

**A large-scale medieval dam-lake cascade in central Europe: water level dynamics of river Havel,
Berlin-Brandenburg region, Germany**

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ABSTRACT

An interdisciplinary study was carried out to trace the hydrological changes of the river Havel in northeastern central Europe over the course of the last c. 2000 years. This research was driven by the hypothesis that the present-day riverscape is to a large degree a result of medieval and modern human transformation of the drainage system. The river system forms a series of dammed lakes and river sections

which were greatly altered through hydraulic engineering in the past. Along the middle course of the Havel, sixteen sedimentary sequences available for geoarchaeological and paleoecological research were analyzed in order to reconstruct regional water level dynamics. Chronological control was ensured through a multitude of palynological, dendrochronological, archaeological, and radiocarbon data. The sections upriver from the Brandenburg/H. and Spandau weirs, representing sites with historic watermills, reveal substantial water level changes during the late Holocene. Generally, lower water levels before and higher levels during the medieval German colonization of that area (c. A.D. 1180/1250) can be inferred. This water level increase, which is primarily attributed to dams constructed for watermills and secondarily due to a multitude of fish weirs, took place rapidly and amounted to a relative height of c. 1.5 m. It enlarged the river's cross-sections and increased the size of existing lakes or initiated secondary lake developments when already aggraded, and thus caused a flooding of large parts of land. The rising water level even influenced the settlement topography to a large degree. Several medieval rural settlements were abandoned due to flooding. In total a c. 150 km-long dammed lake cascade was formed.

INTRODUCTION

Artificial damming has and continues to have an enormous impact on hydrology, ecology and the socio-economics of nearly all rivers and streams in western and central Europe. First large-scale *intentional* human impact on riverscapes at least in parts of these areas is attributed to the late Roman period (e.g. Havinga & Smits, 2000), comprising canals, mill dams and reservoirs, aqueducts, and waste water systems. However, an all-encompassing change of the flowing waters and their catchments occurred as late as during the medieval period (e.g. Lewin, 2010; Hoffmann, 2014). As known for the late 11th century A.D., for instance, 5600 watermills with attached weirs were operating in 3000 locations in the rather small area of southeastern England alone (Reynolds, 2002). As another example, Brykala (2014) estimated c. 1500 watermills for central and northern Poland in the last 800 years, although this represents only a fraction of the total number of mills expected in the whole river Wisła (Vistula) catchment area. Further, current research on the historic transformation of riverscapes was particularly inspired by findings

on the stunning impact of the watermill industry in the eastern United States during the late 17th to early 20th century A.D. By A.D. 1840, more than 65,000 watermills existed in that area, substantially altering the trajectory of geomorphic, hydrological and ecological processes for the impacted valley bottoms (Walter & Merritts, 2008; Merritts et al., 2011).

Several case studies on the historic transformation of riverscapes were conducted with regard to the western and central European context. But these studies differed greatly in their methodical approach and spatial focus (e.g. Hesselink, 2002; Chaussé et al., 2008; Leitholdt et al., 2011; Hohensinner et al., 2013). As a specific matter besides historic floods and structural floodplain changes (e.g. Brown, 1997; Howard et al., 2003; Lewin, 2010) some studies shed light on the manifold effects of historic damming by the operation of watermills, such as reservoir construction, sediment budgeting and water level changes, as well as socio-ecological consequences (e.g. Bleile, 2005; Downward & Skinner, 2005; Brykala & Podgorski, 2008; Bishop et al., 2011; Lüth, 2011; Oliver, 2013; Rynne, 2015). Information on the pre-modern ecologic reference status of aquatic landscapes is particularly essential before developing restoration measures. This specifically applies to the implementation of measures in accordance with the European Union Water Framework Directive (e.g. Bennion & Battarbee, 2007; Poepl et al., 2015), aiming at a good ecologic status of the European waterbodies.

It was occasionally hypothesised by different scientific disciplines that the present-day hydrography of the metropolitan area of Berlin and its surrounding is a product of medieval and modern human transformation of the drainage system, modified to meet the needs for energy and food supply (milling, fishing), urbanisation and inland navigation (e.g. Schich, 1994; Brande, 1996; Driescher, 2003; Nützmann et al., 2011; Kaiser et al., 2012). If so, the extended dammed courses of the Havel and Spree rivers may represent one of the largest historical dam-lake cascades globally with regard to length and water volume. Recent opportunities to examine this matter arose during the course of archaeological rescue excavations accompanying the revitalization of eastern German towns and general construction work since German reunification in 1990. Moreover, paleoecological research on wetland dynamics recently provided insights on long-term riverscape changes in that region.

The overall question addressed by this study is: What can sedimentary sequences tell us about the water level dynamics of the river Havel during the Holocene, particularly during the last two millennia? More specifically we wanted to 1) identify, analyze and evaluate recent data suitable for this matter, and 2) interpret and discuss the results with respect to long-term anthropogenic and ecological changes of the riverscape. Thus, for the first time an interdisciplinary study has been conducted aiming to analyse the human transformation of a large river system in northeastern central Europe during the medieval and modern period.

STUDY AREA

Physical settings and late Quaternary fluvial evolution

The study area is located in the North European Plain at an altitudinal range from 25 to 125 m a.s.l. The Weichselian glaciation, dating c. 24-18 ka (Hughes et al., 2016), has had a strong impact on the formation of the glacial surface sediments and landforms. Sandy deposits of glaciofluvial, glaciolacustrine, eolian, and colluvial facies prevail in the study area. River and stream valleys in this recently glaciated area are characterized by frequently alternating degradational (erosion) and aggradational (accumulation) stretches, by frequent shifts in the valley direction and by the common presence of (dead-ice) lake basins. As the transport energy is currently low and a multitude of sediments traps in the form of lake basins occur, the flowing waters carry mostly sand as the maximum grain size when eroding locally and form lacustrine deltas when entering lake basins (Kaiser et al., 2007).

Three main ice-marginal Pleistocene spillways of northern central Europe flowed together in the studied area, forming a network of wide valleys with vast Holocene peatlands that are now drained and mainly used for agricultural purposes (Figure 1). Major rivers in the study area are the Havel and Spree which drain via the river Elbe into the North Sea. The river Havel originates in the Mecklenburg Lake District to the north at 62 m a.s.l. and joins into the Elbe after a length of 334 km at 22 m a.s.l. The total catchment area including Spree tributary amounts to 24,350 km². Its bed slope is generally low (Figure 2). The mean annual discharge at Havelberg next to the mouth in the Elbe is 94.5 m³ s⁻¹. The middle and lower course of

river Havel is characterized by the occurrence of numerous mostly shallow (initially glacial) lakes of different sizes (max. 7.9 km²) and of different genetic, hydrological and ecological type. Main tributary of the river Havel is the river Spree which originates in the German Uplands to the south at 430 m a.s.l., joining Havel at Spandau (river length 400 km, catchment area 10,100 km², mean annual discharge at Spandau 42.2 m³ s⁻¹).

In general, the fluvial relief of the region underwent a complex late Quaternary history of glacial, fluvial, lacustrine and aeolian processes with strongly increasing human impact since the medieval period (Supplemental Figures 1, 2, 3). Only little evidence on late Quaternary floodplain stratigraphy along the river Havel exists thus far. It reveals that intensified river bed dynamics in the late Glacial and early Holocene, which included dead-ice melting and pronounced river channel migration, were followed by a mid-Holocene reduction of the lowermost river-bed gradient downstream of Brandenburg/H. through an eustatically driven rise of the river Elbe's river bed (Küster & Pötsch, 1998; Weiße, 2003; Supplemental Figure 2). Paleolimnological analyses of paleomeanders in its lower course indicate that a widely forested catchment and low seasonal precipitation rates may have caused low summer discharges in the river Havel during the period A.D. 300 to 1200 (Schönfelder & Steinberg, 2004). Only in the lower course of the river Havel ('Elb-Havel-Winkel' in German) did distinct course changes occur occasionally during the Holocene and throughout historic times up until the early 18th century A.D., when the river Elbe followed older courses in the deeper lying Havel valley as a result of strong floods (Wiegank, 2009).

The late Holocene water level dynamics of the river Havel and similar medium-sized rivers in the wider region (e.g. lower Spree and Dahme) which entail a low river-bed gradient, a multitude of glacial lake basins and wide peatland basins within the river valley, as well as rather large mean annual discharges (>10 m³ s⁻¹), potentially result from both natural (climatic, geomorphic, biotic) and anthropogenic factors. By contrast, tectonic forcing can be seemingly excluded as an explanatory factor in this morainic area which is covered by thick Cenozoic and Mesozoic sediments (Kaiser et al., 2012). Before man became a major agent in the very late Holocene it can be assumed that in particular the climate controlled the water balance, causing changes of river water levels and of nearby groundwater levels (e.g. Jeschke, 1990;

Howard et al., 2003; Starkel, 2003; Kalicki, 2006; Macklin et al., 2006; Kaiser et al., 2014; Jones et al., 2015).

Generalized settlement history and human impact on the riverscape

From the study area, representing the Havelland region, first evidence for human re-occupation after the last glaciation is available from the Lateglacial (for chronology of the prehistoric period see Supplemental Figure 1). Whereas the initial occupation is already discussed for the early Hamburgian (Bølling/Meiendorf), although not proven so far (Terberger et al., 2004), several sites from the *Federmesser* technocomplex (late Allerød) and the Ahrensburgian (Younger Dryas) were detected. Mesolithic sites (Preboreal to late Atlantic) are widespread in the region, but traces of Neolithic settlements occur only locally (Cziesla, 2012). Probably during the transition phase to the Subboreal first agriculture appeared (Beran, 2012). For the Bronze Age, ending at the beginning of the Subatlantic, a very dense settlement pattern particularly along the rivers and streams is apparent (Bönisch, 2012). Agriculture and craft, large settlements and fortifications as well as a ‘road’ network partly of trans-regional importance indicate a well-differentiated cultural landscape in the Havelland region at that time. There is also evidence for soil erosion by human impact, triggering colluvial and eolian processes as well as matter and nutrient import into flowing waters and lakes (Kirilova et al., 2009; Enters et al., 2010; Tolksdorf & Kaiser, 2012). The noticeably rare occurrences of early Germanic settlement remains during the Pre-Roman Iron Age (early Subatlantic) were interpreted to be caused by rising water levels in this low-lying region (Buck, 2000). For the Roman period (c. A.D. 0-450) – ‘Roman’ (‘Kaiserzeit’ in German) is the traditional (pre-)historic term used, although this region was never settled or ruled by the Romans – a rather dense settlement pattern along the flowing waters appeared again, ending with the movement of the people during the Migration period (c. A.D. 450-700; Brather & Hegewisch, 2012). The subsequent Slavonic period (c. A.D. 700-1180), with a temporally rather dense settlement pattern, central locations (*emporía*) and a well-developed cultural landscape, was terminated by the medieval German colonization from c. A.D. 1180 to 1250 (Kersting, 2012).

Since high medieval times, mill dams evidently influenced the flow regime and water levels including groundwater of larger sections of the whole river Havel (e.g. Schich, 1994; Driescher, 2003; Küster & Kaiser, 2010; Keller, 2014). With respect to the study area evidence on this matter from history, archaeology, historical geography and geosciences were obtained; their discussion in the scientific literature goes back almost an entire century (for the older research history see Herrmann, 1959). Contrary to the overwhelming majority of researchers who assume and prove *intentional* human impact on the flow regime not before historical times, namely only from the 12th/13th century A.D. onwards, Goldmann (1986) hypothesizes that damming, canalization and irrigation took place in the region as early as the late Bronze Age, c. B.C. 1200-800.

The first watermill in the Berlin-Brandenburg region is mentioned in A.D. 1174/1176 at Klinke village in the Havelland area (Schich, 2008; Figure 3). The earliest archaeological record of a watermill in the region, located next to Jüterbog at a tributary of the river Nuthe (Fläming area), dates from nearly the same time in A.D. 1182/1186 (Jeute, 2015; Figure 3). Along the middle and lower course of the river Havel watermills, mill dams and bypass canals are first mentioned for the 13th and early 14th centuries A.D. (Spandau A.D. 1232, Rathenow A.D. 1288, Brandenburg/H. A.D. 1309; Schich, 1994; Driescher, 2003; Figure 2). All watermills in this region used vertical mill wheels; along the middle and lower course of the river Havel and the river Spree surely the undershot type. Particularly in Brandenburg/H. a complex hydraulic infrastructure was established during the medieval period and afterwards, consisting of mill dams, causeways, a total of ten (partly contemporaneous) watermills used for different purposes, a bypass canal, bridges, piers, and, rather late in A.D. 1550, even a chamber lock. Numerous ditches were part of the town's fortification and fed by the river Havel (Müller, 2009; Figure 4D, Supplemental Figure 4). In the adjacent Spree valley a watermill in the medieval town center of Berlin is first mentioned in A.D. 1285, whereas its mill dam is mentioned soon after, in A.D. 1298 (Schich, 1994).

Several periods of hydraulic engineering since the 18th century A.D. produced the present-day intensive waterway infrastructure of the study area (e.g. Uhlemann, 1987). Advanced discharge steering and

increasing drainage measures led to a marked reduction of the water level amplitude between low and high water of the river Havel in the last two centuries (Supplemental Figure 5).

Land use and resulting land cover within Havel and Spree valleys and their tributaries are strongly correlated with the degree of urbanization in that area. Within the metropolitan area of Berlin settlement and infrastructure has strongly reshaped the natural wetland structures. Outside the urban agglomerations the valleys are intensively agriculturally and silviculturally used. The extended wetlands along the middle and lower course of Havel were transformed by drainage and water construction measures particularly in the 19th and 20th centuries A.D. Nowadays, pristine river sites are completely absent in the region (Schönfelder & Steinberg, 2004).

METHODS AND DATA

Stratigraphical data were derived from newly recorded archaeological sections and from a variety of published and unpublished sources (e.g. excavation reports, palynological corings). Latest research focused on archaeological sections at Burgwall (Berlin-) Spandau, section Palast Barberini at Potsdam, as well as sections Mühlendamm and Saaringen at Brandenburg/H. Table I lists all records that were considered for this study (see also Figure 3). According to their careful evaluation these records represent the most qualified data available from the region. Data on specific archaeological records, comprising information on archaeological methods, structures, artifacts and site formation/interpretation, can be obtained from the references given in the results chapter and in Table I. Usually, the sections presented are described from the lower/older to the upper/younger layers. For the purpose of this study to derive local water level data and to integrate them in a regional context a combination of methods basically from hydrography, sedimentology, paleoecology, and chronology was applied.

Hydrography

Hydrographic data used in this study primarily comprise mean river water levels at various sites and water levels for different flow regimes (low to high water) at Brandenburg/H. The data were obtained from the

Brandenburg/H. and Berlin branches of the Waterways and Shipping Authority (WSA). For the hydraulic modelling of several mill damming scenarios at the Brandenburg/H. weir a digital elevation model (DEM 10) from the Federal Agency for Cartography and Geodesy (BKG) was used together with a Geographic Information System.

Sedimentology

The sections were recorded and sampled either in the course of archaeological excavations or through wetland drillings, using a peat corer. The sections were described and graphically depicted applying a generalized lithological legend. The Palast Barberini section (2012) was described in more detail and sampled (14 samples) according to the German soil classification system (Ad-hoc-AG Boden, 2005). Sedimentological analyses were performed on the matrix <2 mm (Supplemental Table I) in order to assist the designation of sedimentary facies and diagnostic soil horizons. A dry-sieving test was applied to determine the sand-dominated grain-size distribution. The classification of sand grain-size is defined by the class sizes <0.2 mm, <0.63 mm and <2.0 mm, respectively (Ad-hoc-AG Boden, 2005). Content of organic matter was estimated by combustion at 550 °C (loss-on-ignition/LOI). CaCO₃ was determined volumetrically by a Scheibler-apparatus. Soil pH was analyzed potentiometrically in 0.01 M KCl (soil : solution ratio = 1 : 2.5).

Palynology

For a few decades special attention has been given to the biostratigraphy of lake and mire deposits in the study area, particularly applying palynology as an efficient tool for Holocene paleohydrology. Meanwhile more than 40 pollen diagrams are available from this region, reliably ensuring chronological control and paleoecological interpretation of wetland deposits along the Havel and Spree rivers (Brandt, 1996). Further paleoenvironmental proxies, such as diatoms and chironomids, were applied in the region as well but to a very limited, i.e. local extent so far (Schönfelder & Steinberg, 2004; Kirilova et al., 2009).

Pollen analysis was performed on seven sediment cores taken by a Jewsey sampler (50 x 5 cm; Lang, 1994). Preparation of the pollen samples (n = 120) with 1 ml volume each followed the HCl-, KOH-, HF-acetolysis procedure (Fægri & Iversen, 1989). Pollen counting was carried out at 500 x magnification at a minimum of 500 tree pollen sum and additional herb pollen and fern and *Sphagnum* moss spores per sample. The regional pollen zones 1-15 (Brande, 1996) are correlated with central European pollen zones I-X (Lang, 1994). The transition IX/X is to be synchronized with about A.D. 1180 to 1250 of land-use history in the course of the German colonization of that area (Supplemental Figure 1) that is supported by geochronological and historical data (Brande, 1996; Giesecke et al., 2012).

Radiocarbon Dating and Dendrochronology

Radiocarbon (^{14}C) dating is available from a total of ten samples (Table II). The ^{14}C ages presented were calibrated (B.C./A.D. values) with the programme Calib 7.1 using the IntCal13 data set with a range of 2 sigma standard deviation for analysis (<http://calib.qub.ac.uk/calib/>). The given calibrated ^{14}C ages represent the age ranges with the highest corresponding probability (cf. Argyle, Forman, & Thompson, 2010).

Thirteen dendrochronological datings, primarily from oak tree remains, were used (Table III). The samples were identified using wood anatomical methods (Schweingruber, 1978). The new site chronologies were compared with regional tree chronologies covering the last millennia (e.g. Büntgen et al., 2011).

We are aware that the comparison of these different age data categories is somewhat problematic.

Whereas the dendrochronological samples can be dated to the exact year or have a standard deviation of only 10 years in maximum, the radiocarbon datings have a standard deviation ranging between 25 and 70 years (with an age interval up to 140 years). However, in order to ensure for the comparison of sites with different dating potential there is no other reasonable way but to consider these different age data categories. Regarding the timescale of interest, i.e. the last c. 2000 years, the different data precision is generally considered as reasonable.

RESULTS

Records at Berlin Study Sites

Between the medieval town center of (Berlin-) Spandau (first documented mention in A.D. 1197, town foundation in A.D. 1237) and the adjacent Spandau Citadel to the east a floodgate dams the river Havel (Figure 4). The current difference between mean head water (31.4 m a.s.l.) and low water (29.4 m a.s.l.) is 2 m. A (mill-) dam with an attached bypass-canal ('Flutrinne' in German) used for shipping was first mentioned in A.D. 1232 for this site (Uhlemann, 1987; Schich, 1994). The stratigraphical records from Berlin presented in the following apply both to the head water (Bollenfenn, Heiligensee, and Teufelsbruch sites) and the low water level (Burgwall Spandau site) of the river Havel (Figure 3).

Bollenfenn

A sediment core was extracted from Bollenfenn kettle-hole mire, located in a side depression of Lake Tegeler See which is drained by the river Havel. The palynologically dated stratigraphy (Figures 3, 4A) reveals several sedimentological changes at the base at 8 m depth from a very late Pleistocene eolian phase (not depicted in Figure 4A), via early and mid-Holocene lacustrine phases to a late Holocene phase of peat formation that was terminated by anthropogenic drainage in the 18th century A.D. (Brandt, 1988). This profile represents a typical lacustrine-telmatic sequence, the likes of which has often been recorded in lake and kettle-hole mires of the region (e.g. Brandt, 1986).

According to its macro and microfossil content, the c. 3 m-thick peat layer consisting of different sub-layers reflects the succession from a lake overgrowing mire to an inundation mire. At a depth of 0.6 m below surface the peat composition changes markedly: moderately decomposed radicle (rootlet) peat (below) with abundant remains of the plant genera *Carex* and *Thelypteris*, as well as poorly preserved pollen, changes to slightly decomposed radicle-brown moss peat (above) with well-preserved pollen. Hydrologically, this shift reflects a rising groundwater level in the kettle-hole mire. As the water level at Bollenfenn corresponds to the level of Lake Tegeler See, a corresponding rising water level of the river

Havel can be assumed. This water level has been at a minimum of c. 30.5 m a.s.l. if one takes peat shrinkage (causing some drop of the terrain surface) after drainage into consideration. The change of the peat types corresponds palynostratigraphically to the transition from pollen zone IX to X (c. A.D. 1180/1250; Brande, 1988, 1996).

Heiligensee

This sediment core originates from a stratigraphic transect from a drained lake mire at the northern shoreline of Lake Heiligensee that is connected with the river Havel. After late Holocene silting up through lacustrine sedimentation (gyttja) and peat formation, a renewed lake phase can be inferred from the upper c. 0.3 m-thick gyttja layer (Brande, 1980; Figures 3, 4A). The onset of this secondary lake phase corresponds palynostratigraphically to the transition from pollen zone IX to X (Brande, 1996). As the thin gyttja layer suggests, this lake phase lasted only for a few centuries at most at this site. For the lake phase a minimum water level of c. 30.5 m a.s.l. can be inferred. But the actual level probably was somewhat higher, reaching 31 to 32 m a.s.l. Consequently, the local mire, as well as extensive areas of the surrounding banks of the river Havel, were flooded. After a new overgrowing peat formation phase the site was drained probably in the 19th and 20th centuries A.D. and became dry.

Teufelsbruch

This core (Figures 3, 4A) was obtained from a stratigraphic transect in a small mire depression, located c. 0.7 km west of the river Havel. It is surrounded by dune ridges dating from the late Pleistocene (Brande, 1995). The local groundwater level both in the mire and in the adjacent dune sands was once nearly level with the nearby river Havel, but has recently dropped due to local groundwater abstraction from a nearby waterworks. The altitude of the mire surface varies between 31 and 32 m a.s.l.

After late Pleistocene to early Holocene lacustrine, peat and eolian sedimentation, representing two terrestrialization cycles of a former small lake, an only 1 m-thick fen-peat cover follows. According to pollen analysis, this peat represents the whole Holocene with a much reduced peat accumulation rate

during the mid-Holocene, indicating phases of peat decomposition. A sharp change in the peat sequence characterizes the transition from pollen zone IX to X (Brande, 1996). Strongly decomposed peat is displaced by slightly decomposed peat. The contents of macro and microfossils point to a change from mire vegetation rich in *Calluna* (heather) to vegetation rich in *Sphagnum* (peat moss), representing a shift from relatively dry to very wet conditions. Moreover, a marginal mire extension by paludification on mineral ground occurred, as indicated by a stratigraphical transect (Brande, 1995).

Burgwall Spandau

Two fortified structures are located at Spandau: a late Slavonic (10th/11th century A.D.) precursor to the Spandau Citadel and an early to late Slavonic and German stronghold ('Burgwall' in German, 8th-13th centuries A.D.), lying c. 1 km south of the medieval town center (von Müller & von Müller-Mučí, 2005). Both partly contemporaneous sites are located within the strategically important confluence area of the river Havel and the river Spree (Figures 3, 4). Intensive archaeological excavations at Burgwall Spandau took place from the 1960s to the 2000s, reconstructing eight medieval settlement phases which span over about 500 years.

The stratigraphy of layers at this site is very complex, varying depending on specific parts of the stronghold complex (e.g. trench, rampart, interior, abandoned river channel). Chronological control is available by archaeological, dendrochronological and pollenanalytical data, as well as through radiocarbon dating (e.g. von Müller, 1987; Brande, 1999; Michas, 2011). Three sections providing information on water level dynamics are presented here (Figure 4A). They originate from the older (section 20/11; von Müller, 1987) and the newer period (sections 26/12 and 1838/I/2005; Michas, 2011) of archaeological research.

Section 20/11 provides a look at the stronghold rampart, showing a sequence of artifact-bearing anthropogenic deposits and naturally formed peat layers (Figure 4A). The c. 60 cm-thick peat layer at the base reveals that the river Havel lay c. 0.5 to 1 m below the current mean water of 29.4 m a.s.l. in the 8th and 9th century A.D. A further peat layer above indicates a water level somewhat higher than today for

the late 10th century A.D. Compiling information from several sections of this site, von Müller (1987) reconstructed the local water level dynamics using the settlement phases as chronological control. A gradual rise (10-30 cm) is suggested for several episodes in the 8th to early 10th centuries A.D., as well as in the 11th century A.D., but a rather steep rise (70 cm) is suggested for one episode in the mid to late 10th century AD (Figure 4A). Section 26/12 is from an additional trench of the rampart. In the lower part of the section a thick peat layer interspersed with fluvial sand layers occurs, which were probably deposited by flood events. The upper surface of this peat dendrochronologically dates at about A.D. 1245 ± 10 (Figure 4A, Table III). Above, late medieval and younger artefact-bearing sands follow that were primarily formed through anthropogenic deposition. The lower peat reveals a local water level prior to A.D. 1245 ± 10 somewhat below that of the current mean. In section 1838/I/2005 the basal peat layer reveals a water level of the river Havel in the Roman period somewhat lower to that of today (Brande, 2010, Figure 4A).

Records at Potsdam Study Sites and Surroundings

Palast Barberini

Between the 1980s and 2010s, several trenches containing both archaeological and fluvial layers could be observed in the medieval town center of Potsdam in the course of archaeological excavations. During construction work around ‘Alter Markt’ square, sections were extracted that lie adjacent to the so-called ‘Alte Fahrt’ section of the river Havel, which has a mean water level of 29.4 m a.s.l. (Figures 3, 5). Throughout the medieval and early modern period Potsdam’s riverside served as a waste-disposal dump for the townspeople, aggrading from the fringe of the settlement into the floodplain (Hensel, 2013). This artificially formed land has a maximum lateral extension of 45 m, corresponding to a lateral growth of 6 m per century in the period between the 13th and 19th century A.D. In August 2012 a section at the Palast Barberini site, temporarily drained by groundwater pumping, was recorded. Additional information was already obtained in 1989 from an adjacent section located just c. 1 m to the southwest (Weiße, 2012). Section 2012 contains three main sedimentary units (Figures 5A, 6A, 6B, 7). The lowest unit (sample 14) consists of gravelly fluvial sand without any organic and artefact contents. As the adjacent section from

1989 suggests (Figure 6C), this sand originates from fluvio-glacial deposition of the late Pleistocene Havel-Nuthe glacial spillway. Above a several decimeters thick layer of rather fine grained fluvial sand follows (samples 12, 13) with plant litter and charcoal, as well as wood remains. This fluvial sand is interpreted as overbank alluvium (Miall, 1996). The upper layer, with a thickness of c. 100 cm, consists of organic-rich sandy waste layers and organic-poor sandy fluvial layers (samples 1-11), even representing overbank alluvium. A prominent fluvial sub-layer at a depth of 50-70 cm (sample 6), encompassed by thin organic-rich bands consisting of very likely translocated plant detritus and very humic sand, might originate from a (single) flood event.

The section is dated by archaeological remains, radiocarbon ages and dendrochronology (Figures 5A, 6A, 6B, 7). Pottery fragments show a consistent sequence from the 12th/13th to the 16th/17th centuries A.D., with the exception of a basal artefact layer of prehistoric to Slavonic age (Figure 6B). The oldest radiocarbon age (A.D. 852-970) confirms a Slavonic age. The three upper radiocarbon dates of nearly identical age span a mutual age interval of A.D. 1030-1225 that is, in comparison to the archaeological dating, partly too old. But radiocarbon dating amid an overbank alluvium and former waste-disposal dump can go wrong, considering that older materials (wood remains in this case) might have been inserted into younger layers. Although redeposition of artifacts and sediments must be assumed to a certain extent in this type of deposit, the consistent sequence of single artefact layers dating from the 12th/13th to the 16th/17th centuries A.D. shows that this effect was rather marginal in this section. Furthermore, dendrochronology of a prominent oak pile in the section (archaeological feature No. 164 in Figure 6B) revealed an age of A.D. 1197 ± 10, confirming, together with two further datings of adjacent piles in the same stratigraphical context (A.D. 1199, A.D. 1200; Table III), the archaeological age estimate of the lower medieval artefact layer (late 12th/early 13th century A.D.) and the local existence of a wooden construction at that time.

Most parts of the stratigraphy at Palast Barberini site (section 2012) reveal a subaquatic sedimentary environment, aggrading both by natural input of fluvial sand and anthropogenic input of waste material at the edge of the medieval and early modern town. In comparison with section 2012 section 1989 shows

several layers that were originally interpreted as peat layers of different thickness bearing ample wood remains (Weiße, 2012; Figure 6C). However, as the sedimentological data (loss-on-ignition, LOI) and further features from section 2012 show (Figure 7), they probably represent dark organic-rich fluvial sands or gyttjas (but normally having below 10 % LOI) rather than peats.

Wannsee (Alter Hof)

Two sections from ‘Alter Hof’ mire, located in a side depression at the southern shoreline of the river Havel near Lake Wannsee, provide data on local landscape changes during the late Holocene (Böse & Brande, 1986; Figure 3). According to section 91, after mid-Holocene terrestrialization following lacustrine sedimentation, the mire became wetter again in the late Holocene (pollen zone X; Figure 5A). This change is reflected lithologically in the transition from decomposed fen peat (pollen zone VIII and IX) with high pollen corrosion, indicating a relatively low groundwater level or stronger water level fluctuations, to slightly decomposed brown moss peat (pollen zone X) with low pollen corrosion. The thin layer of eolian sand on top of section 91 can be related to late medieval to modern eolian dynamics in the surroundings, corresponding to numerous similar findings in the region (e.g. Böse, 2002; Tolksdorf & Kaiser, 2012). Section 71, located at the edge of the mire, predates this eolian dynamics with a radiocarbon date of A.D. 1162-1318 (Figure 5A, Table II).

Pfaueninsel

Several palynostratigraphically dated sections from Pfaueninsel Island provide evidence on late Holocene water level changes in that part of the river Havel course, representing a lake chain (Figure 3). Sections E (‘Erdzunge’) and P (‘Parschenkessel’) contain peats (fen peat and alder carr peat) which fall into pollen zone IX (c. B.C. 800 to A.D. 1180/1250; after Brande, 2008; Figure 5A). Both peat beds are overlaid by lacustrine sand layers which are 1.2 to 2.1 m thick. Indicated by the transition from peat to sand, the local water level at c. A.D. 1200 was between c. 1 to 2 m below the current mean water level of the river Havel.

Schlaatz

The archaeological excavation of an early Mesolithic site with a well-preserved aurochs (*Bos primigenius*) skeleton (killed by hunters; Benecke, 2004) provided data on the Holocene fluvial stratigraphy of Nuthe tributary. This site is located c. 3 km southeast of its river mouth into Havel (Figures 3, 5A). A previously older dating of the faunal remains into the Younger Dryas chronozone was latterly corrected to the early Preboreal, moderately correcting even the palynostratigraphical record (Kloss, 1987; Weiße, 1987; Benecke, 2004; Table II). According to this *in-situ* assemblage of bones and artefacts at 27.5 m a.s.l., the early Holocene water level of Nuthe, and thus of the nearby river Havel, was at least c. 2 m lower than it presently is.

Records at Brandenburg/H. Study Sites

Within the medieval town center of Brandenburg/H. a complex hydraulic system dams the river Havel, separating it into head water (mean: 29.2 m a.s.l.) and low water (mean: 28.1 m a.s.l.) with a current mean water level difference of c. 1 m. The main dam structure north of Neustadt town district, consisting originally of parts with watermills and causeways used for traffic crossing the Havel wetland, dates from the medieval period (Figures 3, 8). According to archaeological and historical data available thus far, the mill dam was constructed around A.D. 1200 (Schich, 1994; Dalitz, 2009; Müller, 2009; Geue, 2011). The stratigraphical records from Brandenburg/H. presented in the following refer both to the low water (Dominsel site) and the head water level (Mühlendamm and Saaringen sites) of the river Havel.

Dominsel site

The Dominsel section, which was recorded during an archaeological excavation in 1991, consists of a lacustrine to (semi-)terrestrial sequence with some fluvial sand layers. Pollen analysis and artifacts enable the dating of the sequence (Figure 8A). The palynostratigraphy reveals that the gyttja in the lower part of the section dates from the 9th to 11th centuries A.D. (Jahns, 2015), which is confirmed by Slavonic artefacts. Above, the peat layer contains a lot of waste material, so that this layer can be regarded as

indication of waste-disposal into a peatland environment. Here, somewhat similar to the Palast Barberini site at Potsdam described above, waste was deposited into the marginal waterfront part of the late medieval town. As the height difference of c. 1 m between the upper part of the late medieval to modern waste-bearing peat layer and the current mean water level of the river Havel reveals, the local low water could have been higher in the past. The sand layer on top of the sequence is thought to derive from drainage measures in the course of local land reclamation efforts in modern times.

Mühlendamm

Three dam sections impound the river Havel west of the Neustadt and Dominsel town districts (Figure 8, Supplemental Figure 4). The dam lengths vary from 50 to 150 m. Documents and maps dating from the 14th to 17th centuries A.D. show that a total of six watermills were attached to the dams. The first mention of a watermill dates from A.D. 1309, whereas an associated dam is first mentioned in A.D. 1324 (Müller, 2009). Some modern mill buildings have been preserved until now. As the utilizable water level difference between head and low water was and remains low (recently c. 1 m), the mills were surely equipped with undershot waterwheels.

During construction measures in 2009, the mill dam immediately north of Neustadt was partly cut by an archaeological trench, providing information on local stratigraphy, dam structure and dating (Figures 8A, 9). The dam crest, i.e. road, is c. 2 m above head water; the dam width is c. 40 m. The upper c. 2 m of dam fill uncovered by the trench consists of anthropogenically deposited materials (bricks, construction woods, sandy waste deposits, erratic stones), humic and fluvial sands, and plant remains of different size.

Numerous ceramic artefacts primarily of medieval to modern age are comprised too. Several dendrochronological datings of construction wood (piles, planks) from the trench reveal an age interval from A.D. 1466 to 1693 (Table III). A much older oak pile (A.D. 904), already retrieved in 1991 from the dam filling c. 90 m to the north, could be related to a Slavonic wooden bridge as precursor of the German mill dam. An 8.5 m-deep coring at the western edge of the trench showed alternating layers of gyttjas and humic sands covered by fluvial sand and debris/waste material. The clay layer at the bottom probably

marks the substratum of the river Havel. Above a depth of 4.8 m artifacts occur; initially Slavonic and later German ceramics. As all available sedimentological, archaeological and building history information suggest, the dam's height and width was gradually extended over time. Finally, the dam was covered extensively with houses.

Burgwall Saaringen

During an archaeological prospection remains of a stronghold were discovered located directly on the banks of the river Havel which had since been covered by a modern village (Dalitz & Kersting, 2012). The rampart of the stronghold was built as a wooden timber frame filled with sand. Dendrochronological analysis reveals an age of A.D. 890 ± 10 (Table III), dating the rampart to the mid-Slavonic period. But ceramics found indicate that the local settlement history in place of the stronghold is much more diverse, spanning from the Neolithic, via the early and late Iron Age, and the late Medieval Age up to the present. Section 1999/2, representing a profile within the rampart, consists of sandy occupation layers with intermediate peaty and muddy occupation layers (Figure 8A, Supplemental Figure 6). The lower sand layers represent the terrestrial soil horizons of a Cambisol with prehistoric (Neolithic to Germanic) and early Slavonic artefacts. Most probably, this sandy packet was formed in a gradually aggrading sedimentary environment with syndimentary soil formation. In this settled area the stratified sand probably originated from either eolian or human impact or from fluvial dynamics. As the terrestrial soil horizons and occupation layers lie well below the current mean water level of the river Havel, they clearly indicate a lower water level before A.D. 800 than today. The peaty and muddy occupation layers above prove a subsequent water level rise which took place even until the (late?) Slavonic period (c. 10th-12th centuries A.D.). Further archaeological research in 2013 confirmed late Germanic and early to mid-Slavonic artefact layers slightly below and above the current mean water level of the river Havel (section 2013/26; Figure 8A).

DISCUSSION

Synthesis on Regional Water Level Dynamics

Plotting the water level data from the sites analyzed in time-altitude diagrams reveals at times great deviations for the middle course of the river Havel over the past c. 2000 years (Figure 10A-D). At a first glance some data seems to accurately reflect temporal trends (e.g. Palast Barberini record, Figure 10B), while other data seems contradictory (e.g. the vertical sequence of data from some Berlin records; Figure 10A). Furthermore, some data cluster very densely (nearly all Potsdam records; Figure 10B), revealing nearly identical records for adjacent sites.

At Spandau the records from the (current) head water area partly reveal lower water levels for the 12th century A.D., whereas records from the low water area (Burgwall) tend to be similar to today's (Figure 10A). The vertical arrangement of data from sites upstream the Spandau weir (Figure 10A) is partly caused by postdepositional changes at these mire sites (sediment compaction, changing terrain height through drainage). The maximum medieval water level rise for the head-water area at Spandau is c. 1 m. Further data provides a more detailed picture of the local dynamics at Burgwall Spandau between the 7th to 11th centuries A.D. (von Müller, 1987), representing the low-water area. It becomes evident that a general water level increase occurred along with a marked rise in the second half of the 10th century A.D. (Figure 10D). A similar process occurred in the nearby lower course of the river Elbe, interpreted as a short phase of heavy natural flooding events between c. A.D. 950 and 980 (Schneeweiss & Schatz, 2014). Several *in-situ* peat layers at Spandau, mostly accompanied by artefacts and dating from the 2th/4th to the 12th centuries A.D., were found up to c. 1.5 m below the present mean level of the river Havel (von Müller, 1987; Brande, 1999, 2010). This can be interpreted as evidence that water levels of the river Havel were lower in comparison to the present, except during the second half of the 10th century A.D.

Correspondingly, excavated construction remains from former buildings suggest a rising water level in the 11th and 12th centuries A.D. (von Müller & Müller-Mučič, 2005; Michas, 2011).

At Potsdam and surroundings there are indications of relatively low water levels from the 9th to 12th/13th centuries A.D. and a water level rise afterwards (Figure 10B), which encompasses a rise of c. 1 m and 1 to 2 m according to the records from Palast Barberini and Pfaueninsel, respectively. Contrary to

Brandenburg/H. and Spandau, a weir never dammed the river Havel at Potsdam. Instead, the lower course of nearby Nuthe tributary was dammed for the operation of watermills (Driescher, 2003; Figure 3). The water level of the river Havel around Potsdam is steered through the weir downstream at Brandenburg/H. The records obtained from Saaringen show slightly lower and similar river and groundwater levels for the 1st millennia B.C. and A.D. in comparison to today (Figure 10C). Local occurrences of higher energy deposits (e.g. in the Palast Barberini section) are restricted to thin layers of coarser sands of fluvial origin, probably originating from floods, and to basal glaciofluvial sand. They do not affect the integrity of the record.

Further evidence on regional paleohydrology during the mid to late Holocene is available from vast drained peatlands (Havelländisches Luch, Rhinluch), located immediately north of the study area. Various palynological and paleopedological findings (see details in Kaiser et al., 2012) indicate low regional groundwater levels and reduced fluvial activity in the mid-Holocene, which is also evident in peat stratigraphies of many mires of the Berlin region (Brande, 1995). During the late Subboreal and Subatlantic an increase in groundwater level occurred, caused by relatively wet-cool conditions (Zolitschka, Behre, & Schneider, 2003) and a regional damming-effect of the rising Elbe river bed (Küster & Pötsch, 1998). The drainage of the river Havel and its tributaries was impeded, causing a rise in the regional groundwater level. Gramsch (2002) summarized archaeological and paleoecological findings from the Rhinluch area, showing a groundwater rise of c. 3 m in that area for the last c. 4500 years. Compiling archaeological data from the nearby Spree valley, Herrmann (1959) described occupation layers from the late Bronze Age to early Iron Age (c. B.C. 1200 to 450) and late Slavonic period (c. 10-12th century A.D.), which were found c. 1 m below the present river water level. Thus, both several of our records presented in the results chapter and further evidence presented above prove that the late Holocene water levels of the river Havel and river Spree were markedly lower before c. A.D. 1180/1250 (c. 1-2 m) than they are nowadays. However, evidence from the river Havel at Spandau suggests that already before a rather short phase of higher water levels occurred in the late 10th century A.D., which is paralleled by a similar record from the lower course of the river Elbe (Schneeweiss & Schatz, 2014).

Medieval Mill Damming

Mill damming at Brandenburg/H. is crucial, as this hydraulically influences the whole middle Havel course up to Spandau. By using the historical flow path via Lakes Schwielowsee and Wannsee to Spandau, this dammed Havel course amounts to a length of c. 70 km. The current shortcut via Sacrow-Paretzer canal dates from the 1870s A.D. (Uhlemann, 1987). Inferred from the reconstructed water level dynamics at Burgwall Spandau from stronghold phase 5a to 5b, it was suggested that mill damming began at Brandenburg/H. already in c. A.D. 1180 (von Müller, 1987). This hypothetical dating of a first mill dam parallels the town foundation of Brandenburg/H. (c. A.D. 1170) which is supported by historical and archaeological research (Dalitz, 2009; Müller, 2009) and thus seems plausible. Although compelling evidence on a man-made water level increase of the river Havel in the High Middle Ages is available, it should be mentioned here that even records of simultaneously increasing water levels from central Europe exist that were attributed to climatic impact (e.g. Magny, 1998; Driescher, 2003; Kalicki, 2006; Starkel et al., 2006; Kaiser et al., 2012, 2014). The reason for that are most likely wetter summers during the 13th and 14th centuries A.D. and a first cold spell around A.D. 1300, coinciding with the onset of the Little Ice Age (Büntgen, et al., 2011).

According to Driescher (2003), there is some controversy over the height of the medieval mill damming, i.e. the water level difference between low and head water at the mill dam at Brandenburg/H. The minimum height estimate is 1 m (equal to the current height), whereas the maximum estimate is 3 m. Figure 11 shows real (1 m of current damming) and potential (2 and 3 m damming) flooding areas using a terrain model for these hydraulic scenarios. The damming heights of 1, 2 and 3 m corresponds to altitudes of c. 29, 30 and 31 m a.s.l., respectively. The 1 m damming is reflected in the present-day water areas (lakes, ponds, rivers, streams, ditches) of this area. However, the configuration of water areas produced by a potential medieval damming of 2 and 3 m is certainly a rough approximation due to topographical changes in the last c. 800 years that could not be removed in the hydraulic model. These changes are caused, for instance, by sedimentation, peat shrinkage, river engineering, settlement, waste disposal, and

extraction of raw materials. The water areas depicted in Figure 11 (east of Brandenburg/H. and except the areas downriver from Brandenburg/H. and Havelländisches Luch) amount to 162 km² (1 m damming), 197 km² (2 m damming) and 214 km² (3 m damming). A medieval damming height of 2 m seems possible, for both topographical (particularly considering the terrain configuration at Brandenburg/H.) and historical/technological reasons. By contrast, 3 m of damming is very unlikely, as both the topography (causing widespread water releases through bypasses into lower areas) and archaeological records at Brandenburg/H. (Dalitz, 2009) reveal. According to stratigraphical records presented in the results chapter and additional data (Dalitz, 2009; Müller, 2009), the medieval and early modern damming height at Brandenburg/H. probably lay at c. 1.5 m.

Data on medieval mill damming heights and the way mill dams were constructed (internal structures) in the wider region are generally rare (Schalies, 2009; Geue, 2011; Vahldiek, 2011; Ansorge, 2012), even in a wider European context (e.g. Clay & Salisbury, 1990; Kristensen, 1996; Rynne, 2015). According to archaeological records (Herrmann, 1959; Malliaris, 2000; Hofmann, 2005; Schuster, 2005), it is evident for the mill dam at the river Spree in the town center of Berlin that its construction took place in the period A.D. 1220-1230. This is slightly before both mills (A.D. 1285) and the mill dam (A.D. 1298) were mentioned for this site (Herrmann, 1959). The damming height was c. 1.5 m, raising the river over a length of about 30 km upstream (Alaily & Brande, 2002). For Lübeck, damming heights of two dammed sections of the river Wakenitz in the late 13th century A.D. amounted to 2.4 and 4.2 m, thus transforming the formerly meandering lower river course into lakes (Schalies, 2009). The damming of Wakenitz had repercussion c. 30 km upstream, impacting also Lake Ratzeburger See. In Rostock, the mill dam at the river Warnow dendrochronologically dates back to c. A.D. 1250 (Ansorge, 2012). The medieval damming height here was c. 1 m, damming Warnow up to c. 40 km upstream.

Thus, with respect on their spatial damming effects, these three examples from northeast Germany almost mirror the situation as described for the river Havel. Evidently, the hydrological effects of medieval to modern watermills in the region can be classified according to the impoundment effect: besides numerous small-scale dammings of streams and minor rivers which often form chains of small dam impoundments,

there is a large-scale effect also, forming dam lakes with a longitudinal range up to some tens of kilometers.

The question now arises how to evaluate the dimension of the medieval dam-lake cascade along the river Havel from a global perspective. Generally, in dry regions of Asia and Europe first river dams were erected in the very late Neolithic and early Bronze Age, culminating in a first intensive dam-lake construction period in the Iron Age (c. 1200 B.C. to 500 A.D.). Associated dams attained a maximum height of 40 m (Subiaco dam near Rome/Italy, c. 60 A.D.) and a maximum dam crest length of 26 km (Anfeng dam in Anhui Province/China, c. 600 B.C.; Schnitter, 1987). The latter comprised a total dam lake length of c. 100 km (Needham, 1986). A few medieval to early modern dams reached similar construction dimensions elsewhere in the world (Schnitter, 1987; Fletcher et al., 2008). The c. 150 km-long dammed lake cascade (partly connected by river channels) of the lower and middle river Havel between Rathenow and Oranienburg (Figures 1, 2) is, despite its relatively low dam heights and lengths, one of the largest anthropogenic dam-lake structures in historic times globally. This applies to both water area and volume. In comparison to other records (Rouvé, 1987), the c. 70 km-long middle river course between Brandenburg/H. and Spandau is the largest medieval dam lake in central Europe known thus far.

Environmental and Settlement Changes

The medieval water level rise of the river Havel caused by mill damming had immediate as well as long-term effects on the regional riverine environment (Figure 12). For c. 800 years the weirs at Brandenburg/H. and Spandau have been and will continue to be in operation.

As evident from historical sources and stratigraphical records, particularly from palynological records presented in the results chapter, the medieval water level rise, i.e. river damming, must have taken place rapidly. Within a few years this caused the widening of river sections, the enlargement of existing lakes or even secondary formations when already aggraded, and thus a flooding of large portions of different kinds of land. In specific relief positions erosion along the riverbanks and lake shores intensified, causing both local abrasion and sedimentation. The investigated mire sections reveal a shift either from mires to open

waters (lakes, ponds) or from relatively dry and partly wooded to very wet mires. Generally, inundation mires were growing into formerly minerogenic land by peat transgression (paludification). Rising groundwater levels were re-wetting dried up kettle-hole mires, thereby stimulating the growth of oligotrophic bog vegetation (Alaily & Brande, 2002; Brande, 1986, 1996; Wolters, 2005).

With respect to the water quality and limno-ecological properties of the river Havel one could assume that damming has significantly changed the aquatic environment, possibly from a mesotrophic to a eutrophic state or vice versa. However, according to paleolimnological studies the middle and lower course of the river Havel can be classified as naturally highly eutrophic long before German colonization, i.e. at least for c. 4000 years (Schönfelder & Steinberg, 2004). Deforestation of large wetlands, which culminated in the 18th century A.D., and the drainage of such areas, which culminated in the 20th century A.D., caused polytrophic conditions by importing nutrients. Further eutrophication took place after 1950 A.D., when the use of mineral fertilizers in agriculture and particularly the input of sewage and wastewater from the cities located along the river Havel and river Spree heavily affected the river. But this general regional pattern was surely much more diverse locally as further paleolimnological research has shown. Some relatively deep side lakes, while connected at the surface to the river Havel, remained mesotrophic to slightly eutrophic during the Holocene up until the recent past (Kirilova, et al., 2009; Enters et al., 2010).

One important human activity accompanying mill damming has been fishery using fish weirs. This occurred, on the one hand, attached to the mill dams and, on the other hand, to a large extent along the river. At lower Havel course a large number of fish weirs were present in the medieval period, totalling about 200 to 400 at the end of the 14th century A.D. Still in the first half of the 19th century A.D. a total of c. 100 large fish weirs were removed from the river Havel around Brandenburg/H. and Rathenow (Nützmann et al., 2011). Important hydraulic effects of the fish weirs were local damming of the river and flow deceleration. Whether the sectorial medieval damming of the river upstream of Rathenow influenced the abundance of migratory fishes, such as salmon (*Salmo salar*), sturgeon (*Acipenser sturio*) or sea lamprey (*Petromyzon marinus*), is probable as well (e.g. Hoffmann, 1996; Wolter, Bischoff, & Wysujack, 2005; Hansen et al., 2014).

Furthermore, it should be mentioned here that the streams and rivers of the region can potentially be influenced by hydrogeomorphological effects (e.g. Gurnell, 1998; Persico & Meyer, 2013) of the European beaver (*Castor fiber*), which occurred in the river Havel catchment throughout the Holocene up to the present (Dolch et al., 2002). However, as archaeological and historical evidence for mill dams at Spandau and Brandenburg/H. for the 13th/14th centuries A.D. is available (see chapter 'Medieval Mill Damming') and the historical topography at these sites was most likely unsuitable for beaver damming (i.e. rather large local river width and depth), damming of the river Havel by beavers can be excluded. Depending on the water level dynamics soils, vegetation and fauna of riparian sites changed across large areas (e.g. Küster & Pötsch, 1998). As a result the possibilities for human utilization changed, e.g. for agriculture, gathering and hunting activities, construction work, exploration of raw materials, and traffic. The rising water level even influenced the settlement topography to a large degree. As shown by our results and by further research (Herrmann, 1959; Sasse, 1987; Gramsch & Beran, 2010), along the lower and middle course of Havel and its tributaries a number of prehistoric and mid to late Slavonic sites were found below medieval river sand, peat and gyttja. But also several early German rural settlements, located in the floodplains and founded in the late 12th to early 13th centuries A.D., were abandoned in the late medieval period, i.e. 14th to 15th centuries A.D. (Mangelsdorf, 1994; Driescher, 2003). One factor for this must have been unfavourable site conditions for sustainable agriculture due to flooding (Figure 12).

CONCLUSIONS

Understanding the historical water level dynamics helps comprehend how waterscapes in northern central Europe and beyond were anthropogenically transformed, and which pre-modern hydro-ecological reference status can be presumed. For the Havel and Spree riverscape historical river damming has persisting hydrographical effects and strongly influenced the ecological, economical and social development in that region.

Within an interdisciplinary framework focussing on detecting, analyzing and interpreting sedimentary sections along the middle course of the river Havel, we were able to provide clear evidence on late

Holocene water level dynamics, its drivers and effects. In general, the sections indicate lower water levels before and higher levels parallel to the medieval German colonization of that area, from c. A.D. 1180 to 1250. This water level increase took place rapidly and amounted to a relative height of c. 1.5 m. It caused the widening of river sections and the enlargement of lakes, and thus a flooding of large parts of land. The riverine environment changed dramatically, even necessitating the abandonment of a multitude of rural settlements and of agricultural land next to the riverside.

Until now the lower and middle course of the river Havel is dammed by weirs located in the towns of Rathenow, Brandenburg/H., Spandau and Oranienburg, which were founded in the late 12th and early 13th centuries A.D. These weirs were built and the corresponding river sections were dammed in order to operate watermills using undershot water wheels. A secondary driver of the medieval water level increase was the multitude of fish weirs. In total a c. 150 km-long dammed lake cascade was formed, which is one of the largest anthropogenic dam-lake structures in historic times globally. Thereof, the c. 70 km-long middle river course between Brandenburg/H. and Spandau is the largest medieval dam lake in central Europe known thus far, considerably enlarging existing glacial lakes along river Havel.

From a general perspective, the hydraulic effects of medieval to modern watermills in northern central Europe can be classified by the impoundment effect: besides numerous small-scale dammings of streams and minor rivers which often form chains of small dam impoundments, there is also a large-scale effect, comprising dam lakes with a longitudinal range of up to some tens of kilometers. Several larger river valleys in the lowlands were drowned in this way, representing a legacy of hydraulic energy production in medieval and modern Europe.

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Figures

Figure 1: Drainage area of river Havel in northeastern Germany with sub-catchments of rivers Havel and Spree. All watermills and mill complexes (i.e. more than one mill per site) are indicated along the two main rivers. Moreover, the watermill distribution along the tributary Nuthe and Dahme rivers has been exemplarily displayed (data: own compilation). In contrast to river Havel, the greater number of mills along the upper courses of river Spree and of the tributaries is enabled by a higher river bed gradient.

Figure 2: Hydrographical curve (water level) of the lower and middle course of river Havel. Watermills and dams are mentioned for the towns of Rathenow, Brandenburg/H., Spandau and Oranienburg since the 13th and 14th centuries A.D.

Figure 3: Present-day hydrographical topography of the Berlin-Brandenburg area including distribution of peatlands with records on Holocene water level dynamics in the Havel and Spree river valleys. Watermills at other Havel tributaries are not mapped except at the confluence with river Nuthe at Potsdam.

Furthermore, both the oldest documented mention of a watermill (Klinke, A.D. 1174/1176) and the oldest archaeologically proven watermill (next to Jüterbog, A.D. 1182/1186) are shown.

Figure 4: Records from the Berlin study sites. (A) Sections analyzed. (B) Historic map detail from Messtischblatt Charlottenburg (1920, Reichsamt für Landesaufnahme) with indication of the medieval mill dam location at Spandau (red circle; today: sluice construction). (C) Oblique aerial view of the town center of Berlin-Spandau (photograph: H. Stiller, 2005).

Figure 5: Records from the Potsdam and surroundings study sites. (A) Sections analyzed. (B) Historic map detail from Messtischblatt Potsdam Nord/Süd (1903, Reichsamt für Landesaufnahme) with indication of the Palast Barberini section (red dot). (C) Oblique aerial view of the town center of Potsdam (photograph: J. Wacker, 2010).

Figure 6: Palast Barberini section at Potsdam. (A, B) Section recorded in August 2012 (A = photograph, B = archaeological record); (C) section recorded in February/March 1989 (after Weiße, 2012; modified).

Figure 7: Sedimentological-pedological, geochronological and archaeological analysis of Palast Barberini section at Potsdam recorded in August 2012.

Figure 8: Records from the Brandenburg/H. study sites. (A) Sections analyzed. (B) Historic map detail from Messtischblatt Brandenburg/H. (1922, Reichsamt für Landesaufnahme) with indications of the medieval mill dam locations (red circles) and of the sections analysed. (C) Oblique aerial view of the town center of Brandenburg/H. (photograph: J. Wacker, 2010).

Figure 9: Topography and stratigraphical information of Mühlendamm (mill dam) site at Brandenburg/H.

Figure 10: Late Holocene water level dynamics of river Havel derived from records in the Berlin-Brandenburg area. Each cross symbol represents a water level derived by means of a stratigraphical record

which is dated by geochronology, palynology, dendrochronology and archaeology, respectively. (A) Summarized records at Spandau; (B) summarized records at Potsdam and surroundings; (C) summarized records at Brandenburg/H.; (D) detailed record from Burgwall Spandau; note differing time scale (A-C = own compilation; D = data from von Müller, 1987).

Figure 11: Modeling of potential water areas along the middle course of river Havel for different impoundment (mill damming) scenarios.

Figure 12: Conceptual model showing selected hydrological, sedimentological, ecological and settlement changes in the middle river Havel valley caused by anthropogenic impoundment (mill damming).

Tables

Table I: Stratigraphical records on Holocene water level dynamics of river Havel and its tributaries (numbers) and additional records in some adjacent river and stream valleys (capitals).

Table II: Radiocarbon data of the sections investigated from river Havel. The calibrated ^{14}C ages (two sigma deviation) given in the text and figures represent the age ranges with the highest corresponding probability (cf. Argyilan, Forman, & Thompson, 2010) that are indicated in the table by bold numbers.

Table III: Dendrochronological datings from tree remains of the sections investigated from river Havel.

Supplementary Material

Supplemental Figure 1: Stratigraphic scheme for the Berlin-Brandenburg area showing the chronostratigraphical, biostratigraphical and historical/archaeological division of the Lateglacial and Holocene (correlation of time, biozones and pollen zones is based on Giesecke et al., 2012, adapted).

Supplemental Figure 2: Conceptual model of late Quaternary river valley and basin development in the Elbe-Havel area (own compilation based on Weiße, 2003).

Supplemental Figure 3: Geology of the sites investigated (Geological Overview Map 1:300.000, Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg/LBGR).

Supplemental Figure 4: Medieval to modern topography and hydraulic infrastructure along river Havel in the town center of Brandenburg/H. (after Müller, 2009; changed).

Supplemental Figure 5: Water level dynamics of river Havel at Brandenburg/H. for the head water since 1820 AD (data: Wasser- und Schifffahrtsamt Brandenburg/H.).

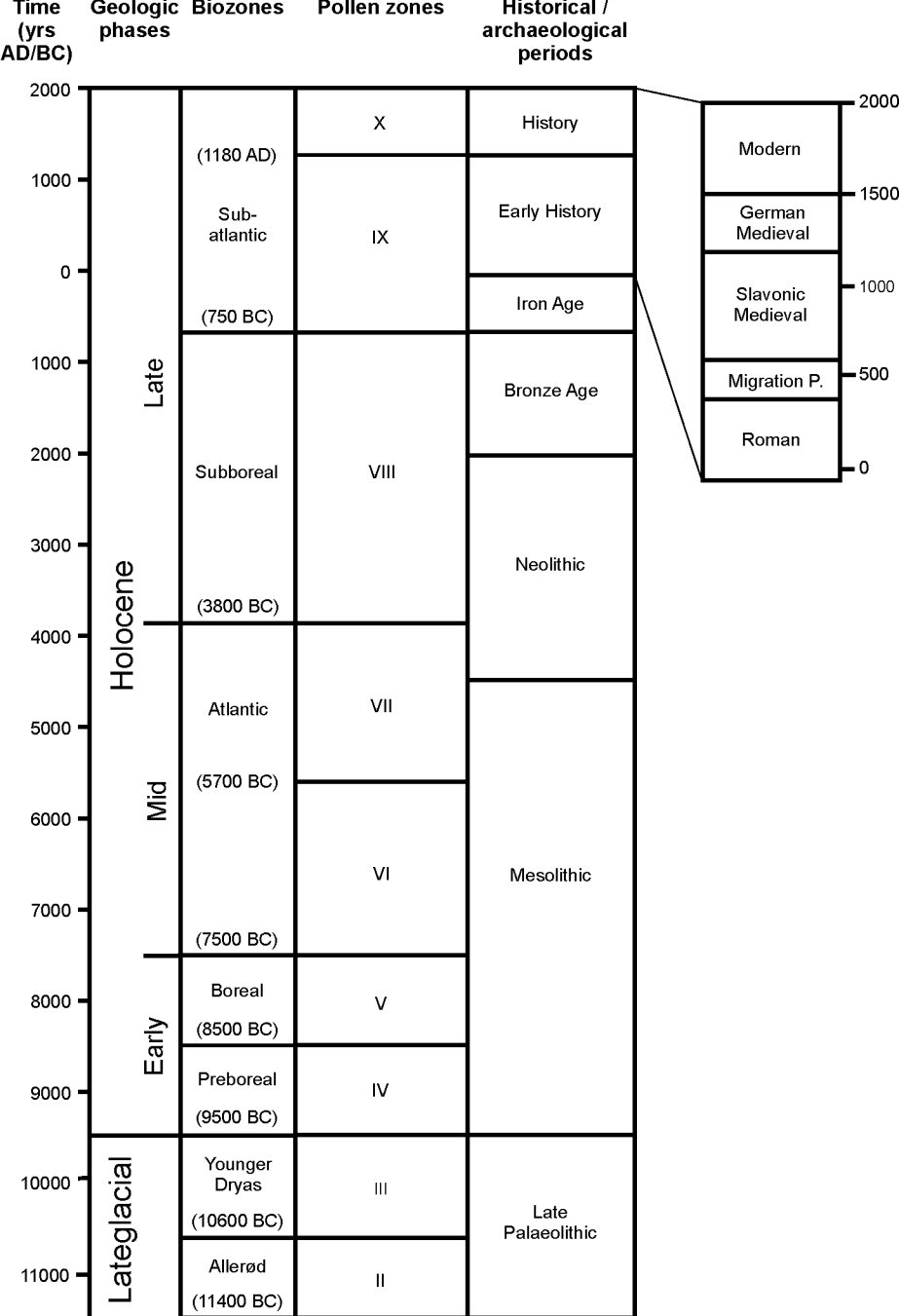
Supplemental Figure 6: Archaeological cross-section of the Saaringen stronghold with indication of section 1999/2. The trench cuts the wall of the stronghold.

Supplemental Table I: Sedimentological data of section Palast Barberini at Potsdam.

Site ID ¹	Section	Research context	Reference
1	Bollenfenn	Palynology	Brande, 1988
2	Heiligensee	Palynology	Brande, 1980
3	Teufelsbruch	Palynology	Brande, 1995
4	Burgwall Spandau 20/11	Archaeology	von Müller, 1987
4	Burgwall Spandau 26/12	Archaeology	this study
4	Burgwall Spandau 1838/I/2005	Archaeology, Palynology	Brande, 1999, 2010; this study
5	Palast Barberini	Archaeology, Geomorphology	this study
6	Wannsee 91 (Alter Hof)	Geomorphology, Palynology	Böse & Brande, 1986
6	Wannsee 71 (Alter Hof)	Geomorphology, Palynology	Böse & Brande, 1986
7	Pfaueninsel E (Erdzunge)	Palynology	Brande, 2008
7	Pfaueninsel P (Parschenkessel)	Palynology	Brande, 2008
8	Schlaatz	Archaeology, Geomorphology	Kloss, 1987; Weiße, 1987; Benecke, 2004
9	Dominsel	Archaeology, Palynology	Jahns, 2015; this study
10	Mühlendamm	Archaeology	this study
11	Saaringen 1999/2	Archaeology	Dalitz & Kersting, 2012
11	Saaringen 2013/26	Archaeology	this study
A	Berlin-Alt Hermsdorf (Tegeler Fließ)	Palynology	Brande, 2012
B	Berlin-Mitte (Mühlendamm)	Archaeology, History	Hofmann, 2005; Schuster, 2005; Vahldiek, 2011
C	Berlin-Köpenick	Archaeology	Herrmann, 1959; Malliaris, 2000
D	Berlin-Schmöckwitzer Werder	Pedology, Palynology	Alaily & Brande, 2002
E	Berlin-Lichterfelde, Bäke Bach	Geomorphology, Palynology	Böse & Brande, 2010
¹ see Figure 3			

Section	Material	Lab ID	Age	Age range calibrated	Reference
			[B.P.]	[B.C./A.D.]	
Burgwall Spandau 1838/I/2005	Charcoal	Bln-5889	1759 ± 36	A.D. 143-156 (0.017), 167-195 (0.041), 209-384 (0.942)	Brande, 2010
Burgwall Spandau 1838/I/2005	Charcoal	Bln-5890	1719 ± 24	A.D. 252-307 (0.399), 311-388 (0.601)	Brande, 2010
Palast Barberini	Wood	Poz-55895	915 ± 30	A.D. 1030-1188 (1.000)	this study
Palast Barberini	Wood	Poz-55896	865 ± 25	A.D. 1049-1083 (0.096), 1125-1136 (0.016), 1150-1225 (0.869) , 1231-1245 (0.019)	this study
Palast Barberini	Wood	Poz-55898	915 ± 30	A.D. 1030-1188 (1.000)	this study
Palast Barberini	Wood	Poz-55899	1150 ± 25	A.D. 777-792 (0.079), 801-849 (0.167), 852-970 (0.754)	this study
Wannsee 91	Peat	Hv-13627	3280 ± 70	B.C. 1737-1715 (0.022), 1695-1421 (0.978)	Böse & Brande, 1986
Wannsee 71	Peat	Hv-13626	745 ± 60	A.D. 1162-1318 (0.906) , 1352-1390 (0.094)	Böse & Brande, 1986
Schlaatz	Bone (aurochs)	KIA-5665	9936 ± 40	B.C. 9652-9596 (0.069), 9546-9480 (0.067), 9463-9290 (0.863)	Benecke, 2004
Schlaatz	Bone (aurochs)	KIA-9562	9979 ± 57	B.C. 9756-9716 (0.039), 9698-9299 (0.961)	Benecke, 2004

Section	Tree species	Lab ID	Begin year	End year	Assumed felling date
		[DAI Berlin]	[A.D.]	[A.D.]	[A.D.]
Burgwall Spandau 26/12	Oak	52084	1110	1225	1245 ± 10
Palast Barberini	Oak	69437	1131	1198	1199
Palast Barberini	Oak	69438	1033	1200	1200
Palast Barberini	Oak	69439	1105	1184	1197 ± 10
Saaringen 1999/2	Oak	19752	800	870	890 ± 10
Saaringen 1999/2	Oak	19753	814	866	886
Saaringen 1999/2	Oak	19756	769	876	896
Mühlendamm	Oak	44778	1498	1594	1619
Mühlendamm	Pine	49886	1442	1529	1529
Mühlendamm	Oak	49887	1366	1446	1466 ± 10
Mühlendamm	Alder	49897	1636	1693	1693
Mühlendamm	Oak	49898	1560	1655	1675 ± 10
Mühlendamm	Oak	59539	817	884	904 ± 10



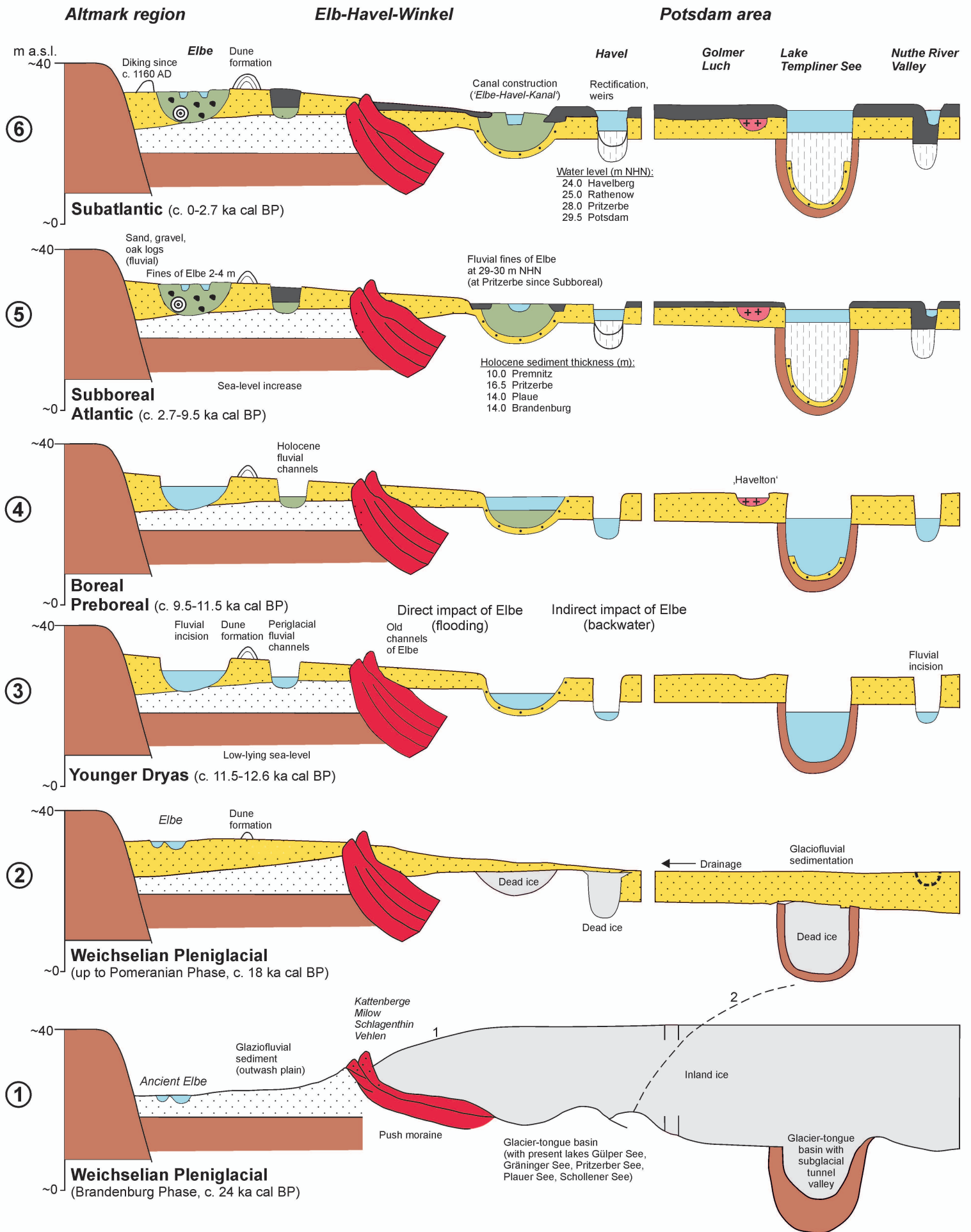
Source: Giesecke et al., 2012 (adapted)

Giesecke, T., Wolters, S., Jahns, S., & Brande, A. (2012). Exploring Holocene changes in palynological richness in northern Europe – Did Postglacial immigration matter? PLoS ONE, 7, e51624.

Conceptual model of late Quaternary river valley and basin development in the Elbe-Havel region; geological cross-section (own compilation based on Weiß, 2003)

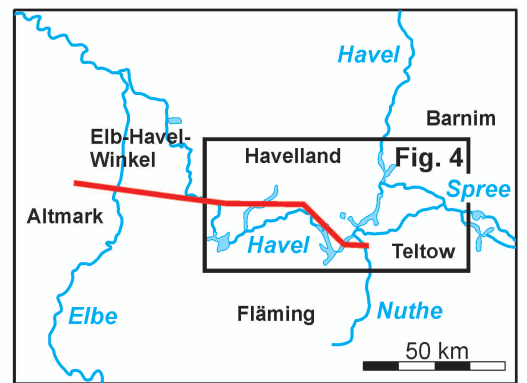
West

East

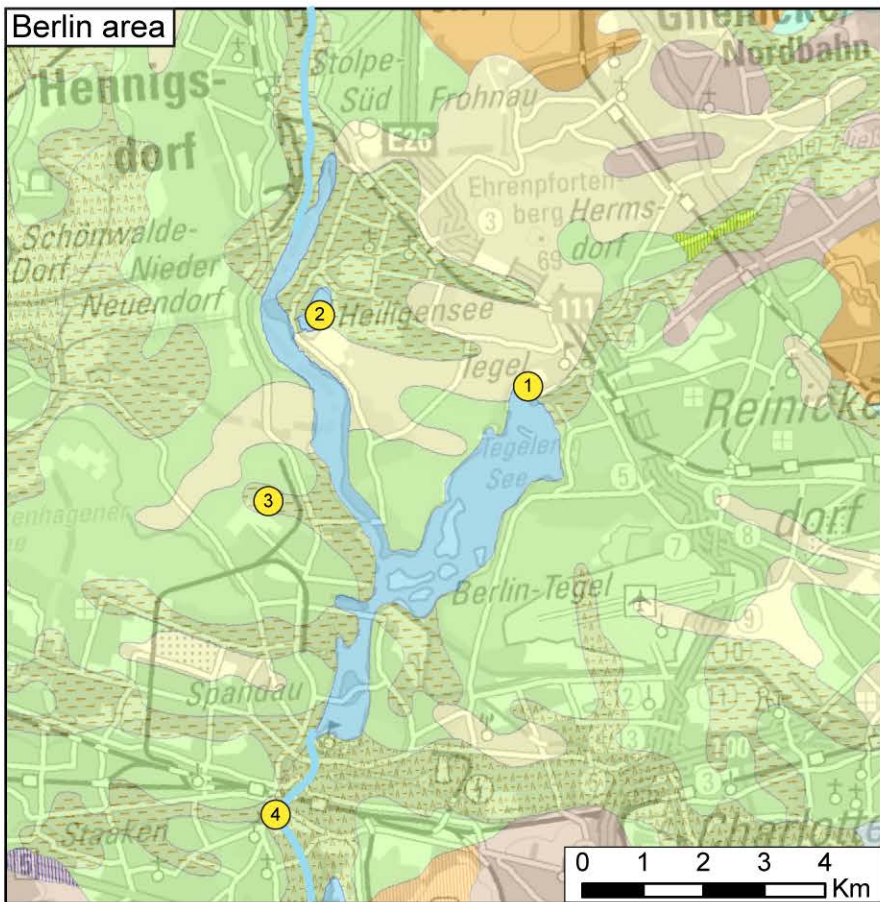


Lithological legend

	Water		Fluvial fines of Havel		Ice
	Peat		Clay, gyttja		Till
	Fluvial fines of Elbe		(Glacio-) Fluvial sand		Outwash plain sand
	Holocene oak log, gravel		Push moraine		



Geological cross-section displayed in the conceptual model

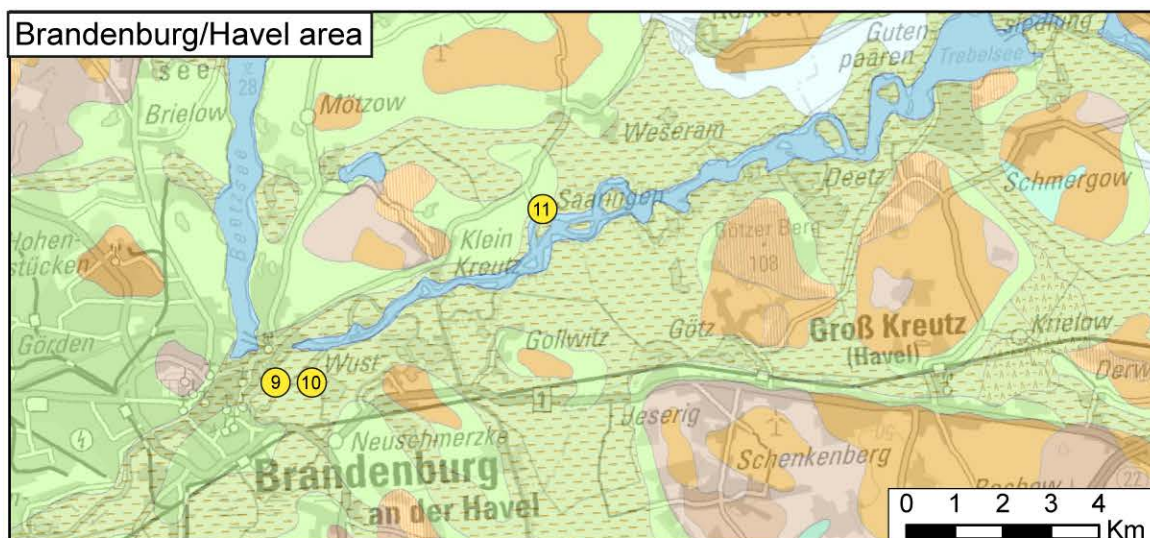
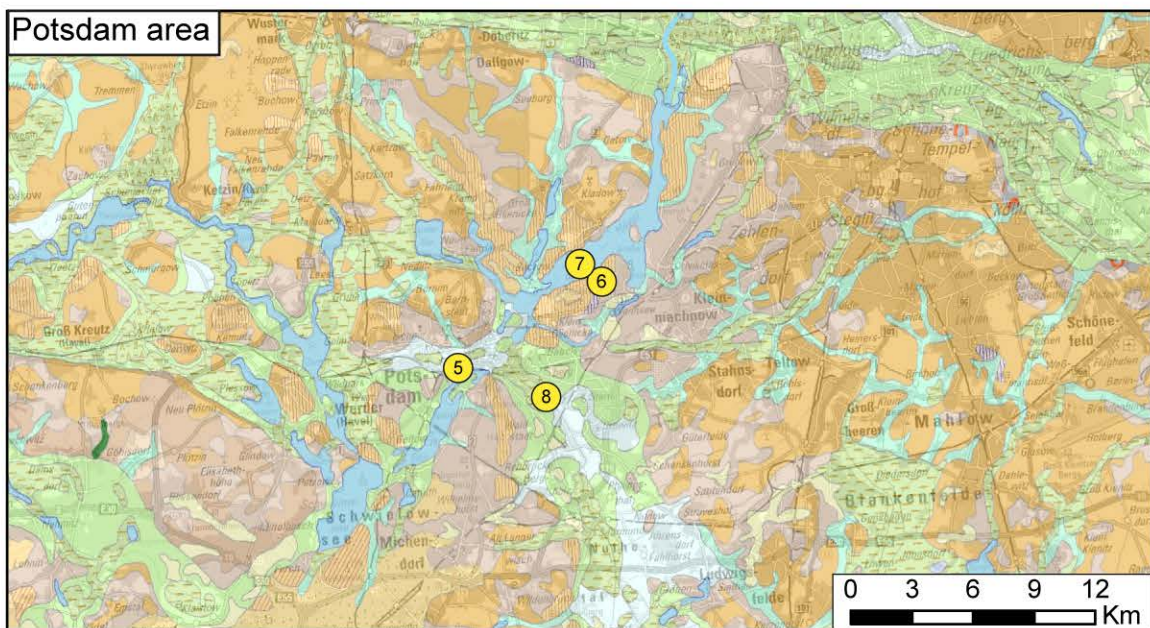


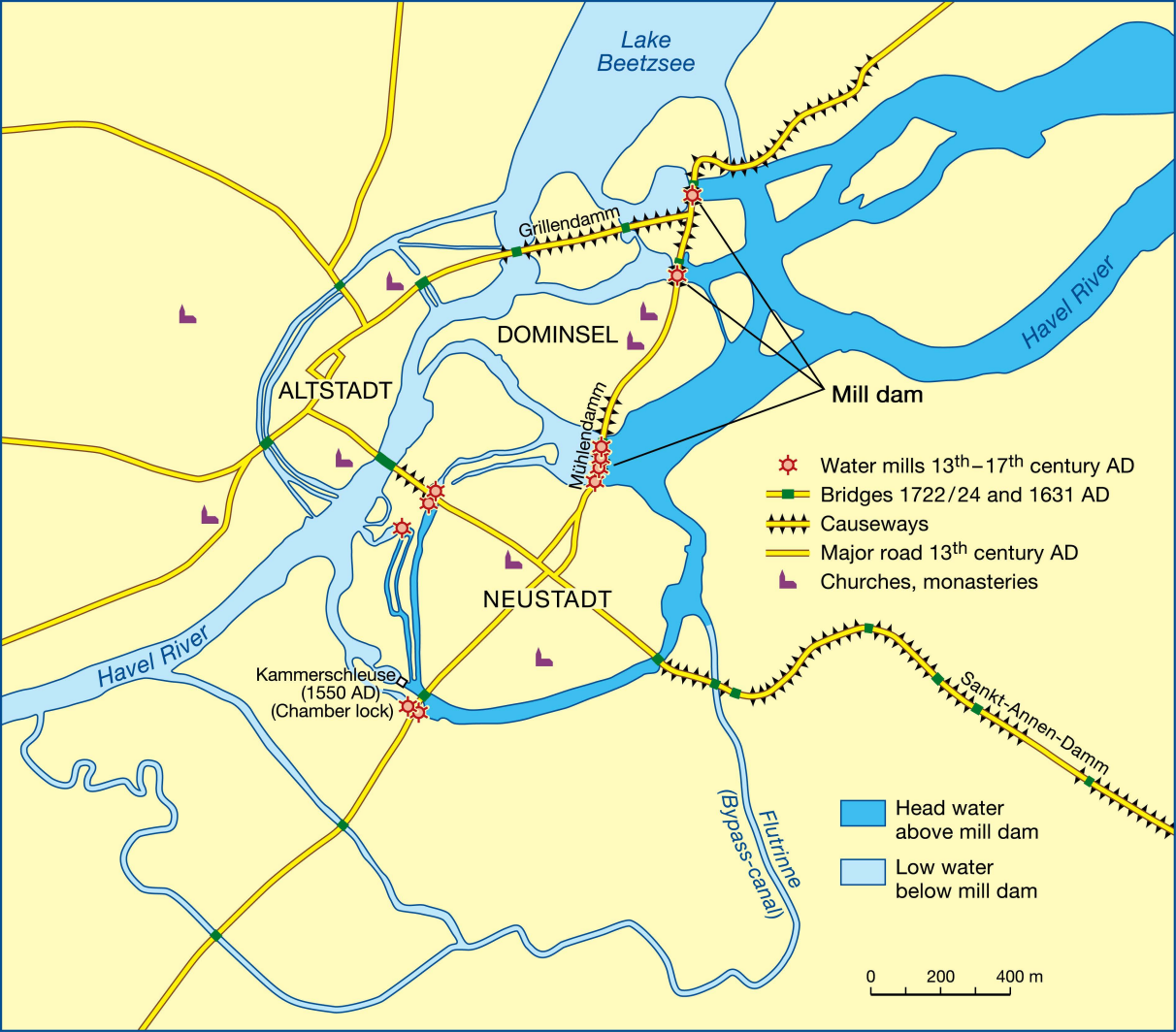
Legend

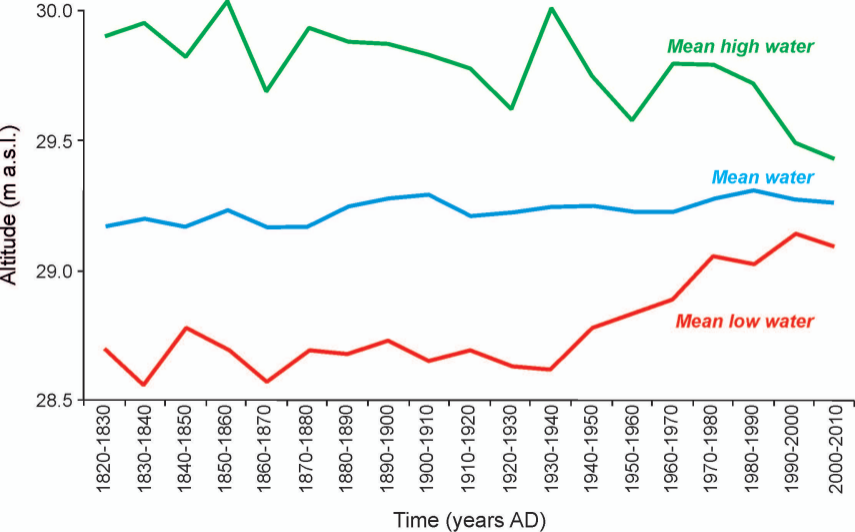
- Basal till (Weichselian)
- Push moraine till (Weichselian)
- Glaciofluvial sand and gravel (Weichselian)
- Glaciofluvial sand and gravel (Sandur) (Weichselian)
- Glaciolacustrine sand and silt (Saalian)
- Fluvial sand (Holocene)
- Periglacial to fluvial sand and gravel (Weichselian to Holocene)
- Glacial valley sand (Weichselian)
- Aeolian sand (Weichselian and Holocene)
- Peat over gyttja (Holocene)
- Peat (Holocene)
- Lake
- River

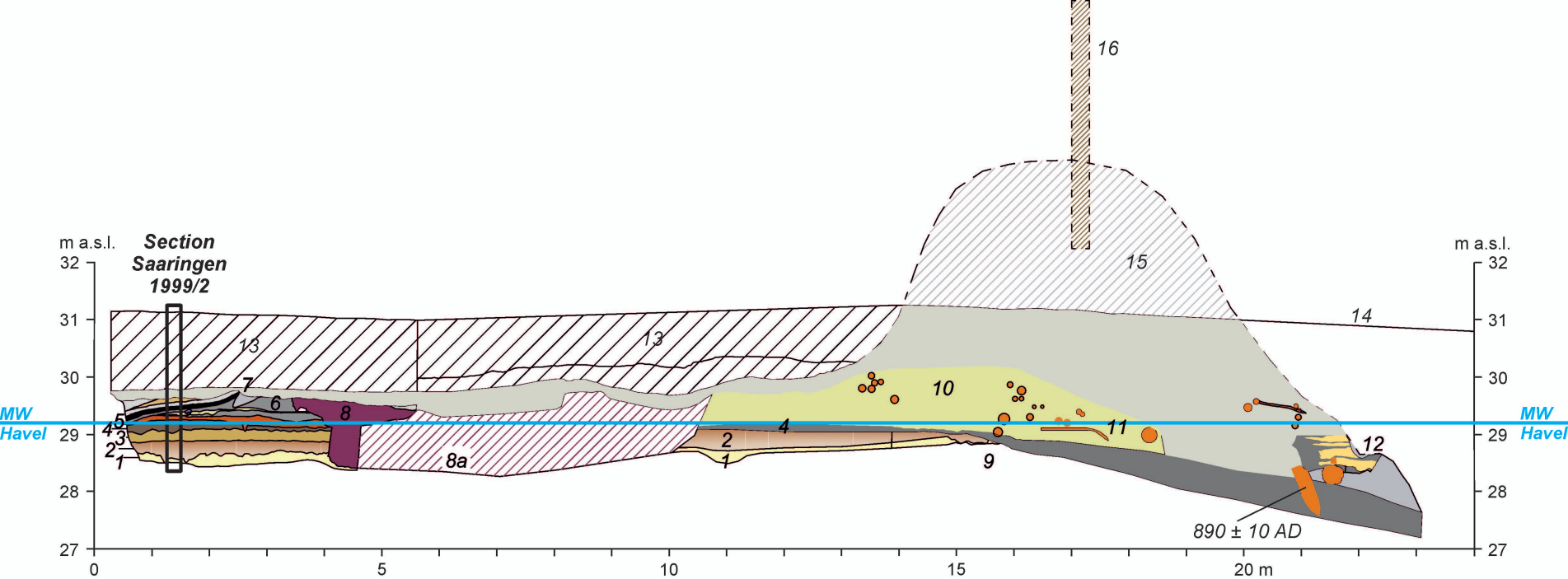
① Records analysed

- | | |
|--------------------|-----------------------|
| 1 Bollenfenn | 8 Schlaatz |
| 2 Heiligensee | 9 Dominsel |
| 3 Teufelsbruch | 10 Mühlendamm |
| 4 Burgwall Spandau | 11 Burgwall Saaringen |
| 5 Palast Barberini | |
| 6 Wannsee | |
| 7 Pfaueninsel | |



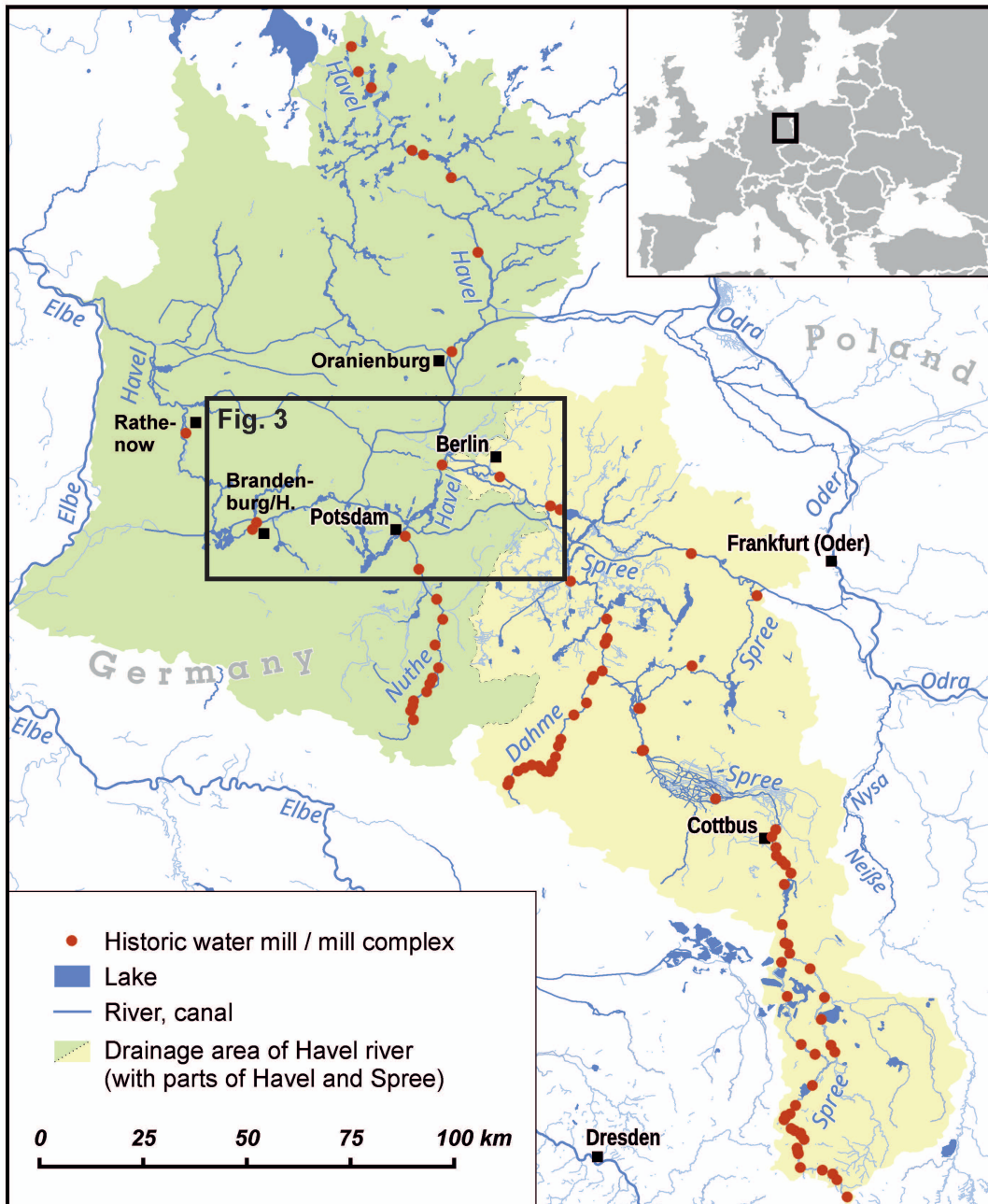


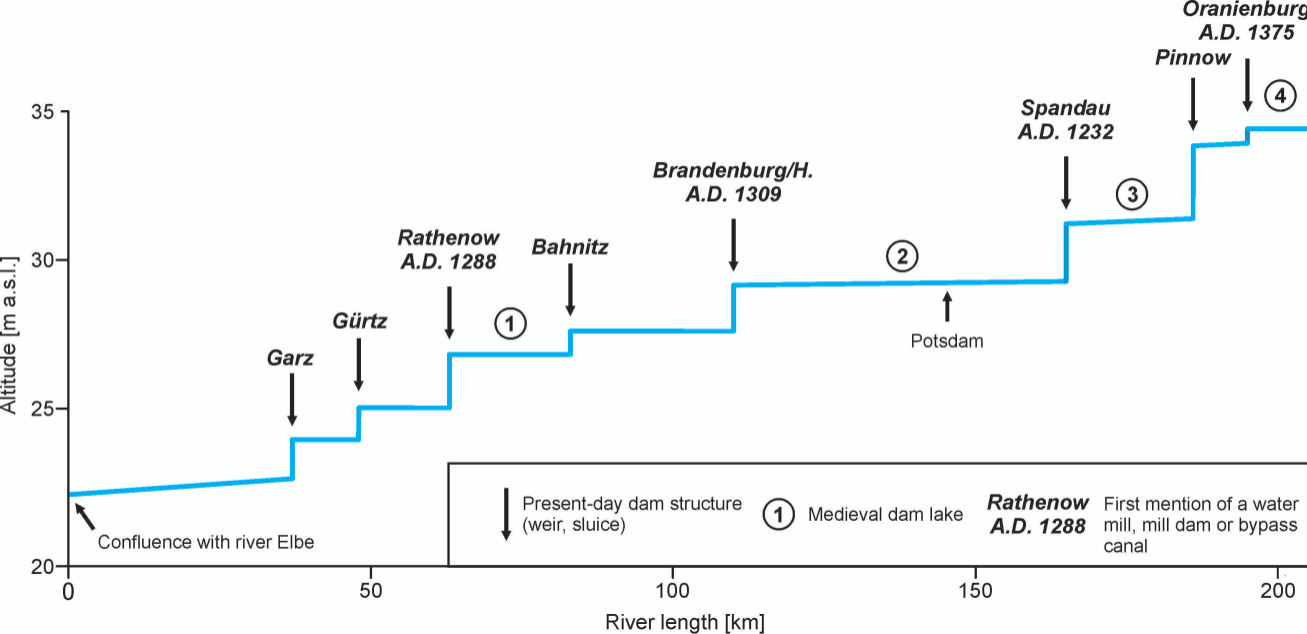


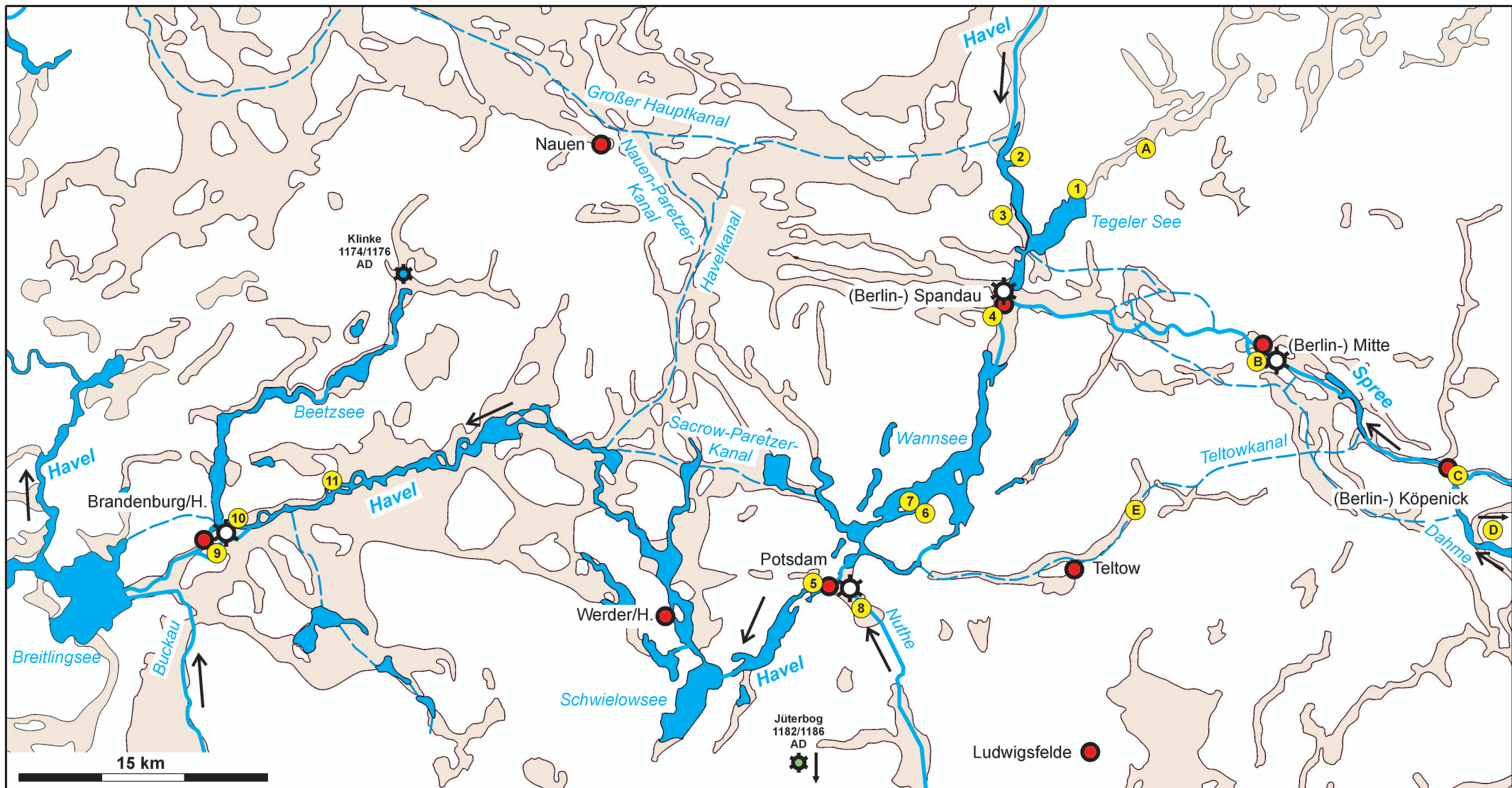


- 1 Fluvial sand
- 2 Terrestrial sandy soil horizon (Bw) with Neolithic to early Slavonic artefacts (c. 5th mill. BC to 8th century AD)
- 3 Sandy occupation layer, 9th century AD
- 4 Humic sandy occupation layer, 9th century AD
- 5 Peaty occupation layer, 9th century AD
- 6 Muddy occupation layer, 9th century AD
- 7 Burned debris of the wooden breastwork of the rampart, 10th century AD
- 8 Pit
- 8a Not excavated
- 9 Riverbank
- 10+11 Remains of the timber frame filled with sand
- 12 Base of the rampart, constructed by wood, peat and minerogenic materials
- 13 Modern debris
- 14 Actual terrain surface
- 15 Reconstruction of the rampart
- 16 Reconstruction of the breastwork









Sampling depth	Sediment classification	Soil horizon	Sample	Colour	Grain-size composition,		Grain-size composition,			Textural class	Gravel	LOI	CaCO ₃	pH
					total Clay-Silt sum <0.002 mm - <0.063 mm	Sand <2 mm	Fine <0.2 mm	Medium <0.63 mm	Coarse <2 mm					
[cm]	[genetic]	[KA5]		[Munsell]	[%]	[%]	[%]	[%]	[%]	[KA5]	[%]	[%]	[%]	[KCl]
0-12	Overbank alluvium	yGo	1	10YR4/3	3.9	95.6	42.6	52.7	4.7	Ss (mSfs)	5.7	2.2	0.2	7.3
12-30	Overbank alluvium	yGo	2	2.5Y4/2	2.9	96.9	39.6	58.3	2.2	Ss (mSfs)	2.0	1.6	0.8	7.6
30-42	Overbank alluvium	Go	3	10YR3/2	5.4	94.2	49.3	48.0	2.8	Ss (fSms)	2.4	2.5	0.0	7.5
42-50	Overbank alluvium	yGo	4	2.5Y4/2	5.1	94.5	54.8	42.8	2.4	Ss (fSms)	2.6	2.1	0.0	7.6
50-51	Overbank alluvium	fF	5	2.5Y2.5/1	6.7	92.2	34.4	48.3	17.4	Ss (mSgs)	21.2	31.2	0.0	7.1
51-69	Overbank alluvium	Go	6	2.5Y6/2	2.6	97.0	22.7	73.8	3.6	Ss (mSfs)	2.8	0.5	0.0	8.0
69-71	Overbank alluvium	fF	7	2.5Y2.2/1	8.2	89.8	52.2	43.5	4.3	Ss (fSms)	3.6	12.3	1.2	7.6
71-89	Overbank alluvium	yGr	8	2.5Y4/2	10.2	88.2	51.5	45.5	3.0	Su2	7.3	3.0	0.0	8.0
89-91	Overbank alluvium	Gr	9	2.5Y5/1	1.9	97.8	47.3	50.6	2.1	Ss (mSfs)	2.4	0.6	0.2	8.1
91-108	Overbank alluvium	yGr	10	2.5Y4/2	5.7	92.4	53.8	43.4	2.8	Ss (fSms)	2.5	4.6	0.0	6.2
108-117	Overbank alluvium	yGr	11	2.5Y2.5/1	3.3	96.5	61.8	33.6	4.6	Ss (fSms)	6.1	5.2	0.0	4.9
117-132	Fluvial sand	Gr	12	2.5Y5/1	5.8	94.0	54.2	33.9	12.0	Ss (fSms)	3.8	1.6	0.0	5.2
132-140	Fluvial sand	Gr	13	2.5Y5/2	1.7	98.2	76.2	21.2	2.6	Ss (fSms)	1.4	1.2	0.0	5.9
140-275	Glaciofluvial sand	Gr	14	2.5Y6/3	0.3	99.6	8.9	43.3	47.9	Ss (mSgs)	15.0	0.2	0.1	6.5







Legend

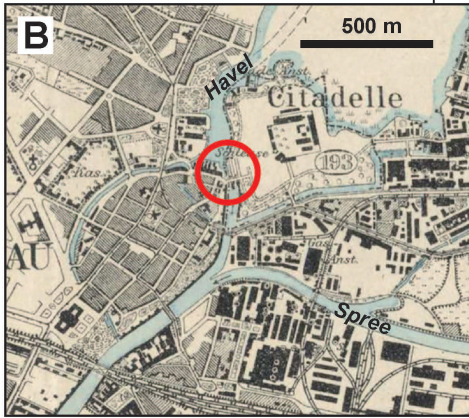
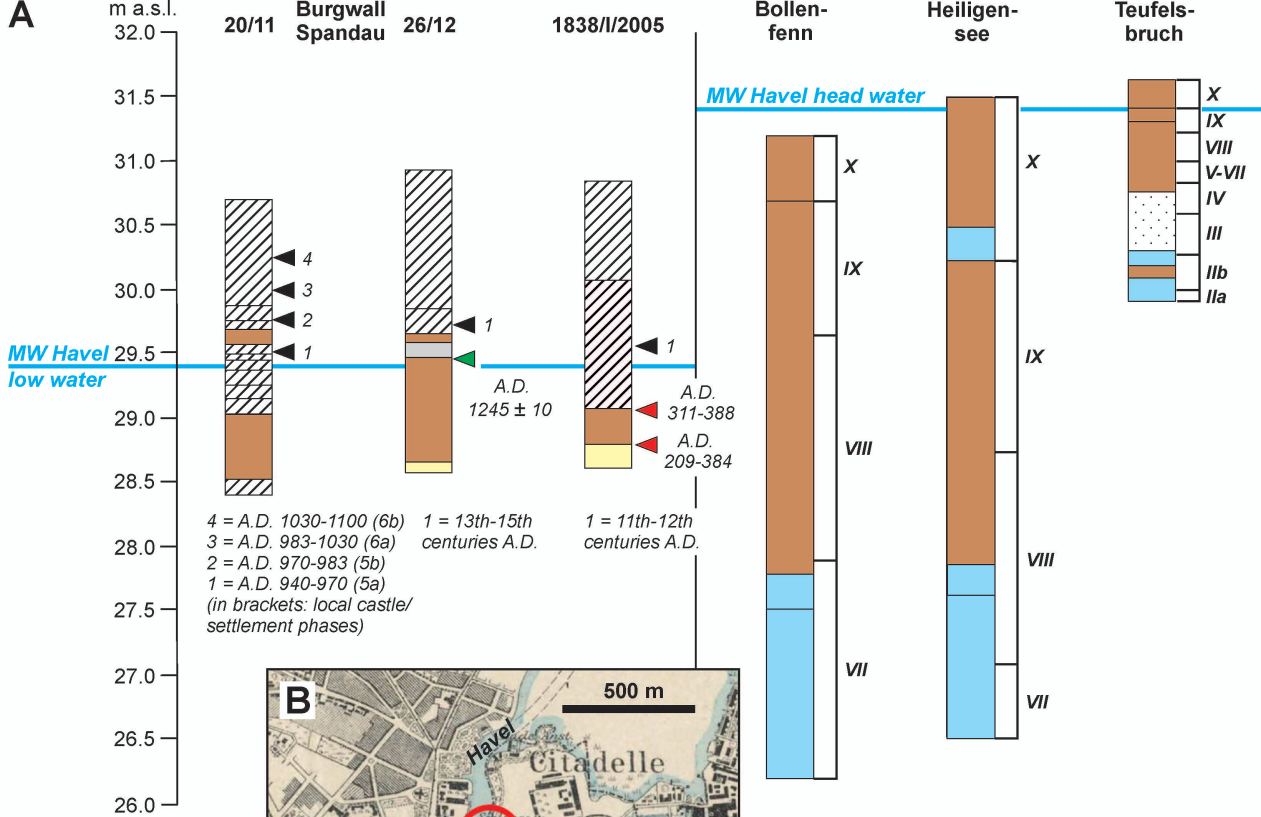
-  Town, town district
-  Historic water mill / mill complex with mill dam at Havel and some of its tributaries
- 1174/1176 AD**  First mention of a water mill by document (Klinke village)
- 1182/1186 AD**  First archaeological record of a water mill (next to Jüterbog/Fläming)
-  Canal
-  River
-  Lake
-  Peatland

① Records analyzed

- 1 Bollenfenn
- 2 Heiligensee
- 3 Teufelsbruch
- 4 Burgwall Spandau
- 5 Palast Barberini
- 6 Wannsee
- 7 Pfaueninsel
- 8 Schlaatz
- 9 Dominsel
- 10 Mühlendamm
- 11 Burgwall Saaringen

Ⓐ Further records

- A Alt Hermsdorf / Tegeler Fließ
- B Mühlendamm
- C Köpenick Altstadt
- D Schmöckwitzer Werder
- E Bäke



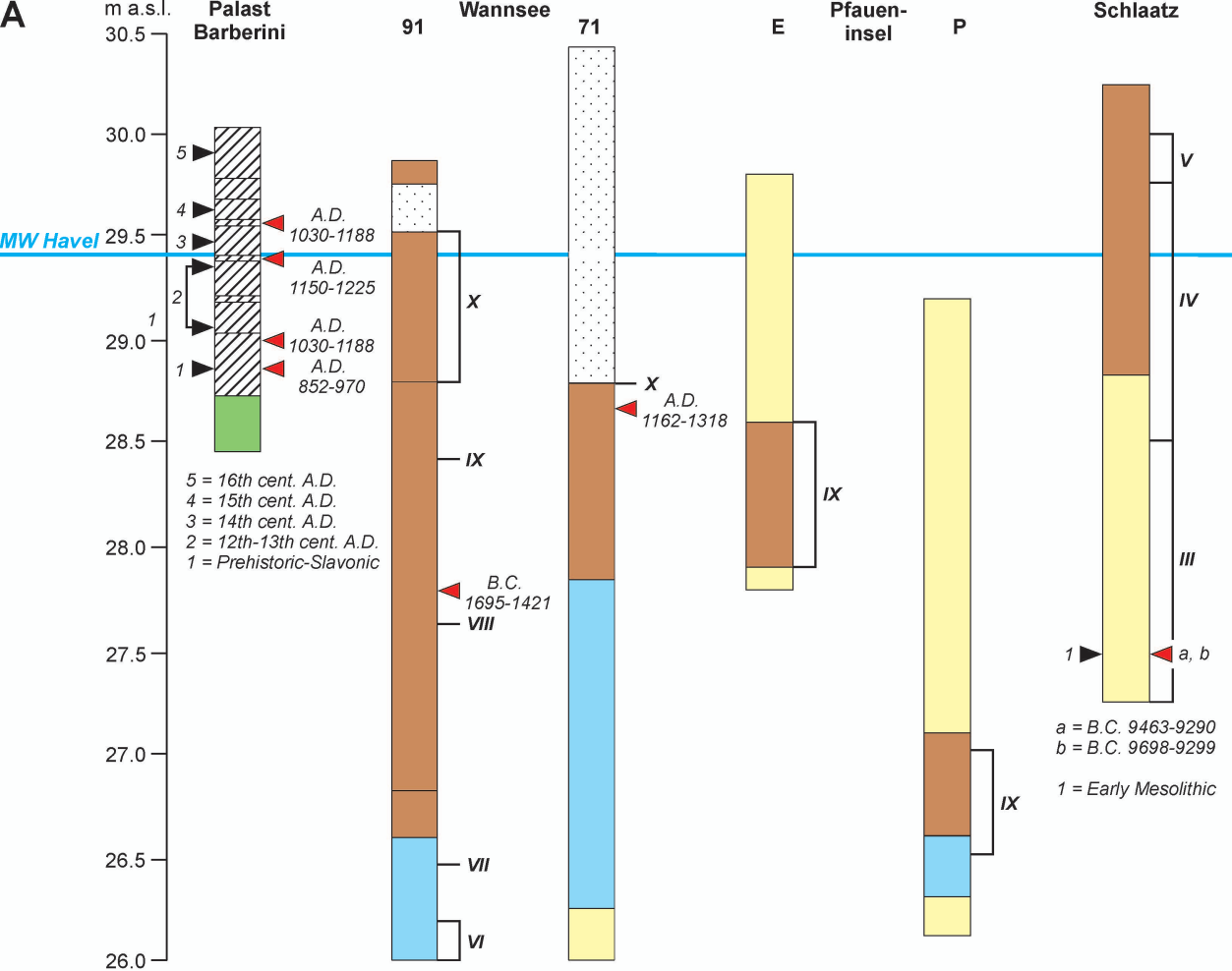
Lithology and dating:

- Fluvial and lacustrine sand
- Eolian sand
- Peat
- Gytija
- Loam
- Artifact-bearing debris, waste layer
- Radiocarbon dating
- Dendro dating
- Archaeological dating

Regional pollen zones:

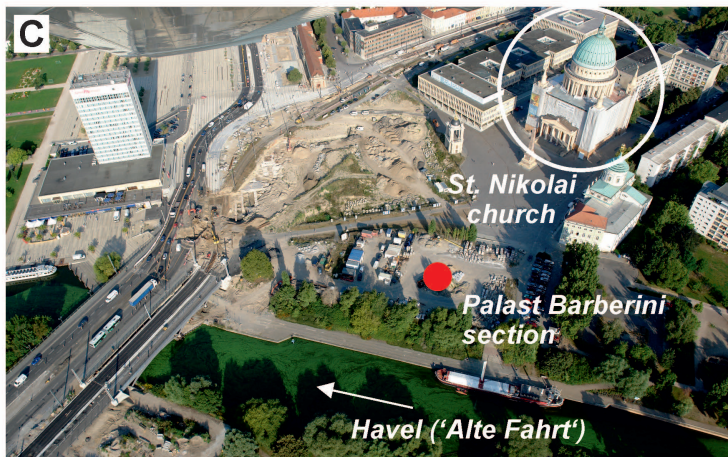
- X Late Subatlantic
- IX Early Subatlantic
- VIII Subboreal
- VII Late Atlantic
- VI Early Atlantic
- V Boreal
- IV Preboreal
- III Younger Dryas
- IIb Late Allerød
- IIa Early Allerød





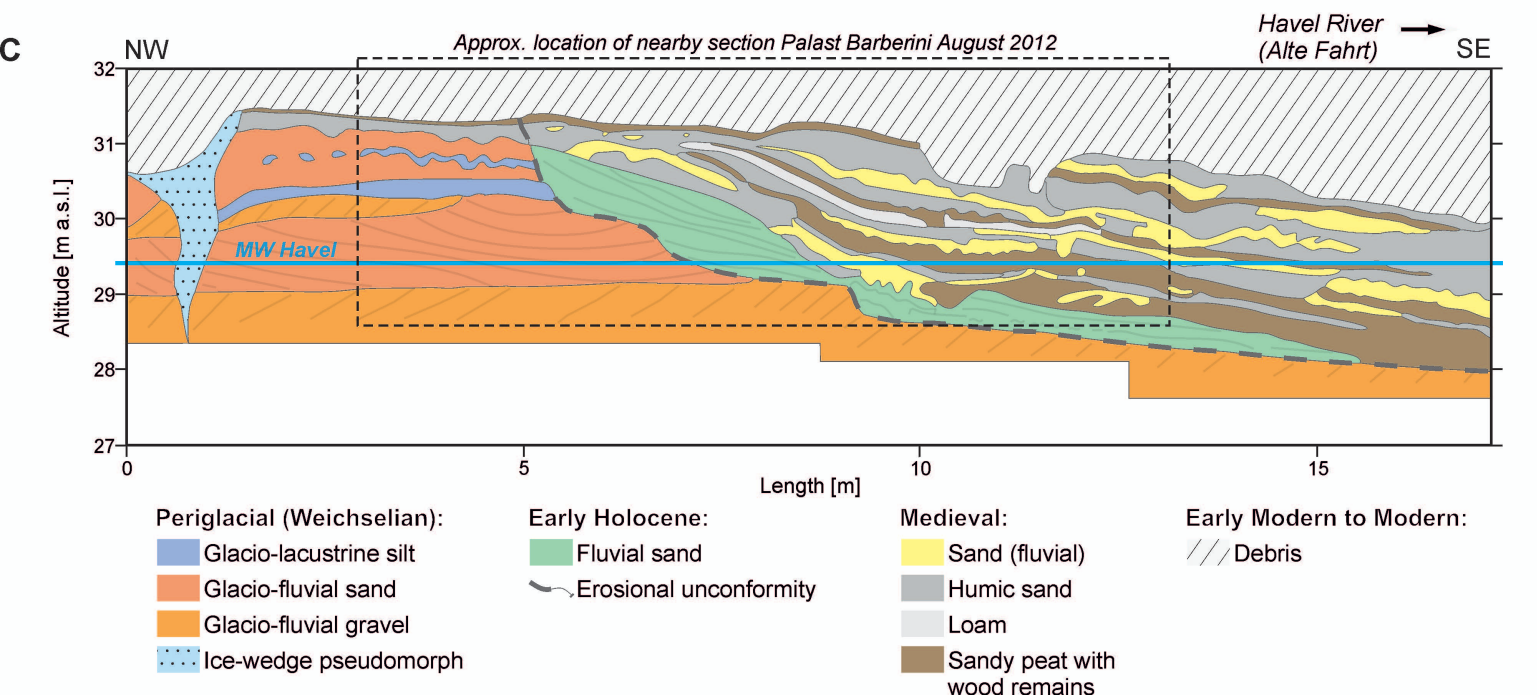
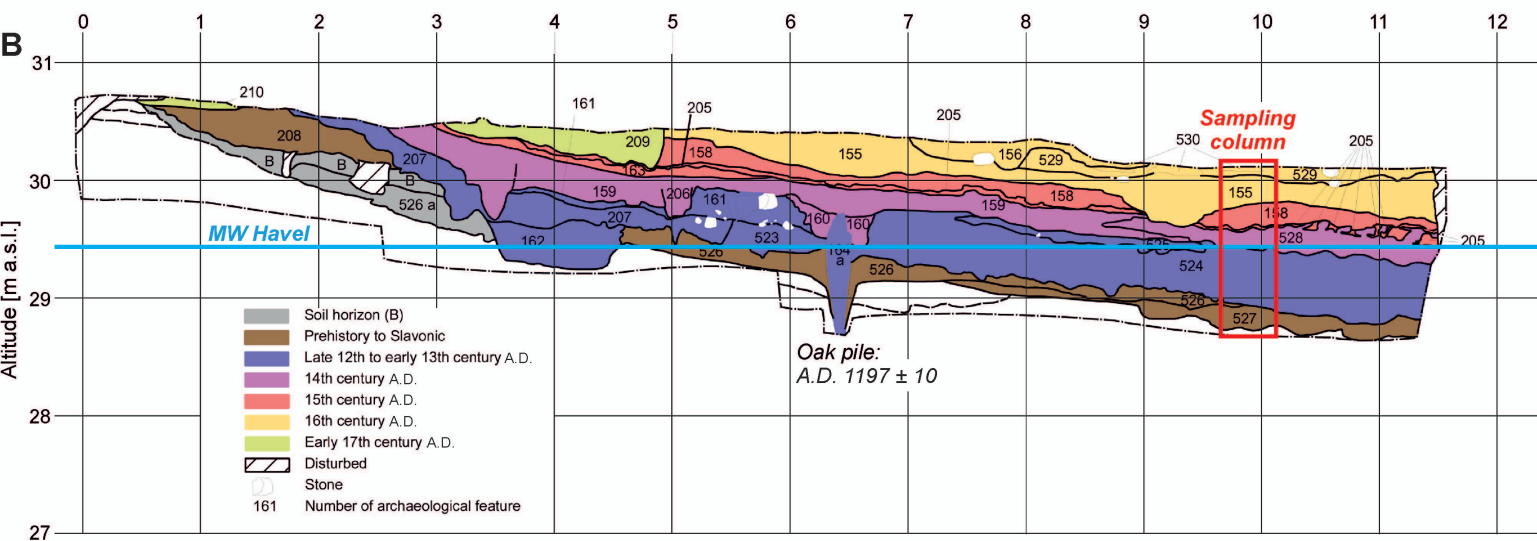
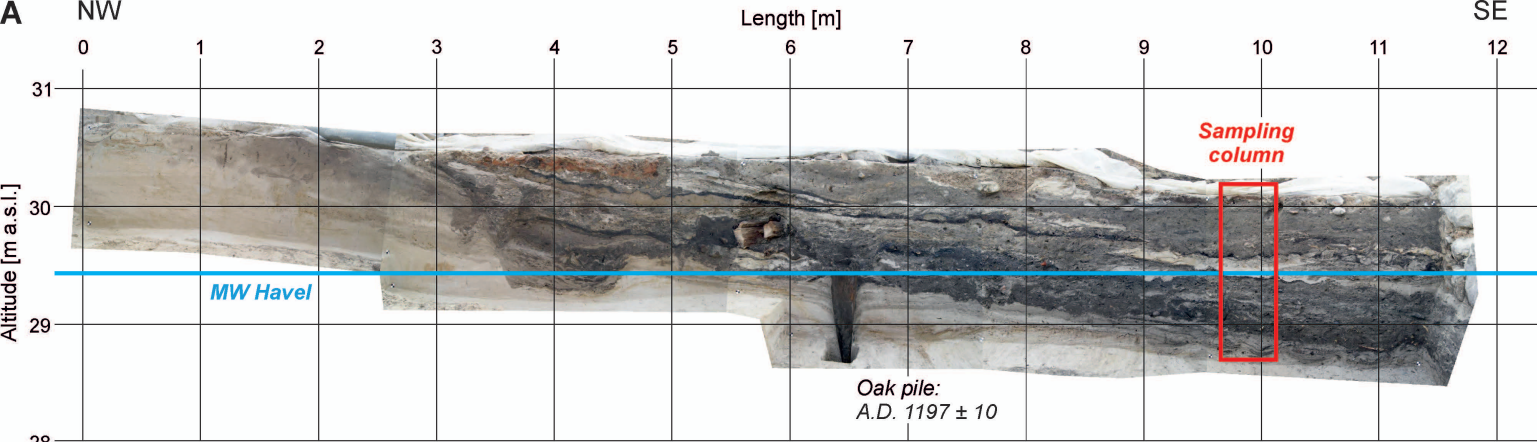
Lithology and dating:

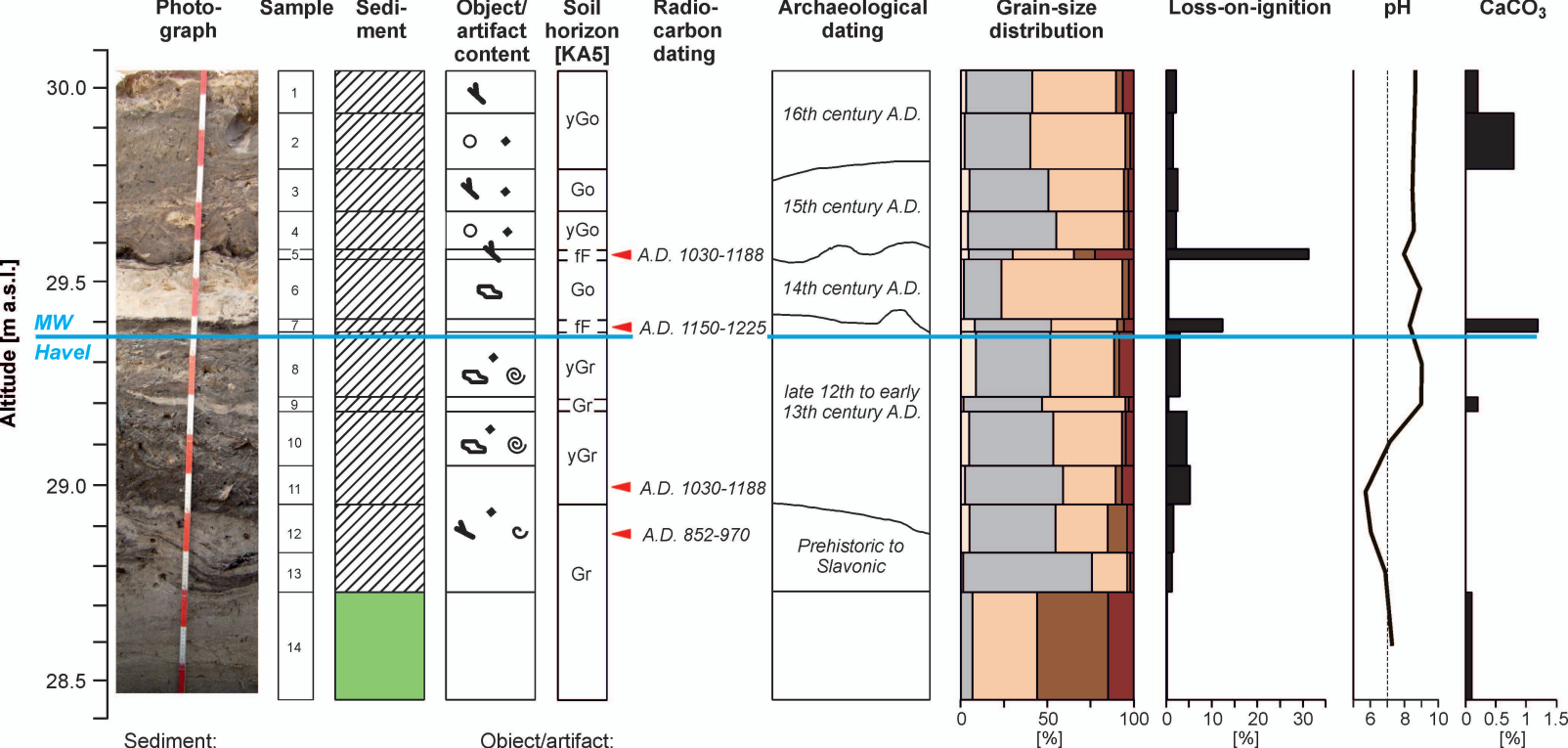
- Sandy overbank alluvium (artifact-bearing)
- Fluvial and lacustrine sand
- Glaciofluvial sand
- Eolian sand
- Peat
- Gyttja
- Radiocarbon dating
- Archaeological dating




Regional pollen zones:

- X Late Subatlantic
- IX Early Subatlantic
- VIII Subboreal
- VII Late Atlantic
- VI Early Atlantic
- V Boreal
- IV Preboreal
- III Younger Dryas





Sediment:

 Sandy overbank alluvium (artifact-bearing debris/waste layer - fluvially removed)

 Glaciofluvial sand

Object/artifact:

 Wood (artificially reworked)

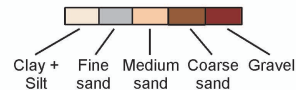
 Charcoal

 Pottery fragment

 Metal slag

 Snail

 Reed



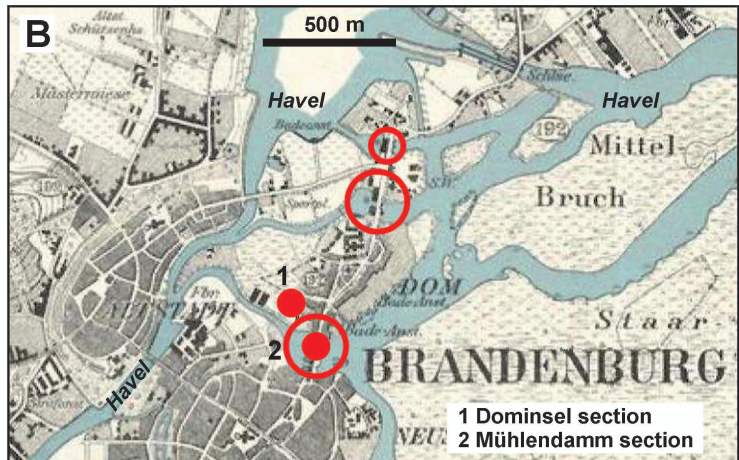
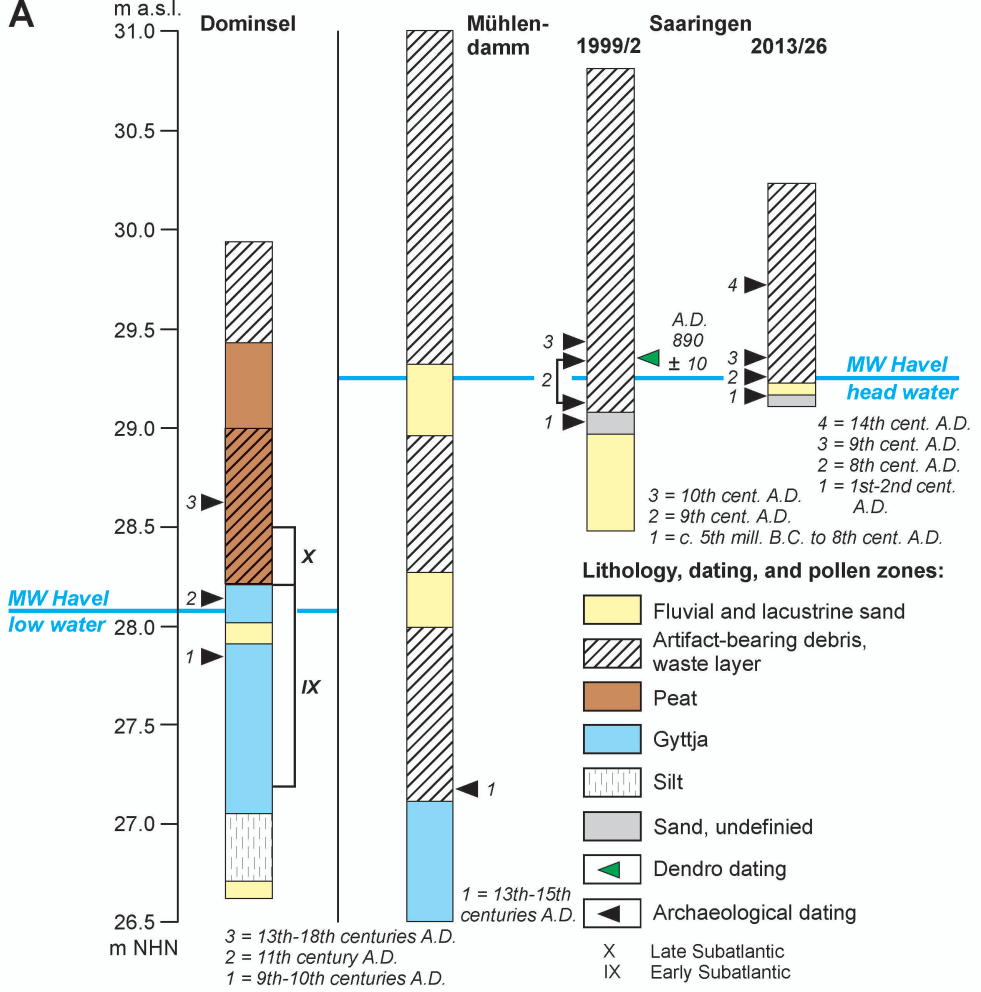
Clay + Silt

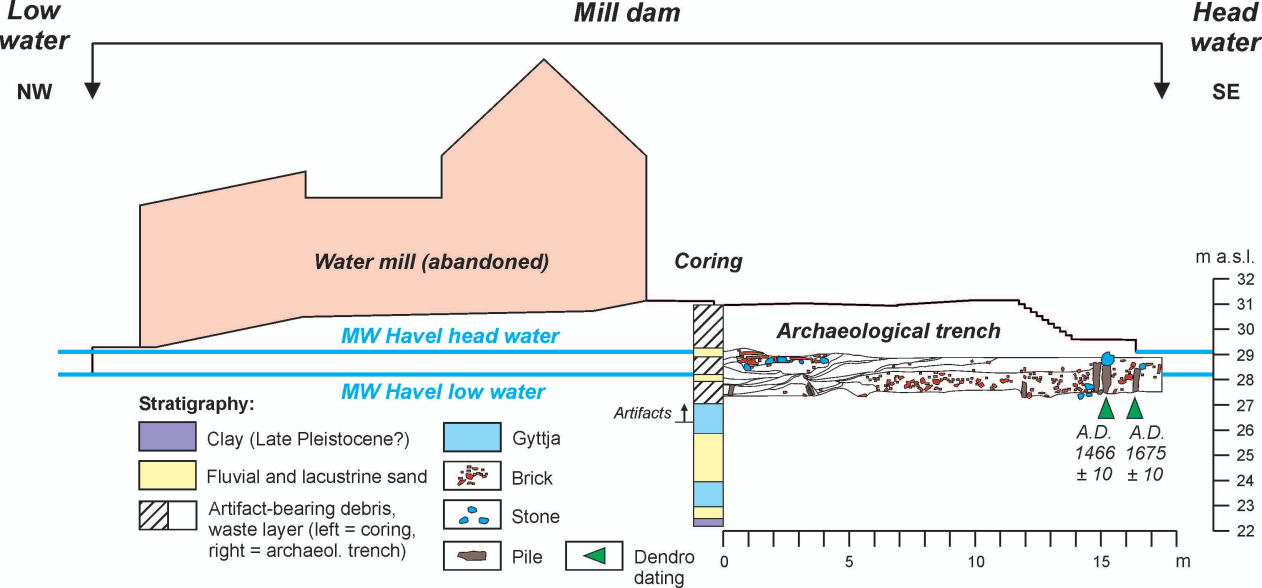
Fine sand

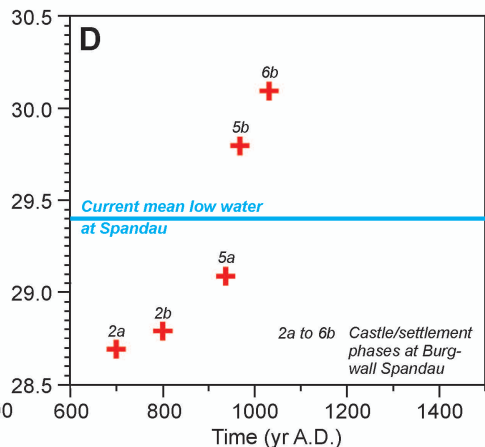
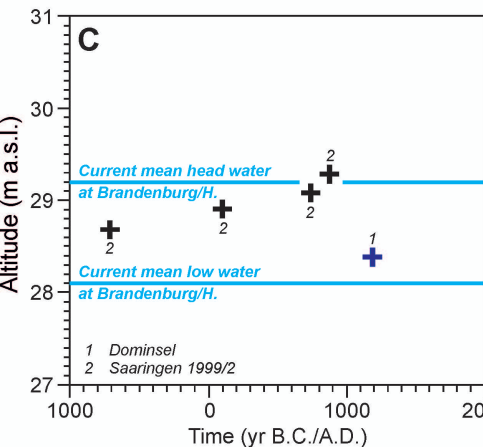
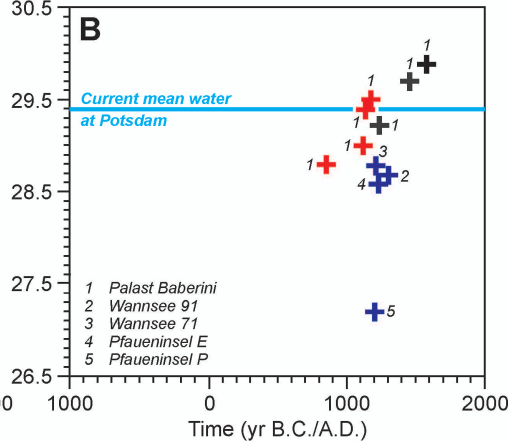
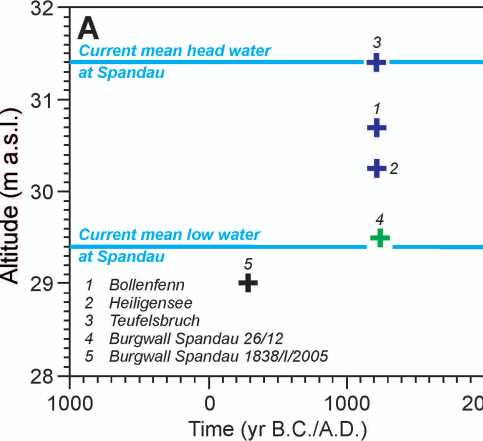
Medium sand

Coarse sand

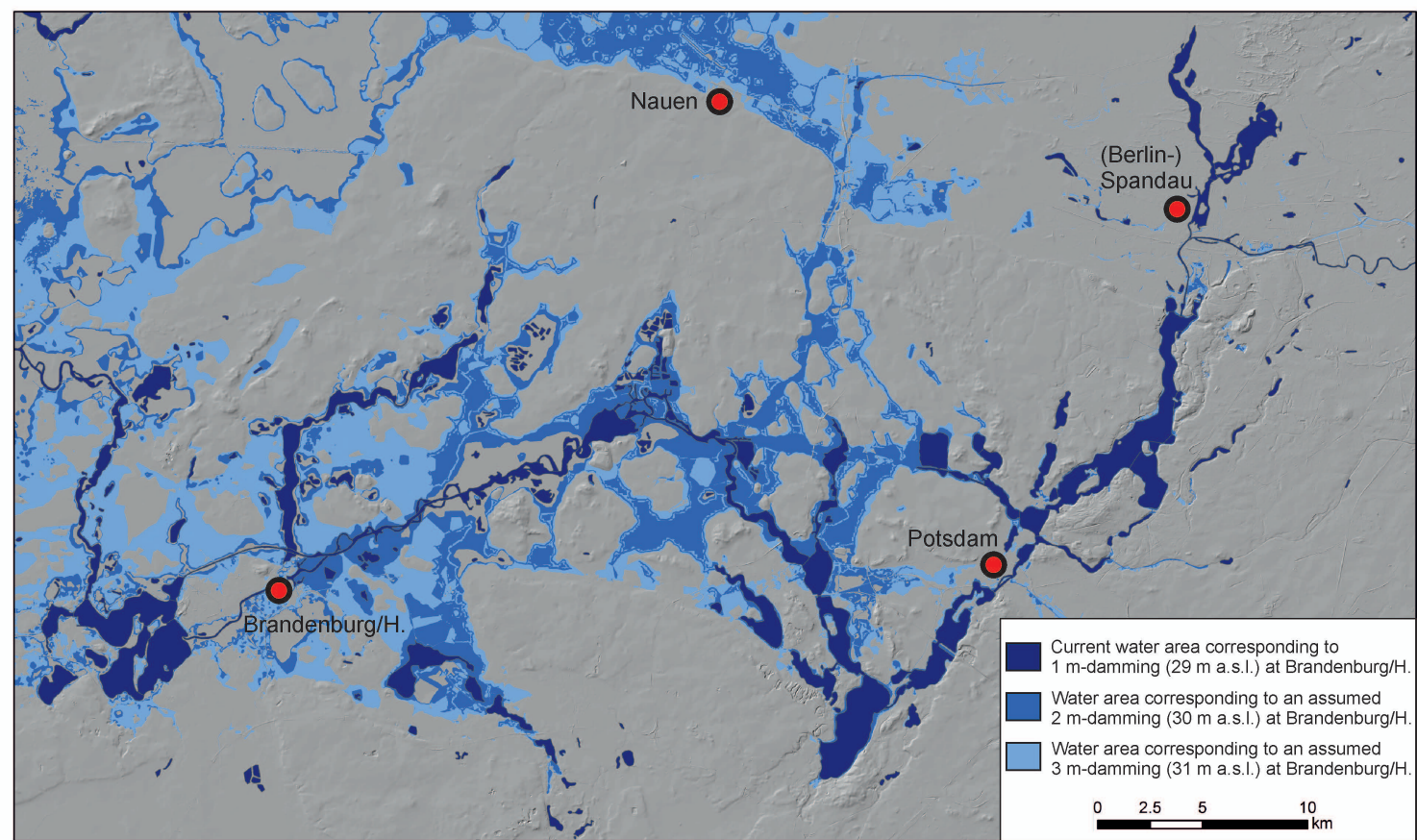
Gravel





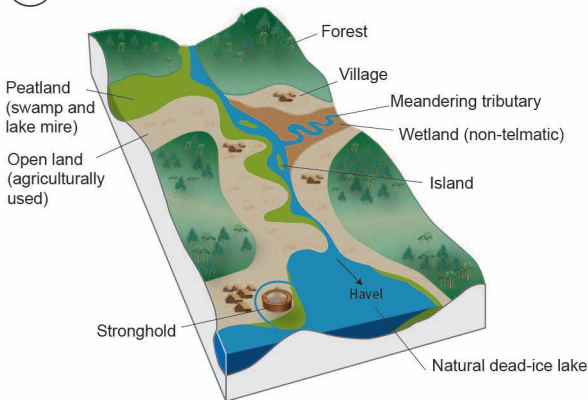


- + Geochronological record (^{14}C)
- + Pollen analytical record
- + Dendrochronological record
- + Archaeological record



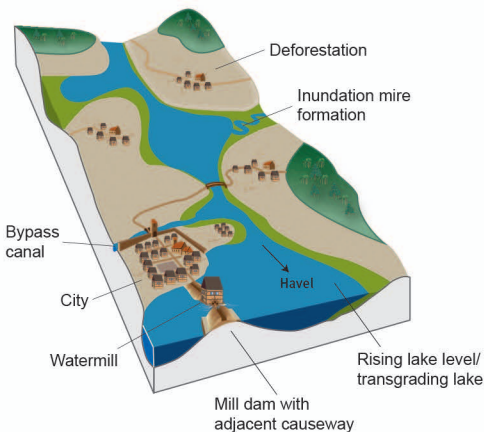
1

11th – 12th century A.D. (Late Slavonic Medieval)



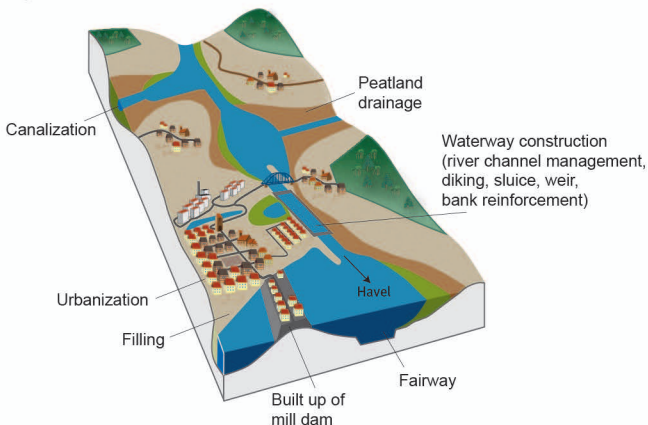
2

13th – 14th century A.D. (German Medieval)



3

20th – 21st century A.D.



Forest



Open land



Peatland



Water

Non-telmatic
wetland

Settlement



Way, road