The geomorphological and sedimentological legacy of the historical Lake Lorsch within the Weschnitz floodplain (northeastern Upper Rhine Graben, Germany)

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Abstract. The artificial historical Lake Lorsch (1474/79 to 1718/20 CE) in the northeastern Upper Rhine Graben (Germany) is known from various historical sources, e.g. for fish farming, as a significant anthropogenic imprint of the Weschnitz floodplain. Nevertheless, there have been no geomorphological and sedimentological investigations about the (quasi-)natural context for the creation of the lake, its importance as a potential sediment archive and the subsequent use of the lake area until modern times. No relics of the lake can be observed in today's landscape. We investigated the geomorphological setting of the area using a high-resolution digital elevation model, groundwater level data, geophysical prospection, as well as sedimentological information from four sediment cores. This allows us to determine that the location of the lake is geomorphometrically deeper in relation to its receiving waters of the Old Weschnitz and was strongly fed by groundwater. Sedimentary analysis (core LOR 21A, unit 2) exhibits lake deposit, with characteristics indicative for a limnic environment and a high groundwater table. At the same time, adjacent stratigraphy shows drainage channel deposits (core LOR 20A, unit 3), which reflects anthropogenic controlled inflow via a channel (*Renngraben*). Our results based on a relative elevation model fit well with the historical records, that inflow for the anthropogenic channel was via the Old Weschnitz (topographically higher than the lake area) and that the artificial Landgraben-canal (topographical lower than the lake area) was overflowed with a bridge. It is a good example of how humans started as fluvial and water related agents at least for 500 years in the Weschnitz floodplain.

Zusammenfassung

Der anthropogen angelegte historische Lorscher See (1474/79 bis 1718/20 n. Chr.) im nordöstlichen Oberrheingraben (Deutschland) ist aus verschiedenen historischen Quellen, z. B. zur Fischzucht, als bedeutende anthropogene Prägung der Weschnitzaue bekannt. Dennoch fehlen geomorphologische und sedimentologische

Untersuchungen über den (quasi-)natürlichen Kontext der Entstehung des Sees, seiner Bedeutung als potentielles Sedimentarchiv und die Nachnutzung des Seegebietes bis in die Neuzeit. Heute sind keine Relikte des Sees mehr in der Landschaft zu beobachten. Mit Hilfe eines hochaufgelösten digitalen Geländemodells, Grundwasserstandsdaten, geophysikalischer Prospektion sowie sedimentologischen Analysen aus vier Bohrkernen haben wir die naturräumlichen Gegebenheiten des Gebiets untersucht. Daraus lässt sich ableiten, dass der Standort des Sees geomorphometrisch tiefer liegt als sein Vorfluter, die Weschnitz, und stark grundwassergespeist war. Die Sedimentanalyse (Kern LOR 21A, Einheit 2; LOSE 4 und LOSE 5, Einheit 3) zeigt Seeablagerungen mit Merkmalen, die auf ein limnisches Umfeld und einen hohen Grundwasserspiegel hinweisen. Gleichzeitig zeigen die angrenzenden Ergebnisse Rinnenablagerungen von einem (Kern LOR 20A, Einheit 3), welcher den anthropogen gesteuerten Zufluss über einen Kanal (Renngraben) darstellt. Unsere Ergebnisse basierend auf einem relativen Geländemodell passen gut zu den historischen Aufzeichnungen über die Nutzung des Lorscher Sees, dass der Zufluss für den anthropogenen Kanal über die Alte Weschnitz (topographisch höher als das Seegebiet) erfolgte und dass der künstliche Landgraben-Kanal (topographisch tiefer als das Seegebiet) mit einer Brücke überströmt wurde. Die Untersuchungen sind ein gutes Beispiel dafür, inwieweit der Mensch seit mehr als 500 Jahren das hydrologische System in der Weschnitzaue und seinen angrenzenden Regionen beeinflusst hat.

1 Introduction

River floodplains are highly dynamic landscapes and important nodes for livelihood, innovation and conflict in the history of settlement (Werther et al, 2021). European floodplains in particular have been transformed over very long periods of time by natural and anthropogenic processes. At the beginning and for large parts of the Holocene, floodplains are almost undeveloped and only since the mid to late Holocene - mainly due to increased soil erosion caused by deforestation and agriculture - typical overbank silt-clay deposits with the disappearance of former wetlands exist. Larger interventions have occurred in an initial phase since the Middle Ages, and significantly with the industrialization of rivers. Based on these conditions, today it is often almost impossible to reconstruct the natural conditions (Brown et al. 2018).

As part of the DFG Priority Program (SPP 2361) “On the Way to the Fluvial Anthroposphere”, focussing on the development of floodplain landscapes of German medium-sized rivers during the Middle Ages and early modern period, the River Weschnitz in the Upper Rhine Graben (URG) in southwestern Germany is the largest river entering the southern *Hessisches Ried*, a landscape representative for a coupled human-water system. . Hydrological changes with high groundwater tables, natural fluvial processes and anthropogenic impacts have influenced historic human-environment interactions. Since Roman times, river regulation and water management in *Hessisches Ried* - affected the floodplain of several natural river courses including the construction of anthropogenic watercourses (e.g. Hanel, 1995; Heising 2012; Appel et al., 2024a, 2024b) and the special location of fortifications, exemplified by the Roman Fortlet and Medieval Lowland Castle at the Zullestein site (Prien & Appel et al. 2025)

Whereas a very early modification of the main Weschnitz river course during Roman times was discussed, but refuted recently (Helfert, 2014; Appel et al., 2024b), the influence from human activity during Medieval period is particularly high. The foundation of the Lorsch Abbey (763-764 CE) next to the Weschnitz at the end of the Carolingian period sets the beginning of the region's great supr-aregional importance within Europe. Lorsch Abbey – today UNESCO world heritage site - is the legitimate power base of the Carolingians and the abbey's possessions stretched from the North Sea to south of the Alps. As the core zone of the medieval empire, it is also possible to observe the negotiation of zones of influence between two electorates that were decisive throughout the empire (Electorate of Mainz, Electorate of Palatinate). Due to this high historical significance, a good understanding for the natural conditions under which the Abbey as center of power was created is important for transdisciplinary research, due to the strong human influence of the water dominated floodplain landscape towards a fluvial anthroposphere (Schenk, 2024). This enables contribution to the required better understanding how institutions and governance processes interact with hydrological processes (Di Baldassarre et al. 2013).

One phenomenon in the historical sources and maps is a lake that existed south of Lorsch. Although the former lake area is dry today, this so-called *Lorscher See* is sufficiently documented in older literature and current research, especially by historians (Lepper, 1938; Fecher, 1942; Koob, 1956; Platz, 2011; Schenk, 2024). As the lake is no longer present in the landscape today and its remnants are barely visible, our research targeted natural and anthropogenic factors for the creation and abandonment of Lake Lorsch.

For this, we aim to (1) identify and locate the Lake Lorsch from a geomorphometric perspective by use of a high-resolution digital elevation model; (2) determine the role of (past) groundwater levels; and (3) locate and characterize sedimentological remains of possible lake deposits. Through the additional integration of historical sources, we can compare the results from morphometry and sedimentology with historical sources to see any possible link. This helps in general to see, if the historical sources are in agreement and to which extent historical sources are suitable to detect specific landforms of interest. Overall, this addresses the legacy of Lake Lorsch and we discuss its significance in historical times, but also its contribution to the modern fluvioscape palimpsests in the Weschnitz floodplain, where the overlapping of several natural and anthropogenic structures becomes recognizable as layers among each other with their certain path dependencies.

2 Regional setting

2.1 Natural environment

The general geological and geomorphological setting of the southern *Hessische Ried* with its location in the northeastern URG and the associated graben shoulder of the Odenwald mountains are given in numerous regional studies (e.g. Dambeck and Thiemeyer, 2002; Pflanz et al., 2022; Appel et al. 2024b). The River Weschnitz has its source in the Odenwald mountains at a height of 465 m a.s.l. and a total length of 59.8 km with a catchment area of 438 km². At Lorsch river gauge, the average discharge during the years 1985 to 2025 is MQ 3,2 m³/s, max. observed discharge of HHQ 48,7 m³/s and a mean high-discharge MHQ 25 m³/s (HLNUG 2025). After a short course northward, the Weschnitz flows in south-westerly direction near Fürth and enters the URG at the city of Weinheim, with a large alluvial fan of Pleistocene age (Barsch and Mäusbacher, 1988) (Fig. 1).

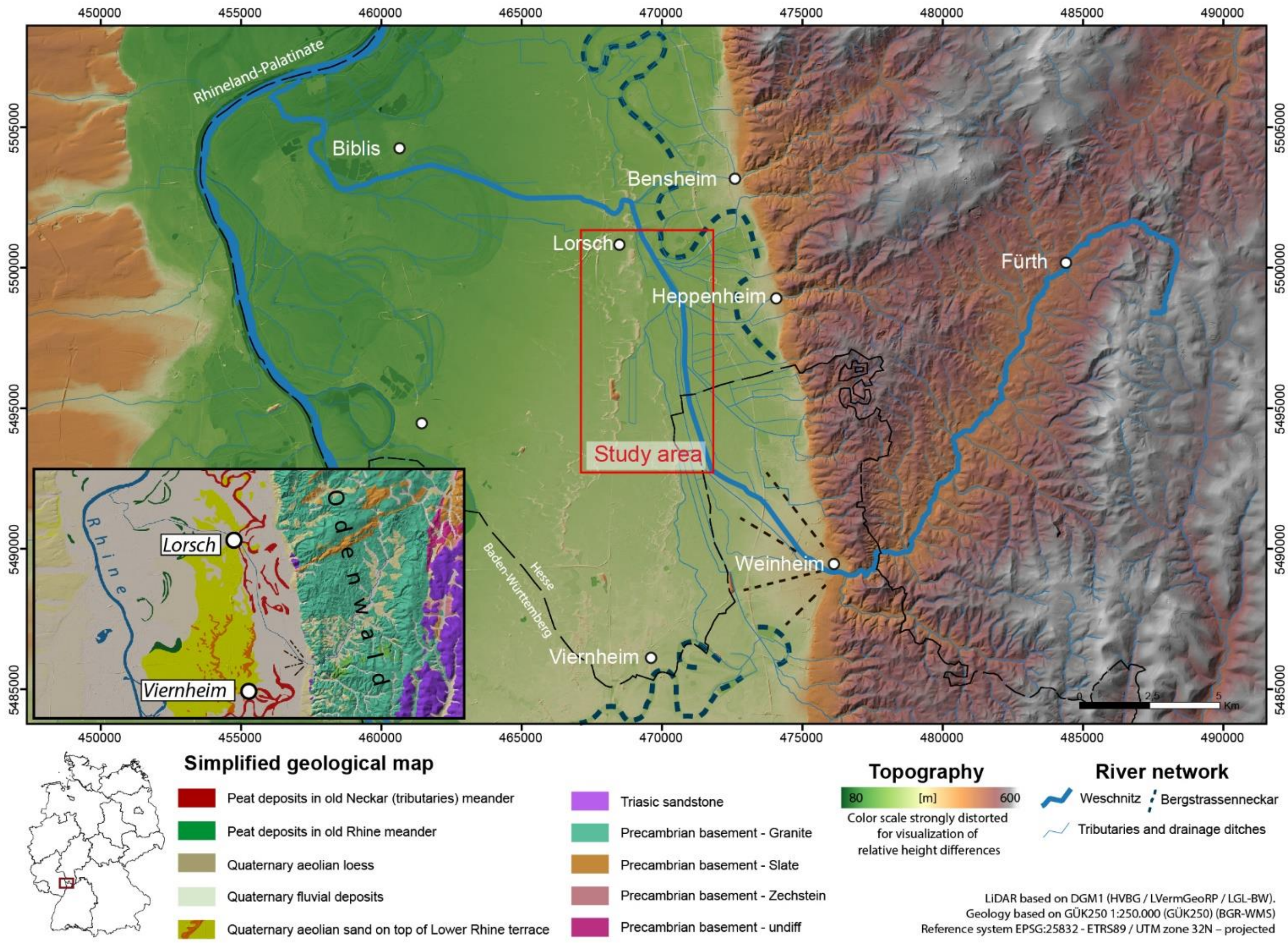

Figure 1: Topographical overview about the Weschnitz catchment between the Odenwald mountains and Upper Rhine Graben with simplified geological map (General Geological Map of Germany 1:200 000 (GUEK200), modified after Engel et al. 2022). LiDAR based on DGM1 (HVBG / LVermGeoRP / LGL-BW). Reference system EPSG:25832 - ETRS89 / UTM zone 32N – projected.

Within the URG, the Weschnitz flows into northwestern, then northern directions, parallel to the dune belt on top of the Lower Terrace of the River Rhine. During Holocene times, the Weschnitz followed a wider channel of the so called Bergstraßenneckar (BSN), which represents the course of the Neckar between Heidelberg and the paleo-Neckar mouth near Trebur until the onset of the Holocene (Dambeck and Bos, 2002; Dambeck and Thiemeyer, 2002; Bos et al., 2008, Engel et al., 2022; Appel et al. 2024b). In the area of Viernheim, the URG consists of the largest accommodation space and depocenter for Quaternary sediments (so called Heidelberg basin) due to strong tectonic subsidence (Hoselmann, 2009; Gegg et al., 2024). This correlates with the absence of clear BSN palaeo-meander between Weinheim and Heppenheim and is evidenced by low-sinuosity palaeo-channels depicted on historic maps (Mangold, 1892).

Around 3000 BC, the Weschnitz changed its course near the city of Lorsch cutting through the Lower Terrace towards its current mouth near Biblis (Appel et al., 2024b). Today, the floodplain of the Weschnitz is accompanied by numerous anthropogenic channels and dikes, some of them dating back to historical times. However, some palaeochannels of its original course are still visible on satellite images.

The study site is situated between two dune belts, a western one with dunes up to 10 m high and a smaller dune belt towards the eastern boarder of former Lake Lorsch with dunes up to 6 m high. The aeolian sediments are part of a large aeolian field between Viernheim and Lorsch, about

25 km long and 7 km wide. The dunes in the URG on top of the lower Rhine Terrace are of Lateglacial age (Holzhauer et al., 2017; Pflanz et al., 2022).

Hydrologically, the *Hessische Ried* is characterized by a high natural groundwater level and a large regional groundwater reservoir within the Quaternary sand and gravels of the URG (Wirsing and Luz, 2007). However, the natural groundwater level and the fluvial architecture was locally affected by melioration measures by Landgraf Georg I during the 16th century CE (Noack, 1966), the Rhine rectification by Johann Gottfried Tulla between 1817-1876 and associated river incision with accompanied groundwater lowering (Rösch, 2009) and more intensive melioration measures (*Generalkulturplan*) between 1933-1939 (Hanel, 1995). The largest interventions affecting the groundwater aquifers have taken place since the 1960s in the course of abstraction for drinking water and integrated agricultural irrigation (Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz, 2005).

2.2 Historical background

A short summary of specific important historic activities related to the Lake Lorsch based on historic sources and literature is given in Figure 2. Due to the natural environment, the area of Lake Lorsch was already rich in water and part of a large marshy area. Before the foundation of the Lorsch Abbey between 763 and 764 CE, some sources indicate that fish farming occurred even in the early Middle Ages in the Weschnitz floodplain, though the region of the lake is not mentioned specifically (Schenk, 2021, p. 45; *Codex Laureshamensis* I 53; *Codex Laureshamensis* I 123b). It can be assumed that small lakes existed ephemerally or periodically in the swampy surroundings. This is also reflected in a document from 1265 CE, which mentions a planned drainage of the Lorsch marsh ("*Palus Laurissensis*") (Lepper, 1938). However, the historical sources do not directly refer to the area by name (Lepper, 1938; Fecher, 1942; Schenk, 2024). It is also reported that the area was used for fish farming by the Lampertheim farmers in the 15th century (Fecher, 1942) and that the Burgrave of Starkenburg had even constructed a lake for the same purpose before 1463 CE (Schenk, 2024).

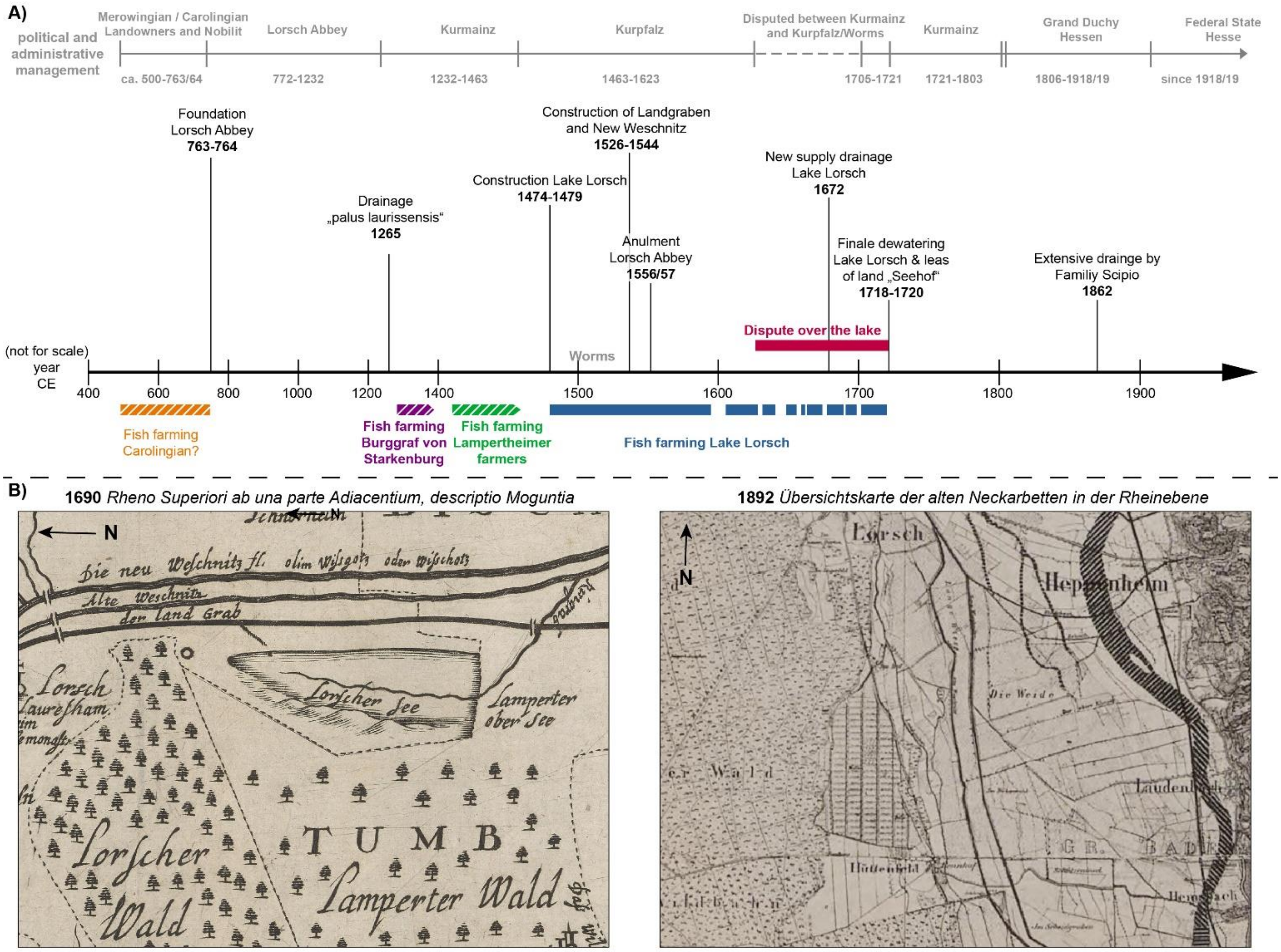

Figure 2: A) Timeline for the historical overview of the political and administrative management in relation to Lake Lorsch and relevant historical events; B) Details from old maps: 1690 (Nikolaus Person Rheno Superior)and 1892 (Mangold 1892) showing the Lake and post-Lake phase.

In 1232 CE, Lorsch Abbey and all its possessions went to the Electorate of Mainz, so that the area of Lake Lorsch now also belonged to the Archbishop of Mainz. It was therefore the Mainz cathedral chapter that drained the Lorsch marsh in 1265 CE - probably unsuccessfully, because in the following period, people still spoke of the “Bruch” (“Swamp”; Lepper, 1938). In 1463 CE, there was another change of ownership when Lorsch Abbey and the entire Bergstrasse (Starkenburg district) were pledged to the Count Palatine Frederick I. A document from Friedrich I (1425–1476 CE) in 1474 CE mentions the beginning of the official construction of Lake Lorsch as an artificial lake for fishing. While the charter also notes the amount of money paid to the church of Lampertheim for the usage rights, it is very likely that the fish was used to feed the Friedrichsburg, which was later named Neuschloss - a hunting lodge in the Lorsch Forest where the document was signed (Schenk, 2021; 49. GLA K 67 812). Besides the “Neuschloss” the lake could now supply the court in Heidelberg with plenty of fish (Knauss, 1992; Lepper, 1938;). While the lake was fed in the southeast by an inflow from the Weschnitz, the water in the north flowed back into the River Landgraben. It is also known that the lake was not used continuously but was drained completely in order to guarantee the quality of the lake water and to use it as pasture when it was drained (Fecher, 1942; Lepper, 1938). The information on the time frames for dry and filled periods ranges from every three years to “from time to time" (Lepper, 1938; Fecher, 1942, p. 43). Between the years 1595 and 1609 CE, Lake Lorsch was dry throughout. In the following period, Lake Lorsch was repeatedly drained for one or more years (e.g. Lepper, 1938: 1599-1611, 1669, 1699, 1702, 1707, 1709, 1719), although the exact dates differ.

The year 1623 CE marked the beginning of a decades-long dispute over the ownership rights to Lake Lorsch. Starting in 1718 CE, the Elector of Mainz had the lake finally drained and in 1721 CE, the lake was finally abandoned, and many of the boundary stones marking the maximum western extent of the Lake following on legal dispute at the beginning of the 17th century can still be found in the lake area today (Schenk, 2024). The area was used as a meadow and farmland, which was henceforth called "Seehof", i.e. Hofgut am See (Lepper, 1938). However, the low yield of the land, its fragmentation through inheritance of the following generations and the growing population in a very poor economic situation, led to the decision, that people from Seehof started to emigrate to America between 1852 and 1855 CE. The subsequent utilization was difficult, and the area was sold to the family Scipio with the condition that all left inhabitants of Seehof had to leave their village as well (Lepper, 1938). Subsequently, the Scipio family had the Seehof area levelled and drained with great effort and they built a modern drainage system with a new supply ditch, which was completed in 1862 CE.

3 Materials and methods

3.1 GIS

The topographic relation between the proposed lake area with its surroundings in terms of height above/below Weschnitz floodplain is used as geomorphometric parameterderived from the LiDAR based high-resolution 1 m digital elevation model (DEM) from Baden-Württemberg and Hessen (DGM1: HVBG / LVermGeoRP / LGL-BW). A relative elevation model (REM) based on the documentation by Dan Coe Carto 2016 (https://dancoecarto.com/creating-rems-in-qgis-the-idw-method2016 referred to Olson et al., 2014; Slaughter and Hubert, 2014) was produced for the characterization of the floodplain from both, the "old" and "new" Weschnitz, by detrending the baseline elevation. The approach uses stream thalweg as river baseline of the old and new Weschnitz, which were manually digitized, and the points serve as reference height for the current water level. This is used for the computation of the topography along the stream line using the Inverse Distance Weighting (IDW) method. The initial DEM is subtracted from the IDW-DEM to map areas below or above the reference stream line. Herewith, areas related to the height above/below the current reference of both streams are computed. All computation steps were performed with the software QGIS 3.4.10.

3.2 Hydrology and Groundwater

Modern groundwater changes are mapped based on the *Fachinformationssystem Grund- und Trinkwasserschutz Hessen (GruSchu)* from the Hessian Agency for Nature Conservation, Environment and Geology (HLNUG). Area wide maps for the depth of the groundwater table in the *Hessisches Ried* exists for single years starting in 1957, whereas groundwater data from single wells start in the 1970s. Weekly groundwater data from well 544184 (Lorsch), located in the central part of our study area, are extracted from *GruSchu* for the period 07.10.1974 to 30.12.2024. Although these data do not represent the actual groundwater levels in historical times, they give an impression of the general characteristics in the area.

3.3 Field investigations and sedimentological analysis

Sedimentological and stratigraphic investigations were caried out across a transect at the central part of the proposed Lake Lorsch following a historic map from 1700 (Lepper 1938), which shows a large drainage channel (*Renngraben*) as artificial water supply (Figure 6 A).

3.3.1 Geophysical prospection using Electrial Resistivity measurements (ERT)

Geophysical prospection allows a non-invasive 2D-profile for sub-surface prospection with the aim of studying the different stratigraphic and sedimentological structures. At the field site, ERT was done by use of a multi-electrode geophysical device (Syscal R1 Plus Switch 48, Iris Instruments) with two profiles using a Wenner–Schlumberger configuration with an electrode spacing of 1 m (following Kneisel 2003), for ERT transect 46 and 48 (Fig. 6 C). The two ERT profiles were inverted and merged using the RES2DINV software by applying least-squares inversion using a quasi-Newton method (Loke & Barker 1996).

3.3.2 Direct push hydraulic profiling (DP-HPT)

Direct push logging allows an in-situ measurement for different parameters (e.g. electrical conductivity, injection pressure, soil color) as minimal inversive sub-surface prospection with real-time stratigraphic information during (geoarchaeological) fieldwork (e.g. Fischer et al. 2016; Rabiger-Völlmer et al. 2020). DP-HPT logging was conducted with a Geoprobe 540 MT mounted on an automotive drill rig (type RS 0/2.3, Nordmeyer) and a K6050 hydraulic profiling tool (HPT, Geoprobe) The probe measures electrical conductivity (EC) with four electrodes in linear arrangement and a Wenner electrode array. Above the electrodes, water is injected at a constant flow rate through an injection screen and hydraulic pressure is measured (McCall, 2011; Geoprobe Systems, 2015). Pre- and post-log calibration at the surface and measurement of the hydrostatic pressure in the groundwater by dissipation tests allows a correction of the total pressure (P_{total}) with the atmospheric (P_{atm}) and hydrostatic pressure (P_{hydro}), resulting in the corrected injection pressure (P_{corr}). Data acquisition for EC and hydraulic pressure is at 2 cm vertical resolution.

3.3.3 Sediment coring

Sediment cores with closed steel augers (1 m) in combination with plastic inliners (50 mm diameter) were collected at the same location as DP-sensing with an automotive drill rig (type RS 0/2.3, Nordmeyer). The two master-cores LOR 20A and LOR 21A are located 27 m apart in a west-east transect. In addition, two short-cores were collected manually using a vibracorer, with LOSE 4 and LOSE 5 15 m respectively 30 m west of master-core LOR 20A (Fig. 6 C). After opening cores were cleaned and photo-documented. Description of sedimentary and pedogenic features followed Ad-hoc AG Boden (2005) KA5.

3.3.4 Laboratory analyses

Magnetic susceptibility (MS) was measured at 1 cm intervals on the core surface (LOR 20A, LOR 21A, LOSE 4 and LOSE 5) using a Bartington MS2 instrument with a MS2K surface sensor (Bartington Instruments Ltd., Witney, UK). Herewith, ferromagnetic minerals, e.g. iron oxides, as typical weathering product are detected, as well as (iron-)oxides related to aerobe conditions within a fluctuation groundwater level (Evans and Heller, 2003). Slightly degradation of the MS signal due to anaerobic conditions (e.g. Wang et al. 2018) are considered to be uniformly across the stratigraphy for our case.

Sediment samples from representative units (LOR 20A and LOR 21A) were extracted for grain size analysis following the Köhn method (Köhn, 1929; DIN ISO 11277, 2002) and for measuring organic matter based on loss on ignition values at 550°C ($LOI_{550°C}$) (Blume et al., 2011). The grain-size distribution represents a proxy for the depositional environment with fine-grained sediments associated with low-energy environments and vice versa. Measurements of $LOI_{550°C}$ can indicate (paleo-)-surfaces and/or anaerobe conditions within a possible lake environment.

Element composition for LOR 20A, LOR 21A, LOSE 4 and LOSE 5was measured using a portable X-ray fluorescence device (Thermo Fisher Scientific - Niton

XL3t GOLDD; soil mode 10 s main filter; 10 s high filter; 10 s low filter). Measurements were conducted at 2 cm vertical resolution on the surface of the cleaned cores covered by Polypropylene X-ray film roll (TF-260, 6µ). Methodological issues with regard to grain-size effects, porosity or the water content for the XRF-measurements are minimized by the use of element ratios instead of absolute data for single elements (e.g. Weltje and Tjallingii, 2008; Profe et al., 2016; Bertrand et al., 2024). The element ratios are used to detect syn- and post-depositional changes in the sedimentary environment and the high-resolution vertical sampling might detect thin layers for potential lake deposits.

We make use of three element ratios as representative proxies for potential lake deposits, non-perennial lake sedimentation and/or high groundwater levels in the given sedimentary context.

K, Rb and Ti represent elements that are likely to be absorbed to fine-grained sediments, especially clay, where K and Rb are slightly more easily weathered than Ti (Fischer et al., 2012; Kabata-Pendias, 2010). Thus, changes in the log K/Ti ratio are interpreted as grain-size proxy, with lower ratios indicating finer grain sizes. Log Ca/Ti is generally seen as weathering proxy, with leaching of Ca and relative enrichment of Ti representing stronger weathering. The combination of both ratios allows to detect masking effects, e.g. an enrichment of Ca along with constant or even increasing Ti values. . Whereas a higher amount of Ca can also derive from Ca-rich allochthonous sediments, the log Rb/Sr ratio can indicate autochthonous secondary carbonate precipitation, as Sr is highly absorbed to Ca (Fischer et al., 2012; Kabata-Pendias, 2010).

Selected samples from both master-cores were chosen for their potential microfossils, but these yielded no findings. Numeric age control for sediment samples by use of radiocarbon dating is not available so far.

4 Results

4.1 Geomorphological parameters for relative elevation models

Based on the high-resolution DEM, the spatial context for the area of Lake Lorsch in between the western and eastern dune belt becomes visible (Fig. 3A). The River Landgraben as well as the old and new courses of the River Weschnitz flow east of the smaller dune belt along a generally small topographical gradient with decreasing altitudes towards the north. The extent of Lake Lorsch matches with an area situated between 94.5 and 95.5 m above Höhennormalnull (m NHN). Mapping of the boundary stones from 1721 CE (complemented to Schenk, 2024) marks the extent towards the northwestern part of the lake at the end of its existence.

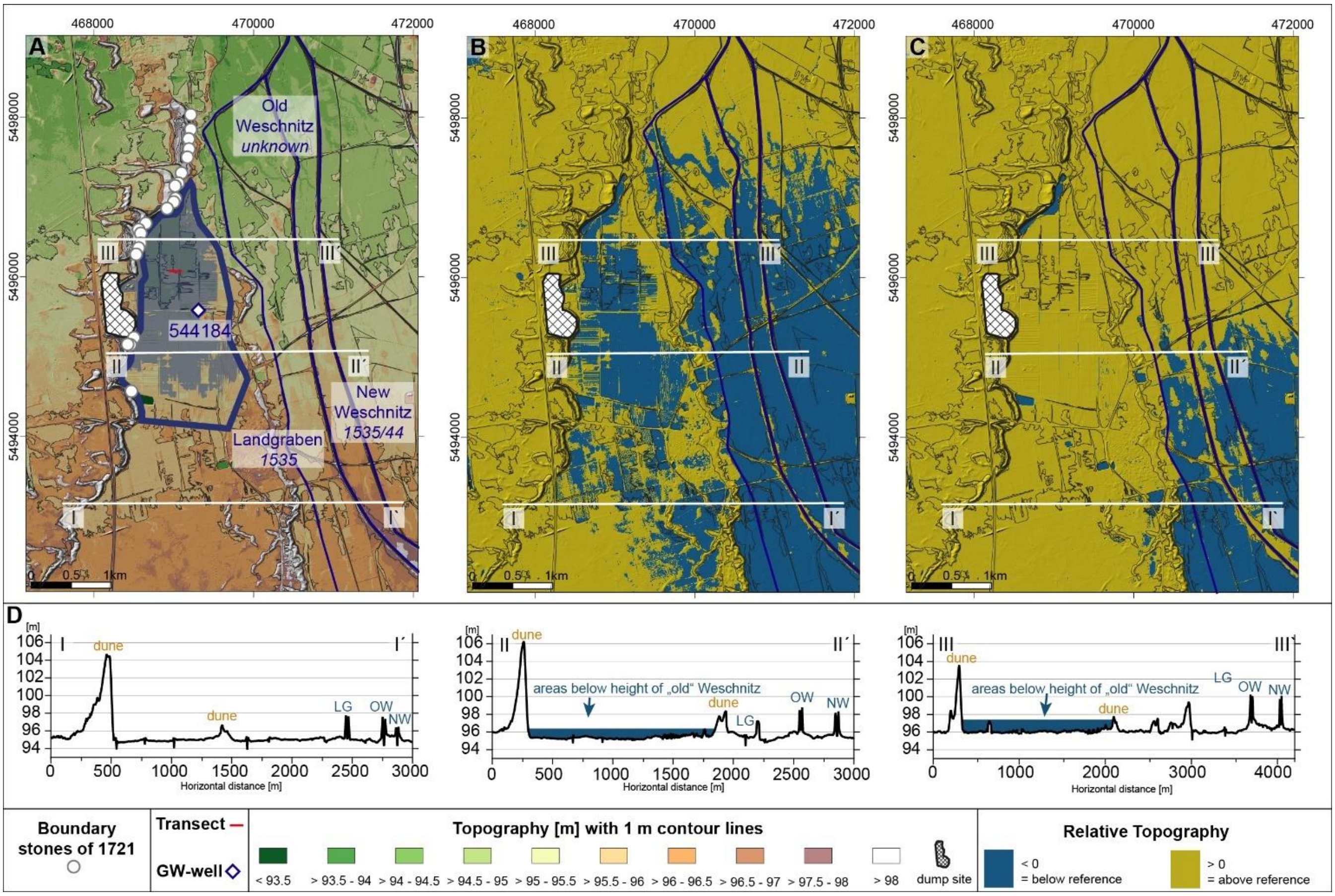

Figure 3: A): DGM1 with 1m contour lines for the Lake Lorsch area, mapping of boundary stones from 1721 (based on Schenk, 2024) and maximal extent for the lake (solid blue line) within the 94.5 to 95.5 m. a.s.l. height level (semi-transparent blue area); B) REM related to the course of the old Weschnitz; C); REM related to the course of the new Weschnitz; D) Topographical cross-sections in the southern, non-lake area (I-I`), middle lake area (II-II`) and northern lake area (III-III`).

The old Weschnitz (unknown date since it existed) REM for the topographic relation to the old Weschnitz as reference level (Fig. 3B) indicates large areas situated below its (current) water level. This applies to the directly adjacent floodplain, but also to the area in between the dune belts. The dune itself is located above the old Weschnitz level. In comparison to the old Weschnitz, the relative topography referred to the new Weschnitz (Fig. 3C) shows smaller areas below the reference, as the new Weschnitz flows at a topographic lower level. Only in the southeastern part of the study area, areas below the height of the new Weschnitz are observed.

Three topographic cross sections (from South to North: I-I´, II-II´ and III-III´; Fig. 3D) show the relation of the old and new Weschnitz streams to the surroundings. Each profile starts in the west with a dune of 4-8 m height with a flatter western and steeper eastern slope, as typical of the parabolic dunes in the URG. Heights of the eastern dune belt are smaller. Whereas the southern cross section I-I` is just at the same topographic height as the Weschnitz canals, the middle cross section and northern cross section are located significantly lower than the old Weschnitz. In comparison with the old Weschnitz the presumable lake area lies much lower, showing height differences up to 1.2 m in the middle and up to 1.8 m lower in the southern cross section. Importantly, the elevation of the Landgraben is considerable lower compared to the old Weschnitz and similar to/just below , the lake area.

4.2. (Past) Groundwater levels

In April 1957, the region had some of the highest groundwater levels since extensive observations started and before groundwater extraction increased from the 1970s onwards. The area of Lake Lorsch had groundwater levels between 0 to 0.5 m below ground surface (m b.s.) with some flooding in the northern part of the area (Fig. 4).

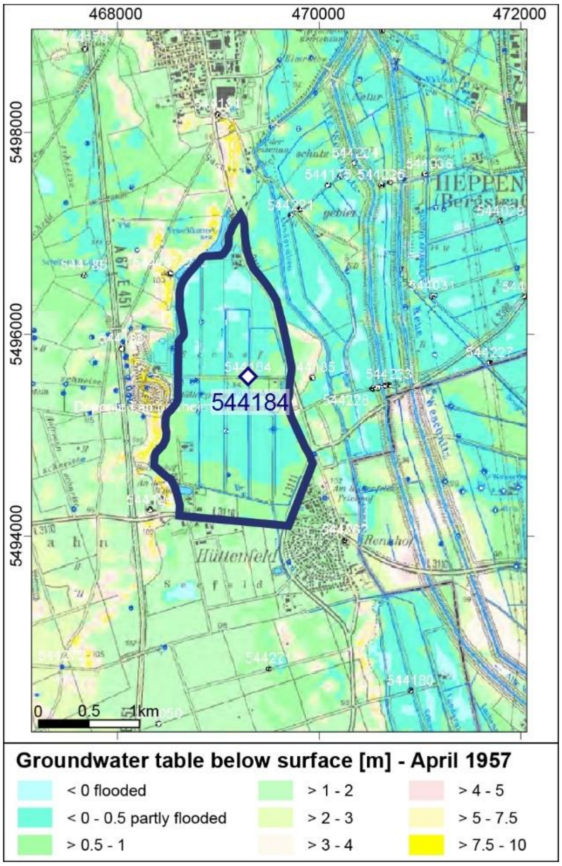

Figure 4: Detail from hydrological map series Hessian Rhine and Main Plain for April 1957 Editing: Wolf-Peter von Pape, HLUG, Department of Hydrogeology, Groundwater, January 2013 Hessian State Office for Environment and Geology, Wiesbaden 2013

Weekly groundwater measurements at well 544184 range between 0.83 and 3.31 m b.s. for the period from 07.10.1974 to 30.12.2024 (Fig. 5). The groundwater level from April 1957 is around 0.5 m b.s. The groundwater level varies in an annual rhythm with longer general fluctuations showing low groundwater level (1992-94) or higher levels (2001-2003). Groundwater levels up to 1 m below surface only exist in 6 years for a short period of time with 24 data points (May- Jun. 1893, Feb 1988; Mar. 2001; Jan.-Feb. 2002; Mar. 2003 Jun. 2013). Lowest groundwater levels of 3 m below ground exist more often with 127 data points in 8 years (1967; 1977; 1978; 1991; 1992;1993;1994; 2022). Mean groundwater level for the whole observation period is 2.2 m b.s.

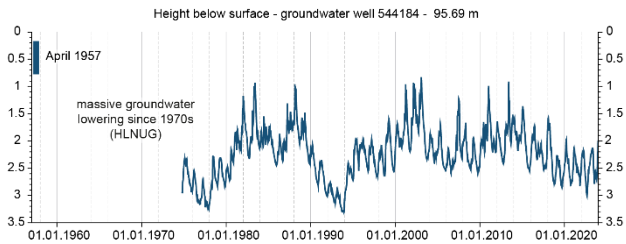

Figure 5: Groundwater well station 544184 (Lorsch) with weekly data from 07.10.1974 to 30.12.2024 (HLNUG)

4.3 Stratigraphy

4.3.1 Geophysical prospection

The compiled ERT-transect from LOR-ERT 46 and LOR-ERT 48 (Figure 6 C) has a length of 80m and a depth of 4 m. The minima apparent resistivity is 28.8 Ωm, whereas the maximum is 491.3 Ωm. The lower part of the profile in a depth of 4 to 3 m consists of low values around 35 to 50 Ωm. In the central part of the transect, these lower values reach up to a depth of 1m, covered by high resistivity over 300 Ωm in the uppermost meter. East and West of this central part, resistivity is around 100 to 200 Ωm in a depth of 3 to 1m, followed by lower values in the uppermost meter.

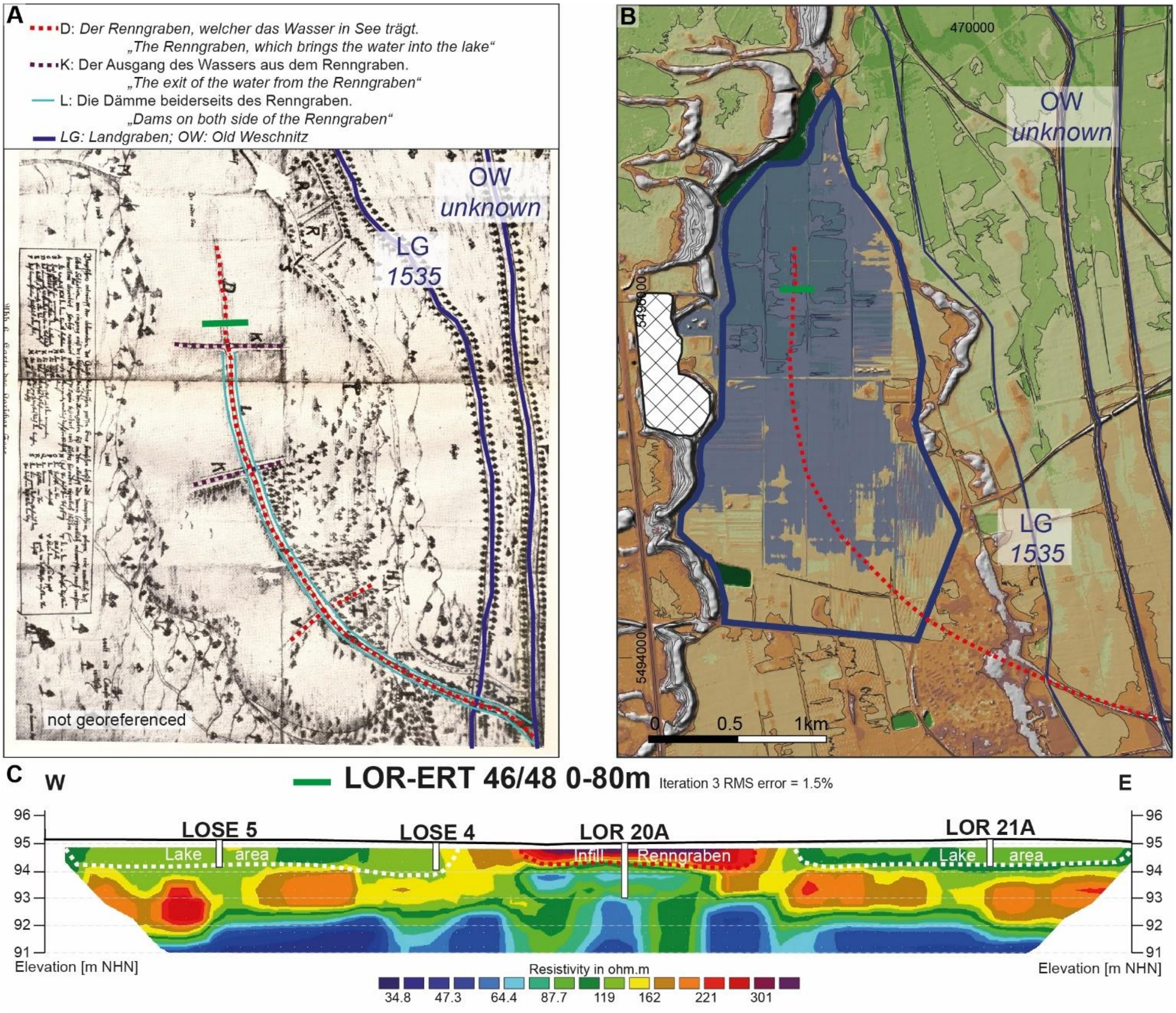

Figure 6: A) Lake Lorsch on an old map from 1700 (from Lepper, 1938) with emphasis on artificial channel (Renngraben) for water input at Lake Lorsch in comparison with B) digital elevation model (for Legend see figure 3) with location of postulated course of the Renngraben. C) ERT-transect ERT 46/48 with location of sediment cores.

4.3.2 LOR HPT 20 and LOR HPT 21

In Figure 7, results for the master-cores derived from DP-sensing, core documentation and laboratory analyses including grain-sizes, $LOI_{550°C}$ and geochemistry are depicted, as well as MS and XRF-data from short-cores LOSE 4 and LOSE 5

Data from LOR HPT 20, logged to 2 m b.s., shows a decreasing EC starting from the base with 10 to 1.9 10^{-5} SI at a depth of 1.15 m b.s. Between 1.15 and 1.05 m b.s., a slight increase up to 3.2 10^{-5} SI is followed by a strong increase up to the maximum of 10.3 10^{-5} SI at 0.95 m b.s. Values remain in a range around 8 10^{-5} SI with a clearer decrease between 0.80 and 0.70 m b.s. down to 1.1 10^{-5} SI. EC values are constant with minor fluctuations up to the start of the EC-log at 0.26 m b.s.

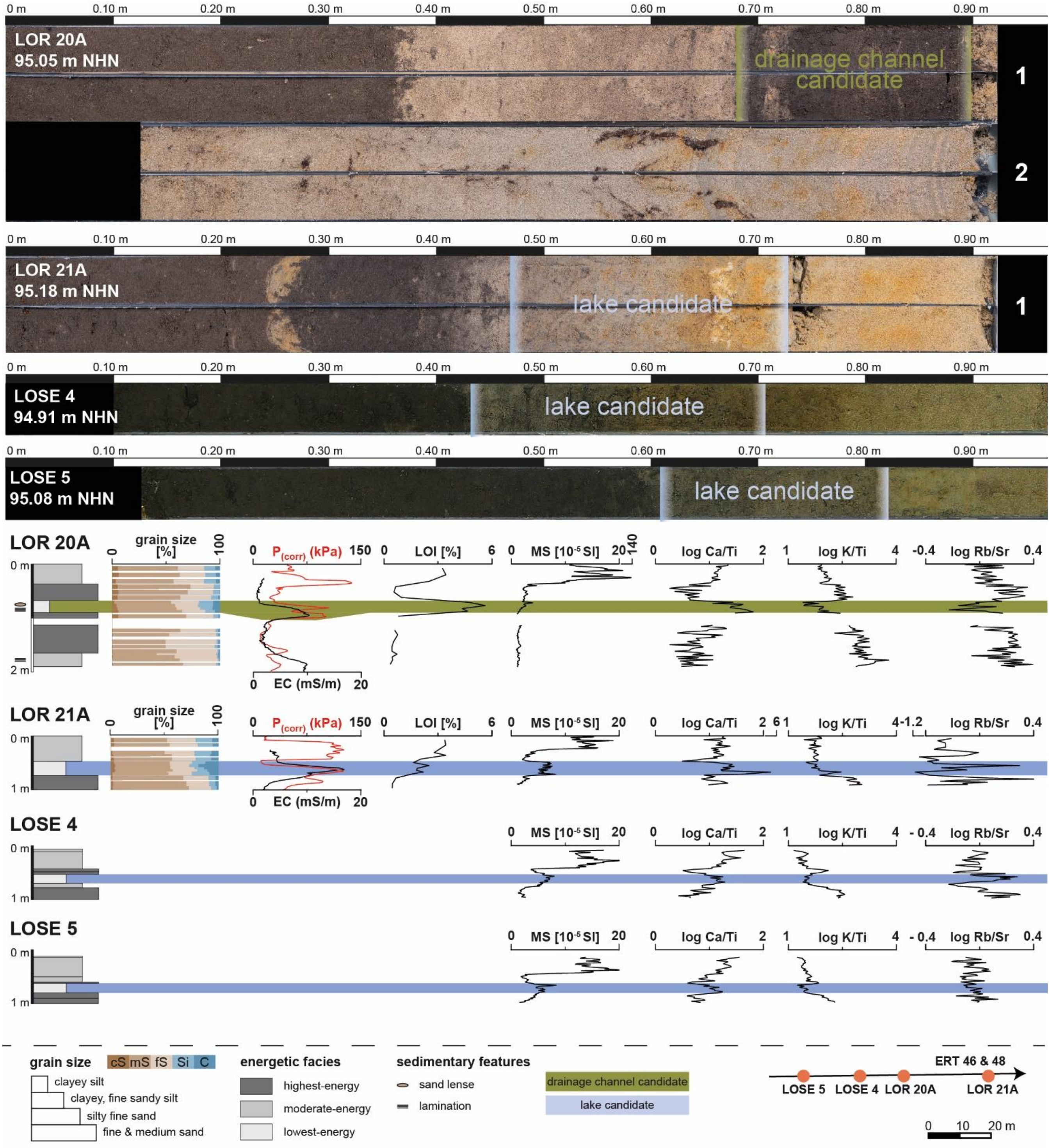

Figure 7: Stratigraphy of sediment master cores LOR 20A and LOR 21A with results from Direct push hydraulic profiling (DP-HPT) and laboratory analyses (grain-size distribution, log, MS, log Ca/Ti, Log K/Ti and Log Rb/Sr) and short-cores LOSE 4 and LOSE 5.

At the base of LOR 20 between 2.00 to 1.40 m b.s., $P_{(Corr)}$ varies in the range of 20 to 30 kPa with two maxima at 1.85 m b.s. (39 kPa) and at 1.58 m b.s. (45 kPa). Between 1.40 to 1.28 m b.s., $P_{(Corr)}$ shows a minor increase from 10 to 30 kPa, followed by a strong increase up to 101 kPa (0.96 m b.s.) in the same depth of the EC maxima. After a short decrease to 54 kPa, there is another maximum at a depth of 0.80 m with 105 kPa, before a stronger decrease follows, comparable to the EC values to a depth of 0.70 m b.s. The maximum values for $P_{(Corr)}$ from LOR HPT 20 follow after 30 cm between 22 to 50 kPa in a depth between 0.38 to 0.30 m b.s. (108 to 137 kPa). The uppermost 0.3 m consist of slightly decreasing values in the range of 70 to 25 kPa. LOR HPT 21 was logged to a depth of 1m. The base starts with EC values around 3 mS/m and shows a continuous increase up to the maximum of 16.5 mS/m at a depth of 0.60 m b.s. Only one minor peak at 0.89 m represents a minimal decrease between 1.00 to 0.60 m b.s. EC strongly decreases in the following section from its maximum to around 5 mS/m at the depth of 0.50 m b.s., where minor fluctuations between 3-5 mS/m characterize the uppermost part up to a depth of 0.26 m b.s. $P_{(corr)}$ from LOR HPT 21 represents in general two pattern. At the bottom of the profile, values starting from 37 kPa (1.00 m) increase up to its maximum of the whole profile at a depth of 0.66 m with 126 kPa. In between, a first maximum at a depth of 0.84 m b.s. (97 kPa) and a smaller decrease to a local minimum of 71 kPa (0.76 m b.s.) occurs. From its maximum, values strongly decrease until 0.54 m to 16 kPa and a followed by a smaller decrease to the minimum of 11 kPa at a depth of 0.49 m b.s. This is followed by a second strong increase and a slightly fluctuation peak in the range of 90 to 120 kPa between a depth of 0.43 to 0.10 m b.s.

4.3.3 Sedimentological results of sediment master-cores LOR 20A and LOR 21A

The stratigraphy of LOR 20A with a total length of 2 m and five sedimentary units starts at the base (unit 5) with an alternating layer of fine to medium sand and thin silt laminae between 1.89 to 1.65 m b.s. In total, grain-sizes are dominated by sand with around 97 % and minor amounts of silt (1.7 %) and clay (1.3 %) resulting from the thin laminae. This unit has no calcium-carbonates (c0) and shows secondary iron-oxides especially in the sand layers, whereas the fine silt laminae are grey. Between 1.65 m to 0.90 m b.s. (unit 4), grey-brown homogeneous sands (LOR 20A/15: 94.9 % sand; LOR 20A/14: 96.6 % sand) with patches of iron-oxides and roots in the lower part of the unit are present. Calcium carbonate content is absent (c0). Unit 3 between 0.89 to 0.68 m b.s. is characterized by a very dark color, high amount of organic material (h3-4), iron concretions and scattered charcoal flakes. Especially the lower part is slightly laminated. The grain sizes show an increased proportion of silt and clay, with up to 14 % silt and 7 % clay representing the maximum of the entire core. This unit is capped with a brown-grey sand dominated layer (unit 2; 0.68 to 0.37 m b.s.), patchy grey-brown color and irregular small fragments of organic content and small roots. Clay is almost absent (0.5 to 1.7 %) and minor amounts of silt (5.3 to 6.5 %) complete the dominant sand component with 91.86 to 94.25 %. The uppermost unit 1, 0.37 to 0.00 m b.s., consists of brown-dark color, slightly enhanced amounts of clay (3.8 to 4.4 %) and silt (10 to 11%) weakly rooted sand (85.2 to 86.3 %).

$LOI_{550°C}$ ranges between 0.3 to 0.7 % in unit 5 and 4, whereas unit 3 has an $LOI_{550°C}$ between 4.3 to 5.6 % and is higher than unit 2 (0.6 to 1 %) and unit 1 with 2.5 to 3.3 %. MS in the lower units 5 and 4 is overall low with minimally fluctuating values around 1.3 (10^{-5} SI). Unit 3 shows an increase in MS from the base of the unit (0.89 m b.s.) starting at around 1.4 up to 4 (10^{-5} SI) at the top of the unit (0.69 m b.s.). Unit 2 shows again minor fluctuations, in this unit around 2.6 (10^{-5} SI) with a small increase towards the top. Highest values are found in the uppermost unit 1 with a strong increase up to a maximum MS of 127 (10^{-5} SI).

The results for the geochemistry show variable ratios of log Ca/Ti in the lower part of the stratigraphy and a distinct increase towards higher Ca values in unit 3, before a strong decrease mark the transition to unit 2. Similar, log K/Ti shows an markable shift in unit 3, besides a general trend of lower values from the bottom to the top. Log Rb/Sr has in general larger fluctuations throughout all units, but unit 3 is also characterized with minima values pointing to an increase of Sr in this unit.

Sediment core LOR 21A (1 m length) is represented by three stratigraphic units. Unit 3 consists of a yellowish-brown, calcium carbonate free (c0) fine and medium sand between 1.00 to 0.73 m b.s. Silt (around 6 %) and clay (around 3 %) are only minor components of the grain size distribution. On top of this, stratigraphic unit 2 (0.73 to 0.47 m b.s.) shows a distinct shift towards finder grained sediments with 16 % silt and 8 % clay in the lower part of the unit up to 0.67 m b.s., and 10 % silt and up to 19 % clay in the upperpart of the unit around 0.55 m b.s. Here, a fining-upward is visible in the grain-size distribution. This unit shows hydromorphic features with iron-oxides as well as strong reducing conditions. A thick carbonate lense (c5) occurs at a depth of 0.62 m b.s. No sharp transition exists towards the uppermost unit of LOR 21A, starting with a smooth transition at 0.47 m b.s. upwards. A fine sand lense occurs at a depth of 0.25 m b.s., whereas the unit itself is in general dominated by sand (around 80 %), with minor amounts of silt (14 %) and clay (6 %).

The $LOI_{550°C}$ for LOR 21A shows a general increase from the base in unit 3 towards the top of unit 1. It starts with low values of 0.5 % between 1.00 to 0.78 m b.s., shows an increase with two relative maxima in a depth of 0.67 m b.s. (2.2 %) and 0.55 m b.s. (2.5 %) and a highest value at 0.36 m and 0.08 m b.s., both with 3.4 %.

The MS for LOR 21A shows two distinct sections. A slight increase is observed between 1.00 to 0.75 m b.s. (1.5 to 2.5 10^{-5} SI), before a sharp increase up to 8 10^{-5} SI at 0.72 m b.s. exists. MS stays in this range up to 0.50 m b.s., where a sharp decrease to values around 2.5 10^{-5} SI occur. A second sharp increase exists at a depth of 0.24 m b.s., where the maxima values of around 15 10^{-5} SI are given.

Log Ca/Ti for this core has constant variability apart from one large peak towards an increase of Ca at the bottom of unit 2 and a one peak with enhanced Ki at the transition from unit 2 to 1. Log K/Ti shows a continuous decrease from the base towards unit 2 constant values fur unit 1. Largest fluctuations are seen in log Rb/Sr with to significant peaks of enhanced Sr.

4.3.4 Sedimentological results of short-cores LOSE 4 and LOSE 5.

Short-cores LOSE 4 and LOSE 5 (Fig. 7), with a length of 1 m each, show a comparable structure of the stratigraphy. Both cores show well sorted fine & medium sand at the base between 1 to 0.78 m b.s. (LOSE 4), respectively 1 to 0.8 m b.s. (LOSE 5) as unit 4. These sands are free of carbonate (c0) with some spots of Fe and Mn enrichment and MS between 1 to 3 10^{-5} SI. Unit 3 (0.80 to 0.53 m b.s. LOSE 4; 0.8 to 0.62 m b.s. LOSE 5) consists of clayey fine sandy silt, a local maximum with higher MS ranging from 5 to 8 0^{-5} SI. This is superimposed by a thin unit 2 consisting of carbonate free well sorted medium sand between 0.53 to 0.43 m b.s. (LOSE 4) and 0.62 to 0.60 m b.s. (LOSE 5). Here, MS shows a slight decrease in both cores. The uppermost unit 1 (0.43 to 0.06 m b.s. in LOSE 4; 0.5 to 0.12 m b.s. in LOSE 5) consists of organic-rich silty fine sand and MS of 10 to 20 10^{-5} SI, showing the maximum of both cores. The uppermost 0.12 m b.s. respectively 0.06 m b.s. are lost due to sediment compaction and resulting core loss.

The geochemical proxies log Ca/Ti and log K/Ti show almost identical patterns in both cores. Starting from the base, log Ca/Ti are slightly increasing in unit 4, with a distinct increase and local maxima in unit 3, followed by a sharp decrease at the boundary between unit 3 and unit 2 with a second minima. Unit 1 is characterised with increasing log Ca/Ti values in both cores. Log K/Ti decreases from the base of both cores towards a local minimum in unit 3, followed by an increase at the transition from unit 3 to unit 2, where a general trend to lower values towards the top is observed. The log Rb/Sr shows largest fluctuation across both cores with some sharp changes at the boundaries of sedimentological units, e.g. unit 4 to unit 3 in core LOSE 4.

5 Discussion

The geomorphometric analyses show that the proposed area for Lake Lorsch between the two dune belts fits very well with historic sources and maps (comp. Fig. 3 and 5). The lake extent (around 3 km^2) follows an area, which is (today) below the drainage stream of the old Weschnitz. The morphometry and REM prove, that only water from the Old Weschnitz could be used for water regulation of Lake Lorsch without additional damming or pumping, as the lake area is topographically lower than the Old Weschnitz. Due to the low elevation of the Landgraben below the lake area, it would have needed pumping to feed water into the lake system. Although this argument is based on the current relief, these elevation differences can also be assumed for the lake phase due to the low sedimentation (Fig. 7). The historic map from 1700 shows, that the artificial drainage channel (D: "The Renngraben, which brings water into the lake") crosses the Landgraben from 1535 with a small bridge/canal. This is also visible in the historic map from 1690 (Figure 2, *Nikolaus Person Rheno Superior).* As the Lake Lorsch (1474/79) also pre-dates the construction of the Landgraben (1535), the Landgraben couldn´t be used in the initial phase of the lake.

The high groundwater level led to long-lasting surface water in the area before the construction of the canals. Thus, historic sources on drainage of the wetlands south of Lorsch "*palus laurissensis*", and the fish farming from Starkenburg and Lampertheimer farmers in the 13^{th} and 14^{th} century are clearly associated with a groundwater dominated wetland, with generally higher groundwater levels in the URG during the medieval period (Tegel et al., 2020). The strong fluctuation of the log Rb/Sr also point to these varying groundwater levels across time.

Two phenomena ensure that today's groundwater level is significantly lower than in the past and does not account for the time of the Lake. Incision of the rivers Neckar and Rhine following major regulation measures in the early 19th century led to substantial groundwater lowering in the whole URG (Barsch and Mäusbacher, 1979; Dister et al., 1990). In addition, modern groundwater level within the Hessische Ried is strongly modified by humans with large scale groundwater lowering due to intensive water exploitation for drinking and irrigation purposes. This has been reinforced since the 1970s (HLNUG). Before, in spring 1957, the region had some of the highest groundwater levels since extensive observations started, which might be comparable to historic conditions.

Besides the long-term anthropogenic groundwater lowering over centuries, climatologically induced annual fluctuations in groundwater levels are characteristic for the region today, but also very likely in the past. The lake was an artificially controlled lake during its main utilization phase. The inflows and outflowsrecorded in historical sources (e.g. Lepper 1939 and historic maps within), could allowed to maintain the lake in the long term during annual groundwater variability even without sealing it off at the bottom. However, to what extent the lake level changes were dominated by natural processes or anthropogenic regulations, remains quantitatively unknown at this point. Shallow lake conditions were ideal for carp farming, especially in summer, as carp grow best in shallow and warm waters (Oyugi et al.; 2012). According to historical sources, the deeper fish pits required for wintering were located to the east of the present-day Seehof site.

The complex situation with several drainage channels, the depression of the lake itself, and relation to past groundwater levels also play an important role for the interpretation of the sedimentary sequence. Two layers, unit 3 in LOR 20A and unit 2 in LOR 21A, have important similarities, but also striking differences and might be associated with the history of Lake Lorsch.

Stratigraphic unit 2 in LOR 21A shows a fining-upward sequence of sediments dominated by silt and clay, higher EC and $P_{(corr)}$ values and enrichment in organic material. A striking feature in core LOR 21A is the distinct secondary carbonate precipitation in the depth of 0.67 m b.s., just at the significant shift in grain-size distribution between unit

2 and unit 3. These secondary carbonate features are commonly observed in the URG as indication for distinct substrate boundaries within the groundwater fluctuation zone called *Rheinweiß* (Dambeck, 2005; Engel et al. 2022). In relation to the development of groundwater levels, it is interpreted as a historic marker for higher groundwater levels. The associated fining-upward sequence of unit 2 in LOR 21A on top of this carbonate precipitation and the high amount of clay allows us to identify this unit as a potential lake deposit. This observation is also valid for unit 3 of LOSE 4 and LOSE 5, which have a similar enrichment of silt and clay with associated higher MS, enrichment of Ca and enriched Ti values related to clay rich sediments.

A second possible source for the carbonate precipitation is bicarbonate (HCO_3^-) dissolved in the water. With the presence of photosynthesising *Charophyceae* and aquatic plants and their associated uptake of CO_2, secondary carbonates precipitate (e.g. Bohnke and Hoek, 2007). This process is also discussed for fluvio-limnic environments in the URG (e.g. Engel et al., 2022). Here, both explanations are in good agreement for the expected sedimentological signal of Lake Lorsch and the interpretation of stratigraphic unit 2 form LOR 21A as lake deposits.

Sedimentation in unit 2 from LOR 21A seems continuous and comparable to unit 3 from LOSE 4 and LOSE 5. No evidence for an interruption of lake deposits is visible with a gradual transition towards unit 1. Following general sedimentation rates in natural lakes of about 1 mm/a (e.g. Jenny et al., 2019), the order of magnitude for deposits of the Lake Lorsch with its existence for about 250 years between 1474/79 to 1718/20 CE is around 25 cm. Therefore, we propose that even during a dewatering of the lake, remnants of (shallow) lakes existed in a possibly heterogeneous spatial pattern. In addition, it is also not known from historic sources, if the whole area was drained from time to time, or if this relates to specific areas of the lake, e.g. separate fish ponds. Lowest depositional energy pointing to limnic conditions in unit 3 in LOR 20A are given by the highest amounts of clay and silt, in accordance with higher EC and higher $P_{(corr)}$values indicating finer grain-sizes. Both DP-proxies show the decrease in grain-sizes from 0.70 to 0.80 m b.s. The lower boundary of the fine-grained sediments in the DP-data are lower than in the core. Whereas DP-data show the exact depth, coring is affected by compression and/or core loss, so that the exact depth of each stratigraphic unit based on core data can be inaccurate. We interpret the slight shift for the lower boundary of unit 3 in the core at 0.90 m and 0.96 m b.s. in the DP-data as evidence for a compression of this unit. The log K/Ti ratio also indicates finer-grained sediments associated with relative increasing Ti values related to clay rich sediments. At the same time, the higher values of the log Ca/Ti ratio indicate an enrichment of Ca in this unit in phase with the increasing amount of silt and clay. Altogether, this points to depositional conditions associated within a possible lake environment. Nevertheless, the high $LOI_{550°C}$ for this unit (absolute maximum for the whole core) and its dark colour indicate very high amounts of organic and a deposition near/at the surface.

Here, striking differences in the ERT-profile indicate that LOR 21A, LOSE 4 and LOSE 5 with the lake candidate deposits, are associated with much lower resistivity values in contrast to LOR20A, which represents the central part associated with the highest resistivities of the transect. These higher values are associated to the uppermost 0.7 m from LOR 20A showing sand dominated sediments and thus, higher resistivity. Below, the organic and clay to silt rich sediments of unit 3 from LOR 20A represent the drainage channel candidate. We interpret these deposits as anthropogenic infill of a channel, most presumably the former *Renngraben*, even though the historic map from 1700 can not be georeferenced for exact location. Unit 2 from core LOR 20A could represent such backfilling for the channel, as the transition from unit 3 to 2 is very sharp, with unit 2 consisting of organic fragments and an overall mixed character. The assumed "young" age of this unit could also explain the sharp transition to the (modern) plough horizon and less pedogenic features below 0.37 m b.s. As radiocarbon ages from unit 3 of sediment core LOR 20A are not yet available, a water supply channel of the lake phase (late 15th to early 18th century) is likely, buta drainage channel of the post-lake phase (19th to 20th century) remains possible. The repeated draining and conversion of the area since 1892 attributed to the large-scale irrigation and drainage system (Fig. 2 B) installed by the Scipio family and to the subsequent backfilling of the drainage channels since the middle of the 20th century. However, these drainage channels are much smaller in comparison to the high resistivity anomaly observed in the central part of the ERT-profile, thus it is more likely, that this represents the Renngraben channel from the lake phase. .

6 Conclusions

The geomorphological context of the artificial Lake Lorsch (14774/79 to 1718/20) points to a lake favoured by a high groundwater level, in accordance with historical sources from the pre-lake phase, that give indications for a landscape under permanent water abundance. During the main-phase for the use of the lake, information about controlled inflows and regulation of the water level, including a complete draining of the lake, highlight the ability for a sufficient water management and engineering during this time. An example of this is that the inflow of Lake Lorsch took place via the old Weschnitz, topographically higher than the lake area, and that the Landgraben, which was created later and is topographically lower, had to be bridged. Thus, it represents an early example of strong intervention in the natural water system affecting the Weschnitz floodplain and its surroundings. However, any quantitative information to what extent natural hydrological variability or human intervention dominated respectively varied throughout time, remains open and could be addressed with future palaeohydrological modelling. Here, our results from a morphometric and sedimentological perspective serve as important input data.

The location of Lake Lorsch between the two dune belts and to the west of the former natural course of the Weschnitz means that the lake was not strongly affected by sediment-laden water flowing through it during floods. Sedimentary unit 2 in core LOR 21A and unit 3 in core LOSE 4 and LOSE 5 were identified as a potential lake deposit, exhibiting characteristics indicative for a limnic environment with high groundwater table. This undisturbed unit gives evidence for permanent water levels at this location. However, the drainage channel deposits from core LOR 20A reflect the artificial nature of the lake and/or subsequent drainage of the area during the post-lake phase.

The integration of geomorphological parameters, groundwater related proxies and comparison with (sub-) modern groundwater levels in addition to sedimentological results helps to understand the numerous historical traditions from an integrative landscape perspective. It reveals, that the legacy of Lake Lorsch is spatially and temporally heterogeneous and characterized by a strong anthropogenic influence during and after the use of the lake, thus, a good example for a complex fluvial anthroposphere, where humans started to act as fluvial and water related agents at least 500 years before present. Code / Data availability

The data that support the findings of this study are available from the authors upon request.

Author contributions

The concept of the study presented in this paper was developed by FH, OB and AV. GIS-investigations were done by FH. Fieldwork and laboratory analyses were carried out by PF, EA, OB, BM and AV. Research on the historical background was carried out by BJ, NH, GS, TB, RP and UR. Figures and tables for this paper were created by FH and EA. All authors commented on and approved the manuscript.

Competing interests

Two authors (OB + GS) are guest editor of the special issue “Floodplain Architecture of Fluvial Anthropospheres”. The peer-review process was guided by an independent editor. The authors have also no other competing interests to declare.

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