at the confluence with the Dommel is 0.8 m^3/s with a mean annual flow velocity of 0.5 m/s (Wolfert, 2001). The Beekloop discharges into the Keersop halfway through the pilot area. The villages Bergeijk and Westerhoven lie north of the Keersop.

The Kleine Dommel or Rul stream is located within the Roer Valley Graben. The sources of the different tributaries lie near the Dutch-Belgian border. The Kleine Dommel does not have tributaries in the pilot area. The average discharge varies between 1 and 3.5 m^3/s (Gijsbers, 2015). Villages lie on both sides of the stream, such as Tongelre and Nuenen.

Historic land use

Throughout the Middle and Late Holocene, the southern Dutch stream valleys and their surroundings have been important for human habitation and exploitation. They offered high biodiversity, drinking water for humans and livestock, suitable soils for arable crops (generally on adjacent higher flanks), pasture and hayland (in floodplains), and a means for transport and communication (Bossenbroek & Rensink, 2008).

Since late prehistoric times (Bronze and Iron Ages, c. 2000–19 BCE), many of the well-drained sandy soils near the stream valleys were inhabited by small-scale agricultural communities. Until the Roman period (c. 19 BCE–450 CE), the stream valleys were still largely covered with alder forests (Janssen, 1972; Verbruggen & Kooistra, 2012). Archaeological evidence for late prehistoric and early historic human activity in the stream valleys is relatively rare, even though several wooden Roman-period bridges have been found (Eeltink et al., 2009; Roymans & Sprengers, 2012).

The Middle Ages (c. 450–1500 CE) witnessed an increase in habitation density, especially from 900 CE onwards. Small settlements appeared on the well-drained sandy soils. The alder forests gradually disappeared due to human activity and the wet soils in the stream valley were increasingly used as

pasture (Janssen, 1972; Theuvs *et al.*, 1988) or coppice (Pedroli & Borger, 1990).

The arable fields were located in open field complexes (Dutch: *essen*) on the dryer, higher soils. These open fields expanded and the soils were levelled (Hiddink *et al.*, 2005; Spek, 2004; van Doesburg, 2007). In the course of the Middle Ages, many villages in the southern Netherlands were moved from the high well-drained sandy soils to the transitional zone between the high soils and the wetter stream valleys (De Bont, 1993; Theuvs, 1988). Additionally, the peat located on top of the poorly drained plateaus was excavated and used as fuel (Leenders, 2013).

Plaggen agriculture originated on the arable fields during the Middle Ages (Spek, 2004; van Doesburg, 2007). The arable fields were fertilised with a mixture of sods, sand and manure; the accumulation of this material resulted in thickened A horizons (Pape, 1970). In the Southern Dutch sand landscape, 32% of the sandy soils are covered with a plaggic horizon and 21.6% of the soils classify as Plaggic Anthrosol, 2–4 times more than in other Dutch sand regions and 10 times more than in the province of Drenthe (van Doesburg, 2007). Studies have dated the raising with plaggic material before using luminescence dating, their results show that the raising started around 1500 CE and became more common from 1600 CE onwards (Bokhorst *et al.*, 2005; Theuvs *et al.*, 2011; Van Mourik *et al.*, 2012a, 2012b).

The *plaggen* agricultural system became redundant after the introduction of artificial fertilisers, during the late 19th and 20th centuries. In addition, the streams were channelised (Wolfert, 2001). Currently, agricultural meadows dominate the stream valleys while some forests and (semi-) natural meadows are present as well.

Methods

Description of the humic sand covers

The subsurface lithology and soil types in the stream valley were described based on corings in both study areas. The boreholes were 100–250 cm deep and made with an Edelman auger (\varnothing 7 cm) for clastic deposits or a gauge (\varnothing 3 cm) for peat. The locations of the boreholes were logged with GPS (\pm 5 m accuracy) and combined with a digital elevation map (DEM; AHN, 2020; Van Heerd & Van't Zand, 1999) to determine the elevation. Most boreholes are located within 500 meters of the stream in transects perpendicular to it. Each transect includes a minimum of four boreholes, of which at least one is situated outside the stream valley.

We mapped the sand covers and recorded their lithological properties. The boreholes were described in 10 cm intervals following using a standard method (Berendsen & Stouthamer, 2001). In addition, the occurrence of plant remains, charcoal, artefacts, gravels, sorting of grain sizes and mixed/messy lithologies were described. Soil texture and organic matter contents were estimated in the field. The median grain size in sandy deposits was visually compared to a sand ruler. The horizons and soils were described and classified following the World Reference Base for soils (IUSS Working Group WRB, 2022).

Criteria for the lithogenic units

The study area consists of different geological deposits. For our research, it was most relevant to distinguish Holocene

deposits from Pleistocene fluvial-aeolian deposits. Within the Holocene deposits, we distinguished between peat and fluvial deposits. All geological deposits were extensively described by Bisschops (1973), Schokker *et al.* (2007) and Candel *et al.* (2020), and we followed their criteria to interpret these different units.

Generally, we found the valley being filled in with peat and fluvial deposits. Here peat is defined as material with more than 15% organic matter. The fluvial deposits were characterised by a high presence of small-fragmented plant material, which was interpreted to be fluvially reworked. Fluvial deposits could consist of gravel, sand or loam. Due to the high content of organics, the Munsell colour value was generally lower than 4 (darkgrey, darkbrown or black). It was out of the scope of this research to further distinguish channel deposits from overbank deposits, though it is very likely that the loamy fluvial deposits can often be interpreted as overbank deposits.

The Pleistocene deposits consist of fluvial-aeolian deposits, which mostly formed under periglacial conditions (Schokker *et al.*, 2007). They have in common that they are generally light-coloured and have a low organic matter content and limited plant remains. The aeolian part is generally well-sorted fine sand ($<$ 350 μ m) with a light colour value (value of $>$ 4.5 by Munsell) associated with the Wierden Member. The aeolian deposits may also be even more fine-grained with a high loam content, which classifies as sandy loam and is known as the Liempde Member in this area (Schokker *et al.*, 2007). The Pleistocene river deposits (Sterksel Formation) are generally gravelly and consist of coarse-grained sand ($>$ 350 μ m) (Bisschops *et al.*, 1985).

Luminescence dating

Samples for optically stimulated luminescence (OSL) dating were collected from two test pits in the same parcel (Pit N100, N101; Figure 3). This site was chosen as the soil contained an Atg horizon (A-horizon with anthropogenic added material and gley, see Results section) on a parcel without recent disturbances and a transition from high to low plaggic Anthrosols. In addition, the overlying A-horizon is thicker than 40 cm, limiting the chances of distorting effects of recent ploughing.

The Atg horizons were sampled using one sample in pit N100 and three samples in pit N101. The plaggic horizons on top of the mixed horizons were dated with one sample in each pit to determine the *terminus ante quem* of the formation of the mixed horizons. The samples were collected by hammering in a tube with a length of \sim 20 cm and a diameter of \sim 5 cm.

Sample preparation and measurements were performed under safelight conditions at the laboratory of the Netherlands Centre for Luminescence dating (NCL) at Wageningen University. Details on the used procedures and parameters are described in Appendix A.

The dose rate was measured using a gamma spectrometer. The material from the outer 3 cm of the sampling tubes was used for dose rate measurements. We assumed that the *in situ* water and organic content are a reasonable indication for historic water and organic contents. The sampled material contains rusty mottles, indicative of a poorly drained soil. The used soil moisture contents, which are between 20 and 30%, reflect this.

Quartz and feldspar with a grain size of 212–250 µm were selected for equivalent dose measurements. Equivalent doses were measured using automated luminescence readers (Risø TL/OSL DA-15) equipped with ⁹⁰Sr/⁹⁰Y beta source, Blue-LED diodes, and IR-Laser (Bøtter-Jensen et al., 2000, 2003). Measurements on quartz were performed on all samples based on the standard Single Aliquot Regenerative (SAR) protocol (Murray & Wintle, 2003), using 2 mm aliquots. Feldspar from the mixed horizon in pit 101 was measured using single-grain post-infrared infrared at 175 degrees celsius (pIRIR175) measurements (Brill et al., 2018; Reimann et al., 2012). This protocol is best suited for material in plaggic soils where different burial ages are expected (Choi et al., 2024).

The ages of the samples were determined using the bootstrapped minimum age model (MAM; (Cunningham & Wallinga, 2012) using the Risø analyst software (Duller, 2018) and the R luminescence package (Kreutzer et al., 2023). A sigma_b value of 0.15 ± 0.04 for quartz OSL and 0.20 ± 0.04 for feldspar single grain pIRIR was used, based on the observations of Choi et al. (2024) on well-bleached grains in the Dutch sandy landscape context. The MAM was employed due to the high probability of mixing of materials with different ages and incomplete bleaching in the mixed horizons.

Archaeological and historical analysis

Archaeological and historical geographical sources may provide information on the genesis of the humic sand covers in the pilot areas. We consulted two different source types to collect information on historical (agricultural) developments, and how these may have changed the soil profile:

- Archaeological sites in the Kleine Dommel and Keersop stream valleys, documented in the Dutch archaeological data repository Archis III (<https://archis.cultureelerfgoed.nl>)

- Various types of historic maps (approximately from 1830, 1850, 1900, 1925, 1950 and later) and accompanying descriptions, containing information on the landscape history of the pilot areas (mainly through <https://rce.webgis.nl/nl/map/erfgoedatlas> and <https://topotijdreis.nl>)

The main characteristics of known archaeological sites in the pilot areas were recorded (Appendix C). We restricted this inventory to sites dating from the Early Middle Ages (450–1050 CE), Late Middle Ages (1050–1500 CE) and Early Modern Period A (1500–1650 CE). The cartographic analysis mainly covered the 19th and 20th centuries.

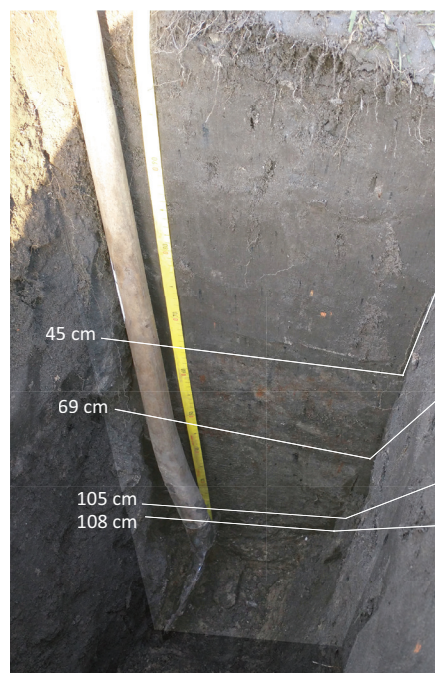
Results

The data underlying this paper can be accessed using this link <https://doi.org/10.4121/cedb3cac-650d-4405-9510-126240e926a5>

The properties of humic sand covers

In total, we described 96 soil profiles within 500 meters of both streams. We found humic sand covers in 68 soil profiles. The humic sand cover has the following properties:

- Texture: sandy or loamy sandy with silt contents up to 30%.
- Thickness: on average 77 cm (1 standard deviation (sd), 22 cm), with a minimum of 45 cm, a maximum of 130 cm and a median of 75 cm.
- Visible pieces of charcoal were found in 44 out of the 68 humic sand covers.
- Visible traces of brick and/or glazed pottery were found in 22 out of 68 sand covers. Some ceramics could be dated to the Early Modern period.
- Plant remains or pieces of wood have not been observed.



Horizon	Colour	Texture	Remarks
Apg	10YR2.5/1	Slight loamy sand	Contains brick particles, charcoal and a few iron mottles
Aτg	10YR2.5/1	Sand	Contains pottery, brick particles, charcoal, iron stains and inclusions of white sand
Ab	10YR 3/1	Very loamy sand	Contains pottery, charcoal and almost no iron stains or mottles
Ha	10YR 2/1	Peaty sand	
C	10YR 7/1	Sand with ≈ 25% gravel	Fluvial deposit, contains up to 5cm large pieces of wood and gravel

Depth	Horizon	Colour	Texture	Remarks
0-20 cm	1Ha	10YR 3/2	Peaty sand	Contains no brick or charcoal
20-40 cm	2Ha	10YR 3/2	Sandy peat	Contains no brick or charcoal
40-70 cm	1He	10YR 3/1	Peat	Remains of sedge oxidises to black
70-80 cm	2He	10YR 7/2	Peat	Oxidises to black
> 80 cm	C	10YR 7/1	Sand	

W102: location: N 51.32481, E 5.39128

N84: location: N 51.43788, E 5.54541

Figure 2. Two examples of soil profile descriptions. The locations of both soil profiles are indicated in Figures 3 and 4. Profile W102 (left) was found in the Keersop valley in a meadow. Humic sand covers like this are common within the stream valleys. Profile N84 (right) was found in a forest in the Kleine Dommel valley. This is one of the few peat soils in the pilot area without a humic sand cover.

The humic sand covers are classified as A horizons following the WRB soil classification system (IUSS Working Group WRB, 2022). This A horizon can be subdivided into three different sub-horizons, the Ap, Atg and Ab horizons, in respective order from top to down:

1. The cultivation layer (Ap) is generally dark grey (10YR 3/1 or 10YR 2.5/1) rather than black. This horizon is very homogenous, and if present rusty mottles are poorly recognizable.
2. The mixed horizon (Atg) is a heterogeneous horizon, with a mixture of dark-coloured humic sand (10YR 3/1) and light-coloured yellow grey or grey clean sand (10YR 7/1 or 10YR 8/1). The light-coloured sand is well sorted and has a grain size of 105–210 μm , equal to local aeolian Pleistocene deposits (Wierden member). Iron mottles and rust stains are common, indicating that this part is below the ground-water level during parts of the year.
3. The buried A horizon (Ab) is the former topsoil from before the raising. The sub-horizon is homogenous and often more loamy or humic than the rest of the humic sand cover. This horizon is often black but can be dark grey (10YR 2/1 to 10YR 3/1).

The Ab and Atg sub-horizons are not found in every soil profile. Those sub-horizons are not always preserved or never

formed as part of the humic sand cover. The A horizon generally transitions abruptly into the C horizon (parent material), or H horizon (peat) in case the subsurface consists of peat. The boundary is sharp and B or E horizons (illuviation and eluviation horizons) were not observed.

Figure 2 shows an example of a humic sand cover in the study area with a thickness of 105 cm. In addition, the profile description of a peat soil without a humic sand cover is shown. This is one of the few peat soils without a humic sand cover in the pilot areas. The A-horizon on the peat soils is darker and less sandy than in profiles with a humic sand cover. The peat soil does not contain brick or charcoal while those are common in humic sand covers.

The locations of the humic sand covers in the stream valleys

The valleys of the Keersop and Kleine Dommel consist of peat and fluvial deposits. The latter include gravel, sand and loam. The gravel was commonly found underneath peat or below a thin A-horizon, the loam was found underneath peat. The humic sand covers lie on nearly all the peaty valley-fill and most of the fluvial sand (Figures 3 & 4). The humic sand covers are mostly missing on the gravel-rich fluvial deposits found at the border of the brook valley in Westerhoven. In addition, the humic sand covers do not occur on very loamy deposits in the northern part of Nuenen. The humic sand cover is thickest

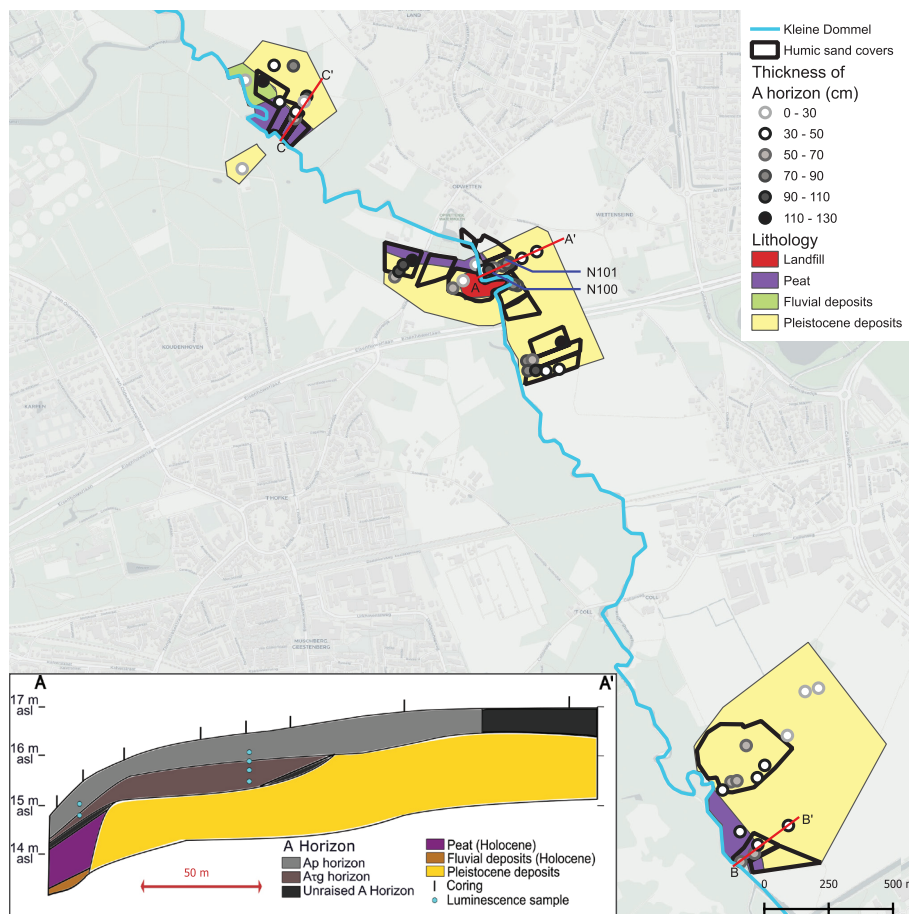


Figure 3. The humic sand covers in the Kleine Dommel valley, west of Nuenen. The locations of the luminescence dating pits (N100 and N101) are indicated. The cross-section covers the parcel where the luminescence samples were taken. The lithologies and raised parcels were interpolated based on the recorded profiles. These were not extrapolated on sites without augerings. See Appendix B for the other cross-sections.

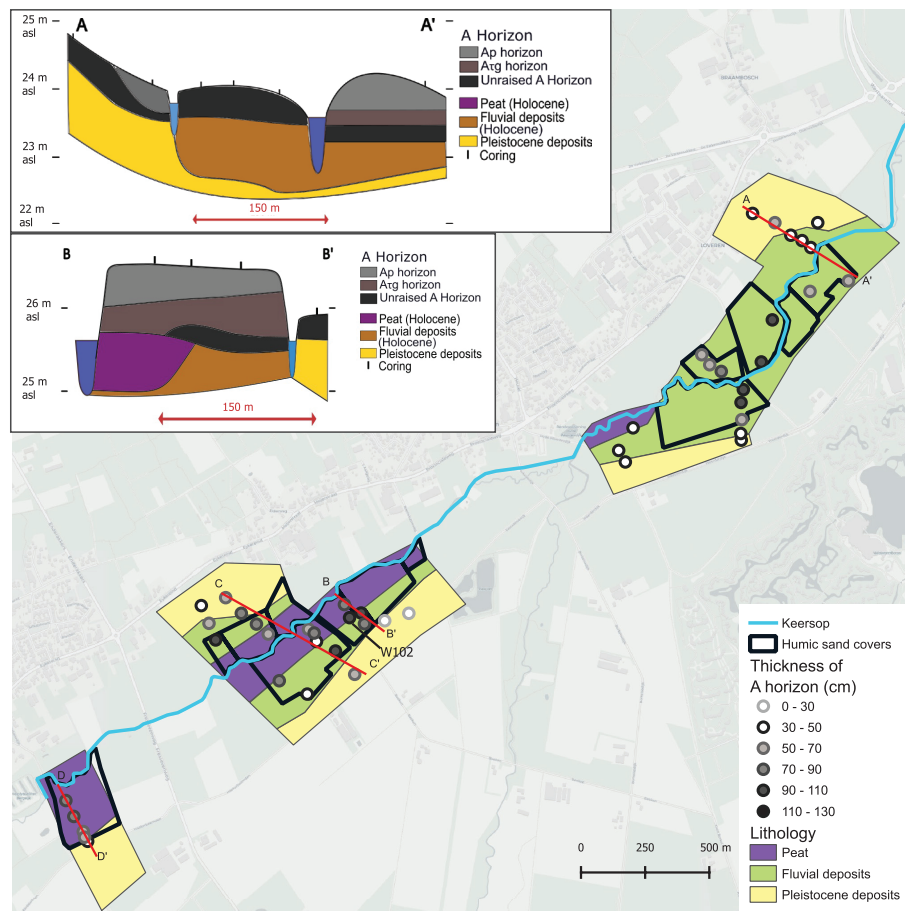


Figure 4. The humic sand covers in the Keersop stream valley, south of Westerhoven. The location of profile W102 (Figure 2) is indicated. Cross-section B contains profile W102. The lithologies and raised parcels were interpolated based on the recorded profiles. The lithologies and raised parcels were interpolated based on the recorded profiles. These were not extrapolated on sites without augerings. See Appendix B for the other cross-sections.

close to the stream and thinner on the Pleistocene deposits and therefore obscures the natural valley edge (Figures 3 & 4).

The humic sand covers on the peaty valley-fill mostly have an Atg horizon (Figure 5), which largely consists of a dark horizon with lighter inclusions as visible in Figure 2. On fluvial deposits many Atg horizons are nearly white coloured. Umbric Gley soils were found at fluvial deposits without a humic sand cover.

Many soils on the Pleistocene deposits do not have a humic sand cover (Figure 5). When the Pleistocene soils have a humic sand cover, they are generally thinner than humic sand covers on peat or fluvial deposits. The thick A-horizons on the Pleistocene deposits closely resemble the Ap-horizon in the valley, as described in Results section. However, rusty stains are often not found in those profiles. Atg horizons are an exception on Pleistocene deposits but they can occur at the border of the stream valley, as a continuation of the Atg horizons on nearby peat soils (e.g. the cross-section in Figure 3). Remnants of palaeosols are often missing in soils with a humic sand cover on top of Pleistocene deposits, because the old soil profile was ploughed into the humic sand cover.

Luminescence derived ages

The luminescence dating focussed on the Atg horizon, because it represents the start of the formation of the humic sand covers.

Figure 6 and Table 1 show the results of the luminescence dating, with the soil profile for context in the figure. Detailed descriptions of the soil profiles are provided in Appendix A.

The standard errors and the overdispersion values are large in the Atg horizon. This is usually attributed to: (1) unequal exposure of grains to sunlight, (2) mixture of grains with different ages, or (3) combination of both. The significant age variation of the quartz OSL measurements indicate that there is high possibility of grains of different ages being mixed, considering that quartz bleaches faster than feldspar (Godfrey-Smith et al., 1988) and therefore, is less susceptible to incomplete bleaching. Quartz OSL dating based on small-aliquot measurements can be challenging in such circumstances due to within-aliquot averaging effects (Cunningham et al., 2011). The single grain feldspar measurements could perform better in this type of environment by measuring individual grains. Therefore, we consider that the age of humic sand covers is better represented by the single grain feldspar measurement results.

The age-depth relationship of the feldspar single grain measurements is inverted, indicating mixing of grains with different ages. In this case the youngest ages would be most representative of the mixing event. The feldspar single grain measurements from NCL-2223045 and NCL-2223047 provide agreeing ages, along with quartz measurement from NCL-2223045. Therefore, the sand covers will have formed between the late 17th century and early 18th century.

	Horizon sequence	Peat	Fluvial deposits	deposits	Total count
Count	Unraised A	3	8	17	28
Median thickness of A horizon (cm)		10	40	40	
Count	Thick A	2	12	27	41
Median thickness of A horizon (cm)		100	55	70	
Count	Atg	5	1	3	9
Median thickness of A horizon (cm)		70	90	80	
Count	Atg + Ab	8	11	0	19
Median thickness of A horizon (cm)		75	95	NA	
Total count		18	32	47	97

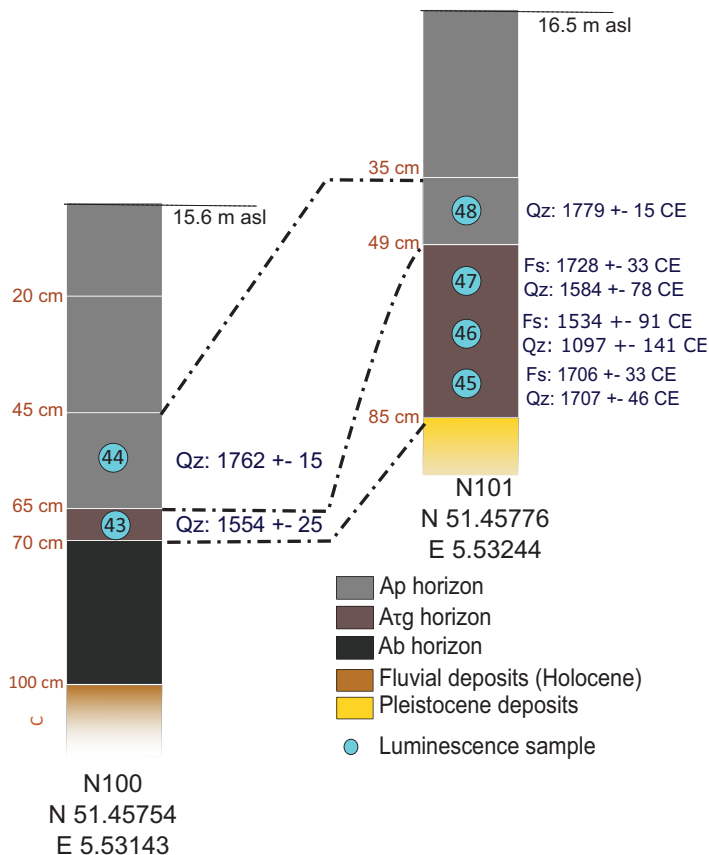


Figure 5 and Figure 6. The counts for the horizon sequences grouped per lithogenic unit. This table includes horizon descriptions in both the Kleine Dommel and Keersop stream valleys. The sub-horizons are described according to the World Reference Base for soils (IUSS Working Group WRB, 2022); Luminescence dating results depicted in the soil profile, the final two digits of each sample are included. The uncertainties are given with 1 standard error (se). The Kleine Dommel flows to the left hand side of the sampled parcels, the location of the pits is indicated in Figure 3. See Table 1 for the detailed results and Appendix A for detailed descriptions of the soil profiles.

Table 1. Luminescence dating results.

Sample	Coordinates (WGS 84 Lat. Lon.)	Pit & horizon	Depth (cm)	Water content (%)	SOM (%)	Overdispersion (%)	Equivalent Dose MAM (Gy)	Dose rate with s.e. (Gy/ka)	Age with s.e. (CE)
NCL-2223043 Qz	N 51.45754 E 5.53143	N100 Atg	65–70	24.2	1.6	63.7 ± 8.1	0.40 ± 0.01	0.85 ± 0.04	1565 ± 35
NCL-2223044 Qz	N 51.45754 E 5.53143	N100 Apg2	51–56	24.5	1.8	31.3 ± 4.4	0.23 ± 0.01	0.88 ± 0.04	1762 ± 15
NCL-2223045 Qz	N 51.45776 E 5.53244	N101 Atg	75–80	29.4	2.0	84.1 ± 11.1	0.24 ± 0.03	0.77 ± 0.03	1707 ± 46
NCL-2223045 Fs	N 51.45776 E 5.53244	N101 Atg	75–80	29.4	2.0	119.6 ± 13.9	0.56 ± 0.07	1.71 ± 0.1	1706 ± 33
NCL-2223046 Qz	N 51.45776 E 5.53244	N101 Atg	63–68	21.6	2.1	91.3 ± 12.1	0.73 ± 0.11	0.79 ± 0.03	1097 ± 141
NCL-2223046 Fs	N 51.45776 E 5.53244	N101 Atg	63–68	21.6	2.1	135.3 ± 14.9	0.99 ± 0.18	1.73 ± 0.1	1534 ± 91
NCL-2223047 Qz	N 51.45776 E 5.53244	N101 Atg	52–57	20.0	2.0	126.0 ± 16.9	0.36 ± 0.06	0.82 ± 0.03	1584 ± 78
NCL-2223047 Fs	N 51.45776 E 5.53244	N101 Atg	52–57	20.0	2.0	139.2 ± 18.4	0.90 ± 0.21	1.76 ± 0.1	1728 ± 73
NCL-2223048 Qz	N 51.45776 E 5.53244	N101 Apg2	40–45	21.0	2.4	92.6 ± 11.9	0.22 ± 0.01	0.90 ± 0.04	1779 ± 15

The equivalent doses are calculated using the bootstrapped MAM (Cunningham & Wallinga, 2012). The ages are determined by dividing the equivalent dose by the dose rate. FS = Feldspar; Qz = Quartz; MAM = minimum age model; SOM = Soil Organic Matter. The results are combined with the soil profile in Figure 6, detailed soil descriptions are given in Appendix A.

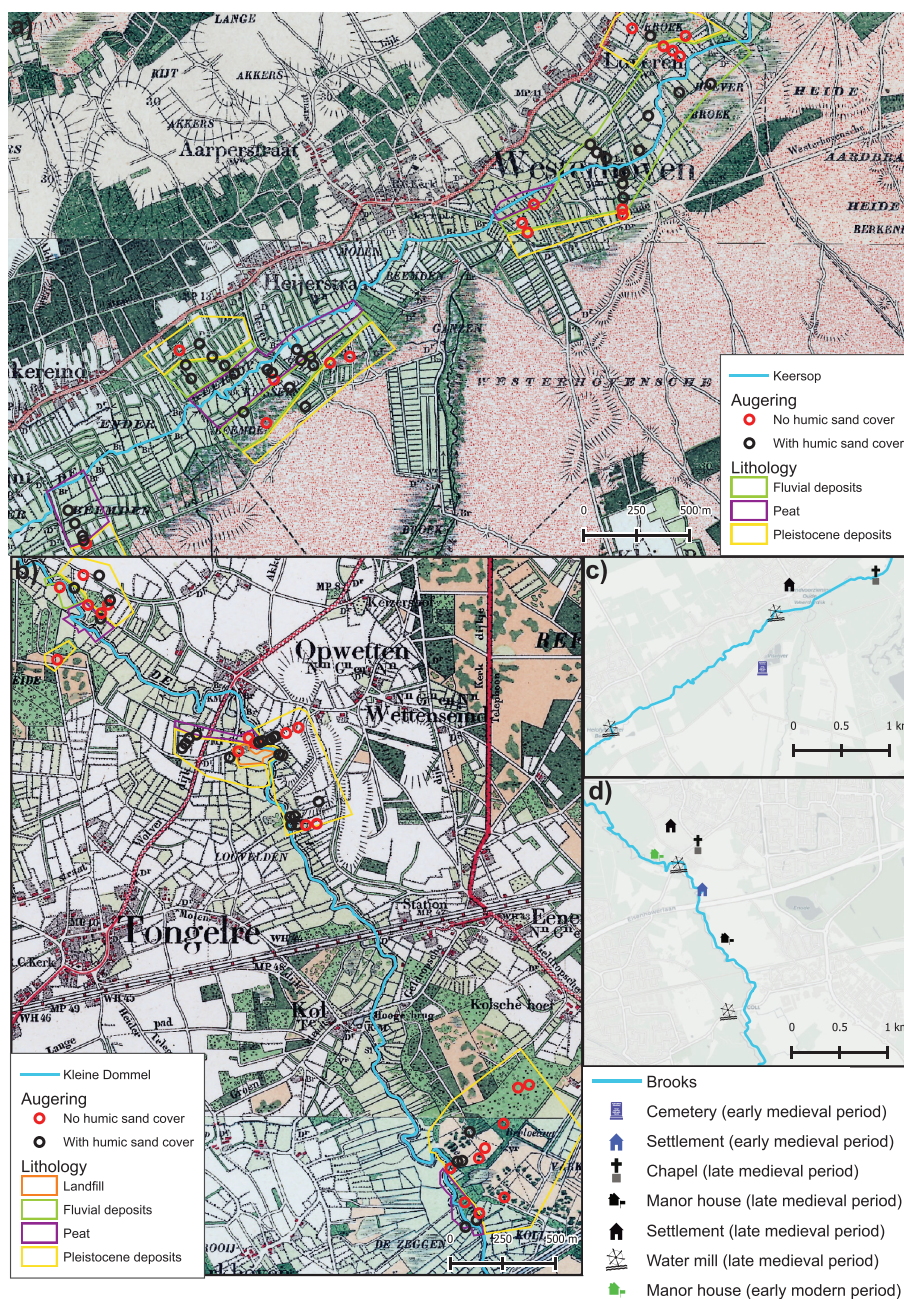


Figure 7. Historical maps (a, b) of both stream valleys, combined with the lithology and occurrence of a humic sand cover in the augerings. The historical maps were first published between 1900 and 1902 (www.topotijdreis.nl). Medieval and Early Modern archaeological sites (c, d) of both stream valleys. The archaeological sites are taken from Archis III (<https://archis.cultureelerfgoed.nl/>; see Appendix B). Early Middle Ages (450–1050 CE); Late Middle Ages (1050–1500 CE); Early Modern period (1500 CE – present).

The measurements for the Apg2 horizon (the former cultivation layer below the current ploughing depth) are more precise than for the Atg horizon. The last surface exposure dates to around 1770 (based on quartz SAR, samples NCL-2223044 & NCL-2223048). This layer is part of a former cultivation layer, so the grains were exposed to sunlight until enough material was added to exclude the sand from the ploughed cultivation layer. The material itself was added earlier than the late 18th century. This indicates that the humic sand covers have formed before the late 18th century.

Archaeological analysis

The archaeological inventory demonstrates that both the Keersop and the Kleine Dommel valley were intensively used in Medieval and Early Modern times (Appendix C; Figure 7). Various archaeological investigations indicate that Westerhoven has a Late Medieval origin, going back to at least the 12th century CE (Keijers, 2015; Van Cruchten, 2021). Two water mills were constructed in the Keersop valley around the 12th–13th century CE (Van Halder, 2010). During a stream valley restoration in this valley many pottery sherds

from the Early Modern period were found in the plaggic layer (Eeltink *et al.*, 2009).

The Kleine Dommel shows a similar pattern. The area around the village of Opwetten shows signs of habitation from at least the 8th or 9th century CE onwards (Archis 3, 2025). Two water mills were constructed in this stream valley as well, both probably dating to the 13th and 14th century (Van Halder, 2010). Furthermore, the remains of two manor houses are recorded in this area (Alma, 2014; Archis 3, 2025). The archaeological evidence indicates the presence of agrarian Medieval villages in close vicinity of the Keersop and Kleine Dommel, as well as clear indications for human use and direct modification of both stream valleys.

Historical analysis

Historic maps show that the Keersop and Kleine Dommel valleys were intensively used for agriculture in the Early Modern period (17th century CE onwards; Figure 7) and more parcels were reclaimed over time. The Keersop valley shows a dense parcellation, consisting of meadows and arable fields, which to the south are bordered by a vast heathland area and to the north by larger field systems and forested areas. The Kleine Dommel valley shows a slightly less regular structure. To the east, near Opwetten, it is mainly bordered by large arable fields, with meadows being restricted to the areas directly adjacent to the stream. The area west of the Kleine Dommel shows a more irregular parcellation, with larger meadows situated close to the stream. Heathlands and forested areas appear slightly further away from the valley. The basic landscape structure and general land-use patterns depicted on the Early Modern historical maps are likely to go back to Medieval times, which is corroborated by the distribution and character of the archaeological sites dating from that period.

If we combine the archaeological and historical patterns with field observations, we find that most parcels with humic sand covers are located at the historic meadows in the stream valley, which often have a peaty subsoil (Figure 7). Those meadows were considered valuable (Bieleman, 1987; Quick *et al.*, 2020). Parcels without a humic sand cover were often used as heathland or forested located at the edge of the open field complexes.

Discussion

Genesis of humic sand covers

Similarities between humic sand covers and plaggic horizons

The humic sand covers found in the stream valleys show large similarities with the well-known higher-located Plaggic Anthrosols, which have been extensively studied by e.g. Pape (1970), Spek (2004) and Van Doesburg (2007). Both the humic sand covers in valleys and higher Plaggic Anthrosols demonstrate a sandy or loamy sand texture, a dark grey colour (Munsell 10YR 3/1 or 10YR 2.5/1), charcoal and pottery/brick fragments, and sharp boundaries between sub-horizons. Based on these parallels, we agree with Spek (2004, p. 748) that humic sand covers in valleys are likely to be raised anthropogenically similar to the higher Plaggic Anthrosols.

Our results show that the upper part of the humic sand cover is well-mixed and often thicker than the common ploughing depth. This indicates repeated raising of the humic sand cover in the valleys after the initial formation, with *plaggen* fertilisation as the most likely factor.

The composition of the brought-up material

Lenses of light-coloured sand can be found in the lower part of the A horizon of Plaggic Anthrosols (Spek, 2004). Local depressions such as fens (Hiddink *et al.*, 2005) or dry valleys (Flammam *et al.*, 2001) within open fields were levelled with plaggic material or sand excavated from the highest parts of the coversand ridges (Theuws *et al.*, 2011; Van Doesburg, 2007). Similarly, sand from elsewhere may have been used to raise the valley soils. The non-humic sand might have been taken from the surrounding drift-sands (Burny, 1999) or from underneath the A horizons of existing Plaggic Anthrosols (Spek, 2004; van Doesburg, 2007). Humic sand from existing Plaggic Anthrosols may have been used to construct new plaggic horizons as well (Pape, 1970; Spek, 2004), even though this will not be visible as light-coloured sand lenses. The added sand was mixed with the original topsoil, resulting in a dark horizon with light stains (Spek, 2004).

For Plaggic Anthrosols outside the valley, the light sand inclusions may also originate from deep delving in the reclamation stage by incorporation of parts of the underlying E, B or C horizons in the plaggic horizon (Hiddink *et al.*, 2005; Spek, 2004). During deep delving, the upper 40–60 cm is mixed with a spade (Theuws *et al.*, 2011). However, this process appears unlikely for the humic sand covers in the valleys. The underlying Ab subhorizon is homogenous dark without light sand, or peat is located underneath the humic sand cover. Both indicate that deep delving did not result in light-coloured sand inclusions and the formation of A_{tg} horizons. The mixed horizons on the fluvial deposits are mostly of later date. These soils were not reclaimed when the historical Bonne maps were made around 1900 (Figure 7c & d). Those profiles tend to have almost white A_{tg} horizons on an Ab horizon, which suggests that younger raisings are lighter coloured.

The reliability of the luminescence results

The mixing of grains with different ages provided challenges within the interpretation of the luminescence results. Three out of six luminescence samples from the A_{tg} consequently have large uncertainties (1 se is 80–140 years) due to within sample averaging effects. The luminescence results of the other three samples are in agreement. Given the light-coloured sand stains, we do expect this horizon has not been exposed to intense ploughing or bioturbation after deposition, otherwise the horizon would have been homogenised. In addition, the ages are slightly older than the cultivated horizon above, which formed approximately six decades later. Thus, we consider the resulting date in the end of the 17th or early 18th century reliable.

Conceptual reconstruction of the floodplain transformation

A reconstruction can be made of the human influence on stream valleys over time, based on our field observations and luminescence dates combined with archaeological and historical information. The reconstruction explains how the studied valleys

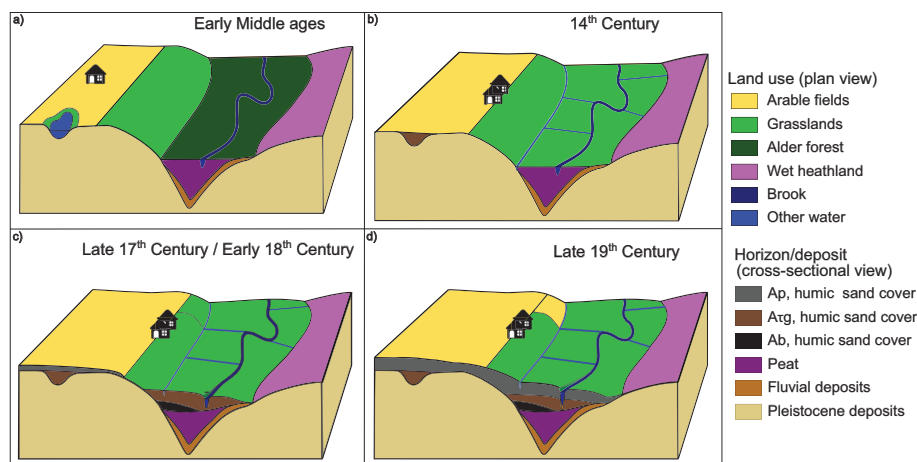


Figure 8. The conceptual reconstruction of the transformation of peat to clastic dominated stream valleys in the southern Netherlands.

transformed from peat- to clastic-dominated during the Late Holocene (Figure 8).

In prehistoric and Roman-period stream valleys, alder forests alternated with open fen meadows were abundant (Janssen, 1972; Verbruggen & Kooistra, 2012). Peat growth was widespread as a result of rising groundwater tables (Makaska & Maas, 2023; van der Linden, 2010; Verbruggen & Kooistra, 2012). Small agrarian hamlets were present on high well-drained soils and the higher sandy soils were used for agriculture (Jongmans et al., 2013). This situation was still present in the Early Middle Ages (Figure 8a).

By the 14th century (Figure 8b), hamlets and villages had shifted to transitional zones between the high well-drained soils and stream valleys (De Bont, 1993; Theuws et al., 2011). Arable fields on high sandy soils expanded and stream valleys were used intensively. Water mills were constructed in the streams. Tax reports and contracts suggest that the valley soils were parcellated, with ditches dividing plots (Theuws, 1988; Weterings & Taat, 1987). Peat decomposition following increased drainage may have made peat soils near streams very fertile and productive meadows.

In the late 17th or early 18th century (Figure 8c) many soils in the stream valley were raised, likely starting at the parcels with peat. This is supported by Early Modern period ceramics found in the humic sand covers in both brook valleys (Results section and Eeltink et al., 2009; van Dijk, 2017). The inclusions in the Atg horizons show that these were often not ploughed after the raising and thus not part of the cultivated layer. This is also reflected in the large variation of equivalent doses in the luminescence dating grains, showing that the grains are not equally bleached by sun exposure. The sand was likely added to make the valley soils more suitable for agriculture. The added sand improved the bearing capacity of the soils, so the fields would be accessible over a longer period during the year. In addition, the groundwater table was lowered as a result of raising the land surface, which made the soils more suitable for grasses or other crops.

As discussed in the Study area section, the surface of Plaggic Anthrosols in the southern Netherlands is considerably larger than in other sandy regions in the Netherlands (van Doesburg, 2007). The arable fields in this region were largely levelled by excavating the highest parts and raising of the depressions in the field complexes (Theuws et al., 2011), while in other regions the original relief is more intact (van

Doesburg, 2007). This implies that the soils in this region were used intensively for agriculture and there was a larger incentive to cultivate soils with a lower suitability for agriculture, including those in the relatively poorly drained brook valleys. The raising of the brook valley soils is widespread. Only in a few isolated areas within the studied valley sections the peat has no humic sand cover. This pattern is also known from other stream valleys in the sandy area of the southern Netherlands (Krabbenborg, 1961, 1965).

The luminescence dating and homogeneity of the Ap horizon indicates that mineral material was continuously added to raised soils (Figure 8d). Fertilisation with enriched sand was already common in the southern Dutch sand area during the late 17th century (Bokhorst et al., 2005; Theuws et al., 2011; Van Mourik et al., 2012a, 2012b). This indicates that the soils in the valley were fertilised with *plaggen* after the initial raising in the late 17th or early 18th century, which ended with the introduction of artificial fertilisers in the early 20th century.

Some heathland areas near the valley edge were transformed into meadows in the early 20th century as seen on old topographic maps. This occurred on sandy soils and these humic sand covers have a white Atg horizon, indicating they were raised later with non-humic sand. Due to the raising of soils in the valley over the last centuries in combination with ploughing, the natural valley edge as can be seen in Figure 8a is difficult to recognise as it is being masked by the humic sand cover (Figure 8d).

Implications

In this research, we found that the studied stream valleys have changed from organic-dominated to clastic-dominated. It is the first time that evidence was found for a direct sedimentological alteration by humans of lowland floodplains, by intentionally bringing in clastic material on a peaty floodplain for agricultural purposes. This finding corroborates the perspective on transformations of river valleys in human-altered settings during the Middle and Late Holocene as a result of anthropogenic effects (Brown et al., 2018; Gregory, 2006; Notebaert & Verstraeten, 2010).

However, most studies are reporting on the indirect effects by humans initiating floodplain transformations, of which the main indirect factor is land use change within the catchment. This factor is predominantly important in landscapes with

significant topography where hillslope erosion as a result of land use change has led to floodplain transformations, which led to the burying of peat below a clastic cover (Foulds & Macklin, 2006; Kondolf *et al.*, 2002; Notebaert *et al.*, 2018; Verstraeten *et al.*, 2017).

Lowlands, i.e. landscapes without significant topography, are generally underrepresented in these studies and the effect of land use change is also more limited here, due to a low sediment connectivity within the catchment. Despite, there may be more areas where this human practice of adding clastic material to the organic-rich floodplains was common within the Northwest European Lowlands. For example, Łachacz *et al.* (2024), found that quite some earth-covered (>10 cm) peatlands in Poland exist. Though their aim was not to determine the genesis of these clastic covers, they mentioned the likelihood of deliberate deposition by humans of these clastic covers as an amelioration practice.

Walter and Merritts (2008) and Brown *et al.* (2018) also found that the engineering of watermills widely caused floodplains to change from organic to clastic-dominated in Northern America and Europe. Though water mills have been present since the 13th century in our study area, we did not find evidence of water mill engineering being a dominant factor for enhancing the sedimentation rates and initiating of the floodplain transformation. The lithological description of the raised soils did not coincide with fluvial overbank deposits, such as described earlier for this catchment in other segments (Candel *et al.*, 2020). In addition, the OSL dating results show the deposits are much younger, from the late 17th or early 18th century, when water mill engineering was already being done for centuries at a large scale (Nienhuis, 2008).

Apart from modern human interventions of introducing weirs, dams, groynes and bank protection measures (Belletti *et al.*, 2020), humans are known to have had significant indirect effects on lowland river channels. It was found that humans have induced avulsions in some instances (Pierik *et al.*, 2018), or increased peak discharges due to large-scale land use changes, turning laterally stable rivers into morphologically active rivers (Candel *et al.*, 2018; Quik *et al.*, 2020; Woolderink *et al.*, 2025). Here we show that humans have not only altered river channels but also directly and intentionally changed entire floodplains in the past, which has not been found before.

This study shows that humans already long ago intentionally and directly changed floodplains by burying the peat below a raised sand cover. These historical changes still affect today's perspective on how a natural stream valley functions. The perspective on natural ecosystems for many of these restoration projects is derived from historical maps, which do not go further back in time than the 19th century (Kondolf, 2006) whereas stream valleys back then were already clastic-dominated (Figure 8). Many stream restoration projects are not focussing at all on restoring peat growth within the valley (Andersen *et al.*, 2017), despite the large potential for peat to form in these lowland settings given its historical prevalence. Peat restoration provides many benefits, including carbon sequestration, biodiversity enhancement, water purification and water retention leading to mitigation of floods, droughts and wildfires (Loisel *et al.*, 2021; Tanneberger *et al.*, 2021; Tittel *et al.*, 2022). However, a large challenge for the restoration of streams with peaty floodplains would be to restore the connectivity between the channel and the floodplain that is now largely affected by the raised floodplains relative to the channel. Even the actual valley edge is difficult to

recognise as a result of the humic sand cover (Figure 8d), complicating valley-wide restoration that is urgently needed today (Wohl *et al.*, 2021).

Research opportunities

Our study results in new questions, which could be addressed in future work. We found three subhorizons within the humic sand covers. Their different properties could be further researched using, among others, chemical analyses and soil micromorphological research. In the Discussion section we assumed that the formation of humic sand covers can be attributed to a larger demand for agricultural land in the southern Netherlands and the Belgian Campine. This assumption could be tested with further historical research or a comparison with later expansions of arable fields within those regions or other regions. Finally, it is still uncertain to what extent the addition of humic sand covers to the floodplain has impacted the morphology of their respective streams.

Conclusions

The interdisciplinary research design applied in this study has identified direct human controls on historical floodplain transformation from peat-dominated to clastic-dominated in a lowland setting in The Netherlands. We found that stream valleys in the southern part of The Netherlands were anthropogenically raised, resulting in 45–130 cm thick humic sand covers. These raisings were thickest closest to the stream and became thinner towards the valley edge. Especially where peat was abundant in the valley prior to human influence, humic sand covers were brought up. The humic sand covers have a similar composition to well-drained Plaggic Anthrosols. Both contain traces of charcoal and ceramics. In addition, most of these humic sand covers have a predominantly dark Atg horizon with inclusions of lighter sand. This layer also occurs in some well-drained Plaggic Anthrosols. Based on our OSL results and lithological description we found that the valley parcels were raised during a single event. Most valley soils were raised with sand during the late 17th or early 18th century, although this practice continued until the 20th century.

Historic and archaeological data show that the stream valleys were intensively used as cultural landscapes. They also suggest that the raisings were initially confined to the peat soils. It seems that many sandy soils were raised later, with the youngest humic sand covers stemming from the early 20th century. We argue that the raisings with sands made the peaty soils more suitable for agriculture by improving the bearing capacity and relative lowering of the groundwater table. After the initial raisings, we found the soils were gradually raised with *plaggen* for fertilisation. This historical practice of *plaggen* fertilisation shows large similarities to the raisings of Plaggic Anthrosols on the higher-elevated cover-sand ridges.

The outcomes corroborate with perspectives on how valleys changed as a result of anthropogenic effects such as enhanced hillslope erosion and watermill engineering, though previous studies never showed humans had such direct intentions to change the nature of floodplains. These past human alterations are a complicating factor in today's restoration of ecosystems in stream valleys.

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Competing interests

The author(s) declare none.

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