



A multidisciplinary approach to reconstructing Late Glacial and Early Holocene landscapes

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ARTICLE INFO

Article history:

Received 19 June 2012

Received in revised form

29 August 2012

Accepted 1 September 2012

Keywords:

Electromagnetic induction

Near-surface geophysics

DEM

Coring

Palaeotopographical modelling

Landscape reconstruction

ABSTRACT

Understanding palaeotopographical variability forms the basis for understanding prehistoric societies. Alluvial and lacustrine environments, in particular, are key areas with both a high archaeological and palaeoecological potential. However, the often deep stratification of these sites, the high water table and the complex sedimentological variations can hamper a detailed reconstruction of the spatial relationship between prehistoric settlement and their environment. Combining different remote and proximal sensing techniques and coring data, can offer detailed insight into such landscapes. More specifically, the integration of mobile geophysical methods allows the collection of unprecedented continuous information on large-scale palaeolandscape variability. In this study we present a combined approach in order to map and model prehistoric landscapes and river systems in and around a Late Glacial palaeolake in north-western Belgium. Based on filtered and unfiltered digital elevation models, a survey area of 60 ha was selected, in which detailed mobile multi-receiver electromagnetic induction survey was conducted. The results allowed for the delineation of palaeochannels in the area and enabled modelling the depth of these features in the survey area, providing insight into their flow characteristics. ¹⁴C sampling enabled the dating of the evolving river system to the transition between the Late Glacial and the Early Holocene. Through additional coring, this river system could be traced further through the palaeolake area. Based on these results a detailed reconstruction was made of the palaeotopography that harboured the Final Palaeolithic and Early Mesolithic occupation of the study site.

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1. Introduction

The importance of alluvial and lacustrine environments in the study of past human–landscape interactions, has made them the focal point of many geoarchaeological studies (Howard and Macklin, 1999). These dynamic environments are often the key to understanding human settlement patterns and subsistence strategies, especially when considering prehistoric societies during the Late Glacial and at the onset of the Holocene. As the visibility of prehistoric hunter–gatherers is largely influenced by taphonomy and the interpretative potential of excavated assemblages (Zvelebil and Moore, 2006), detailed insight into landscape morphology and

palaeotopography provides an invaluable asset to the study of these societies. In a broader sense, such geomorphological mapping programmes can form the basis for understanding human–landscape interactions and aid evaluating the archaeological value of research areas (De Clercq et al., 2011).

Commonly, airborne sensing data (e.g. LIDAR-derived digital elevation models) and satellite imagery are employed as guiding tools in order to understand palaeotopographical variety at a larger scale. However, detailed palaeolandscape analyses with these data can be hampered by historical and more recent anthropogenic alterations in the landscape such as urbanisation, terrain levelling or peat extraction. In addition, remote sensing data can be largely ineffective in areas with increased sedimentation, which makes it difficult to assess the palaeotopography based on elevation data. In these areas, sediment cover can create unique preservation potential for archaeological and palaeoenvironmental remains

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(Challis and Howard, 2006) but unfortunately it can also mask past landscape features.

As a complement to these data, detailed lithostratigraphic information can be added by manual or mechanical coring (Bates et al., 2000), or by trenching and the description of profiles. The latter allows a detailed description of the various stratigraphical units and can serve as a robust foundation for further palaeotopographical and geomorphological studies. But when it comes to tracing the surface expression of these different deposits throughout the landscape, their use is restricted by the length and number of the available sections. Furthermore, their applicability is mainly confined to short sequences (Bates et al., 2007). Here, borehole data provide a valuable addition to the geomorphological dataset, as these have the benefit of offering detailed insight into stratigraphical variability at sampling locations, have a larger depth range and, aided by interpolation methods, allow reconstructing their lateral extent (Bates and Bates, 2000). However, whereas remotely sensed data can be heavily influenced by anthropogenic disturbances and are of limited use in areas of sedimentation, the often low sampling densities of coring surveys restricts lateral accuracy. This limited lateral resolution may prevent a correct reconstruction of the buried topography, especially in areas with a more complex hydrological evolution.

Near surface geophysical techniques are increasingly being applied in geoarchaeological research (Baines et al., 2002; Bates et al., 2007), however, they are still rarely used to conduct large scale and high resolution palaeotopographical surveys. While surveying large areas at very fine resolutions is becoming common practice in purely archaeological geophysical prospection (e.g. Gaffney et al., 2012; Keay et al., 2009; Neubauer et al., 2002), a similar approach is rare when mapping past landscapes, as in most cases, surveys are primarily conducted along transects (e.g. Gourry et al., 2003). Combined approaches, whereby coring is used alongside geophysical and geotechnical data have already been proposed (Bates et al., 2007; Conyers et al., 2008), but these are still mainly aimed at revealing local sedimentological variability and less directed towards creating high resolution palaeotopographical models of larger areas.

To overcome these limitations, we propose an integrated methodology combining remote and mobile near surface sensing data with traditional coring. The novelty of this approach lies in the composition of a highly detailed and large scale geomorphological dataset, whereby a fine lateral resolution is combined with accurate vertical information. We have applied this methodology in the catchment area of a Late Glacial Belgian palaeolake in order to gain insight into the overall geomorphological variability and to create high resolution subsurface models where complex hidden landscapes were expected. Complemented by palaeoecological information, palaeotopographical data should represent a robust foundation for interpreting prehistoric settlement behaviour.

1.1. Study area

Situated in the north-western part of Belgium, the Moervaart palaeolake covers an area of ca. 25 km² and is connected to the Durme river in the south(east) (Fig. 1). Its formation during the Late Glacial partially postdates the creation of east–west oriented dunes and dune complexes, of which the most elaborate accumulated to the north of the palaeolake area, during the Late Pleniglacial and the colder Dryas stages of the Late Glacial (Crombé et al., in press, De Moor and Heyse, 1974; Derese et al., 2010). The dune barrier, called the Great Ridge of Maldegem–Stekene, gradually dammed the northward draining Pleniglacial river system, triggering the palaeolake formation on top of the coversands. At the end of the Allerød or the onset of the Younger Dryas, the lake seems to have dried out, changing the drainage network of the area.

Today, lacustrine deposits containing up to 45% CaCO₃ dominate the centre of the palaeolake. Throughout the area, palaeochannels can be found that have been filled in with silty to clayey sediments, intercalated with gyttja and peaty layers. Often peat layers covering the deposits can still be found, usually amidst a clayey alluvium.

During the Allerød (~12.1–10.7 ka cal BC), Final Palaeolithic *Federmesser* groups started occupying this dynamic landscape (Crombé et al., 2011; Crombé and Verbruggen, 2002). Traces of occupation are mainly found on the northern bank of the palaeolake, which exhibits a Final-Palaeolithic site density unique for the region (Crombé et al., 2011; Van Vlaenderen et al., 2006). This

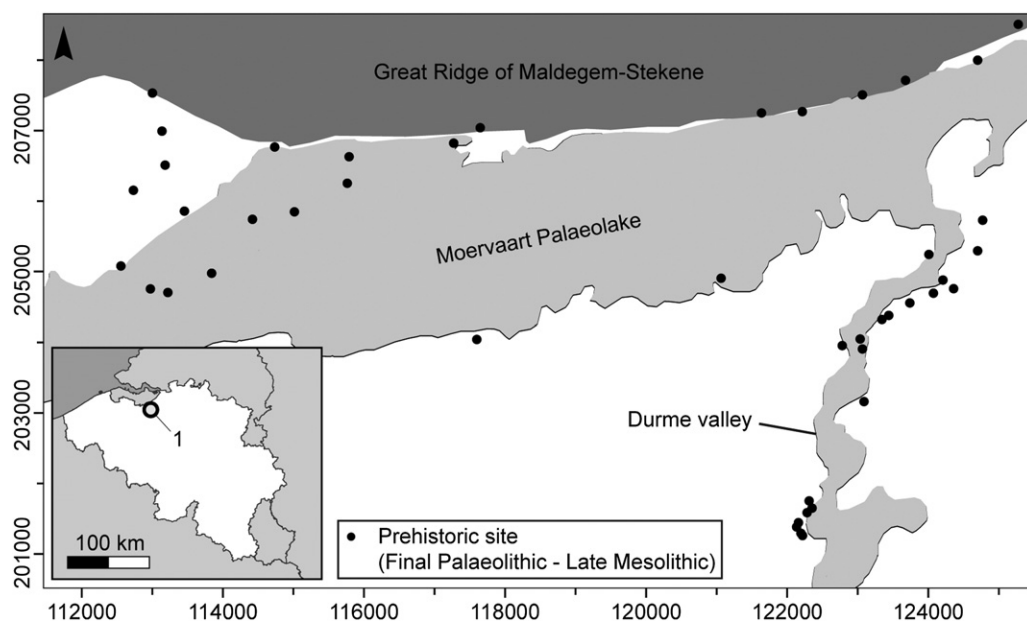


Fig. 1. Schematic representation of the Moervaart study area with the main geomorphological features (coordinates in Belgian Lambert 1972) and location of the study area in Belgium (inset).

distribution pattern was maintained throughout the Early Mesolithic (~ 8.8 – 7.4 ka cal BC), however, as by then the lake had largely disappeared, there was already an occupational shift towards the banks of the Durme river. Afterwards, site density greatly decreased during the Middle and Late Mesolithic (~ 7.4 – 6.5 ka cal BC and ~ 6.5 – 4.5 ka cal BC, respectively), although river banks remained the preferred settlement location. Site complexes were replaced by widely dispersed settlements, installed at important nodal positions between the most dominant features in the landscape. The shifting settlement pattern suggests a strong correlation between the (palaeo-)hydrological features in the area. In order to understand in detail the driving mechanisms behind these prehistoric settlement systems, a thorough understanding of the palaeohydrology of the area was required.

The results of a detailed mapping campaign, aimed at defining the palaeohydrological variation in the western palaeolake extension, are presented here as a case study of the proposed survey methodology.

2 Survey design and methodology

2.1. Digital elevation model, historical landscapes and geomorphology

The basis for the field surveys in the area were high precision airborne LIDAR data, made available by the Flemish GIS agency (AGIV) (Werbrouck et al., 2011), which had an average sample density of 1 point per 2 m^2 and an altimetric accuracy ranging from 7 to 20 cm (AGIV, 2003). After filtering out artificial features and artefacts by using topographical vector data, manually checking the data, and automatically filtering ditches and field borders through slope analysis, thematic (e.g. soil and geomorphological maps) and historical maps were used as ancillary data in order to estimate the natural pre-19th century topography (Werbrouck et al., 2011). The result was a $2 \times 2 \text{ m}$ gridded digital elevation model (DEM), excluding the main present-day anthropogenic features (Fig. 2). The

data were then used to identify fluvial patterns and large geomorphological features, and to interpret the palaeolake dimensions.

2.2. Multi-receiver electromagnetic induction survey

The focus of this survey was a zone of approximately 100 ha in the western part of the study area, where the DEM had indicated a braided pattern of small inactive channels (Fig. 2). At two locations, Stone Age assemblages were found, dating to the Final Palaeolithic and the Early Mesolithic (Van Vlaenderen et al., 2006).

The high clay content of the area, together with the often water saturated conditions, made geophysical methods targeting electrical resistance (ρ) or electrical conductivity (σ) the most suitable (De Smedt et al., 2011). As both high lateral resolution and vertical discrimination potential were needed, a mobile configuration of a multi-receiver electromagnetic induction (EMI) instrument was chosen as the primary prospection technique. The mobility of this configuration made it possible to obtain a high sampling density in a time efficient manner by driving across the survey sites along parallel lines, 2 m apart, with an in-line sampling interval of 0.25 m. This way, the multi-receiver EMI instrument (DualEM-21S, DualEM, Canada) mapped over 1 ha per hour and made possible the mapping of the apparent electrical conductivity (σ_a) of multiple soil volumes simultaneously. The instrument has four receiver coils placed in two orientations (horizontal coplanar [HCP] and perpendicular [PRP]) and at different distances (1 and 2 m) from the transmitter coil. The 1 and 2 m PRP coil pairs measure σ_a of a volume to a depth of 0.5 m and 1 m below the instrument, respectively, while the 1 and 2 m HCP measure to a depth of 1.5 and 3 m respectively (Simpson et al., 2009). After surveying, the data were interpolated to a 0.25 m by 0.25 m grid using ordinary kriging and plotted in ArcGIS (ESRI) to visualise the lateral soil texture variability.

The multi-soil volume σ_a dataset also enabled the examination of the vertical soil variability. By combining the different σ_a measurements, the depth to predefined soil horizons can be predicted. To

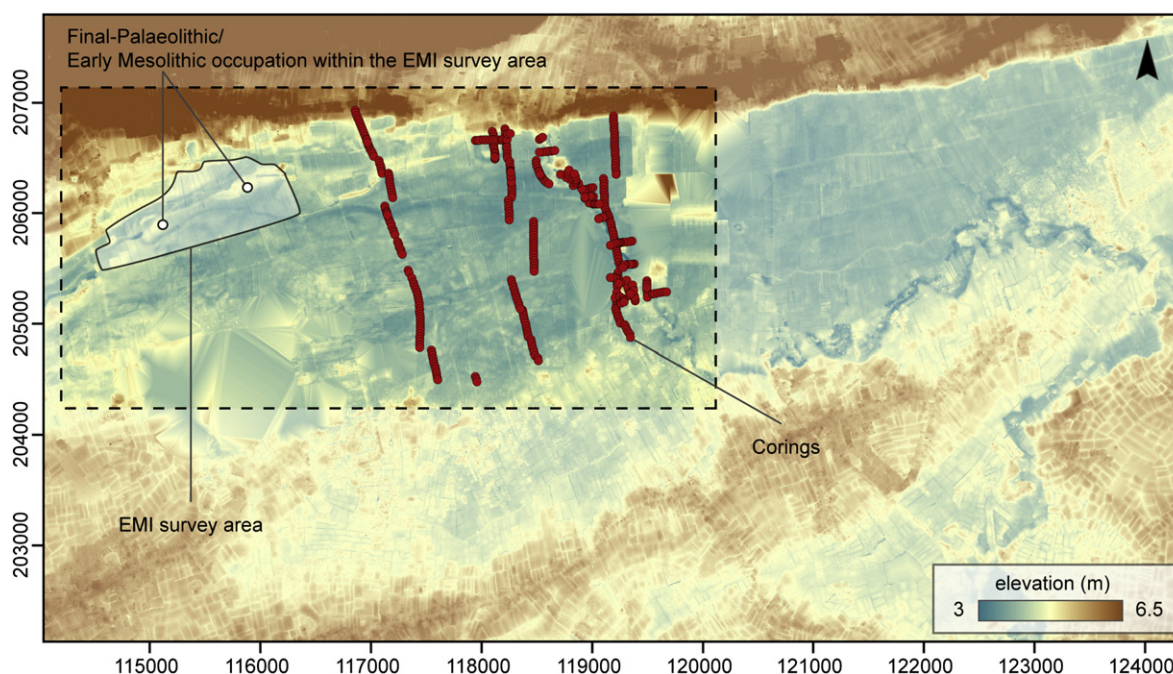


Fig. 2. Digital elevation model of the western part of the study area with indication of the geophysical survey area along with the two prehistoric sites in this zone and coring transects in the central part of the depression (coordinates in Belgian Lambert 1972).

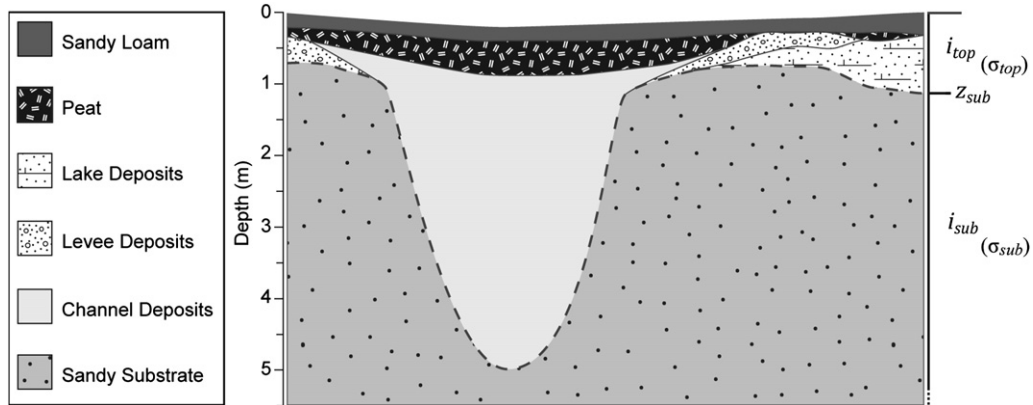


Fig. 3. Example of a 2 layered soil model, where the palaeochannel deposits and overlaying soil layers are combined in a first layer (i_{top}) while the sandy substrate is considered as the second layer (i_{sub}).

this end, a theoretical two (Saey et al., 2008) or three layered soil model (Saey et al., 2012) is composed in which the primary contrasting soil layers are isolated in separate model layers. In the palaeolake area, the main objective was to map and trace the depth of different palaeoriver systems. For this purpose, a two layered soil model was used (De Smedt et al., 2011), combining both the plough layer and the palaeochannel deposits in the first layer (i_{top}), and the sandy substrate in the second (i_{sub}) (Fig. 3).

The combination of the theoretical cumulative response functions (R) of the Dualem-21S coil pairs, derived from McNeill (1980) and Wait (1962), enabled modelling the depth to i_{sub} (i.e. z_{sub}) (Saey et al., 2008). Using these response functions, the contribution of

each layer's σ to the total measured σ_a can be determined. When the conductivity of the first (σ_{top}) and second (σ_{sub}) soil layers is known, z_{sub} can be obtained through:

$$\sigma_a = [R_{x,s}(z_{sub} + z_\alpha) - R_{x,s}(z_\alpha)] \cdot \sigma_{top} + [1 - R_{x,s}(z_{sub} + z_\alpha)] \cdot \sigma_{sub} \quad (1)$$

where $R_{x,s}$ is the response of a coil pair in configuration x (HCP or PRP) with separation s (1 or 2 m), above and below z_{sub} , with the sensor height above the surface (z_α) taken into account.

As the high and strongly fluctuating groundwater level prevented the obtaining of the conductivity values through σ_a probing,

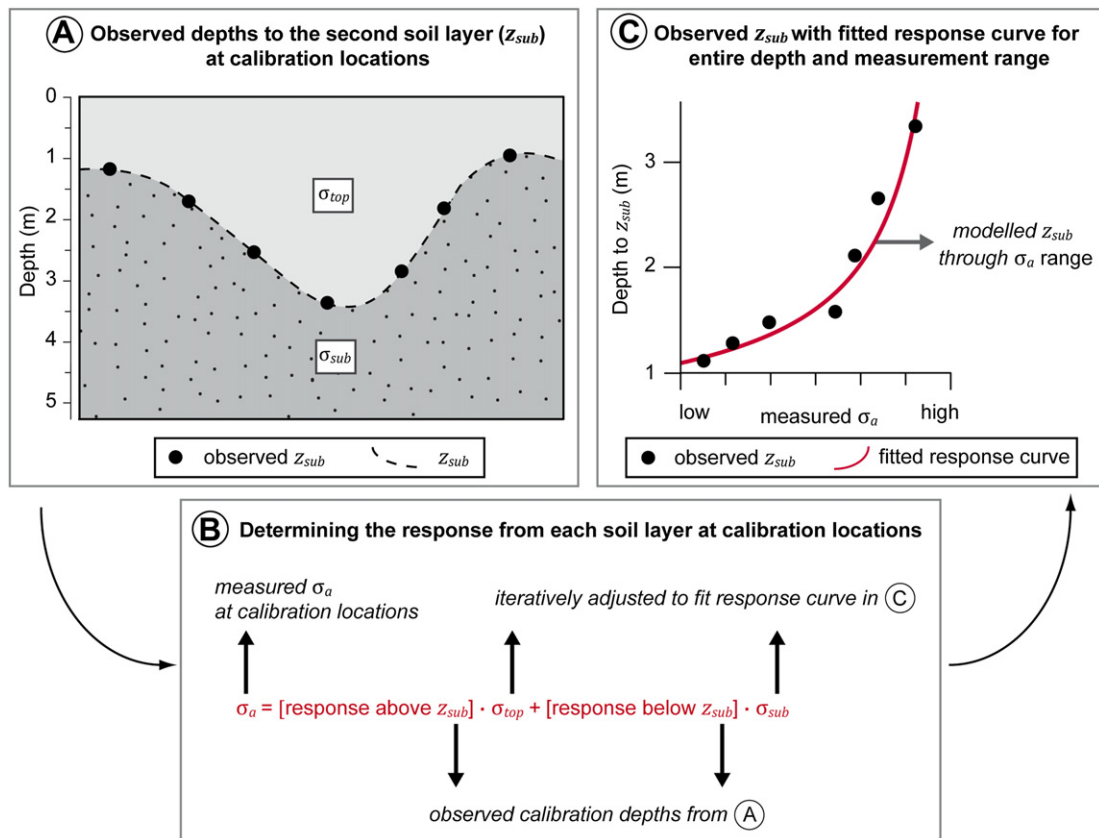


Fig. 4. Schematic representation of the calibration procedure showing the calibration corings used to determine the z_{sub} (A), the depth modelling algorithm combined with the obtained calibration depths to determine theoretical σ_{top} and σ_{sub} values (B) and the resulting theoretical response function curve fitted to the calibration data using these obtained σ_{top} and σ_{sub} (C).

theoretical conductivity values for each survey site were modelled through a calibration procedure (De Smedt et al., 2011; Saey et al., 2008). Therefore, 7 calibration cores were taken over palaeochannel segments to determine z_{sub} (Fig. 4A). By iteratively adjusting σ_{top} and σ_{sub} in order to obtain the smallest sum of squared distance between modelled and observed z_{sub} (Fig. 4B), the response functions of each coil pair were fitted to the calibration data (Fig. 4C). Based on these theoretical functions and the obtained σ_{top} and σ_{sub} , z_{sub} could be modelled for the surveyed area. In order to obtain the true depth below the surface, the modelled depths were subtracted from the unfiltered DEM of these areas. The results were filtered using a median filter with a search window of 10 m in diameter, which removed small local variations and outliers.

2.3. Coring and sampling

To validate and supplement the EMI survey and the proposed depth models, 73 manual coring samples were taken. For validation of the EMI depth models, 23 locations were first set out across a palaeoriver segment so as to evaluate the predicted depths in these sediments (De Smedt et al., 2011). Secondly, 50 additional validation samples were selected using a conditioned Latin Hypercube sampling (cLHS) algorithm (Minasny and McBratney, 2006). This sampling method takes into account both the extent of the study area and the variation of an ancillary dataset – the modelled depth. Consequentially, the resulting sample dataset, is an efficient replication of the distribution of the modelled depths and their spatial distribution.

In the deepest part of the palaeochannels, detailed core sampling was performed to enable the dating of the channel deposits. Samples were taken above and below the deposits, dating the sedimentation period. At each sample location, ^{14}C samples were taken from the bottom of the channel lag, in order to obtain a maximum age for the start of the channel's active phase, and from base of the peat formed above the abandoned channel, dating the end of the sedimentation period.

455 additional core samples were taken east of the EMI survey area (Fig. 2), tracing the different palaeochannels farther through the palaeolake. Here, descriptive coring was conducted every 25 m along north-south oriented transects (Fig. 2) using a 3 cm diameter hand corer or a 7 cm dutch auger, and had a depth range of approximately 1 m–5 m below the surface (Bats et al., 2009, 2011, 2010).

3. Results and interpretation

In the EMI survey area, a total of 60 ha was mapped with the Dualem-21S in 16 days (Fig. 5). The non-surveyed areas were inaccessible due to agricultural activities, leaving a few blind spots in the dataset (Fig. 5B). The overall high σ_a , on average 29 mS/m for the 1 m HCP coil pair, indicating the presence of fine grained, organic and clayey sediments, proved the alluvial nature of the area. While the elevated σ_a values indicated a high organic matter content, slightly clayey deposits and/or calcareous sediments, the lower values indicated more sandy zones. The results confirm the presence of different palaeochannels surrounding small sandy interfluvies, as had already been hinted by the DEM results (Fig. 5A). Morphologically, a distinction could be made between the channels in the north and south of the study area. North of the interfluvial patches, results indicate that a single-channel fluvial system ran parallel to the southern margin of the Great Ridge of Maldegem–Stekene. This pattern contrasts to that seen in the south, where a system comprised of multiple narrow channels, here interpreted as reflecting an anastomosing fluvial behaviour (cf. Nanson and Knighton, 1996), occurs.

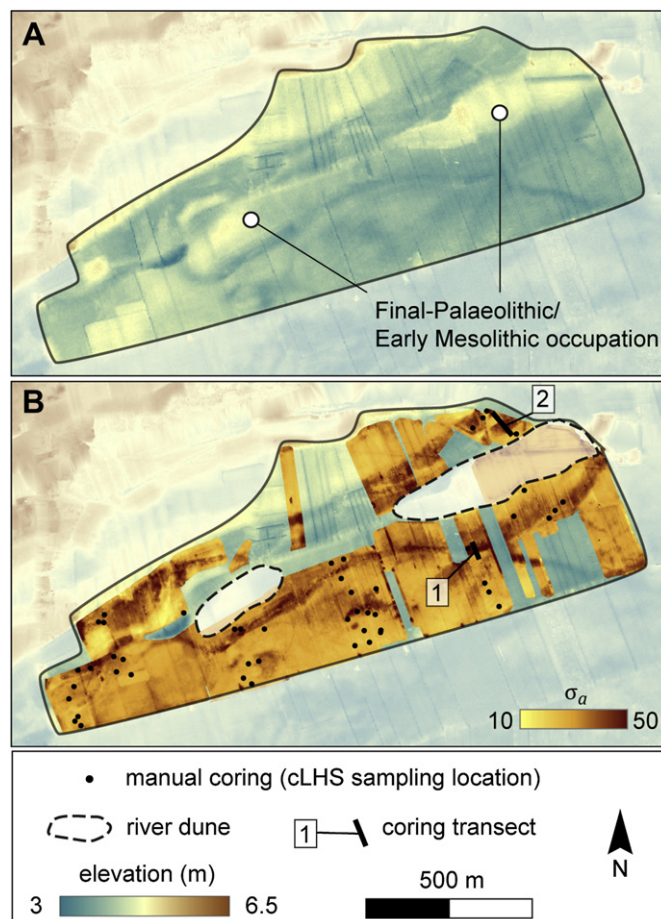


Fig. 5. Digital elevation model of the EMI surveyed area without (A) and with σ_a data from the 1 m HCP coil configuration and indication of further sampling locations (B).

Across palaeoriver segments in the northern and southern palaeoriver channels, 2×7 calibration coring locations were set out along transects 1 and 2 (Fig. 5B). They showed that the multiple anastomosing channels to the south (coring transect 1, Fig. 5B) had a laminated sequence with a high silt and CaCO_3 content, resembling the palaeolake sediments. The deposits in the northern channels, on the other hand, had a much higher organic matter content with intercalated peat and gyttja layers (coring transect 2, Fig. 5B). Based on this difference in lithology, the geophysical dataset was divided into northern and southern parts. By integrating the coring conducted for initial calibration with the depth modelling procedure, it was possible to predict the depth of the Pleniglacial sand for the entire study area (Fig. 6). This procedure was evaluated along a small palaeochannel segment by correlating modelled to observed depths, and proven accurate for modelling the substrate depth below the palaeochannel deposits with a root mean square estimation error (RMSEE) of 0.41 m (De Smedt et al., 2011).

The validation with the cLHS selected samples confirmed this accuracy but revealed a larger estimation error outside of the palaeochannel deposits. This could be attributed to the configuration of the calibration procedure, which focused on the relationship between the σ_a and z_{sub} . In the surrounding areas, the relationship was altered by the heterogeneity of the lacustrine and alluvial deposits overlaying the sandy substrate, causing a lower model accuracy. The obtained RMSEE of 0.57 m is therefore considered acceptable.

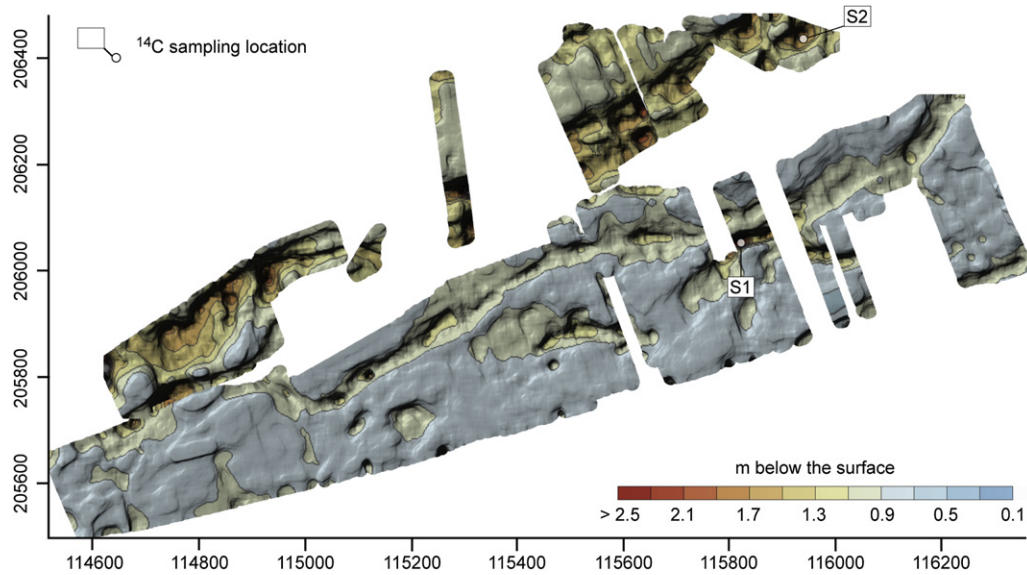


Fig. 6. Depth model of the surveyed area with the ^{14}C sampling locations in the deepest segments of the palaeochannels (coordinates in Belgian Lambert 1972).

Even though the depth variations of the palaeoriver system could be predicted accurately throughout the survey area, a clear description of the flow characteristics of both channel patterns was only partially possible. For one, non-surveyed areas made a detailed discharge analysis impossible, as this requires a continuous dataset. However, based on the depth modelling a distinction could already be made between the northern and the southern palaeochannels. While the individual southern channels are narrow and shallow, the northern channel is wider and deeper, suggesting a larger drainage capacity of the latter.

The flow direction of the detected channels was studied by comparing the depth of the different sections of the palaeochannels.

Only for the palaeochannels north of the river dunes could an inclination be detected. In the palaeotopographical model (Fig. 6), this was the most visible in the easternmost surveyed fields and indicated a preferential eastward flow for these stream channels. Farther towards the east of the palaeolake, DEM data and coring supported the notion that the straight channels were connected to a meandering palaeoriver, extending to the east and bending towards the south in the central part of the depression (Fig. 7). Here coring confirmed the eastward inclination as the depth of the channel deposits tilted from around 0.50 m below sea-level in the north to 1.45 m below sea-level in the southeast (i.e. approximately 4.50 m and 5 m below the surface respectively).

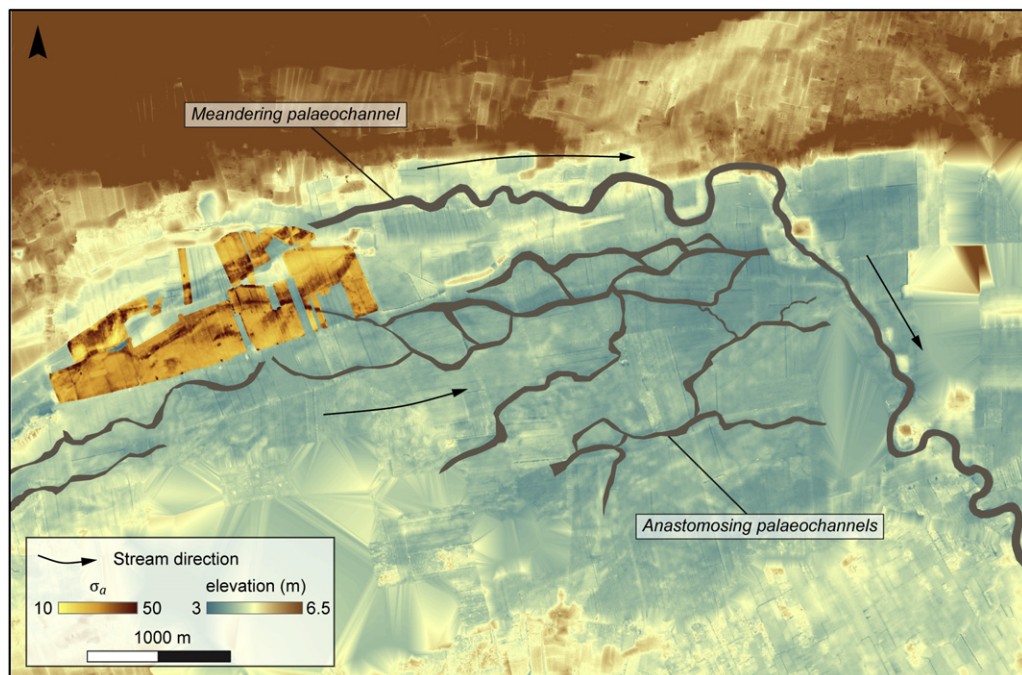


Fig. 7. Overview of the results from the EMI survey (σ_a data from 1HCP coil configuration) connected to the palaeochannels traced using the DEM and coring data, with indication of the stream direction (coordinates in Belgian Lambert 1972).

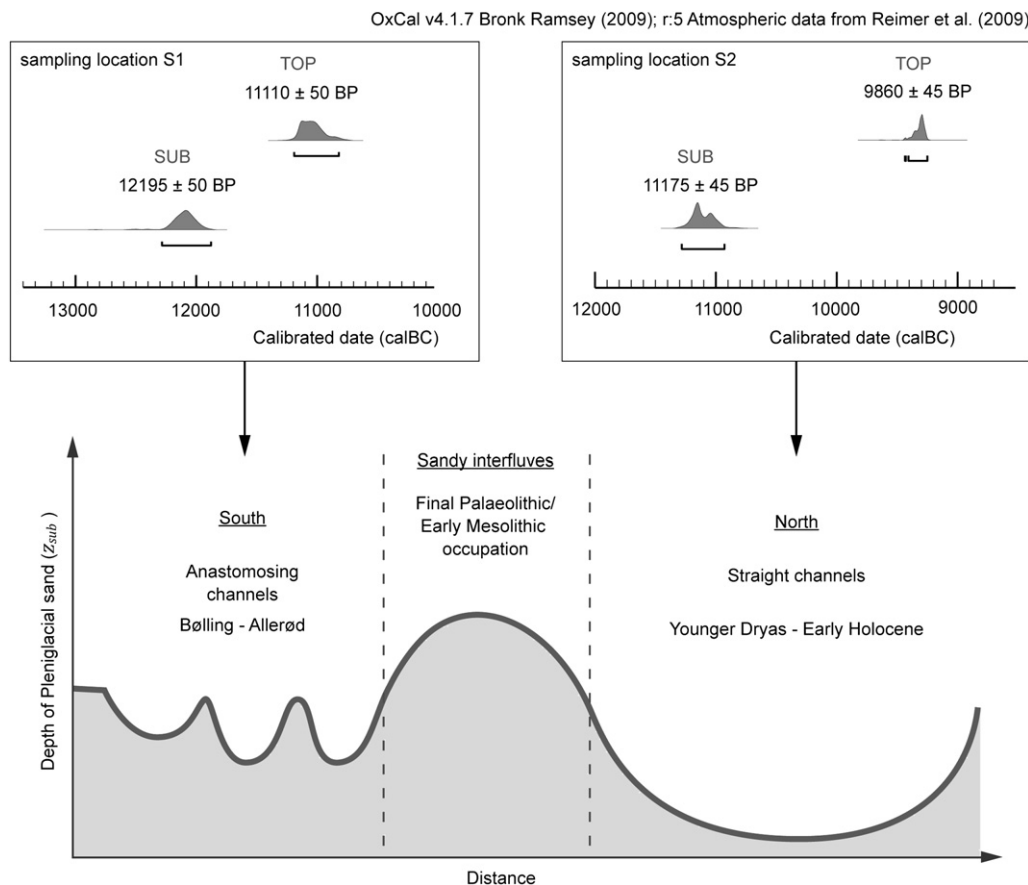


Fig. 8. Above: ^{14}C -dates obtained above (TOP) and below (SUB) the palaeochannel deposits of both the southern (sampling location S1) and the northern (sampling location S2) channels in the surveyed area. Below: Schematic cross-section of the surveyed area showing of the morphology and chronology of the different parts of the palaeoriver system related to the prehistoric occupation of the sandy interfluvies (Bronk, 2009; Reimer et al., 2009).

For the southern palaeochannels, and by extension the anastomosing palaeochannels further south in the area (Fig. 7), a straightforward interpretation of flow direction was more difficult. Apart from a deeper section where two channels of the river system intersected and a westward descent from 1.5 m above to 0.5 m below sea-level (2.5 m to 4.5 m below the surface) was detected, no clear declination towards the west or the east was attested. Farther east into the area of the palaeolake, this trend was maintained and similar depths of approximately 1.75 m above sea-level (1.25 m above the surface) were attested. This negligible slope would have promoted avulsion and aggradation within the multiple-channel system (Richards et al., 1993). However, the palaeotopographical data are unsuitable for detailed reconstructions of palaeoflow direction based on slope alone.

Guided by the EMI depth model, ^{14}C dates were obtained from the deepest palaeochannel sections (Fig. 7), which showed a different chronology of both parts of the river system; (Fig. 8) placing the sedimentation of the channel deposits of the anastomosing palaeochannels in the Late Glacial, between the (late) Bølling and the (late) Allerød period (Fig. 8 S1). Channel deposits in the northern palaeochannels were younger, with sedimentation starting in Late Allerød or the Younger Dryas and continuing into the Early Holocene (Fig. 8 S2). Based on these data and the combined results from EMI-survey, coring and DEM analysis, both the channels detected north and south of the sandy interfluvial outcrops were interpreted as different stages of channel reorganisation within the same palaeoriver system. The northern channel, with its elevated individual discharge capacity, seems to record the

concentration of fluvial flow into a single trunk channel subsequent to the gradual abandonment of the southern anastomosing channels near the end of the Allerød (Fig. 8, bottom). In considering the prehistoric occupation in the survey area, the perpetual Final Palaeolithic to Early Mesolithic occupation phases identified here were contemporary to both phases of the palaeoriver system recorded in the EMI survey data.

4. Conclusion

A multi-disciplinary approach, combining remote and mobile near-surface sensing techniques with traditional coring, has allowed for a detailed palaeotopographical reconstruction of the study area. The incorporation of a three-dimensional geophysical survey dataset, enabled a detailed interpretation of the morphology of the area, whereas coring added lithological information and the digital elevation model offered continuity at a larger scale. However, in very heterogeneous areas where no large depth variations are present in the palaeotopographical record, limitations of the method used become apparent. In this study, this can be seen outside the palaeochannels where the correlation between the modelled and observed depths deteriorates. While the heterogeneity of the areas makes it more difficult to establish a relationship between the palaeotopographical variability and the geophysical data, the palaeotopography itself has limited interpretative potential, especially when dealing with avulsive channel systems. Nevertheless, the use of mobile geophysical techniques with vertical discrimination potential alongside more traditional

methods can form a broad basis for interpreting past landscapes and could serve as a guiding tool in covered landscapes where DEM data do not allow a straightforward interpretation of the palaeolandscape. Our methodology allowed for a detailed reconstruction of the palaeotopography harbouring known Final Palaeolithic and Early Mesolithic occupation sites. Combined with ^{14}C dating, we were able to obtain a detailed view of the changing landscape around these settlements. The simultaneity between the palaeohydrological system and the archaeological remains shows the close relationship between prehistoric settlement locations and the alluvial features in the area. Despite the drastic change in drainage system, from a multi-channel system during the (late) Bølling and the (late) Allerød period to a single deep gully system in the Late Allerød/Younger Dryas and continuing into the Early Holocene, both sandy interfluvies remained attractive for human occupation throughout the Final Palaeolithic (Feder-messer) and Early Mesolithic. In order to develop a deeper understanding of the driving mechanisms for settlement patterns in the entire palaeolake area, a fuller description and reconstruction of the palaeotopographical and hydrological evolution is vital. It is the combination of these new and revisited survey methods and their integration alongside palaeoecological and chronological techniques that can offer a more complete foundation for interpreting prehistoric human–landscape interactions.

Acknowledgements

The authors would like to thank Russell Palmer for his invaluable help with the text.

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