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We Came for the Lake—Late Pleistocene Landscape Reconstruction in Lieth Moor, District Pinneberg, Germany

Stine Detjens [1,2,*], Sonja B. Grimm [1,2], Aslı Oflaz [3], Dennis Wilken [2,4], Tina Wunderlich [2,4], Wolfgang Rabbel [2,4] and Berit V. Eriksen [2,5]

1 Leibniz-Zentrum für Archäologie (LEIZA-ZBSA), Schlossinsel 1, 24837 Schleswig, Germany; sonja.grimm@leiza.de
2 CRC 1266–Scales of Transformation, Kiel University, Leibnizstraße 3, 24118 Kiel, Germany; dennis.wilken@ifg.uni-kiel.de (D.W.); tina.wunderlich@ifg.uni-kiel.de (T.W.); wolfgang.rabbel@ifg.uni-kiel.de (W.R.); berit.eriksen@zbsa.eu (B.V.E.)
3 Institute of Pre- and Protohistoric Archaeology, Kiel University, Johanna-Mestorf-Straße 2-6, 24118 Kiel, Germany; aoflaz@gshdl.uni-kiel.de
4 Institute of Geosciences, Kiel University, Otto-Hahn-Platz 1, 24118 Kiel, Germany
5 Schleswig-Holstein State Museums Foundation Schloss Gottorf, Schlossinsel 1, 24837 Schleswig, Germany
* Correspondence: stine.detjens@leiza.de; Tel.: +49-4621-813-601

Abstract: The Lieth Moor area, located in the district of Pinneberg, Schleswig-Holstein, Germany, is a hotspot of Late Palaeolithic settlement activity. The exceptional abundance of archaeological sites is commonly attributed to the presence of a large palaeolake. However, in the Weichselian Late glacial, there were numerous large lakes in Schleswig-Holstein. Thus, a well-founded explanation for the find concentration in Lieth Moor is still lacking, and forming a research desideratum until today. To improve our understanding of this Late Pleistocene landscape and its appeal to hunter–gatherer groups of that time, we conducted a large-scale archaeogeophysical study focusing on a possible ford of the potential palaeolake. We employed Ground-Penetrating Radar and Electromagnetic Induction measurements, supplemented by existing legacy drill-probing data, to identify and map limnic gyttja (organic lake mud) sediments and their spatial distribution within the area. The findings of our study indicate that during the Late Pleistocene to Early Holocene, the Lieth Moor area comprised a cluster of small ponds rather than a continuous lake. These ponds likely interconnected during periods of increased water levels. The presence of dry islands within the region corresponds with archaeological evidence, suggesting that Late Palaeolithic communities visited some of these islands. The absence of the previously postulated palaeolake places the known findings within a completely new palaeoenvironmental context: instead of the previously suspected ford, we assume that the proximity to the Elbe Palaeovalley played a decisive role in the repeated habitation of Lieth Moor. This area, rich in fresh water and fish, along with the dune chain situated to the west, serving as both a vantage point and windbreak, presented an ideal location for awaiting animals migrating along the river Elbe and/or as a resting place within the settlement system of mobile hunter–fisher–gatherer groups.

Keywords: Late Palaeolithic; geophysics; electromagnetic induction; ground penetrating radar; Federmesser-Gruppen; Ahrensburgian

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1. Introduction

Thus far, the Late Pleistocene is the last time in human history that was marked by systemic shifts in the climatic and environmental regimes on a global scale [1–3]. A thorough examination of a specific palaeolandscape, encompassing its waterbodies and topography as well as their temporal change, can aid in understanding the evolution of Late Pleistocene environmental conditions [4–7]. Furthermore, by examining the spatial distribution of archaeological material within a reconstructed landscape, it becomes possible to infer patterns of resource utilisation, subsistence strategies, and locations of settlements of prehistoric hunter–gatherer groups [8–10]. Hence, we can induce how groups attributed to the Late Palaeolithic (appr. 15,000–11,500 cal. BP in Northern Europe) adapted their settlement patterns to this landscape and the changes therein. However, Late Palaeolithic groups are commonly characterised by a high degree of mobility, and their campsites are accordingly often ephemeral and hard to locate [11–13].

Studying the palaeolandscape helps to identify suitable locations for (1) human settlements during the Late Pleistocene age and (2) areas with good preservation conditions. In particular, former waterbodies often provide favourable conditions for the preservation of organic materials, such as wood, bone, and plant remains [14–16]. By targeting this type of area, the chances of recovering well-preserved artefacts and ecofacts can be maximised, thus also allowing for an absolute dating and better functional understanding of past human activities. Hence, this research paper aims to reconstruct the Late Pleistocene landscape in a specific case study area (Lieth Moor) with a particular focus on its waterbodies and their relation to the settlement remains of Late Palaeolithic hunter–gatherers.

In particular, this study addresses the following research questions:

- What was the nature of the Late Pleistocene landscape in the Lieth Moor area? Was there a continuous palaeolake or rather a cluster of small ponds?
- Were these waterbodies interconnected during periods of high water levels?
- What insights can be gained from the landscape reconstruction regarding the attraction of hunter–gatherer groups to this region? Were there islands where people settled, or fords where hunters could wait for their prey such as herds of reindeer?

To achieve our aim, we employ Ground-Penetrating Radar and Electromagnetic Induction measurements in conjunction with legacy drill-probing data. These methods allow us to identify and map sediment distributions, particularly focusing on the limnic gyttja sediments associated with the hypothesised palaeolake. Gyttjas (German *Mudden*) are sediments deposited underwater with a minimum organic matter content of 5%. They are categorised into distinct groups according to their content of organic, calcareous and siliceous materials [17].

This paper is structured as follows: as a background, we outline the Late Pleistocene to Early Holocene climate and environmental changes and introduce the Lieth Moor area, covering its geology and archaeological material. After presenting the used materials, methods, and the survey results, we jointly interpret the palaeolandscape. Finally, we propose a model of Lieth Moor's landscape development and discuss its implications on Palaeolithic hunter–gatherer settlement behaviour.

2. Study Area

2.1. Late Pleistocene Climate and Vegetation Shifts

To understand the general chronostratigraphy of southern Schleswig-Holstein and the vegetation development within the Lieth Moor area, two pollen profiles comprising parts of the Late Pleistocene and Early Holocene sequence are available from this area [18,19]. Furthermore, a comprehensive palaeoenvironmental study of a Late Pleistocene to early Holocene sequence was possible at the nearby palaeolake Nahe where preservation conditions were excellent [20,21] (ca. 30 km distance, cf. Figure 1). The results from this study compared with the Lieth Moor profiles provide insights into the landscape changes that have affected the Lieth Moor area at the end of the Pleistocene and the onset of the Holocene. Using the INTIMATE event stratigraphy [3], the results can also be compared to the general climatic developments in the North Atlantic region and will be described in the next paragraphs.

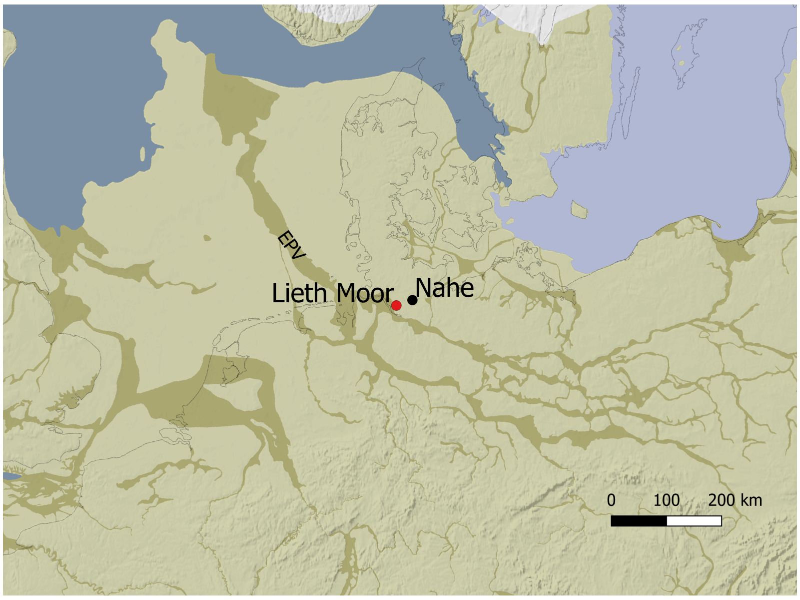

Figure 1. Lieth Moor and Nahe on a map of Northwestern Europe during the Allerød (GI-1c-a) interstadial. At that time, the sea level was reduced due to the inland ice, resulting in what is now the North Sea being dry land. Large amounts of meltwater formed glacial meltwater valleys, such as the Elbe Palaeovalley (EPV). The map and drainage systems were compiled by ZBSA after [22–27] and after [28–32], respectively (https://zbsa.eu/allerod; accessed on 1 August 2023).

The onset of the Late Pleistocene interstadial biozone is marked at palaeolake Nahe by the presence of sediments from the Meiendorf event (14,510–13,940 cal BP) [20]. The predominant vegetation consisted of pioneer plants, in particular *Hippophaë* sp., indicating the ongoing development of soils. The overall environment during this interstadial was characterised by a climatic amelioration (GI-1e). But with an open tundra environment still prevailing, reindeer were the primary targets for hunting [33].

This amelioration event ended in a short, cold, and dry fluctuation (GI-1d) that is reflected in the palaeolake Nahe pollen profile, with some decades delay, by a dry steppe vegetation dominated by grasses and herbs (Dryas 1, 13,940–13,830 cal BP) [20]. In Lieth Moor, at Klein Nordende LA 37, the presence of numerous *Hippophaë* sp. stems suggests the disappearance of the previous pioneer vegetation during this event [19].

During the subsequent Allerød interstadial (13,830–12,540 cal BP) [20], the climate further ameliorated, leading to the stabilisation of soils, ecotopes, and the landscape as a whole. Although the hydrology shows some fluctuations over this long period (GI-1c-a), the water levels generally increase, reflecting higher precipitation rates. In the Lieth Moor area, the earliest artefacts, from Klein Nordende LA 37, were found at the transition to the Allerød [19]. In the beginning of this interstadial, *Betula* sp. pollen dominates the pollen spectrum but is outnumbered further up in the profile by *Pinus* sp. pollen. This development correlates with the development in palaeolake Nahe towards open woodlands that are dominated by *Betula pubescens* in the beginning but with an increasing contribution of *Pinus sylvestris* over time [20]. The presence of elk as part of the hunting fauna at the upper horizons of Klein Nordende LA 37 [19], dating to the end of the Allerød interstadial [34], further supports the notion of denser woodlands but also extensive wetlands in the Lieth Moor region at this point. Some large fish bones found in the adjacent riparian zone also confirm the presence of larger waterbodies [35]. However, directly radiocarbon-dated osseous material from other sites in southern Schleswig-Holstein indicates the ongoing presence as well as occasional human exploitation of reindeer [36].

During the following stadial (GS-1), the temperature cooled down once again, with increasing aeolian activities and a severe dryness in the older part of this event [37,38]. In the younger part, the humidity increases again and the climate in Northern Germany becomes more oceanic [20]. The fully developed stadial vegetation zone of the Dryas

3 (12,540–11,560 cal BP) lagged significantly behind the climatic onset of this cold event, showing a gradual transition from interstadial to stadial conditions. In total, it exhibited a mosaic of tundra and steppe elements, with occasional clusters of bushes and trees found in protected and moist locations. This environment was described as park tundra [39], and a cold climate fauna, including reindeer and arctic fox, became dominant again and spread across the North European Plain [33]. However, towards the end of this stadial, a more diverse faunal spectrum is reflected in southern Schleswig-Holstein by directly radiocarbon-dated specimens of horses as an indicator for open landscapes [40] and of bison (*Bison bonasus*) as well as elk as indicators for woodlands with a strong wetland component for the latter ([41], footnote 1).

The very sudden climatic change towards Holocene conditions (GH) was mainly characterised by higher temperatures and the associated thawing of permafrost. The lake levels in Schleswig-Holstein appear to have remained stable [20], suggesting no significant increase in precipitation. Biostratigraphically, the onset is reflected in a rapid increase in *Betula* sp., including tree birches at palaeolake Nahe. Nonetheless, grasses were also increasing, indicating that the vegetation succession towards light birch forests allowed for larger open areas and/or birches that remained primarily in the shrub stage. Hence, this environment still allowed for the presence of reindeer, which remained in the area until the Preboreal oscillation (11,390–11,250 cal BP) alongside an increasing number of woodland and wetland species such as bison, elk, beaver, and red fox [42]. After this period, the Late Palaeolithic assemblages disappear from Northern Germany, and the first Mesolithic sites appear [43].

2.2. Geological Setting

Lieth Moor is located in the district of Pinneberg (Schleswig, Germany), southeast of Elmshorn. It has received extensive geological attention due to its location atop the Elmshorn salt diapir (e.g., [44,45]). The presence of the salt deposit has played a significant role in shaping the Lieth Moor region. Halokinetic movements caused Rotliegend clay marl (known in the area as 'red clay' or 'red loam') and Zechstein limestone ash to rise up to near the present surface [45–47]. Subrosional processes have contributed to the formation of a central trough and an outer uplifted ring in the landscape [44,45]. Additionally, several small-scale karstic sinkhole features are known [48–50].

During the Elsterian and Saalian glaciations, the study area was covered by glaciers depositing moraine and sandur material. In the subsequent Weichselian glaciation, the glaciers did not reach the Elmshorn diapir [51]. Instead, the area was periglacially levelled by glaciofluvial and aeolian sand deposits [52]. Expressions of periglacial processes such as solifluction, stone pavements, and patterned grounds occur commonly [19,44,53–55]. Intercalated with Late Pleistocene aeolian cover sands, there are also deposits of warm temporal soils, gyttjas, and peats reported [54–56]. These findings indicate a complex sequence of various soil and lake formation phases in the central trough.

The gyttja deposits in the central trough were first discovered and geologically mapped in 1953 [57]. The previously postulated lake [58], now termed *Palaeolake Esing*, subsequently underwent a more detailed examination: the southern lakeside region was investigated by [59,60]. The authors of [48,49] examined the northern lake area, while [61] studied the former western to southwestern shore region. Additionally, the investigators of [62–64] extended this mapping to trace its continuation within the Hammoor area. The most recent and comprehensive geological mapping was compiled in 1997 by [45], who integrated the aforementioned data in conjunction with new drillings.

At the onset of the Holocene, water regimes shifted once again due to the rising sea and groundwater levels [50,53,57]. This change led to the renewed deposition of peat and the formation of the wetland. A hiatus between lake deposits and the following peats indicates a phase of subaerial conditions before the onset of peat growth [37,65].

Today, the landscape in the Lieth Moor area is intensively anthropogenically overprinted. The once widespread peat deposits have been almost completely extracted [53]. The area was then intensively drained and is now utilised mainly for green fodder production. Furthermore, lime ash and 'red loam' were extracted from the region for use as fertiliser and in brick production, respectively.

2.3. Archaeological Context

The Lieth Moor area is part of a larger peatland zone resulting in different topographic denominations in the past such as Lieth Moor (e.g., in present-day topographic maps or [66]), Esing Moor [67,68], or Hainholz-Esing Moor [19,58,69]. Peat extraction began prior to the Prussian topographic land survey, resulting in only scattered remains of Lieth Moor visible on the earliest maps [67]. Hence, when archaeology as a science and public archaeological interest began to grow, significant areas were stripped of Holocene sediments, allowing for Late Palaeolithic artefacts to be discovered at the surface. Already in the 1940s, an abundance of archaeological sites in this area had been noted [68]. In the 1960s, this high site concentration was once more identified, with [69] attributing it to the presence of a larger lake. However, this situation is not unique as the melting Weichselian glaciers have left many larger lake systems in Schleswig-Holstein, which makes this argument unconvincing. Therefore, the concentration of archaeological finds in Lieth Moor lacks a comprehensive explanation, which represents a research desideratum that persists to this day.

In Lieth Moor, 88 archaeological sites are recorded (see Figure 2) in the register of prehistoric and historic artefacts and archaeological sites and monuments of Schleswig-Holstein (*Landesaufnahme* = LA). At some of these sites, numerous artefacts have been collected from the surface, occasionally reflecting palimpsest situations. Hence, we established 99 Stone Age assemblages that we attributed to the Stone Age in general (n = 14), the Neolithic (n = 27), the Mesolithic (n = 30), and the Late Palaeolithic (n = 28). Among the Late Palaeolithic inventories, the general Late Palaeolithic (n = 6), Ahrensburgian (n = 12), and Federmesser-Gruppen (n = 10) assemblages have been identified. For the chronology of the technocomplexes, please refer to Table 1. Interestingly, no finds of the first Late Palaeolithic pioneers of the Hamburgian have been identified, although they were present in the Ahrensburg tunnel valley c. 35 km to the southeast where similar living conditions existed during the Late Pleistocene [21,36]. Equally, large (Bromme) tanged points have not been found in this area so far. However, the known sites provide strong evidence for regular human occupation in this area from the Allerød throughout the early and middle Holocene.

Table 1. Chronological sequence of archaeological groups in Northern Germany (for more details see [36,43]; Bromme Culture in Denmark according to [70]) in comparison to the INTIMATE event stratigraphy [3]. Technocomplexes written in grey are not present in Lieth Moor.

	Technocomplex	Chronology (in yrs cal. BP)	INTIMATE Event Stratigraphy (Onset in yrs cal. BP)
Early Mesolithic	Maglemosian	11,400–8500	11.4 ka BP event (11,470)
Late Palaeolithic	Ahrensburgian	12,800–11,400	GH (11,653)
			GS-1 (12,846)
	Bromme Culture	13,200–12,650	GI-1c-a (13,904)
	Federmesser-Gruppen	14,000–12,800	
	Hamburgian	14,700–14,000	GI-1e-d (14,642)

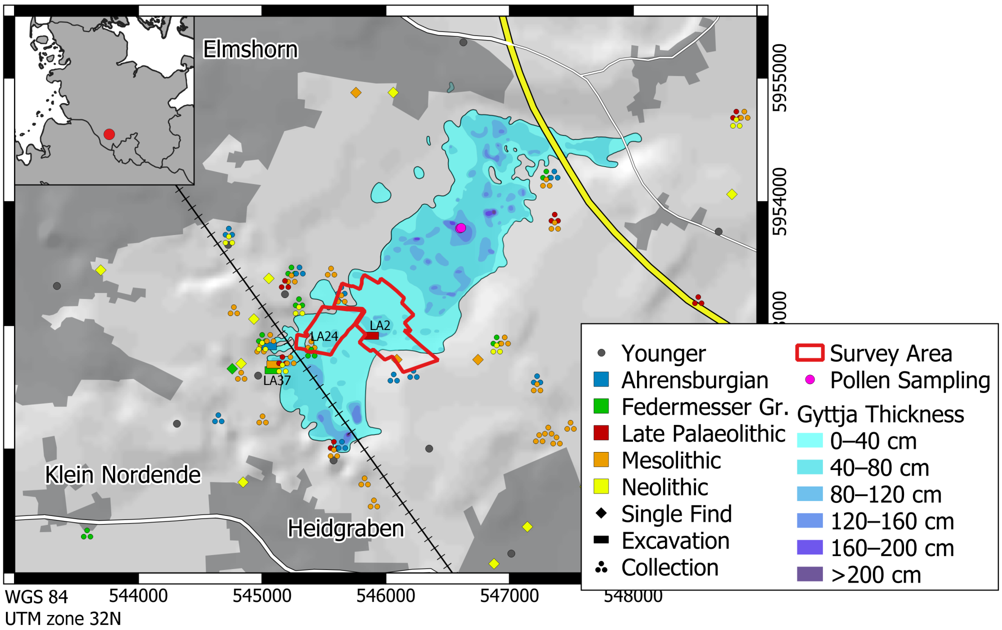

Figure 2. Overview of the Lieth Moor area and known archaeological sites. The palaeolake reconstruction (gyttja thicknesses) after [45] and near the train tracks after [59] is drawn in blue. Pink dots indicate the location of pollen sampling by [18,65].

Only three of the numerous Late Palaeolithic sites were archaeologically excavated: Wolfgang Taute's excavation at Klein Nordende LA 2 in 1960 ([66], pp. 71–76) (cf. Figure 2) is of particular relevance due to its location within our archaeogeophysical survey area. This excavation was initiated by the presentation of worked reindeer antlers, which had already been discovered during well construction in the 1930s. Forty search holes were laid out, the exact locations of which are no longer traceable. In the process, a gyttja deposit was found and extensively investigated with 62 boreholes and six excavation areas. The confined nature of the gyttja deposit led to the interpretation of it as a small pond, and a palynological analysis of the gyttja sediments assigned it to the Dryas 3 stadial ([66], p. 75). On a sandy elevation approximately 50 m north of the gyttja, lithic artefacts have been found since the 1930s in a relatively dense concentration, although they were probably subject to movements by ploughing. Taute considered a few undiagnostic lithic artefacts and a few faunal remains from the gyttja, the worked reindeer antler, and the collected lithic material from the surface as representing the remains of a Stone Age camp ([66], p. 75). He attributed this camp and the worked reindeer material to the Dryas 3 as he assumed the finds and the sampled gyttja to be contemporaneous. Consequently, he attributed the material to one of his subgroups of the Ahrensburgian. Hence, based on the location in a possible ford situation of the reconstructed *Palaeolake Esing*, we considered the setting as similar to the reindeer hunting site of Stellmoor [71] and/or Nahe LA 11 [72]. However, calibrated radiocarbon dates of the reindeer antler material clearly belong to the early GI-1c event, and a re-examination of the lithic material showed no reliable technotypological indication for Ahrensburgian material, making the previous considerations obsolete.

The other two archaeological excavations are located west of the train tracks.

Klaus Bokelmann excavated at LA 37 [19] (cf. Figure 2), in which parts of a Federmesser-Gruppen site preserved beneath Dryas 3 dune sands were uncovered. Late Pleistocene shorelines of a potentially large palaeolake were also identified.

The most recent archaeological excavation was directed by Ingo Clausen and Annette Guldin (the Archaeological State Office Schleswig-Holstein) and took place in 2013 (cf. the blue rectangle in Figure 2). Based on the geological mapping of limnic sediments by [59], the team expected to encounter the western shoreline of the potential palaeolake. However, instead of an undisturbed site or lakeshore, they found heavily displaced layers (pers. comm. I. Clausen).

In summary, the results of the aforementioned excavations are contradictory, illustrating the complex and not yet fully understood geological development of the Lieth Moor area in the Late Pleistocene to early Holocene. Further research is needed to place the reported archaeological finds in a more precise landscape context. In the following, we approach the first step of this research in a largely noninvasive way. On the one hand, this allows us to cover a larger area, and on the other hand, we preserve the archaeological sites for future research.

3. Materials and Methods

3.1. Prospection Concept

To gain insights into the Late Pleistocene landscape in Lieth Moor, we aim at identifying and mapping sediment distributions, particularly focusing on the limnic gyttja sediments associated with the hypothesised palaeolake.

Gyttjas exhibit heightened organic matter and water content relative to the underlying mineral parent material, which results in contrasts in the electrical properties [73]. Additionally, gyttja types vary greatly in their mineral composition and organic matter content [17,74], which can lead to site-specific contrasts at the interfaces between different gyttja layers [73,75–77]. Therefore, we employ geophysical techniques that are sensitive to electrical conductivity and dielectric permittivity contrasts, namely Electromagnetic Induction (EMI) and Ground-Penetrating Radar (GPR) (cf. Figure 3). Unfortunately, the EMI equipment was only available for a limited amount of time, i.e., measuring a confined test area. We prioritised the proximity of LA 2, given its significance as the source region of the reindeer antler artefacts [66].

Figure 3. Impressions from the geophysical fieldwork in Lieth Moor. (**Left**): GPR measurements are performed by dragging the 200 MHz antenna across the ground. (**Right**): EMI measurements were conducted with the device carried at waist height, approximately 1 m above the ground. Photos: Stine Detjens.

Both methods are particularly suitable as they are time efficient and provide continuous images of subsurface properties. GPR enables detailed profile sections of sedimentary structures with good depth resolution, while EMI rapidly offers an overview of lateral variations in electrical conductivity [77,78]. This continuous mapping is a decisive advantage in contrast to sparse point data, for example from soil samplings [79].

Nevertheless, there are limitations to gyttja imaging using EMI and GPR. Electromagnetic waves experience strong attenuation in waterlogged and/or clayey conditions [77,79]. Furthermore, the contrast between gyttjas and underlying mineral parent material may be diminished in areas of high clay content. Despite these limitations, we adhere to the recommendation of [77] to use GPR and EMI in the first geophysical investigation step (step 2 after [77]), as the area is extensively drained and clay forms the basement only locally.

Besides a thorough method selection, geophysical surveys always need additional ground truth to match the measured physical contrasts in the subsurface with corresponding lithological boundaries. To address this, we incorporate legacy drill-probing data to contextualise and validate our findings and provide ground truth information.

In the expansive Lieth Moor region, we delineated a specific focus area based on the legacy data to concentrate our investigation. Our focus is on a transect situated in the central part of the reconstructed *Palaeolake Esing*, as detailed by [45]. This subarea exhibits relatively thin gyttjas, and there are indications of a potential ford or island [45,66]. Unfortunately, the (timely) acquisition of permissions from all landowners and tenant farmers for a comprehensive survey of the entire designated survey area proved challenging.

In summary, our prospection concept combines geophysical EMI and GPR techniques with legacy borehole data to shed light on the Late Pleistocene landscape and better understand the distribution of limnic gyttja sediments within Lieth Moor (cf. Figure 4).

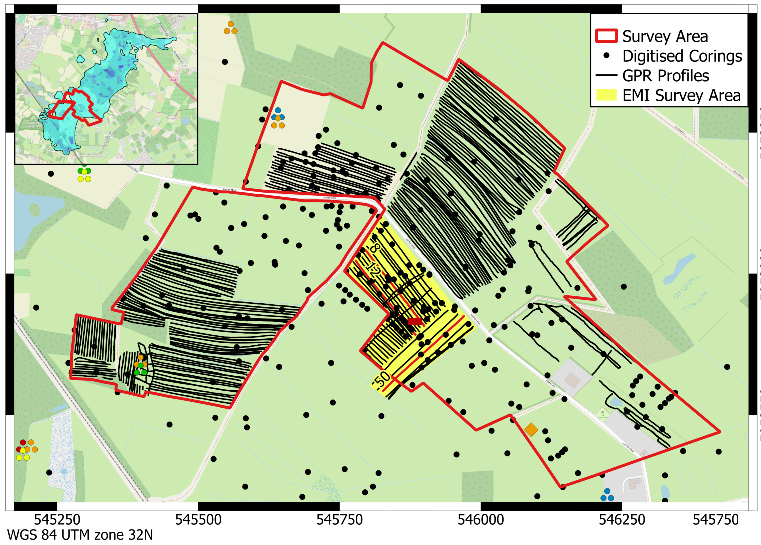

Figure 4. Compilation of the database. GPR profiles 8, 12, and 50 (cf. Figures 5, 6 and 13) are highlighted in red. Locations of archaeological surface finds and excavation sites spanning from the Late Palaeolithic to the Neolithic period are indicated by using the symbolisation key provided in Figure 2.

3.2. Ground Penetrating Radar

Ground-Penetrating Radar (GPR) operates by emitting electromagnetic waves into the ground [80,81]. Subsequently, a receiver records the amplitude and phase of the reflected portion of these waves after the measured two-way traveltime. This method is sensitive to variations in the dielectric permittivity and electric conductivity within the subsurface. Changes in the dielectric permittivity cause contrasts in the wave velocity that result in reflections or scattering of the waves. The electric conductivity influences the level of damping experienced by the waves.

2D GPR profile measurements were conducted by using a GSSI SIR 4000 unit with a 200 MHz centre frequency antenna (cf. Figure 3 left). GPR as well as EMI measurements were positioned by a Stonex SAPOS system mounted to the respective geophysical measurement equipment. We covered the measurement area with GPR profiles at 5 m intervals where possible (cf. Figure 4). Drainage ditches often determined the orientation of the profiles, and in some areas, the heavy growth of rushes prevented further measurements. The acquisition settings were as follows: sampling frequency, 93 Hz; number of samples, 1024; number of stacked scans, 12; time window, 140 ns for profiles 1–31 and then adjusted to 200 ns.

The data were processed by using an in-house program called MultichannelGPR. MultichannelGPR is a collection of MATLAB® Scripts for GPR data processing available on request [82]. The processing of the data included the following steps: time-zero correction; subtraction of the mean trace; bandpass filter of 80–320 MHz (profiles 1–53) or 25–500 MHz (profiles 54–276) (based on spectrum analysis and the observed S/N ratio); spherical divergence correction; and topographic migration by using a constant velocity of 0.063 m/ns as derived from diffraction hyperbola fitting. The processed GPR profiles were exported as segy-files and imported into IHS Kingdom Suite.

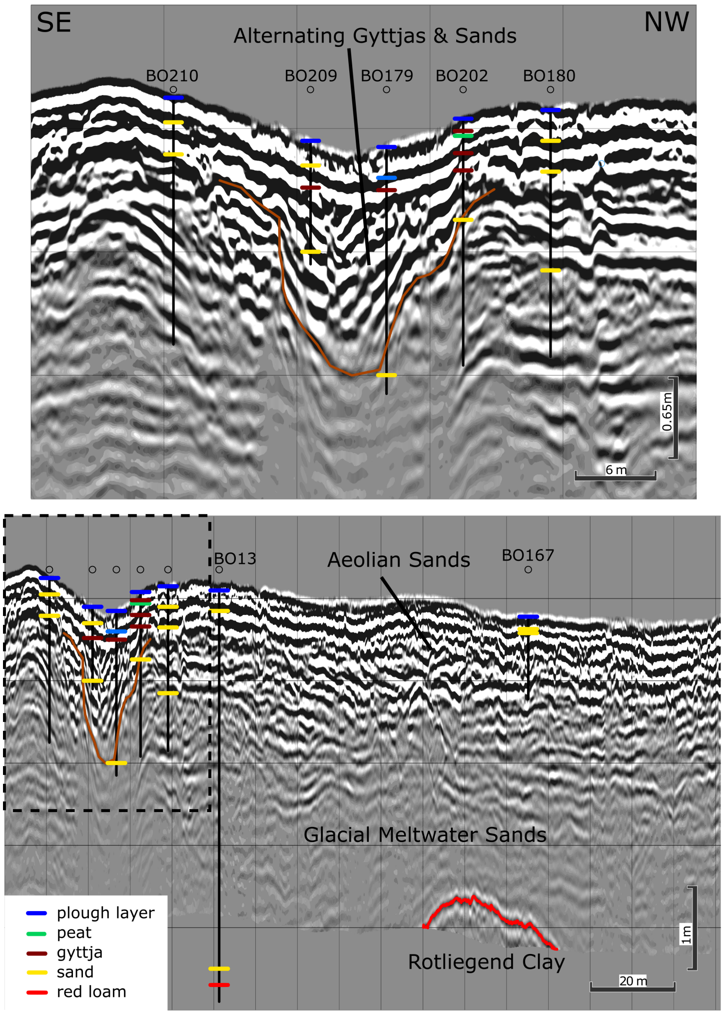

Figure 5. GPR profile 12 crossing the channel structure and adjacent cores. Top: enlarged detail of the channel structure. The red line indicates the reflection originating from the boundary between Rotliegend clay marl ('red loam') and glacial outwash plain sands. The brown line denotes the base of the high-amplitude facies, which corresponds to alternating layers of gyttjas and sands. Depths have been derived by using a constant migration velocity of 0.063 m/ns, as determined via diffraction hyperbola fitting.

3.3. Electromagnetic Induction

Electromagnetic Induction (EMI) is sensitive to the electrical conductivity and the magnetic susceptibility of the subsoil [83,84]. A transmitter coil emits an oscillating magnetic field into the ground, where it generates eddy currents. These currents generate a secondary magnetic field, which interferes with the primary magnetic field. A receiver coil records the superposition of both magnetic fields.

We conducted EMI measurements in horizontal coplanar (HCP) mode by using a CMD Explorer (GF Instruments) device with three coil spacings of 1.48 m, 2.82 m, and 4.49 m. This results in effective depths of 2.2 m, 4.2 m, and 6.7 m according to the user manual. The device was carried at a height of about 1 m, reducing the effective penetration depth by this height (cf. Figure 3 right). Acquisition was performed in continuous mode, wherein the device was moved along the profile continuously, simultaneously measuring the GPS position and data. Data sampling was performed at a 10 Hz sampling frequency.

We covered an area of approx. 3.5 hectares (marked in yellow in Figure 4) with continuous profile measurements spaced approximately 10 m apart.

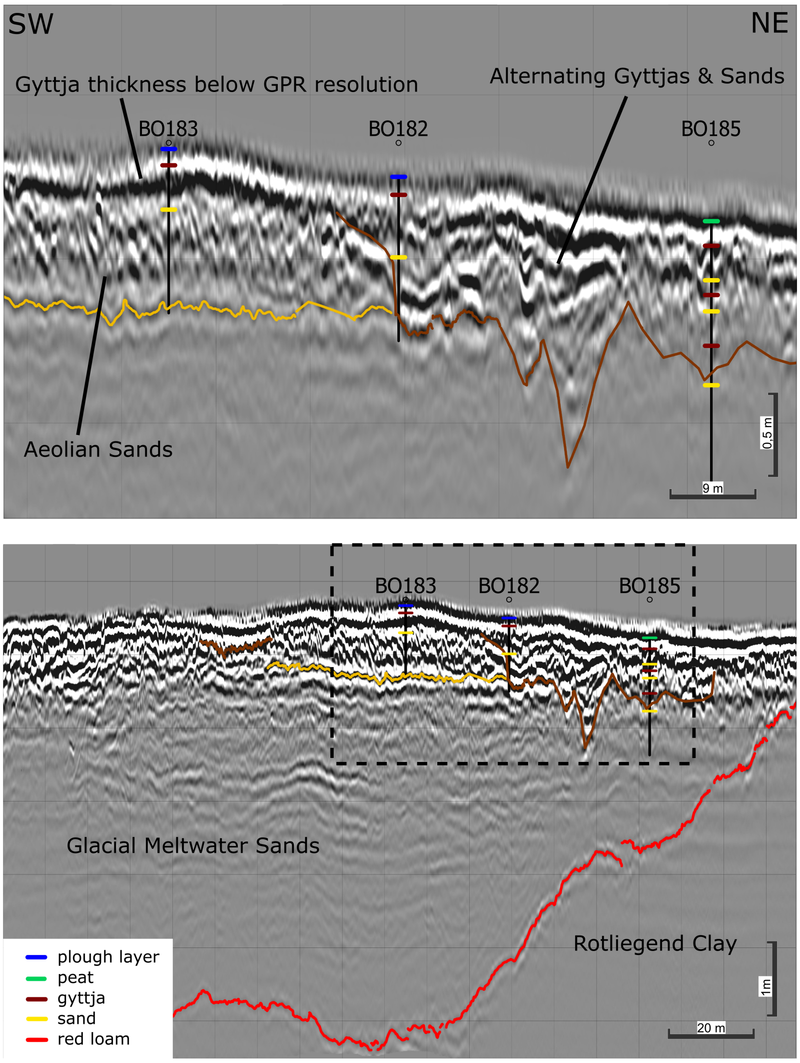

Figure 6. GPR profile 50 and adjacent cores. Top: enlarged detail of the uppermost 2 metres. The red line shows the top of the 'red loam', which emerges extremely close to the surface towards the northeast. The brown line denotes the base of the limnic gyttja and sand facies. Additionally, within this specific subarea, an extra reflector beneath the aeolian sand facies is discernible and is delineated by the yellow line.

The processing of the data included the following steps: correcting RTK-GPS positions for each individual coil pair centre offset as well as the gridding, interpolating, and filtering of the data by using a grid increment of 2.5 m and a 2D median image filter. A drift correction was only performed for the first coil pair inphase component as the effect of instrument drift was less than the observed data error for all the other measured components.

Beyond the mapping of apparent conductivity, we also performed independent 1D conductivity inversions for every 2.5 m by 2.5 m sized bin of the dataset. The minimisation of misfit was implemented by using a 1D stochastic optimisation approach that combines dimension adapting Reversible Jump Markov Chain Monte Carlo with Artificial Bee Colony optimization [85]. Several solution models of simplified model geometry and a variable number of model knots are found by the code for each 1D inversion. These models are resampled in 0.2 m depth steps and used to calculate an average solution model. This mean model together with its variances and covariances is taken as the result for the regarding bin and is represented at the according location in the images presented in this paper. All 1D inversions are independently performed with the following parameters: the minimum and maximum number of model knots were 2 and 4; the bee hive size was set to 400 and maximum iterations to 200; and the number of best models used to calculate the average solution model and (co)variances was 50. Forward modelling during the inversion processes was performed by using the full solution code by [86]. Subsequently, the resulting 1D models were combined into a pseudo-2D profile or pseudo-3D cube representations.

3.4. Legacy Drill Probing Data

Legacy drill-probing data from sedimentary descriptions by [60,61] and from data provided by the Geological State Archives of Schleswig-Holstein (LfU) were digitised in the same IHS Kingdom Suite project for joint interpretation with the GPR profiles. Notably, these datasets were not generated for archaeological landscape reconstruction but rather for the preparation of geological/soil maps or prospection for site-development projects.

4. Results

4.1. Ground-Penetrating Radar Measurements

We delineated the key GPR reflectors and facies apparent in the Lieth Moor study area and evaluated radar profiles in combination with drill-probing data to assign lithological boundaries or facies to the radar signals, respectively. Because the drillings were not performed concurrently with the GPR measurements but instead represent legacy data, the borehole locations frequently do not align precisely with the radar profiles. In our interpretation, we considered boreholes located up to 10 m away in areas of sparse borehole density. In areas with a higher drilling density, this criterion was narrowed down to 3 m. Nevertheless, the information obtained from these corings was essential in understanding the GPR reflection patterns and local lithology.

Figures 5 and 6 showcase GPR profiles 12 and 50 as representative examples. These profiles vividly exhibit the four major radar facies within the study area. The lowermost stratum features a high-amplitude continuous reflector with a transparent GPR facies underneath. This signal is caused by the Rotliegend clay marl, colloquially known as 'red loam' or 'red clay' in the Elmshorn salt diapir area. This interpretation is supported by geological observations, as for example in drilling BO13 (cf. Figure 5, red mark). The transparency of this GPR facies arises from extreme damping due to the high conductivity of the clay. In parts of the study area, the Rotliegend 'red loam' emerges remarkably close to the ground surface, as exemplified in profile 50 (Figure 6).

Overlying the Rotliegend 'red loam', the next GPR facies exhibits an overall low reflectivity, featuring predominantly continuous and nearly horizontal internal reflectors with minimal undulation. These reflections correspond to layers of fine to medium coarse sands, as reported from numerous legacy drillings within the area. The low reflectivity is likely a result of water saturation, as Lieth Moor typically experiences shallow groundwater levels [60]. We construe these sands as glacial meltwater/outwash plain sands, based on the internal reflection patterns and reflector continuity as discernible in the radar profiles. However, it should be noted that only a handful of investigators in the Lieth Moor area have conducted microscopic laboratory analyses of the grain shape to ascertain the genesis of the sands (e.g., [48]). The bulk of the available drilling data comprises field observations. Consequently, differentiating between glacial meltwater sands and aeolian cover sands remains a challenge given the presented database.

The uppermost section of the GPR profiles is characterised by two distinct radar facies. Both display overall higher radar amplitudes compared to the outwash plain sands as they are representing the vadose zone. The first near-surface GPR facies exhibits the highest amplitudes of all radar facies within the Lieth Moor area, displaying complex internal reflection patterns. Numerous legacy drillings have affirmed that this radar facies corresponds to the limnic sedimentary facies, which consists of alternating layers of differing gyttja types and sand layers. The thickness of this facies is often low, and delineating its base is therefore a challenging task. In some areas, gyttja layers are reported in the drillings but are either too thin to be resolved by GPR or are masked by the direct wave (cf. for example in BO183, Figure 6, brown mark). Following the quarter wavelength criterion ($\lambda/4 = v/4f$), using v = 0.063 m/ns as derived from diffraction hyperbola fitting and the antenna centre frequency of 200 MHz, the expected vertical resolution falls in the order of 8 cm. In 21 digitised corings, the gyttja thickness is lower than this 8 cm resolution limit. Within the gyttja facies, a v-shaped, channel-like structure is particularly striking. Here, the gyttja layers attain their maximum thickness in the surveyed area, and intricate layering patterns of various gyttja types intercalated with sand layers become visible particularly well. Below the channel lies a zone of increased radar signal attenuation. Its origin remains unclear, as no available drilling has penetrated this low-reflectivity zone. While most drillings do not reach sufficient depth, the deeper drilling BO13 is unfortunately situated to the west/outside of this zone.

The second near-surface radar facies exhibits small-scale and chaotic internal reflections. Radar reflectivity is generally high, albeit lower than observed in connection with gyttjas or Rotliegend 'red loam'. This radar facies corresponds to the aeolian sands as evidenced in numerous borehole observations. Discerning the transition to glacial meltwater sands is often challenging. Only in some subareas are the different sand deposits demarcated by a discernible reflector (see the yellow line in Figure 6). Possibly, this hints at a stone pavement in this location, just as described at multiple outcrops in Lieth Moor (e.g., [52,55]).

This study is primarily focused on examining sediments originating from either a single continuous palaeolake or multiple palaeoponds situated within the central basin of the Elmshorn salt diapir. Consequently, we placed particular emphasis on the limnic sedimentary facies, characterised by alternating layers of gyttjas and sands. Throughout the entire survey area, we identified the base of the corresponding GPR facies by using Kingdom Suite software. Figure 7 provides a map illustrating the derived depths of the gyttja layer base beneath the ground surface, measured in metres. It is noteworthy that multiple isolated gyttja deposits are discernible in our observations. Of particular importance is the observation that gyttja is found at significantly greater depths within an elongated, channel-like structure, which follows a northeast–south-oriented quarter-circle path.

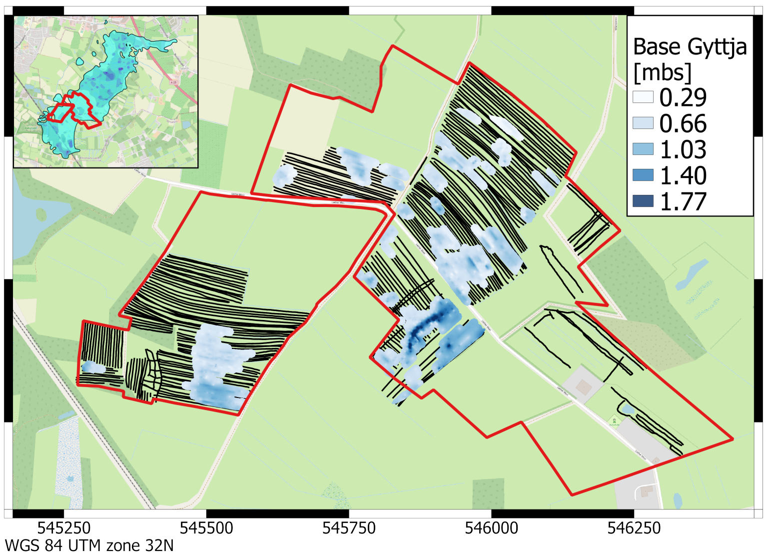

Figure 7. Depth of the gyttja base in metres below ground surface as derived from GPR profile interpretation.

4.2. Electromagnetic Induction Measurements

Processed plan views of the EMI results are presented in Figure 8. The (apparent) electrical conductivity values range from 4.3 to 38.3 mS/m, exhibiting an east- and southward increase. Notably, an elongated linear feature and several localised high-conductivity zones are discernible. This conductive linear feature encompasses a region of reduced conductivity. Regarding the inphase data, significant noise is observed, and inphase values do not appear to exhibit a correlation with the local lithology. Noteworthy are the extreme inphase and increased conductivity values (marked by an upright triangle in Figure 8), which are attributed to modern construction waste, as fieldwalkers observed burnt bricks in that area.

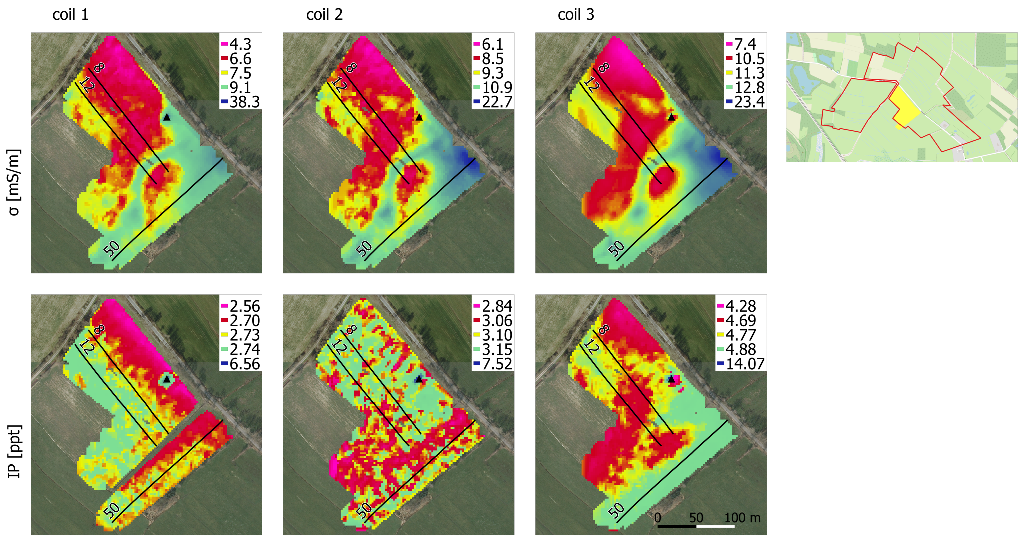

Figure 8. EMI data after processing. This figure illustrates the electrical conductivity (σ; **top**) and inphase (IP; **bottom**) data obtained from the three coil pairs, presented from left to right. Black lines indicate GPR profiles 8, 12 and 50. An upward triangle denotes the location of extreme inphase and increased conductivity values, which we assign to modern construction debris. In the overview map of the study area, the displayed subarea is drawn in yellow.

To facilitate a comparative analysis with GPR and borehole data, we present vertical sections of the EMI inversion. The upper zone of profile 12 (Figure 9) exhibits low conductivity (<2 mS/m), while the lower part displays high conductivity (>16 mS/m). Given the information from available boreholes, where both layers consist predominantly of fine sands, the conductivity contrast is likely attributed solely to differences in water content. Notably, a transition zone with a conductivity of approximately 9 mS/m closely aligns with a GPR reflector, which together likely indicates the presence of the groundwater table. Additionally, a highly conductive area (~6 mS/m) within the upper part corresponds to the gyttja-filled channel feature detected in the radar data and corings.

The lower part of the section features zones of low conductivity and triggers a discussion of the inversion quality, which is examined in more detail in Figure 10. The provided plots of covariance correlation coefficients use reddish colours to signify a high trade-off between the modelled conductivity values at depth locations denoted on the plot axes. While high coefficients are anticipated on the trace of the matrix, they are not desired elsewhere. At 22.5 m offset, conductivity values at 0 m depth are highly covariant with those at 1.5 m depth and below 5 m. This suggests that conductivity may be even higher in the gyttjas of the upper part and may not decrease in the deeper section of the profile. The pronounced damping seen in the GPR data in this area strongly supports this hypothesis (cf. Figure 5). However, ground truth is lacking as there are no drill samples penetrating the zone beneath the channel feature. At 60 m offset, a similar inversion artefact is observed, although it is less pronounced.

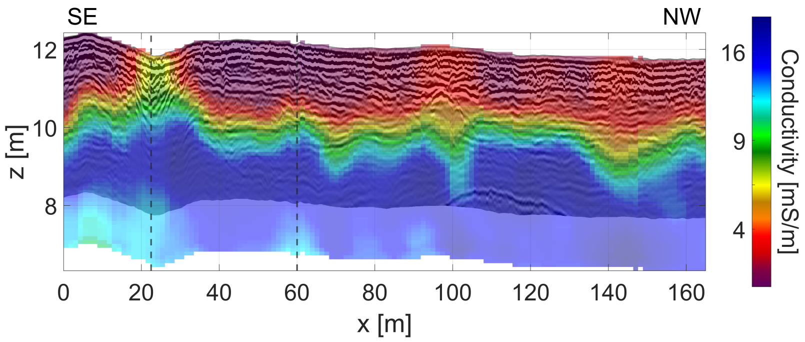

Figure 9. Electric conductivity depth section overlain on GPR reflection profile 12. The electric conductivity section was obtained through an inversion computation from the EMI data. For better visibility of the major features within the dataset, the colourmap is root scaled (denoted conductivity values are corrected and in mS/m). Dashed lines refer to the locations of the covariance correlation coefficient tests shown in Figure 10.

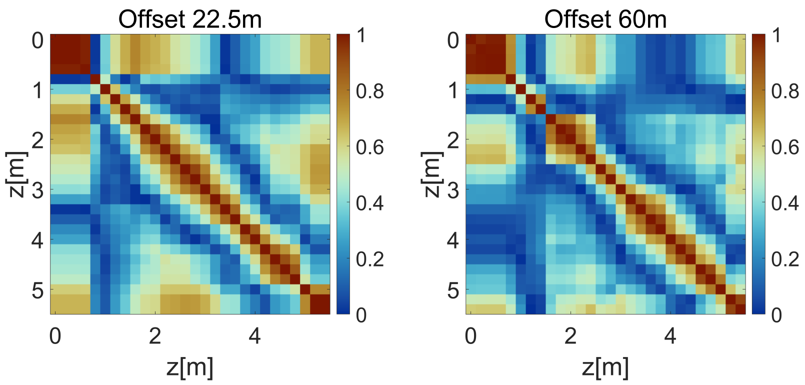

Figure 10. Covariance correlation coefficients of 1D EMI inversions at 22.5 m and 60 m offset within GPR profile 12 (cf. dashed lines in Figure 9). For this test, the number of best models used to calculate the covariances was increased to 200. Reddish colours indicate a high trade-off between modelled conductivity values at the respective depth locations.

Figure 11 provides a vertical section of the EMI inversion, superimposed on GPR profile 50. Here, the emerging clay-rich Rotliegend 'red loam' correlates with notably high conductivity values (>16 mS/m). The presence of gyttja, as derived from the GPR data analysis (cf. Figure 6), is not readily discernible. The high conductivity of the gyttja is overshadowed by the even higher conductivity of the clay marl. Moreover, the gyttja exhibits a significantly reduced thickness in comparison to the channel area (55 cm in BO185 vs. 150 cm in BO179) and is therefore harder to detect. Nonetheless, subtle variations are apparent in the upper section of the profile, and the lowest conductivity values are observed in conjunction with the aeolian dune sands. Similar to profile 12, there are once again zones of low conductivity in the lower segment of the profile, which are considered probable inversion artefacts. Starting from an offset of 50 m, the transition zone, characterised by a conductivity of approximately 9 mS/m, again shows a close correspondence with a GPR reflection, indicating its association with the groundwater table.

In summary, electrical conductivity values range from 1.2 to 28.3 mS/m after inversion. Maximal conductivity values (>16 mS/m) are associated with the emergence of Rotliegend 'red loam' close to the ground surface in the northeast of the measured area. The presence of highly conductive gyttja (~9 mS/m) within the elongated channel feature is visible. Generally, conductivity increases with depth, primarily attributed to moisture content.

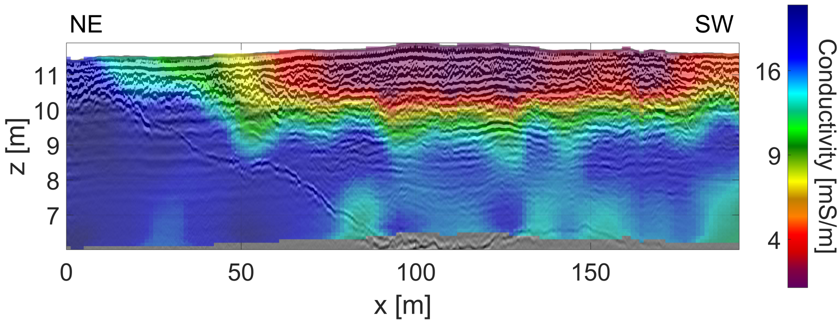

Figure 11. Electric conductivity depth section overlain on GPR reflection profile 50. The electric conductivity section was obtained through an inversion computation from the EMI data. Again, the colourmap is root scaled for better visibility of the major features within the dataset (denoted conductivity values are corrected and in mS/m).

4.3. Joint Interpretation of Geophysical Measurements and Geological Borehole Data

In the following, we use the collected geophysical data and digitised geological data from legacy boreholes to develop a consistent model conception of the Late Pleistocene landscape in Lieth Moor.

The EMI maps, in conjunction with the GPR results, strongly indicate the presence of a former stream in the central basin of the Elmshorn diapir (marked by a line of rhombi in Figure 12). Over time, this stream must have decelerated due to alterations in the water regime, eventually becoming stagnant or nearly stagnant, which allowed for the formation of gyttjas within the channel. Within the study area, we observe sandy regions characterised by low conductivities, which we interpret as islands or shore area (marked by a square in Figure 12). In the eastern section of the EMI measurement zone, we observe a substantial area with elevated conductivity values (indicated by a downward triangle in Figure 12). This suggests a widespread presence of gyttja, likely deposited in a former, more extensive body of water—potentially a lake. A distinctive signal featuring high conductivity and inphase extrema (marked by an upward triangle in Figures 8 and 12) does not pertain to a potential waterbody but can be attributed to contemporary construction debris. In the northeastern subarea (cf. downward triangle in Figure 12), only GPR data confirmed the presence of gyttja, as also clay-rich material influenced the measured conductivity values here. In EMI maps, we identify two small-scale high-conductivity features (cf. dots in Figure 12) that strongly suggest the presence of small silted ponds or pools. The gyttja base depth map obtained from GPR data (cf. Figure 7) reveals further small-scale gyttja deposits, suggesting the presence of ponds scattered across the entire surveyed area. However, it is plausible that gyttja was solely deposited in the most profound areas, i.e., potentially the former waterbodies were somewhat more expansive in size. For some drill locations, there are reports of very thin gyttja layers, which are too thin to be resolved by the GPR method. This observation may indicate periods of elevated water levels when the small ponds were interconnected and/or suggest a more intricate sedimentation process.

In summary, we imagine the Late Pleistocene landscape in Lieth Moor as scattered with small ponds and pools and crossed by a stream. It is likely that the region experienced periodic, possibly seasonal inundation. Several sandy hilltops must have remained unaffected by flooding events.

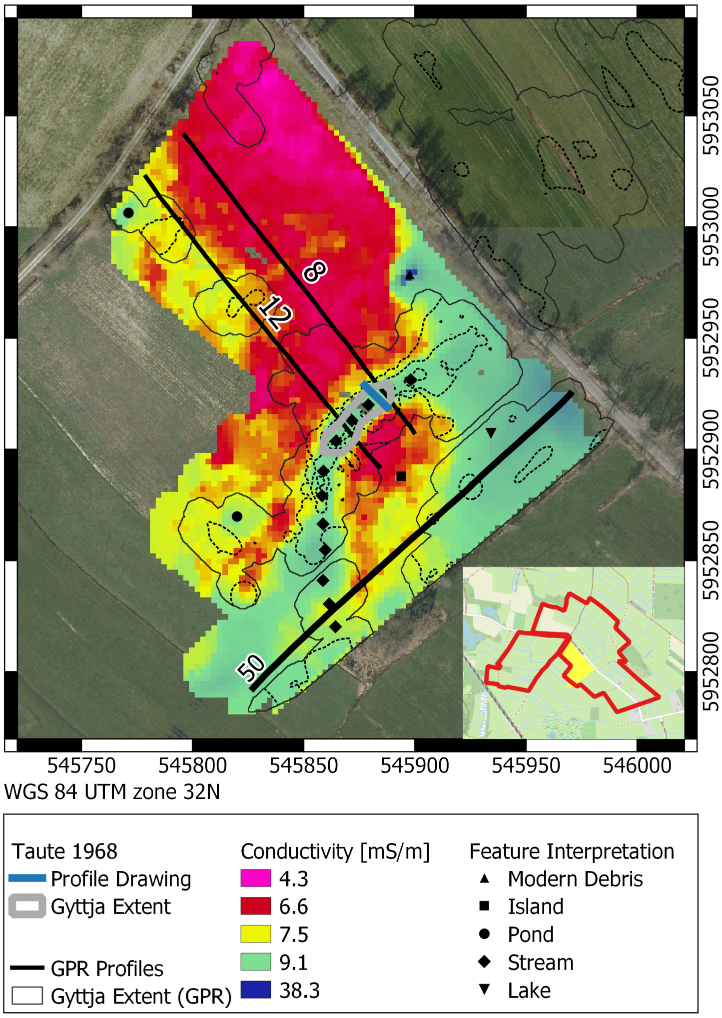

Figure 12. Joint interpretation of Electromagnetic Induction and Ground-Penetrating Radar data. The electrical conductivity of the first coil pair (i.e., averaged over the first ~1.2 m of the subsoil) is colour coded. The extent of the gyttja deposits as derived from GPR interpretation is delineated in black. Depth contours of the gyttja base at 0.5 m intervals are provided as dashed black lines.

5. Discussion

5.1. Methodical Considerations

In assessing the Late Pleistocene landscape of Lieth Moor, we examined the strengths and weaknesses of GPR and EMI, focusing on depth penetration, structural resolution, and gyttja deposit identification.

In terms of depth penetration, GPR generally performed well, reaching depths of up to 5.5 m in well-drained sandy substrates. However, it encountered difficulties in penetrating the Rotliegend 'red loam', as exemplified in profile 50 (cf. Figure 6). In regions with poor ground coupling, caused by vegetation or glacial erratic boulders, as well as high moisture or clay content, GPR achieved depths as shallow as 0.5 m. Similarly, ref. [87] reported a generally high GPR penetration of up to 8 m, which was constrained to the contact with clay-rich mineral soil. We also observed localised variations in depth penetration and reflector visibility, presumably attributed to fluctuations in the moisture and clay content within the limnic gyttja sediments. This extremely location-dependent performance aligns with findings in the literature. For example, the authors of [73] achieved 5 m penetration by using 100 MHz equipment in a drained peat bog, while [77] reached only 2 m in a gyttja-filled kettle hole with a 200 MHz antenna. The penetration depth of the EMI method depends on the signal frequency, the transmitter–receiver distance and orientation, and the measurement height above ground. As detailed in Section 3.3, the used CMD Explorer device penetrates approximately 5.7 m into the subsurface, given the measurement height above ground of 1 m. However, inversion artefacts increasingly occur below a circa 4 m depth.

Concerning sediment identification, EMI effectively resolved the interfaces between sand and gyttja or clay in the vadose zone, as well as the boundary between dry and saturated sands. However, it offers a lower depth resolution and encounters challenges in distinguishing gyttjas atop the Rotliegend clay marl. These findings are consistent with the observations of other researchers who have employed EMI for localising former waterbodies. For instance, the authors of [77] successfully delineated the extent of a gyttja-filled kettle hole by using EMI while noting that lateral contrasts in electric conductivity between the former pond's fill and the surrounding glacial sediments may diminish, especially at shallow depths, due to increased water or clay content in the parent material. References [88,89] effectively utilised EMI to reconstruct the palaeochannel morphology and trace-buried fluvial systems. Combining EMI with Cone Penetration Tests is regarded as the optimal approach for mapping deeply buried prehistoric palaeolandscapes in the polder areas of Belgium by [90]. In a palaeolandscape study focused on the Iron Age, ref. [91] employed EMI and found it capable of distinguishing between sand, gyttja, and dry peat. However, it proved unable to differentiate between types of gyttja, such as lime gyttja, based on their electromagnetic properties. Similarly, in our dataset, the known sequence of different gyttja types within the channel is not discernible.

GPR offers superior depth resolution in comparison to EMI and therefore excelled in discerning between clay-rich Rotliegend material and overlying gyttja deposits. A spectrum analysis revealed a spectral maximum of 140 MHz, indicating a structural resolution of approximately 11 cm for the utilised 200 MHz GPR equipment (cf. resolution considerations in Section 4.1). Within the Lieth Moor study area, four distinct radar facies are evident, corresponding to the Rotliegend 'red loam', glacial meltwater/outwash plain sands, aeolian dune sands, and gyttjas. Previous applications of GPR have also successfully delineated the stratigraphy of peatlands. For example, the authors of [87] highlight a precise recording of interfaces between peat, lake sediments (i.e., gyttja), and mineral soil, aiding in estimating the topography of the glaciomarine basement. GPR's capability to discern interfaces between organic and mineral gyttja and mineral gyttja and glacial sand has been emphasised [73]. Furthermore, GPR has shown proficiency in detecting the peat-to-mineral basement contact [92]. The broadening of reflectors can be attributed to interference from successive GPR reflections at the top and bottom of thin mud layers (i.e., gyttja) [92]. The authors of [93] identify basal clay as a significant GPR reflector, with complex basal reflections indicating gyttja layers above the clay. GPR's capability of distinguishing between peat, lake sediments (gyttjas and mud), and basal glacial sand deposits has been demonstrated by [76]. In summary, the reviewed literature attests to the effectiveness of GPR as a robust tool for detecting various interfaces within peatland environments. However, it is essential to acknowledge that extensive drainage activities and peat extraction have led to a scarcity of peat remnants in Lieth Moor, which may impact the applicability of these findings.

In addition to the aforementioned aspects, the prospection of areas like Lieth Moor also demands the ability to approach challenging terrains and time-efficiently survey large expanses. In this respect, EMI demonstrated distinct advantages, as it is capable of swiftly providing a comprehensive areal overview and, moreover, can be effectively utilised even in densely vegetated areas. Based on our practical experience, the survey speed is approximately 4.2 hectares per hour, and initial maps can be interpreted after about 30 min of processing. Conversely, the application of GPR is more time intensive, primarily due to the demands of data processing and interpretation, which could take weeks in the case of large datasets. While the measuring speed itself is only insignificantly lower, at approximately 3.6 hectares per hour, GPR measurements were significantly impeded by vegetation in some eastern subareas of the site (see Figure 4) as direct ground coupling is necessary for our equipment.

However, even as we weigh the advantages and disadvantages of both methods, we advocate for their combined application. GPR images sedimentary boundaries and bedding characteristics exclusively. Therefore, the electrical conductivity values derived from EMI measurements proved invaluable in determining the soil type. Without this additional information, or data from drill probing, assigning specific radar signals to soil types would be impractical. Conversely, addressing the inherent ambiguities and numerical uncertainties of the EMI inversion can be achieved by comparing EMI images with GPR data and geological information. The combination of GPR with conductivity information from EMI (or in some cases Electrical Resistivity Tomography: ERT) has demonstrated significant value in subsurface studies. For instance, integrating GPR, EMI, ERT, and Induced Polarisation proved effective in investigating peatland [87], emphasising the complementary nature of these methods alongside GPR data. The combination of EMI and GPR can provide insights into basin stratigraphy and lateral variations in pore water salinity within peatlands [92]. The authors of [76] utilised GPR, ERT, and Shear Wave Seismics, underscoring the synergistic contributions of these methods to detailed stratigraphic understanding. They advocate for an integrated approach, emphasising the importance of utilising methods sensitive to different soil properties.

Given the above considerations, a refined prospecting approach is in order for future investigations. In the future, we will employ EMI as the initial step to identify areas with high conductivity, i.e., potential gyttja deposits. Subsequently, GPR measurements will be conducted as a follow-up measure in a targeted manner, particularly in regions of potential gyttja deposits or concentrations of archaeological surface finds. Lastly, (own) drillings shall be performed to ground truth and calibrate the geophysical data and for palynological analyses. These drillings will be positioned strategically and precisely along EMI and/or GPR profiles, respectively. Instead of a gridded approach, the goal is to sample all key GPR reflectors and radar facies. Furthermore, special attention shall be paid to archaeological-find densities and deep areas within detected former water bodies that potentially serve as valuable archives for long palaeoclimate records.

5.2. Comparison of the New Landscape Model with Previous Models

The core message of our study is that, based on the presented geophysical data, the Late Pleistocene landscape in Lieth Moor should be envisaged as featuring a multitude of small ponds or pools intersected by a stream rather than filled by a large palaeolake. This agrees with the conclusions regarding Lieth Moor's landscape of the Late Pleistocene by [69], p. 106. Ahrens takes into account the difference in elevation of about 2.5 m between the northern (lower) basin and the southern (upper) basin, assumes that the Federmesser site LA 33 must have been dry land during the Allerød interstadial, and considers the allochthonous pollen and high mineral content in the gyttja samples studied by [65] as indicating a slow current within the waterbody. Therefore, ref. [69] casts doubts on the existence of an expansive palaeolake across the entire basin, favouring instead a rivulet complemented by ponds nestled within small-scale karstic hollows.

Geological investigators of the Lieth Moor area present maps, based mainly on probe rod soundings, with significant variations in the shoreline layout and island localisation. They concur on one aspect, however: there was one large continuous palaeolake filling the entire central subrosional basin of the Elmshorn salt diapir. Some argue that the *Palaeolake Esing* extended even into the Himmelmoor in the north, while others challenge this thesis (e.g., [57] vs. [45]). Some studies depict an island at the archaeological site Klein Nordende LA 2 [57,60], whereas for other authors, this location appears to have been submerged in the lake (e.g., [45,61]). Similarly, ref. [57] as well as [59] postulate an island at site Klein Nordende LA 24 (see Figure 2), while [61] reconstructs the shoreline there, and [45] maps the location as inundated.

Archaeological investigators, however, paint a different picture (cf. Section 2.3 as well). Out of three archaeological excavations in the area, only Bokelmann's excavation at LA 37 (cf. Figure 2) [19] delivered results that align with the presence of a large palaeolake in the area. The excavation team encountered a Late Pleistocene shore of a waterbody with gyttjas dated to the Allerød. Ichthyofaunal remains were evaluated, whose large number and in part enormous size and species-inherent ecological demands indicate a large body of clear water featuring a solid mineral bottom [35]. However, the encountered Late Pleistocene shoreline could also pertain to a waterbody that only filled parts of the central basin. Bokelmann ([19], p. 1) himself was also aware of this possibility and the lack of ubiquitous gyttja in the central part of the basin as reported by [66]. The excavation by Ingo Clausen and Annette Guldin (the Archaeological State Office Schleswig-Holstein) in 2013 (shown as the blue rectangle in Figure 2) did not encounter the expected shoreline as reconstructed by [59], which supports the conclusions of [61]. Lastly, and most importantly in the light of our working area, Taute's work at Klein Nordende LA 2 [66] contradicts a continuous gyttja layer in the central part of the basin. He did provide drilling evidence of a gyttja deposit but considered it to be locally confined based on his results. The island of LA 2 therefore becomes the mainland, and the encountered gyttja deposit is interpreted by [66] as a pond or pool that existed during the Dryas 3.

Like [66], we cannot affirm a ubiquitous gyttja occurrence for the central part of the basin. This contradicts the assumption of a large *Palaeolake Esing* filling the entire Lieth Moor area in the Late Pleistocene. Still, we do not entirely align with his results, as the pool he reconstructed appears to be part of a stream or rivulet. However, further measurements in the area south of the presented data are necessary to validate this hypothesis. The palaeolandscape reconstruction we present, with numerous small ponds and a stream, also concurs with [69]'s conclusions on Lieth Moor, which were based mainly on a review of the literature available at that time. Furthermore, our data support the notion of gyttja's absence on the dune at Klein Nordende LA 2, which aligns with the results of [57,60,66]. Since it is located in a pond landscape, this dune must not be considered as an island but rather as part of the mainland. Also at the site Klein Nordende LA 24, we do not find any evidence of gyttja in our data, which agrees with the maps of [57,59,61]. Furthermore, the emergence of Rotliegend "red loam" close to the surface towards the east of the survey area aligns well with the mapping by [57].

In addition to comparing our findings with existing geological maps, we can also directly compare a radar profile image with the excavation results. At the Klein Nordende LA 2 site, the excavation report provides a sedimentary profile drawing of the gyttja deposit ([66], p. 74). In Figure 13, we compare a line drawing of the interfaces of this geological section with the closest GPR depth profile we acquired (profile nr. 8, located at a 3 to 5 m distance to the excavation trench). Overall, the observed GPR signals correspond well to the reported sedimentary boundaries. The level of detail is slightly less, which is expected due to the resolution limitations of the method (cf. Section 4.1). A drop-shaped structure in the upper area is not imaged by the GPR data. However, a perfect match should not be anticipated, as there is a distance of 3 to 5 metres between the drawn and the radar profile (see Figure 12). We speculate that the drop-shaped structure might have a conical shape and therefore lie outside the plane of the radar profile, given its width of approximately 1 m. This comparison illustrates that the GPR data reliably images the alternating layers of sand and different gyttjas. However, additional information from excavations or legacy drillings is needed to assign the reflections to particular geological interfaces

At this juncture, we not only want to discuss the limitations of GPR but also critically examine the quality of the geological legacy data used for comparison. In comparing the distribution maps of gyttja, one major source of uncertainty is that the locations of published drilling data are generally of low precision (10 to 100 m; e.g., [60,61,66]) or even missing completely [45,57,66]. In other cases, only a rough comparison between geological and geophysical maps was possible because the underlying drill profile directories were not published [45,59]. It is also worth noting here that the colour scale of the gyttja thicknesses in the map by [45] begins at 0–40 cm. It is therefore unclear whether gyttja was encountered everywhere in the area shown in blue (cf. Figure 2). It cannot be ruled out that there were actually also boreholes in which no gyttja was found.

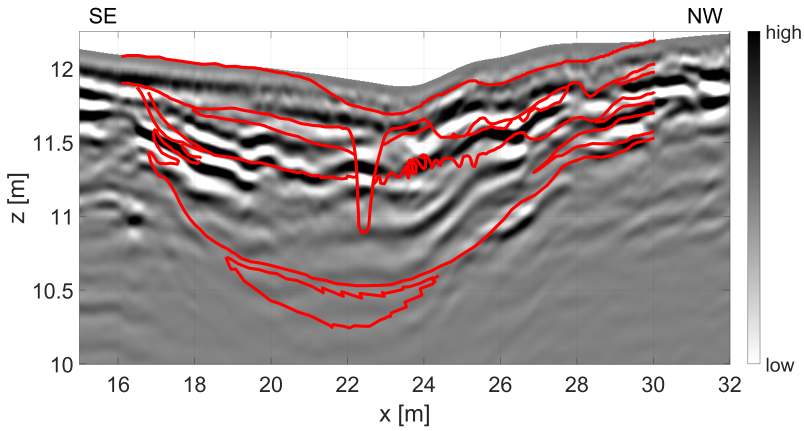

Figure 13. Comparison of GPR signal and Taute's section. A detail from GPR profile 8 is overlain with the sedimentary profile drawing from ([66], p. 74). The drawing is parallel projected onto the nearest GPR profile. For information on the location, see Figure 12. The distance between GPR profile and excavation is ca. 3 to 5 m.

Last but not least, there is a fundamental methodological difference between the geological drilling studies and the presented geophysical data. Geological drillings provide point information exclusively. The density of the drill points is therefore a decisive measure for the resolution with which landscape features can be reconstructed. Following the Nyquist–Shannon sampling criterion, features can only be resolved if their size is at least double the drill point density. Regarding the geological studies conducted in the Lieth Moor area, the drill point density and therefore the resolution at which landscape features are mapped varies strongly (see Table 2).

Table 2. Database comparison of cited geological studies. Values marked with an asterisk (*) were derived from a subset of drill points within the geophysical survey area that could not be digitised as sedimentological information was lacking. Question marks (?) indicate that the drill locations are completely unknown.

	Total nr. of Drillings	Digitised Drillings	Max. Drill Point Distance (m)	Min. Drill Point Distance (m)	Mean Drill Point Distance (m)
[45]	>4000	-	76 *	1 *	15 *
[57]	856	-	?	?	?
[59]	185	-	116	2	23
[60]	271	171	100	1	18
[61]	317	49	183	25	73

Between the borehole locations, interpolation occurs, and extrapolation is undertaken at the edges if necessary, which can result in substantial errors. This discrepancy is evident in the varying mapping results (see an example in Figure 14). None of the authors provide explicit information regarding the interpolation and extrapolation methodologies, indicating a presumed reliance on heuristic approaches. In contrast, the geophysical data we collected were recorded continuously in areas or profiles. Additionally, thanks to the Stonex SAPOS system used, the localisation accuracy is in the lower centimetre range. For the geological comparison studies, on the other hand, the localisation was conducted by tape measure and step counting. The significant advantage of drilling, however, lies in the unparalleled precision with which even the finest layers and subtle changes can be recorded. Geophysical methods never attain this level of vertical resolution.

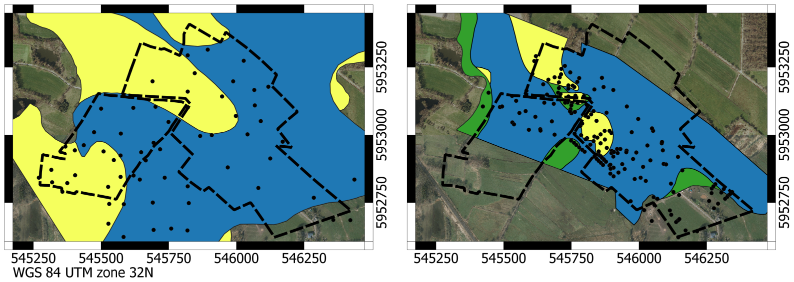

Figure 14. Comparison of geological maps after ([61] **left**) and ([60] **right**). Yellow denotes sandy areas, blue represents gyttja deposits, and green signifies peat deposits. The survey area of the present study is delineated by a dashed line. The impact of varying drill point densities (indicated by dots) is discernible in the resolution of landscape features.

5.3. Landscape Development

Our investigation revealed that during the Late Pleistocene to Early Holocene, the Lieth Moor region featured numerous small ponds rather than a singular, continuous lake. Additionally, the findings strongly suggest the presence of a stream or rivulet. Very thin gyttja layers, as reported from legacy drill data, hint at periods of elevated water levels when these small ponds were interconnected. Taute also alluded to the presence of humic sand, possibly signifying a shore terrace or intermittent flooding [66]. Similarly, a rise in lake levels during the Allerød was posited by [19].

However, the landscape development throughout the Late Pleistocene, i.e., the chronology of gyttja sedimentation in different areas of the basin, remains only loosely outlined. The oldest gyttja deposits seem to be situated in the northern part of the central basin. Algal gyttjas were encountered in this area and palynologically dated to the Dryas 1 [65]. Very close, also in the northern part of the basin, the author of [18,37] investigated sediments indicating the presence of a very shallow lake or pond from the late Dryas 1/early Allerød onwards (cf. pink dots in Figure 2). The stratigraphy of the pond indicates repeated periods when the shallow waters froze and thawed or when the waterbody dried up, resulting in sedimentological hiati [18].

In the central part of the basin, which encompasses our study area, the sole available palynological analysis associates the gyttja sediments with the Dryas 3 stadial ([66], p. 75). However, the antler artefacts supposedly originating from the gyttja were C14 dated to the Allerød (early GI-1c3).

In the southwest of the basin, Bokelmann attributed the encountered gyttjas to the Allerød, or more specifically, likely the early Allerød, as indicated by additional humic horizons stacked above them [19]. It is worth noting, however, that Bokelmann himself acknowledged that alternative interpretations of the pollen profile are plausible, given the potential displacement of layers by salt dome movements. Additionally, fish skeletal remains from the excavation were dated to the late Allerød (GI-1c1-1a) [34,35].

In summary, the available pollen analyses of the gyttja sediments suggest a chronological sequence in the development of waterbodies, rather than the presence of a continuously existing lake throughout the Late Pleistocene. Initially, a waterbody formed in the northern subbasin during the Dryas 1/early Allerød. In Northern Central Europe, the development of organogenic sediments began in many lacustrine archives around this period [94–96]. The southern subbasin was inundated during the late Allerød. Considering a potential hiatus between the latest Allerød and the onset of the Dryas 3 [18], this higher water level can be regarded as similar to the high lake levels before the significant lowering of the water level at the Allerød-Dryas 3 transition seen elsewhere in Northern Central Europe such as in Sandy Flanders or the Swiss Plateau, French Jura, and Pre-Alps [95,96]. Finally, the central part of the basin, which still exhibits elevated areas today, was partially submerged and/or traversed by gullies in the Dryas 3. Other lake environments in Central Europe reveal a lowering of lake levels during the Dryas 3 with another rise in the water table during the middle of that period [95,96]. Hence, it is important to note that palynological data are only available at isolated, widely dispersed sites within the extensive Lieth Moor area. In stark contrast, the geology in Lieth Moor displays significant variability even within small subareas. To substantiate this hypothesis on the temporal sequence of inundation and sedimentation, a comprehensive drilling campaign coupled with palynological analyses and, given the occasionally poor quality of palynological samples, radiocarbon dating would be imperative.

5.4. Archaeological Implications of the New Landscape Model

Regarding the inquiry into why Late Pleistocene hunter–gatherers preferred Lieth Moor, the absence of the previously postulated palaeolake fundamentally recontextualises known finds. The absence of a continuous, large waterbody precludes the existence of a ford or bottleneck scenario, where hunters could strategically position themselves for incoming herds of reindeer. Many of the sandy elevations previously interpreted as islands in the literature have turned out to be part of the mainland in the course of our investigations. In one instance, a small island was identified within the geophysical data. Nevertheless, these sandy elevations served as appealing settlement sites, offering dry and stable ground for a campsite. Finds at sites Klein Nordende LA 2 and LA 24 evidence that Late Pleistocene hunter–gatherers at least briefly visited these high-ground locations.

After all, the revised landscape remains an inviting one. The prevalence of the salt-intolerant algal genus *Pediastrum* within the gyttja deposits [19,65] confirms potable water without evidence of salt dome leaching. Furthermore, reports of sizeable fish from the southwest of the basin imply a substantial food resource, indicating clear water and a solid mineral bottom during the Allerød interstadial [35]. Additionally, three specimens of pike were encountered in the gyttja deposit at LA 2, which is attributed to the Dryas 3 ([66], p. 74). Water served a multifaceted role for the Late Pleistocene population beyond drinking or fishing. The internationally renowned finds from the Ahrensburg tunnel valley also highlight the potential significance of waterbodies for meat storage or as secure discard zones [97–100]. In sandy Flanders, the importance of water availability is probably reflected in a shift in the settlement intensity from lake to river banks during Dryas 3 as a possible result of significant water table lowering [101].

Moreover, in this relatively flat landscape, the elevated dunes would serve as a protective barrier against westerly winds [102,103], creating an environment where people feel secure. Potentially, more bushes and trees could thrive here during the harsh conditions of the Dryas 3 stadial. Consequently, there may have been particularly abundant deposits of the scarce resource wood in Lieth Moor, suitable for use as firewood, construction material for dwellings, and the crafting of tools. Additionally, tree-covered habitats offer a completely different faunal resource than open tundra landscapes and are preferred, for example, by elk that had been attested by several individuals at Klein Nordende LA 37 [19]. In the growing woodlands and light forests of the Allerød, ponds and possibly swampy areas offered open areas and a vegetation that could still attract reindeer [104]. Hence, the Lieth Moor area likely represented a small mosaic landscape in which the subsistence could be diversified.

The proximity to the Elbe Palaeovalley (EPV; cf. Figure 1) likely played a pivotal role in choosing Lieth Moor as a campsite. From the higher grounds of the Lieth Moor area, a good view into this large river plain was possible, but the observers were still outside the wet EPV lowlands and potential swarms of midges.

Based on ethnoarchaeological studies [8] and regional investigations of numerous prehistoric settlement remains [11,105], human groups would have established camps at vantage points offering additional resources during periods of waiting. However, vantage points are typically occupied only briefly due to their exposed nature. More frequently, sheltered locations near a freshwater source are favoured. These criteria align remarkably well with the dune ridge adjacent to the west, as well as Lieth Moor itself. Considering the previously discussed resources in Lieth Moor, it is unsurprising that hunters were inclined to seek repose there while waiting for their prey. For instance, Late Pleistocene reindeer herds predominantly traversed the region in an east–west pattern, probably wintering in the east and migrating along the large river systems and glacial meltwater valleys to the summer pastures in the west [106,107].

Undoubtedly, the prehistoric river Elbe would have constituted a critical migration route throughout the period in question and not just for reindeer. According to [108], river systems form important guidelines of mobility, whether as barriers or as bridges, in the European Upper Palaeolithic. The EPV was one of the two major river systems in Northwestern Europe that probably guided human expansion into the North [109]. It represented a stable orientation in an area poor in significant landmarks (perhaps the red sandstone massif of Heligoland or the gypsum/anhydrite rock formation of Bad Segeberg) and in the still-changing landscape of the Late Pleistocene. So, while the EPV represented an important migration route also for human groups, the Lieth Moor area offered itself as the more liveable resting place.

In conclusion, it is evident that our comprehension of the Late Pleistocene landscape in Lieth Moor has undergone significant revisions and refinements as a result of the largely noninvasive archaeogeophysical study presented here. Still, numerous questions persist, offering avenues for future research in this domain.

6. Conclusions

This study centres on reconstructing the Late Pleistocene landscape within the case study area of Lieth Moor, with a specific emphasis on its waterbodies and their correlation with archaeological finds left by Late Palaeolithic hunter–gatherers. Archaeogeophysical techniques, namely GPR and EMI, were applied in conjunction with legacy drill-probing data. Based on the acquired geophysical data, it is deduced that during the Late Pleistocene to Early Holocene ages, the Lieth Moor region featured numerous small ponds rather than a singular, continuous lake. Additionally, the findings strongly suggest the presence of a stream or rivulet. The presence of very thin gyttja layers, as reported from legacy drill data, hints at periods of elevated water levels when these small ponds were potentially interconnected. As a consequence, the results reshape our understanding of why Late Pleistocene hunter–gatherers favoured Lieth Moor. The absence of the previously postulated large palaeolake, filling the entire basin, fundamentally alters our contextual understanding of reported archaeological sites: we assume that the nearby Elbe Palaeovalley played a key role in the repeated habitation of Lieth Moor. The area was rich in fresh water and fish, and the dune ridge located to the west could serve as a vantage point and sheltered the location from westerly winds. Therefore, Lieth Moor was an ideal place for resting when migrating along major rivers like the Elbe.

As some unanswered questions remain, there is rich potential for further research in this study area: in the future, we plan to acquire additional data south of our study area. This will serve to test the hypothesis regarding the existence of a stream and the continuity of gyttja deposits within the observed channel feature. For this forthcoming measurement campaign, we will implement a refined prospection approach. EMI will be employed as the initial step, identifying areas with high conductivity and potential gyttja deposits. Subsequently, GPR measurements will be conducted in a targeted manner, focusing on regions exhibiting increased conductivity values or concentrations of archaeological surface finds. Furthermore, we propose conducting additional drillings in areas of particular interest, especially where gyttja thickness is increased, to facilitate state-of-the-art palynological and macrofossil analyses. This will provide robust substantiation for testing our hypothesis regarding the high-precision temporal sequence of inundation and sedimentation, which currently relies on a limited number of pollen-sampling locations.

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Abbreviations

The following abbreviations are used in this manuscript:

EPV	Elbe Palaeovalley
LA	*Landesaufnahme*; register of prehistoric and historic artefacts and archaeological sites and monuments of Schleswig-Holstein
EMI	Electromagnetic Induction
ERT	Electrical Resistivity Tomography
GPR	Ground-Penetrating Radar
HCP	Horizontal coplanar

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