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**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 km<sup>2</sup>. Its bed slope is generally low (Figure 2). The mean annual discharge at Havelberg next to the mouth in the Elbe is 94.5 m<sup>3</sup> s<sup>-1</sup>. 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 km<sup>2</sup>) 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 km<sup>2</sup>, mean annual discharge at Spandau 42.2 m<sup>3</sup> s<sup>-1</sup>).

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 m<sup>3</sup> s<sup>-1</sup>), 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 (*emporia*) 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). CaCO<sub>3</sub> 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 ( $^{14}\text{C}$ ) dating is available from a total of ten samples (Table II). The  $^{14}\text{C}$  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  $^{14}\text{C}$  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 km<sup>2</sup> (1 m damming), 197 km<sup>2</sup> (2 m damming) and 214 km<sup>2</sup> (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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## REFERENCES

- Ad-hoc-AG Boden (2005). *Bodenkundliche Kartieranleitung*. 5th edition. Hannover: Schweizerbart.
- Alaily, F. & Brande, A. (2002). Bodenentwicklung am Rande oligotropher Moore im Raum Berlin. *Journal of Plant Nutrition and Soil Science*, 165, 305-312.
- Ansorge, J. (2012). Ausgrabungen und Funde auf dem Rostocker Mühlendamm. *Bodendenkmalpflege in Mecklenburg-Vorpommern*, 59, 251-293.
- Argyilan, E.P., Forman, S.L., & Thompson, T.A. (2010). Variability of Lake Michigan water level during the past 1000 years reconstructed through optical dating of a coastal strandplain. *The Holocene*, 20, 723-731.
- Benecke, N. (2004). Faunal succession in the lowlands of northern Central Europe at the Pleistocene-Holocene transition. In T. Terberger & B.V. Eriksen (Eds.), *Hunters in a changing world. Environment and archaeology of the Pleistocene-Holocene transition (ca. 11000-9000 B.C.) in Northern Central Europe* (pp. 43-51). Rahden: Leidorf.
- Bennion, H., & Battarbee, R.W. (2007). The European Union Water Framework Directive: opportunities for palaeolimnology. *Journal of Paleolimnology*, 38, 285-295.
- Beran, J. (2012). Mittleres und jüngeres Neolithikum. In T. Kersting, T. Langer, J. Müller & S. Pratsch (Eds.), *Ausflüge im Südwesten Brandenburgs. Zauche, Teltow, Fläming. Ausflüge zu Archäologie, Geschichte und Kultur in Deutschland*, 54 (pp. 41-51). Stuttgart: Theiss.
- Bishop, P., Muñoz-Salinas, E., MacKenzie, A.B., Pulford, I., & McKibbin, J. (2011). The character, volume and implications of sediment impounded in mill dams in Scotland: the case of the

- Baldernock Mill dam in East Dunbartonshire. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 101, 97-110.
- Bleile, R. (2005). Die Auswirkungen des spätmittelalterlichen Wassermühlenbaus auf die norddeutsche Gewässerlandschaft. In F. Biermann & G. Mangelsdorf, G. (Eds.), *Die bäuerliche Ostsiedlung des Mittelalters in Nordostdeutschland. Untersuchungen zum Landesausbau des 12. bis 14. Jahrhunderts im ländlichen Raum. Greifswalder Mitteilungen – Beiträge zur Ur- und Frühgeschichte und Mittelalterarchäologie* 7 (pp. 175-192). Frankfurt am Main: Lang.
- Bönisch, E. (2012). Mittel- und Spätbronzezeit zwischen Fläming und Havelland. In T. Kersting, T. Langer, J. Müller & S. Pratsch (Eds.), *Ausflüge im Südwesten Brandenburgs. Zauche, Teltow, Fläming. Ausflüge zu Archäologie, Geschichte und Kultur in Deutschland*, 54 (pp. 52-64). Stuttgart: Theiss.
- Böse, M. (2002). Sumpf und Dünen – Mittelalterliche Landschaftsveränderung im Berlin-Potsdamer Raum. *Proceedings of the DEUQUA Conference, Potsdam, 26-28 August 2002, Terra Nostra* 2002/6, pp. 46-50.
- Böse, M., & Brande, A. (1986). Zur Entwicklungsgeschichte des Moores „Alter Hof“ am Havelufer (Berliner Forst Düppel). In W. Ribbe (Ed.), *Berlin-Forschungen* 1 (pp. 11-42). Berlin: Colloquium Verlag.
- Böse, M., & Brande, A. (2010). Landscape history and man-induced landscape changes in the young morainic area of the North European Plain – a case study from the Bäke Valley, Berlin. *Geomorphology*, 122, 274-282.
- Brande, A. (1980). Heiligensee. In: H. Sukopp, H.-P. Blume, H. Elvers & M. Horbert (Eds.), *Beiträge zur Stadtökologie von Berlin (West). Landschaftsentwicklung und Umweltforschung* 3 (pp. 76-80). Berlin: Technische Universität.
- Brande, A. (1986). Stratigraphie und Genese Berliner Kesselmoore. *Telma*, 16, 319-321.
- Brande, A. (1988). Das Bollenfenn in Berlin-Tegel. *Telma*, 18, 95-135.

- Brande, A. (1995). Moorgeschichtliche Untersuchungen im Spandauer Forst (Berlin). Schriftenreihe für Vegetationskunde, 27, 249-255.
- Brande, A. (1996). Type region D-s, Berlin. In B.E. Berglund, H.J.B. Birks, M. Ralska-Jasiewiczowa & H.E. Wright (Eds.), Palaeoecological events during the last 15000 years. Regional syntheses of palaeoecological studies of lakes and mires in Europe (pp. 518-523). Chichester: John Wiley & Sons.
- Brande, A. (1999). Botanische Untersuchungen auf dem Burgwall Spandau – eine Übersicht. In A. von Müller & K. von Müller-Mučič (Eds.), Neue Forschungsergebnisse vom Burgwall in Berlin-Spandau. Berliner Beiträge zur Vor- und Frühgeschichte 98, Archäologisch-historische Forschungen in Spandau 9 (pp. 130-140). Berlin.
- Brande, A. (2008). Pollenanalysen zur Geschichte der Pfaueninsel. Verhandlungen des Botanischen Vereins von Berlin und Brandenburg, 141, 223-250.
- Brande, A. (2010). Palynologische Untersuchungen auf den Grabungen Biesdorf, Buch und Burgwall Spandau. Miscellanea Archaeologica IV. Festschrift für Wilfried Menghin. Beiträge zur Denkmalpflege in Berlin 32 (pp. 180-195). Berlin: Imhof.
- Brande, A. (2012). Pollenanalysen zur archäologischen Grabung Alt-Hermsdorf am Tegeler Fließtal in Berlin. Verhandlungen des Botanischen Vereins von Berlin und Brandenburg, 145, 19-52.
- Brather, J. & Hegewisch, M. (2012). Römische Kaiser- und Völkerwanderungszeit. In T. Kersting, T. Langer, J. Müller & S. Pratsch (Eds.), Ausflüge im Südwesten Brandenburgs. Zauche, Teltow, Fläming. Ausflüge zu Archäologie, Geschichte und Kultur in Deutschland, 54 (pp. 73-85). Stuttgart: Theiss.
- Brown, A.G. (1997). Alluvial geoarchaeology: Floodplain archaeology and environmental change. Cambridge: Cambridge University Press.
- Brykala, D. (2014). 800 years of watermills' operation on rivers of the Central and Northern Poland. Geophysical Research Abstracts, 16, EGU2014-5938.

- Brykala, D., & Podgorski, Z. (2008). 800 years of watermills' existence on Polish rivers and their role in hydrographical systems' modification. Proceedings International Conference Studying, Modeling and Sense Making of Planet Earth (pp. 1-8). Mytilene/Greece.
- Buck, D.-W. (2000). Vorrömische Eisenzeit. In J. Kunow & G. Wetzel (Eds.), Potsdam, Brandenburg und das Havelland. Führer zu archäologischen Denkmälern in Deutschland 37 (pp. 74-86). Stuttgart: Theiss.
- Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.U., Wanner, H., Luterbacher, J., & Esper, J. (2011). 2500 years of European climate variability and human susceptibility. *Science*, 331, 578-582.
- Chaussé, C., Leroyer, C., Girardclos, O., Allenet, G., Pion, P., & Raymond, P. (2008). Holocene history of the River Seine, Paris, France: bio-chronostratigraphic and geomorphological evidence from the Quai-Branly. *The Holocene*, 18, 967-980.
- Clay, P., & Salisbury, C.R. (1990). A Norman mill dam and other sites at Hemington Fields, Castle Donington, Leicestershire. *Archaeological Journal* 147, 276-307.
- Cziesla, E. (2012). Paläolithikum, Mesolithikum und der Beginn der Jungsteinzeit. In T. Kersting, T. Langer, J. Müller & S. Pratsch (Eds.), *Ausflüge im Südwesten Brandenburgs. Zauche, Teltow, Fläming. Ausflüge zu Archäologie, Geschichte und Kultur in Deutschland*, 54 (pp. 30-40). Stuttgart: Theiss.
- Dalitz, S. (2009). Die Brandenburg in der Havel – Arbeitsstand zu Topografie und Entwicklung der Insel und der Burg. In J. Müller, K. Neitmann & F. Schopper (Eds.), *Wie die Mark entstand. 850 Jahre Mark Brandenburg. Forschungen zur Archäologie im Land Brandenburg* 11 pp. 54-78. Wünsdorf: Brandenburgisches Landesamt für Denkmalpflege und Archäologisches Landesmuseum.
- Dalitz, S., & Kersting, T. (2012). Saaringen: Slawischer Burgwall und Hügelgräberfeld. In T. Kersting, T. Langer, J. Müller & S. Pratsch (Eds.), *Ausflüge im Südwesten Brandenburgs. Zauche, Teltow, Fläming. Ausflüge zu Archäologie, Geschichte und Kultur in Deutschland*, 54 (pp. 138-140). Stuttgart: Theiss.



- Dolch, D., Heidecke, D., Teubner, J., & Teubner, J. (2002). Der Biber im Land Brandenburg. *Naturschutz und Landschaftspflege in Brandenburg*, 11, 220-234.
- Downward, S., & Skinner, K. (2005). Working rivers: the geomorphological legacy of English freshwater mills. *Area*, 37, 138-147.
- Driescher, E. (2003). Veränderungen an Gewässern Brandenburgs in historischer Zeit. *Studien und Tagungsberichte 47*. Potsdam: Landesumweltamt Brandenburg.
- Enters, D., Kirilova, E., Lotter, A., Lücke, A., Parplies, J., Kuhn, G., Jahns, S., & Zolitschka, B. (2010). Climate change and human impact at Sacrower See (NE Germany) during the past 13,000 years: a geochemical record. *Journal of Palaeolimnology*, 43, 719-737.
- Fægri, K., & Iversen, J. (1989). *Textbook of pollen analysis*. 4th edition. Copenhagen: Munksgaard.
- Fletcher, R., Penny, D., Evans, D., Pottier, C., Barbetti, M., Kumm, M., & Lustig, T. (2008). The water management network of Angkor, Cambodia. *Antiquity*, 82, 658-670.
- Geue, T. (2011). Untersuchungen am Mühlendamm in Brandenburg a. d. Havel. Unpublished report. Berlin: Freie Universität, Institute of Prehistoric Archaeology.
- 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.
- Goldmann, K. (1986). Zur Umweltgestaltung während der Spätbronzezeit Mitteleuropas. *Veröffentlichungen des Museums für Ur- und Frühgeschichte Potsdam*, 20, 137-141.
- Gramsch, B. (2002). Archäologische Indizien für natürliche und künstliche Wasserspiegelveränderungen in nordostdeutschen Urstromtälern während des Holozäns. In K. Kaiser (Ed.), *Die jungquartäre Fluss- und Seegenese in Nordostdeutschland*. Greifswalder Geographische Arbeiten 26 (pp. 189-192). Greifswald.
- Gramsch, B., & Beran, J. (2010). Spätaltsteinzeitliche Funde von Wustermark, Fundplatz 22, Lkr. Havelland. *Veröffentlichungen zur brandenburgischen Landesarchäologie*, 41/42, 95-142.
- Gurnell, A.M. (1998). The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography*, 22, 167-189.

- Hansen, M.M., Limborg, M.T., Ferchaud, A.-L., & Pujolar, J.-M. (2014). The effects of Medieval dams on genetic divergence and demographic history in brown trout populations. *BMC Evolutionary Biology*, 14, 122.
- Havinga, H., & Smits, A.J.M. (2000). River management along the Rhine: a retrospective view. In A.J.M. Smits, P.M.Nienhuis & R.S.E.W. Leuven (Eds.), *New Approaches to River Management* (pp. 15-32). Leiden: Backhuys Publisher.
- Hensel, N. (2013). Unterwasserarchäologie ohne Taucheranzug. Mittelalterliche Bootsfunde und anderes vom Potsdamer Havelufer. *Archäologie in Berlin und Brandenburg*, 2013, 110-113.
- Hesselink, A.W. (2002). History makes a river. Morphological changes and human interference in the River Rhine, The Netherlands. *Netherlands Geographical Studies* 292. Utrecht: Utrecht University.
- Herrmann, J. (1959). Wasserstand und Siedlung im Spree-Havel-Gebiet in frühgeschichtlicher Zeit. *Ausgrabungen und Funde*, 4, 90-106.
- Hoffmann, R.C. (1996). Economic development and aquatic ecosystems in medieval Europe. *American Historical Review*, 101, 631-669.
- Hoffmann, R.C. (2014). *An environmental history of medieval Europe*. Cambridge: Cambridge University Press.
- Hofmann, M. (2005). Mittelalterliche Straßen- und Hausbefunde in der Spandauer Straße. In J. Haspel & W. Menghin (Eds.), *Miscellanea Archaeologica II: Festschrift für Heinz Seyer. Beiträge zur Denkmalpflege* 20 (pp. 186-203). Berlin.
- Hohensinner, S., Lager, B., Sonnlechner, C., Haidvogel, G., Gierlinger, S., Schmid, M., Krausmann, F., & Winiwarter, V. (2013). Changes in water and land: the reconstructed Viennese riverscape from 1500 to the present. *Water History*, 5, 145-172.
- Howard, A.J., Macklin, M.G., & Passmore, D.G. (2003). *Alluvial archaeology in Europe*. Leiden: A.A. Balkema Publishers.
- Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., & Svendsen, J.I. (2016). The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas*, 45, 1-45.

- Jahns, S. (2015). Pollen- und Makrorestanalysen auf der Dominsel. *Forschungen zur Archäologie im Land Brandenburg*, 16, 279-282.
- Jeschke, L. (1990). Der Einfluss der Klimaschwankungen und Rodungsphasen auf die Moorentwicklung im Mittelalter. *Gleditschia*, 18, 115-123.
- Jeute, G.H. (2015). Zur Verbreitung der hochmittelalterlichen Mühle aus archäologischer Sicht. In M. Maríková & C. Zschieschang (Eds.), *Wassermühlen und Wassernutzung im mittelalterlichen Ostmitteleuropa. Forschungen zur Geschichte und Kultur des östlichen Mitteleuropa* 50 (pp. 269-277). Stuttgart: Steiner.
- Jones, A.F., Macklin, M.G., & Benito, G. (2015). Meta-analysis of Holocene fluvial sedimentary archives: A methodological primer. *Catena*, 130, 3-12.
- Kaiser, K., Rother, H., Lorenz, S., Gärtner, P., & Papenroth, R. (2007). Geomorphic evolution of small river-lake-systems in Northeast Germany during the Late Quaternary. *Earth Surface Processes and Landforms*, 32, 1516-1532.
- Kaiser, K., Lorenz, S., Germer, S., Juschus, O., Küster, M., Libra, J., Bens, O., & Hüttl, R.F. (2012). Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact – an overview. *E&G Quaternary Science Journal*, 61, 103-132.
- Kaiser, K., Küster, M., Fülling, A., Theuerkauf, M., Dietze, E., Graventein, H., Koch, P.J., Bens, O., & Brauer, A. (2014). Littoral landforms and pedosedimentary sequences indicating late Holocene lake-level changes in northern central Europe – A case study from northeastern Germany. *Geomorphology*, 216, 58-78.
- Kalicki, T. (2006). Zapis zmian klimatu oraz działalności człowieka i ich rola w holocenijskiej ewolucji dolin środkowoeuropejskich, *Prace Geograficzne*, 204. Warsaw: IGiPZ PAN.
- Keller, N. (2014). Die Entwicklung der Mittleren Havel im Spätholozän: Wasserstände und Beziehungen zur Besiedlung. Unpublished master thesis, Marburg University, Germany.

- Kersting, T. (2012). Slawen in Zauche, Teltow und Fläming. In T. Kersting, T. Langer, J. Müller & S. Pratsch (Eds.), *Ausflüge im Südwesten Brandenburgs. Zauche, Teltow, Fläming. Ausflüge zu Archäologie, Geschichte und Kultur in Deutschland*, 54 (pp. 85-97). Stuttgart: Theiss.
- Kirilova, E., Heiri, O., Enters, D., Cremer, H., Lotter, A.F., Zolitschka, B., & Hübener, T. (2009). Climate-induced changes in the trophic status of a Central European lake. *Journal of Limnology*, 68, 71-82.
- Kloss, K. (1987). Der pollenanalytische Befund an der Fundstelle des Ur-Skeletts am Schlaatz bei Potsdam. *Veröffentlichungen des Museums für Ur- und Frühgeschichte Potsdam*, 21, 65-67.
- Kristensen, T.R. (1996). En vandmølle ved cistercienserklosteret i Løgumkloster. *Hikuin*, 23, 183-190.
- Küster, H., & Pötsch, J. (1998). Ökosystemwandel in Flusslandschaften Norddeutschlands. *Berichte der Reinhold-Tüxen-Gesellschaft*, 10, 61-71.
- Küster, M., & Kaiser, K. (2010). Historische und aktuelle Gewässerentwicklung im Havel-Quellgebiet (Mecklenburg-Vorpommern). In K. Kaiser, J. Libra, B. Merz, O. Bens & R.F. Hüttl (Eds.), *Aktuelle Probleme im Wasserhaushalt von Nordostdeutschland: Trends, Ursachen, Lösungen*. Scientific Technical Report STR 10/10 (pp. 116-124). Potsdam: Deutsches GeoForschungsZentrum (GFZ).
- Lang, G. (1994). *Quartäre Vegetationsgeschichte Europas*. Stuttgart: Fischer.
- Leitholdt, E., Zielhofer, C., Berg-Hobohm, S., Schnabl, K., Kopecky-Hermanns, B., Busmann, J., Härtling, J.W., Reicherter, K., & Unger, K. (2012). *Fossa Carolina: The first attempt to bridge the central European watershed – A review, new findings, and geoarchaeological challenges*. *Geoarchaeology: An International Journal*, 27, 88-104.
- Lewin, J. (2010). Medieval environmental impacts and feedbacks: the lowland floodplains of England and Wales. *Geoarchaeology: An International Journal*, 25, 267-311.
- Lüder, B., Kirchner, G., Lücke A., & Zolitschka, B. (2006). Palaeoenvironmental reconstructions based on geochemical parameters from annually laminated sediments of Sacrower See (northeastern Germany) since the 17th Century. *Journal of Paleolimnology*, 35, 897-912.

- Lüth, P. (2011). Die Schwentine – Landschaftsarchäologie eines Flusses im ostholsteinischen Seensystem im Mittelalter. *Siedlungs- und Küstenforschung im südlichen Nordseegebiet*, 34, 181-190.
- Magny, M. (1998). Reconstruction of Holocene lake-level changes in the French Jura: methods and results. In S.P. Harrison, B. Frenzel, U. Huckriede & M.M. Weiss (Eds.), *Palaeohydrology as reflected in lake-level changes as climatic evidence for Holocene times. Paläoklimaforschung-Palaeoclimate Research*, 25 (pp. 67-85). Stuttgart/Jena: Fischer.
- Mangelsdorf, G. (1994). Die Ortswüstungen des Havellandes. Ein Beitrag zur historisch-archäologischen Wüstungskunde der Mark Brandenburg. *Veröffentlichungen der Historischen Kommission zu Berlin* 86. Berlin: de Gruyter.
- Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Michczyńska, D.J., Soja, R., Starkel, L., & Thorndycraft, V.R. (2006). Past hydrological events reflected in the Holocene fluvial record of Europe. *Catena*, 66, 145-154.
- Malliaris, M. (2000). Ausgrabungen in der Altstadt von Berlin-Köpenick. Alt-Köpenick 17-19. In J. Haspel & W. Menghin (Eds.), *Miscellaneae Archaeologica. Festgabe für Adriaan von Müller zum 70. Geburtstag. Beiträge zur Denkmalpflege in Berlin, Sonderband* (pp. 113-184). Berlin.
- Merritts, D., Walter, R., Rahnis, M., Hartranft, J., Cox, S., Gellis, A., Potter, N., Hilgartner, W., Langland, M., Manion, L., Lippincott, C., Siddiqui, S., Rehman, Z., Scheid, C., Kratz, L., Shilling, A., Jenschke, M., Datin, K., Cranmer, E., Reed, A., Matuszewski, D., Voli, M., Ohlson, E., Neugebauer, A., Ahamed, A., Neal, C., Winter, A., & Becker, S. (2011). Anthropocene streams and base-level controls from historic dams in the unglaciated mid-Atlantic region, USA. *Philosophical Transactions of the Royal Society A*, 369, 976-1009.
- Miall, A.D. (1996). *The geology of fluvial deposits. Sedimentary facies, basin analysis, and petroleum geology*. Berlin: Springer.
- Michas, U. (2011). Burg und Burgstadt Spandau um das Jahr 1000 – Neue Ausgrabungsergebnisse. In F. Biermann, T. Kersting & A. Klammt (Eds.), *Der Wandel um 1000. Beiträge zur Ur- und Frühgeschichte* 60 (pp. 35-43). Langenweissbach: Beier & Beran.

- Müller, J. (2009). Wasserbau als Infrastruktur der mittelalterlichen Planstadt – Brandenburg an der Havel. *Mitteilungen der Deutschen Gesellschaft für Archäologie des Mittelalters und der Neuzeit*, 21, 101-114.
- Needham, J. (1986). *Science and civilization in China. Volume 4, Physics and physical technology. Part 3, Civil engineering and nautics.* Taipei: Caves.
- Nützmann, G., Wolter, C., Venohr, M., & Pusch, M. (2011). Historical patterns of anthropogenic impacts on freshwaters in the Berlin-Brandenburg region. *Die Erde*, 142, 41-64.
- Oliver, S. (2013). Liquid materialities in the landscape of the Thames: mills and weirs from the eighth century to the nineteenth century. *Area*, 45, 223-229.
- Persico, L., & Meyer, G. (2009). Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming. *Quaternary Research*, 71, 340-353.
- Poepl, R.E., Keesstra, S.D., & Hein, T. (2015). The geomorphic legacy of small dams – An Austrian study. *Anthropocene*, 10, 43-55.
- Reynolds, T.S. (2002). *Stronger than a hundred men. A history of the vertical water wheel.* Baltimore and London: John Hopkins University Press.
- Rynne, C. (2015). Landscapes of hydraulic energy in medieval Europe. In A. Chavarria Arnau & A. Reynolds (Eds.), *Detecting and understanding historic landscapes* (pp. 225-252). Mantova: Societa Archaeologica.
- Rouvé, G. (1987). Die Geschichte der Talsperren in Mitteleuropa. In G. Garbrecht (Ed.), *Historische Talsperren* (pp. 298-325). Stuttgart: Wittwer.
- Sasse, B. (1987). Die spätslawische und frühdeutsche Zeit. Der archäologische Befund. In: W. Ribbe (Ed.), *Das Havelland im Mittelalter. Untersuchungen zur Strukturgeschichte einer ostelbischen Landschaft in slawischer und deutscher Zeit.* Berliner Historische Studien 13 (pp. 77-175). Berlin: Duncker & Humblot.
- Schalies, I. (2009). Wasserbaumaßnahmen im mittelalterlichen und neuzeitlichen Lübeck. *Mitteilungen der Gesellschaft für Archäologie des Mittelalters und der Neuzeit*, 21, 73-86.

- Schich, W. (1994). Die Havel als Wasserstraße im Mittelalter. Brücken, Dämme, Mühlen, Flutrinnen. Jahrbuch für brandenburgische Landesgeschichte, 45, 31-55.
- Schich, W. (2008). Die havelländische Mühle Klinke und die Frühzeit der Wassermühlen in der Mark Brandenburg. In F. Biermann, U. Müller & T. Terberger (Eds.), „Die Dinge beobachten...“: Archäologische und historische Forschungen zur frühen Geschichte Mittel- und Nordeuropas. Festschrift für Günter Mangelsdorf zum 60. Geburtstag (pp. 437-450). Rahden: Leidorf.
- Schneeweiss, J., & Schatz, T. (2014). The impact of landscape change on the significance of political centres along the lower Elbe River in the 10th century A.D. Quaternary International, 324, 20-33.
- Schnitter, N.J. (1987). Verzeichnis geschichtlicher Talsperren bis Ende des 17. Jahrhunderts. In G. Garbrecht (Ed.), Historische Talsperren (pp. 9-20). Stuttgart: Wittwer.
- Schönfelder, I., & Steinberg, C.E.W. (2004). How did the nutrient concentrations change in northeastern German lowland rivers during the last four millennia? – a paleolimnological study of floodplain sediments. Studia Quaternaria, 21, 129-138.
- Schuster, J. (2005). Archäologische Untersuchungen an der Stralauer Straße. Ein Beitrag zur mittelalterlichen Geschichte und Archäologie Berlins. In J. Haspel & W. Menghin (Eds.), Miscellanea Archaeologica II: Festschrift für Heinz Seyer. Beiträge zur Denkmalpflege 20 (pp. 186-203). Berlin.
- Schweingruber, F.H. (1978). Microscopic wood anatomy. Birmensdorf: Eidgenössische Anstalt für das forstliche Versuchswesen.
- Starkel, L. (2003). Palaeohydrology of Central Europe. In K.J. Gregory & G. Benito (Eds.), Paleohydrology, understanding global change (pp. 77-104). Chichester: Wiley.
- Starkel, L., Soja, R., & Michczynska, D.J. (2006). Past hydrological events reflected in Holocene history of Polish rivers. Catena, 66, 24-33.
- Terberger, T., de Klerk, P., Helbig, H., Kaiser, K., & Kühn, P. (2004). Late Weichselian landscape development and human settlement in Mecklenburg-Vorpommern (NE Germany). Eiszeitalter und Gegenwart, 54, 138-175.

- Tolksdorf, J.F., & Kaiser, K. (2012). Holocene aeolian dynamics in the European sand-belt as indicated by geo-chronological data. *Boreas*, 41, 408-421.
- Uhlemann, H.J. (1987). *Berlin und die Märkischen Wasserstraßen*. Berlin: Transpress.
- Vahldiek, H. (2011). *Berlin und Cölln im Mittelalter. Studien zur Gründung und Entwicklung*. Norderstedt.
- von Müller, A. (1987). Die Ausgrabungen. In A. von Müller & K. von Müller-Mučič (Eds.), *Ausgrabungen und Funde auf dem Burgwall in Berlin-Spandau. Berliner Beiträge zur Vor- und Frühgeschichte Neue Folge 15, Archäologisch-historische Forschungen in Spandau 2* (pp. 9-43). Berlin: Spiess.
- von Müller, A., & von Müller-Mučič, K. (2005). Die Entwicklung von Burg und Burgstadt Spandau im Lichte interdisziplinärer Forschungsergebnisse. In J. Haspel & W. Menghin (Eds.), *Miscellanea Archaeologica II: Festschrift für Heinz Seyer, Beiträge zur Denkmalpflege in Berlin 20* (pp. 120-131), Petersberg.
- Walter, R.C., & Merritts, D.J. (2008). Natural Streams and the legacy of water-powered mills. *Science*, 319, 299-304.
- Weiß, R. (1987). Zur Entstehung von Oberflächenformen und Sedimenten an der Fundstelle des Ur-Skeletts am Schlaatz bei Potsdam. *Veröffentlichungen des Museums für Ur- und Frühgeschichte Potsdam*, 21, 53-64.
- Weiß, R. (2003). Beiträge zur weichselkaltzeitlichen Morphogenese des Elbhave-Winkels (mit Hinweisen zur Havel- und Elbentwicklung). *Brandenburgische Umwelt-Berichte*, 14. Potsdam.
- Weiß, R. (2012). Weichselzeitliche Sedimente, Strukturen und Oberflächenformen Potsdams. In M. Menning & A. Hendrich, A. (Eds.), *Preussens Telegraphenlinie Berlin-Koblenz und Beiträge zur Geschichte und Geologie des Potsdamer Telegraphenbergs und seiner Umgebung. Telegraphenbuch III* (pp. 56-99). Potsdam: Deutsches GeoForschungsZentrum (GFZ).
- Wiegand, F.-M. (2009). Schmelzwasserrinne und Hochflutal – die Pritzerber Laake. *Brandenburger geowissenschaftliche Beiträge*, 16, 55-61.



Wolter, C., Bischoff, A., & Wysujack, K. (2005). The use of historical data to characterize fish-faunistic reference conditions for large lowland rivers in northern Germany. *Large Rivers*, 15, 37-51.

Wolters, S. (2005). Ecological effects of land cover change in medieval and modern times in northeastern Germany. Proceedings of the ESF-HOLIVAR workshop 'Climate-human society interactions during the Holocene', 9-12 May 2005 (pp. 1-5). Ånnaboda/Sweden.

Zolitschka, B., Behre, K.-E., & Schneider, J. (2003). Human and climatic impact on the environment as derived from colluvial, fluvial and lacustrine archives – examples from the Bronze Age to the Migration period, Germany. *Quaternary Science Reviews*, 22, 81-100.

## 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.

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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).

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## **Tables**

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Table II: Radiocarbon data of the sections investigated from river Havel. The calibrated  $^{14}\text{C}$  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).

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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.

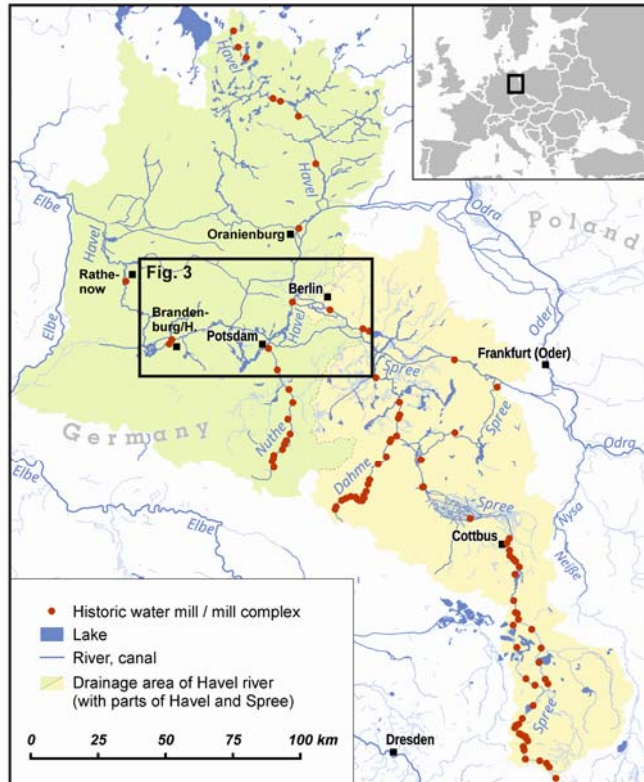


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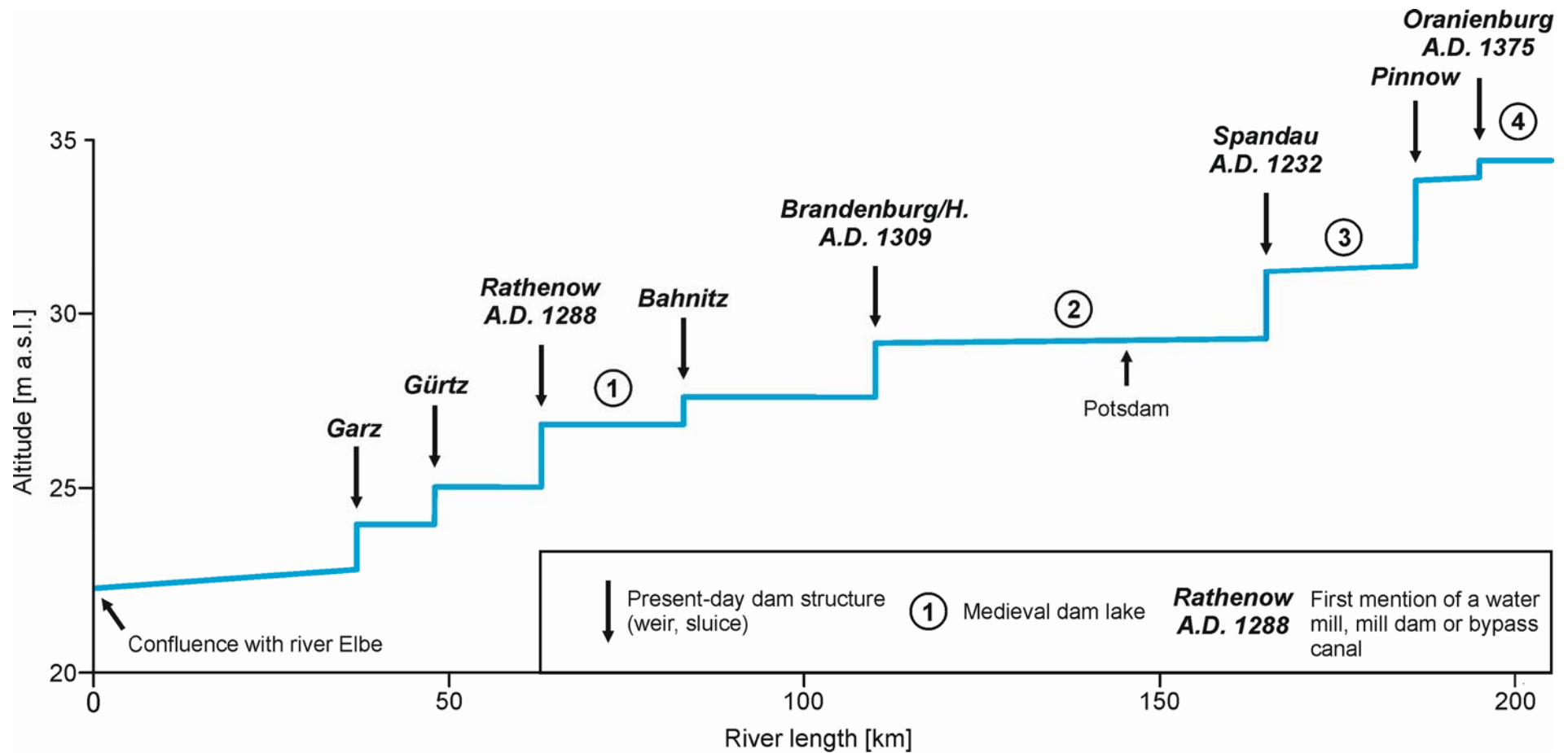
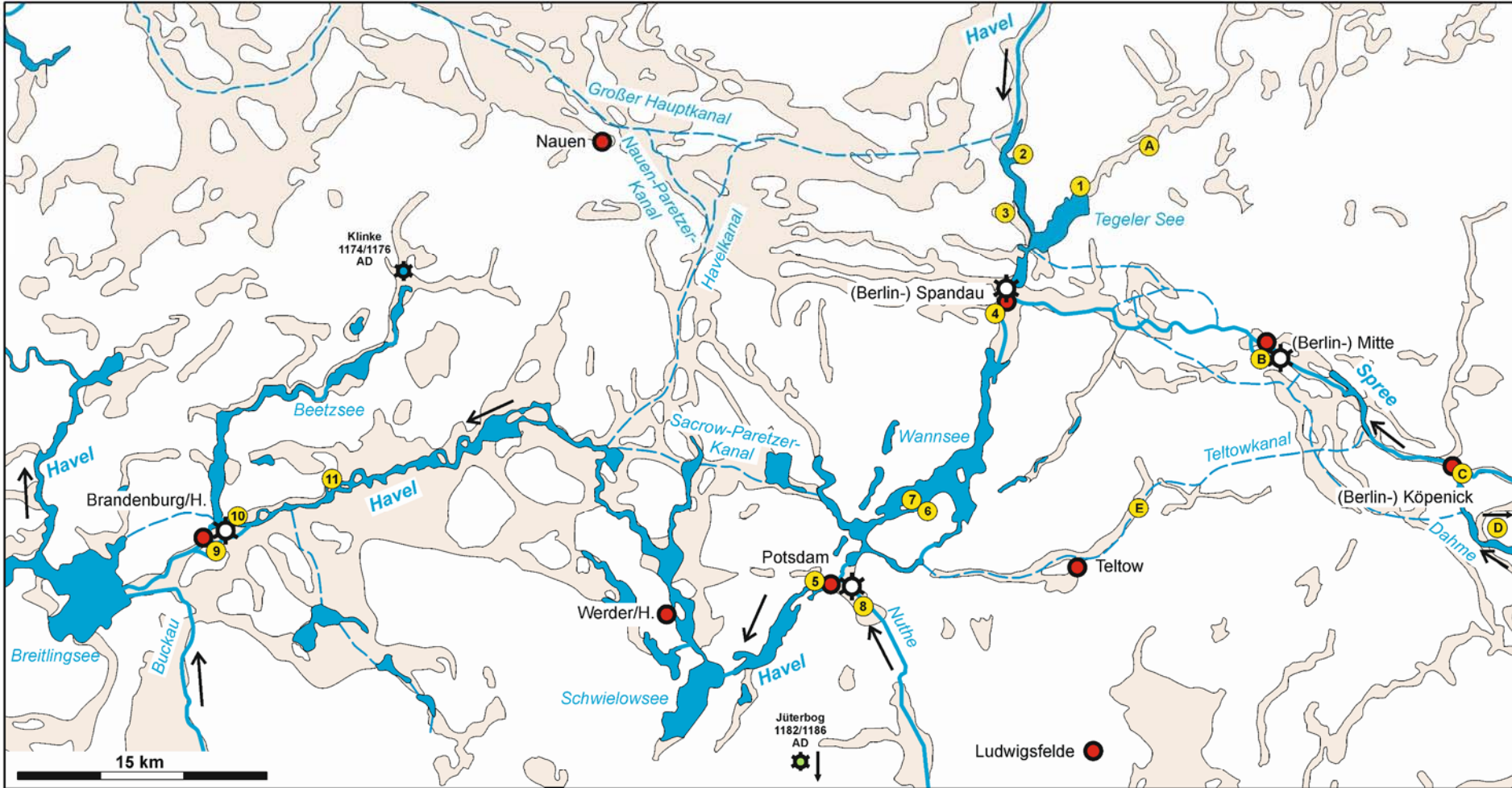


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**Legend**

- 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

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



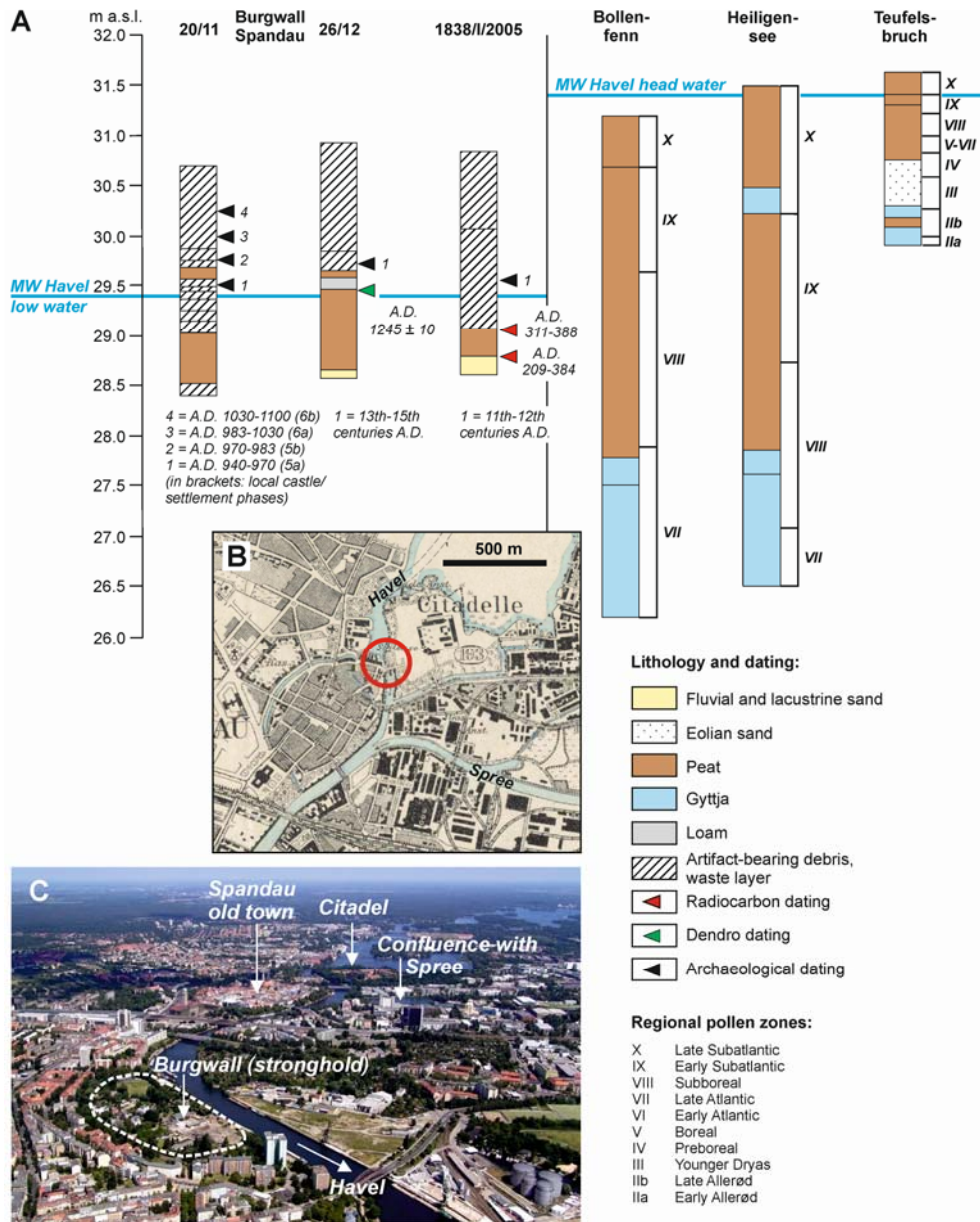
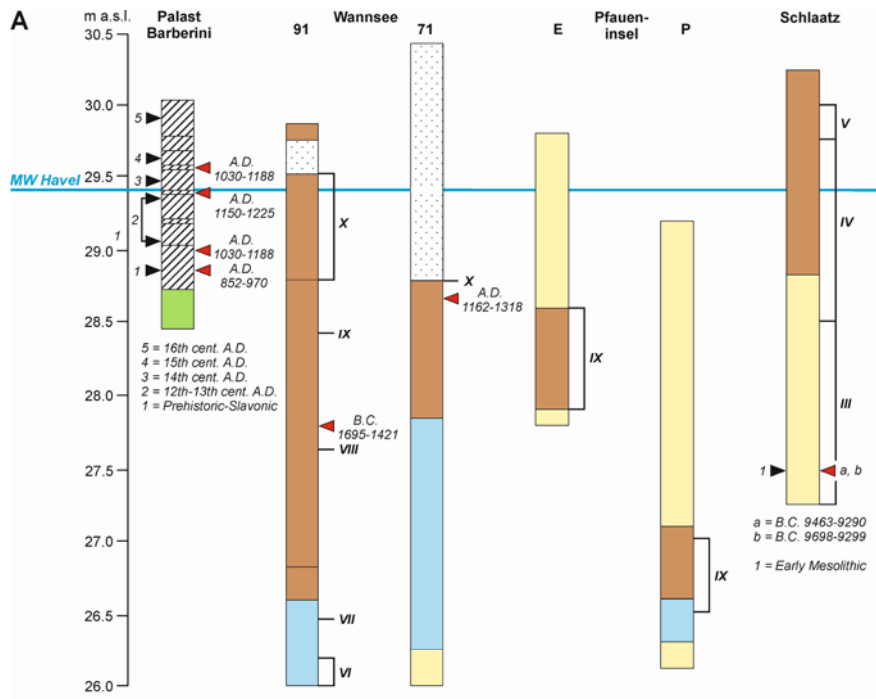


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- Lithology and dating:**
- Sandy overbank alluvium (artifact-bearing)
  - Fluvial and lacustrine sand
  - Glaciofluvial sand
  - Eolian sand
  - Peat
  - Gyttja
  - Radiocarbon dating
  - Archaeological dating

- Regional pollen zones:**
- X Late Subatlantic
  - IX Early Subatlantic
  - VIII Subboreal
  - VII Late Atlantic
  - VI Early Atlantic
  - V Boreal
  - IV Preboreal
  - III Younger Dryas

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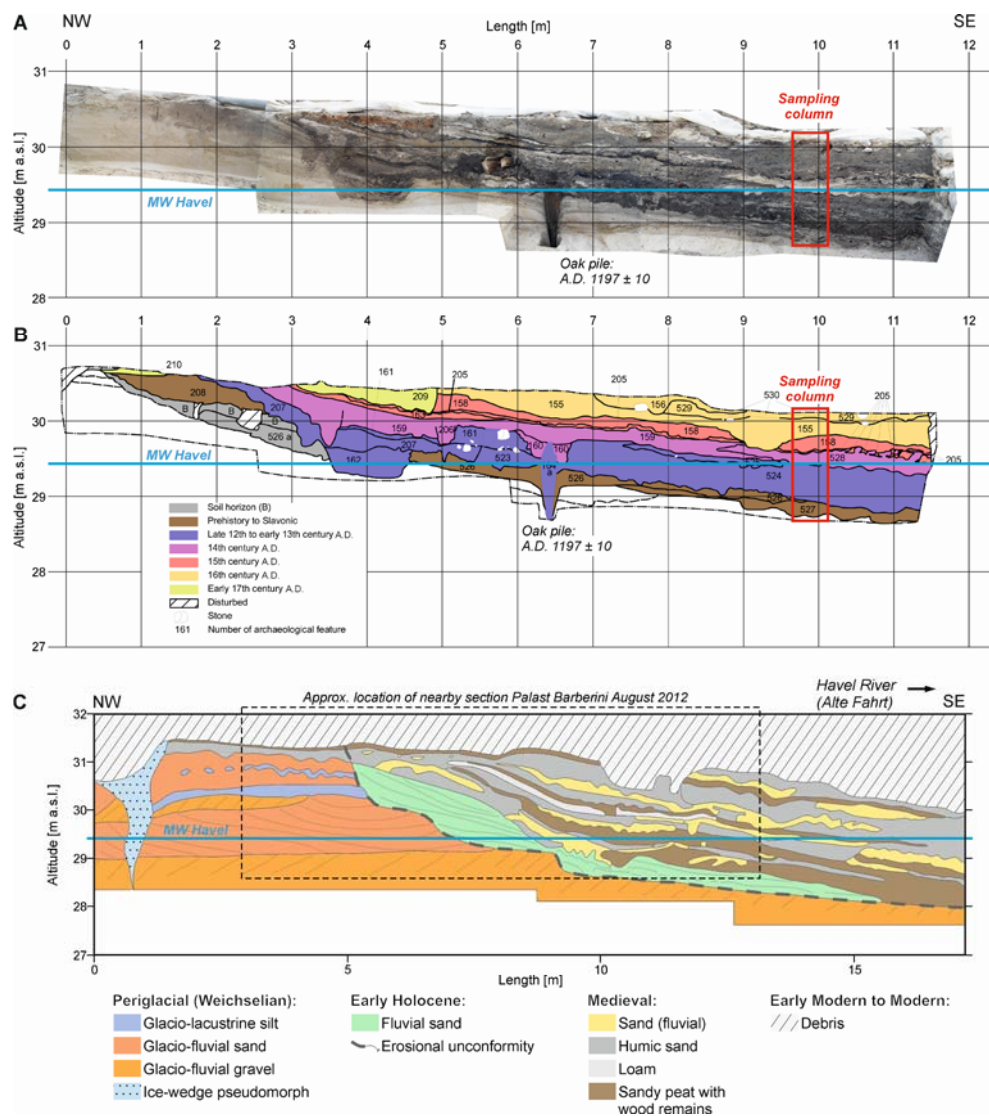


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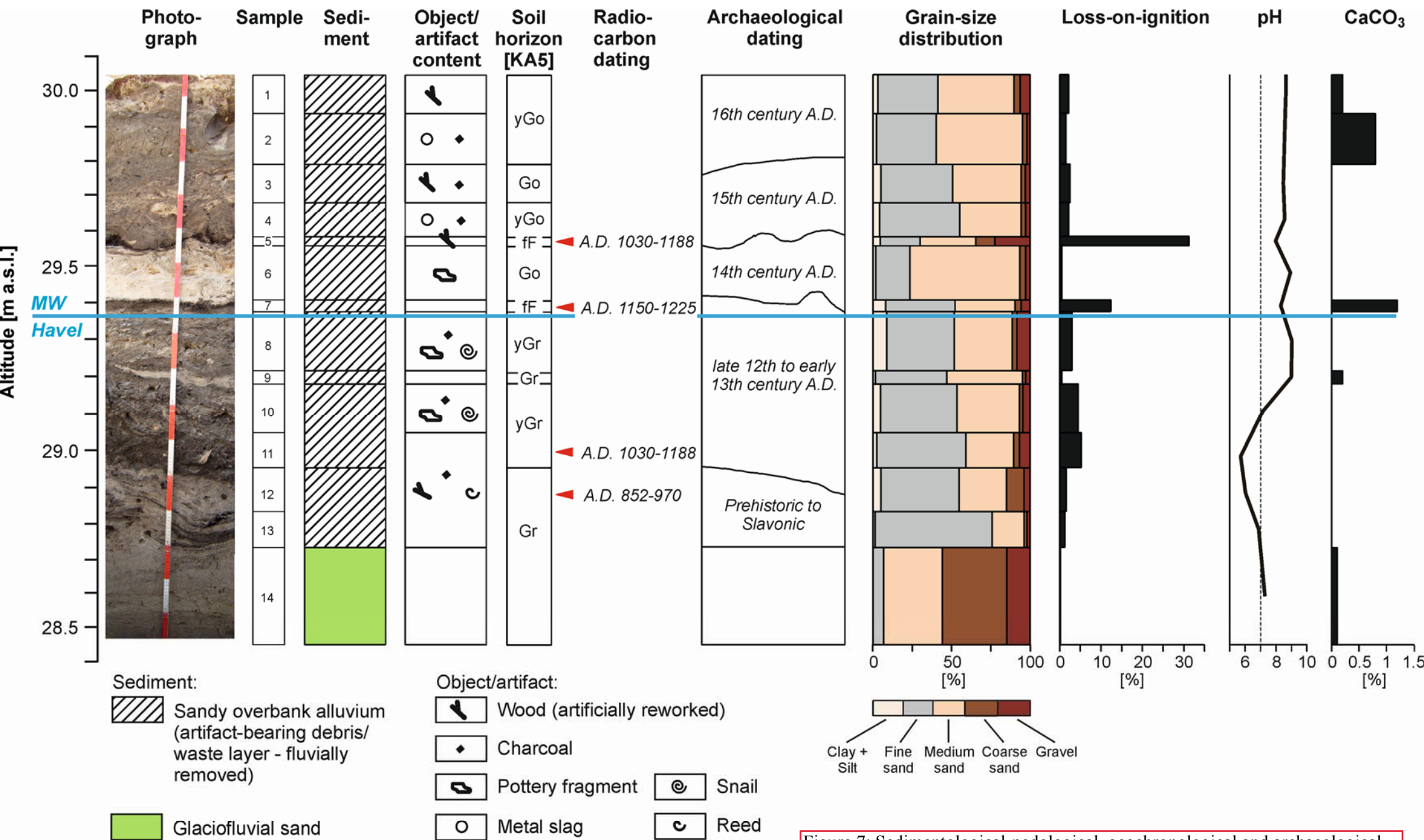


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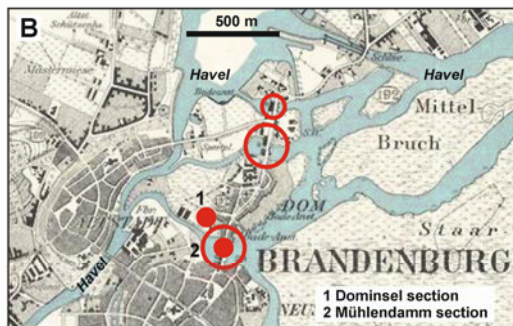
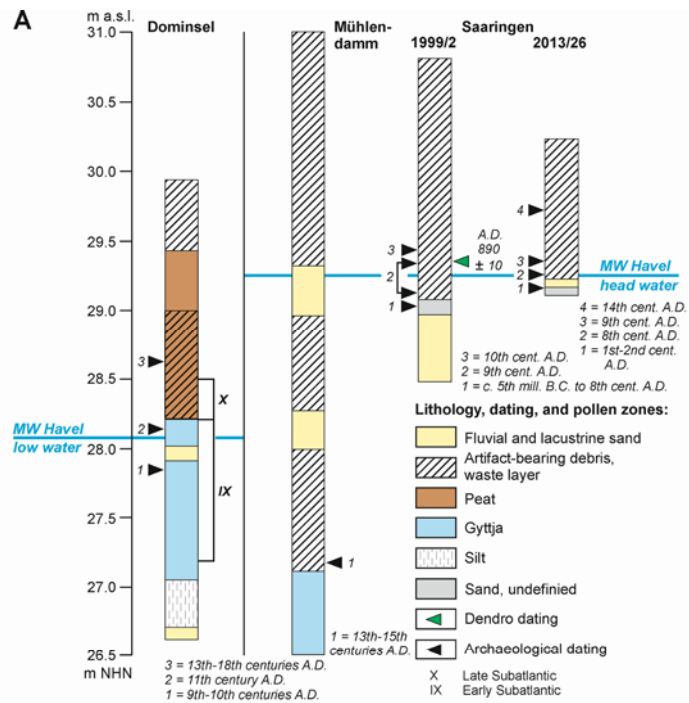


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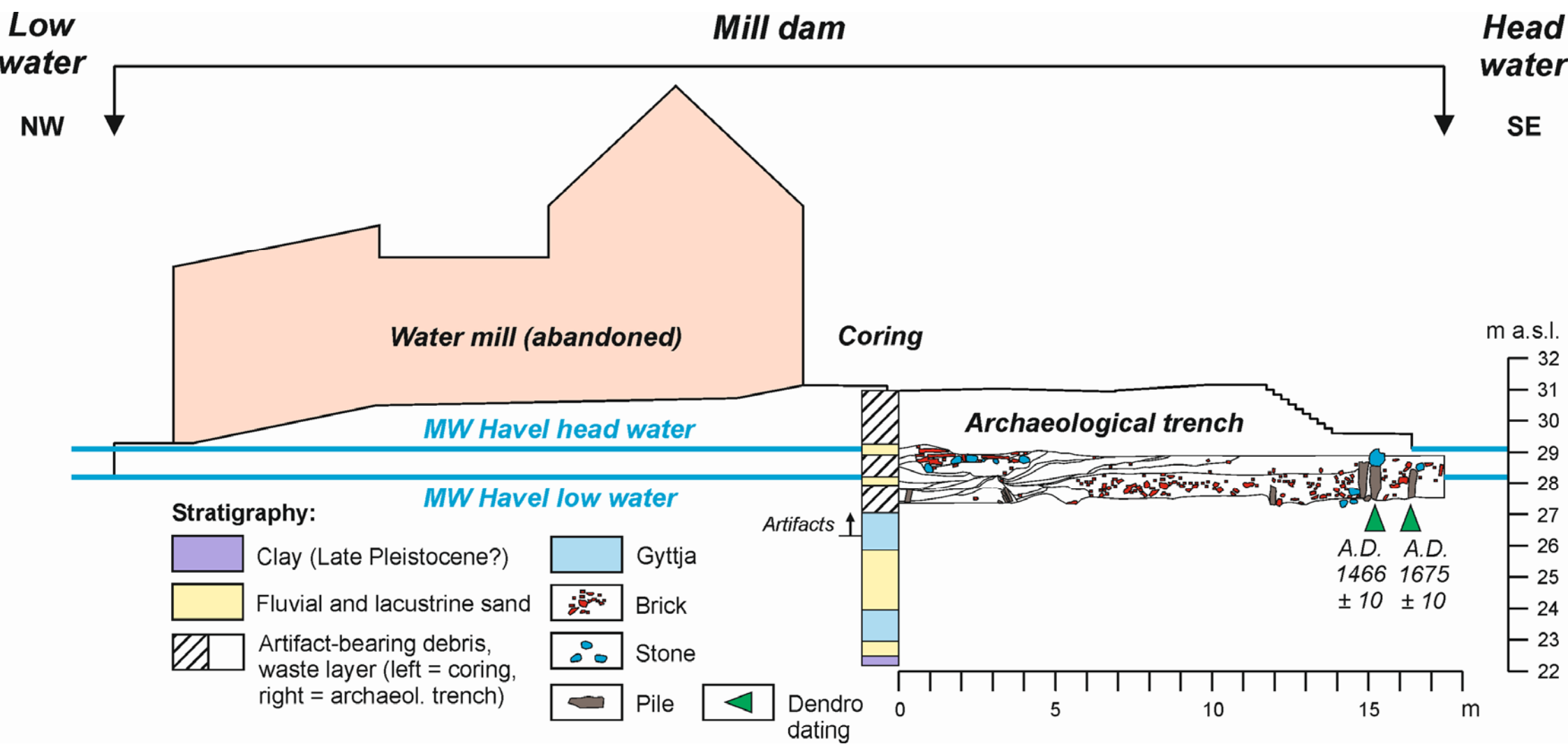


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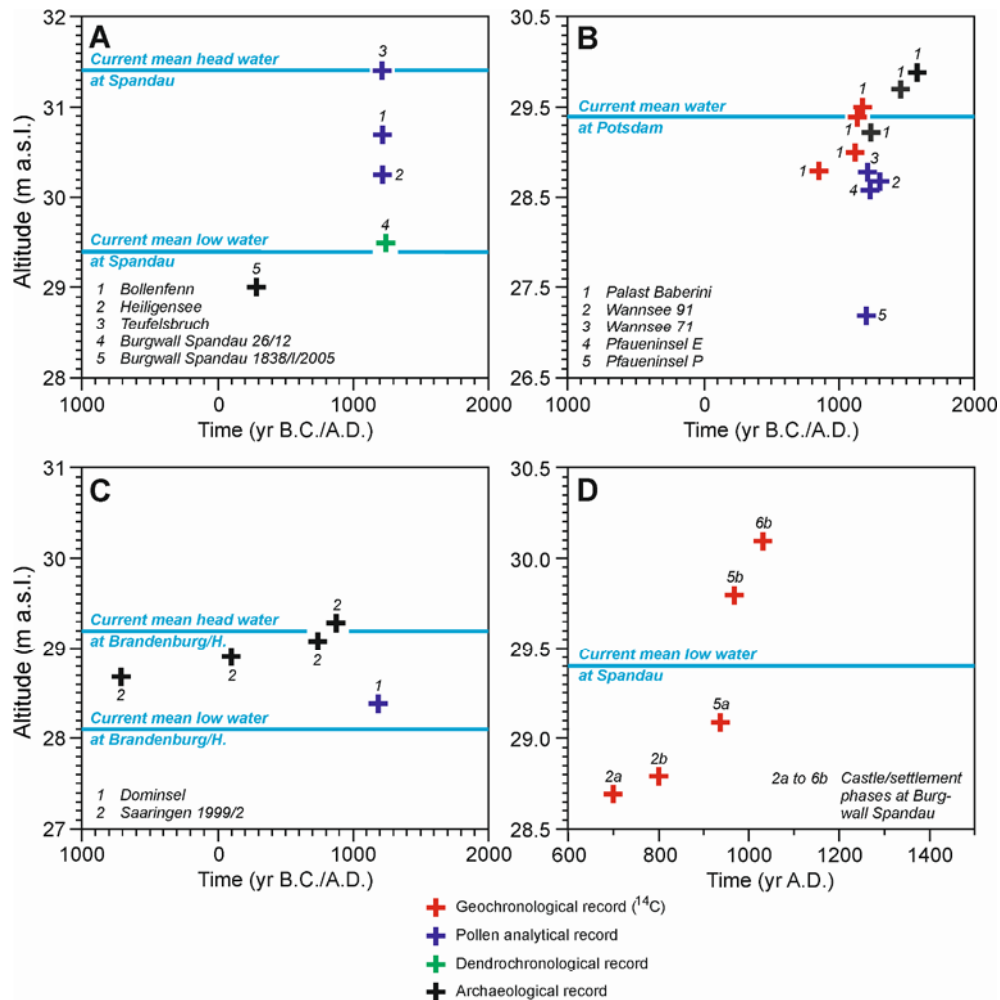


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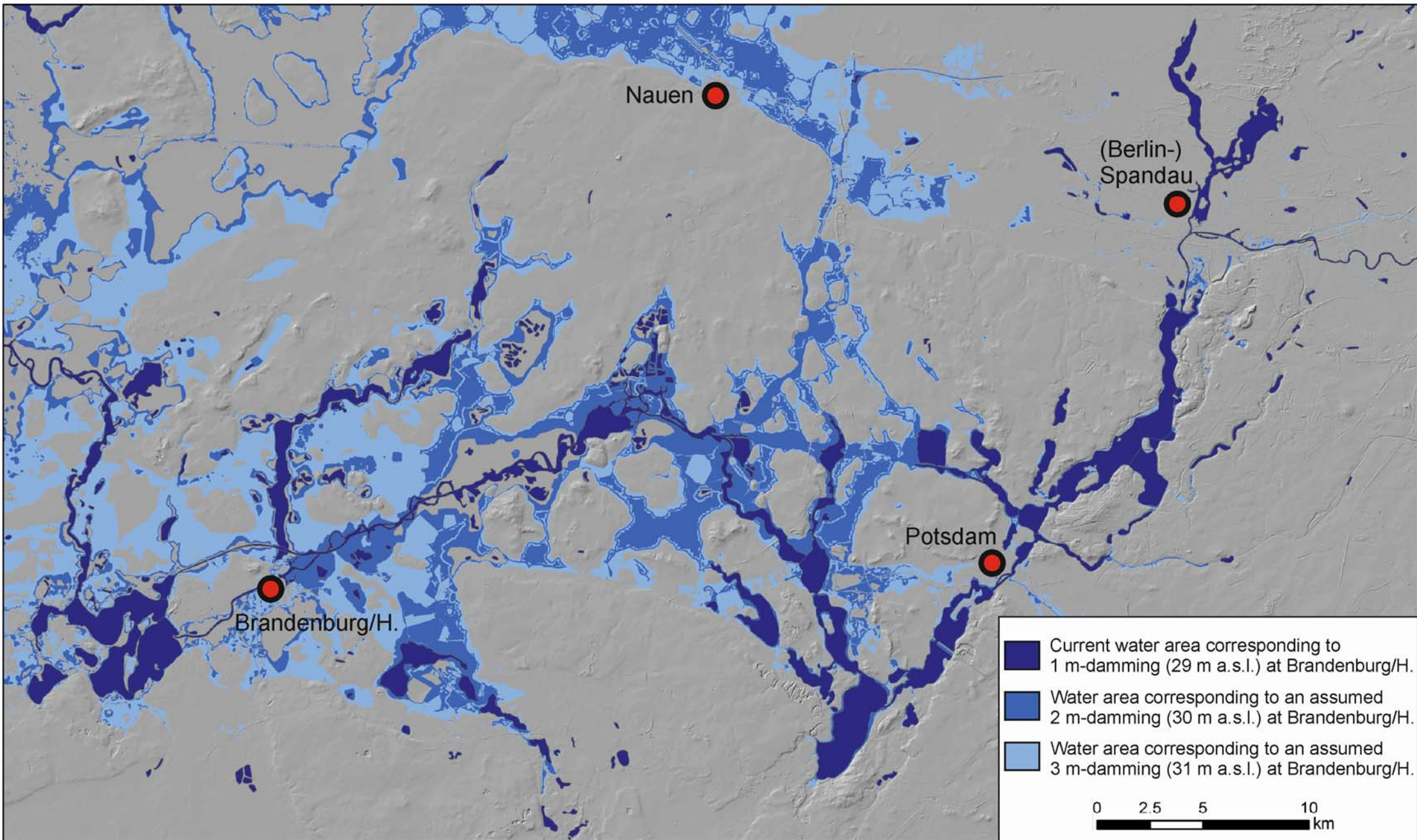


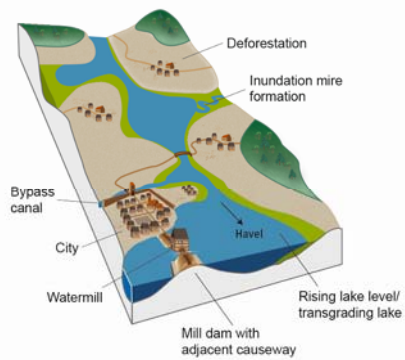
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**1 11th – 12th century A.D. (Late Slavonic Medieval)**



**2 13th – 14th century A.D. (German Medieval)**



**3 20th – 21st century A.D.**

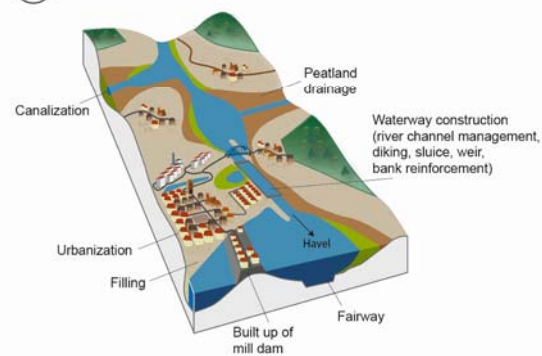


Figure 12: Conceptual model showing selected hydrological, sedimentological, ecological and settlement changes in the middle river Havel valley caused by anthropogenic impoundment (mill damming).



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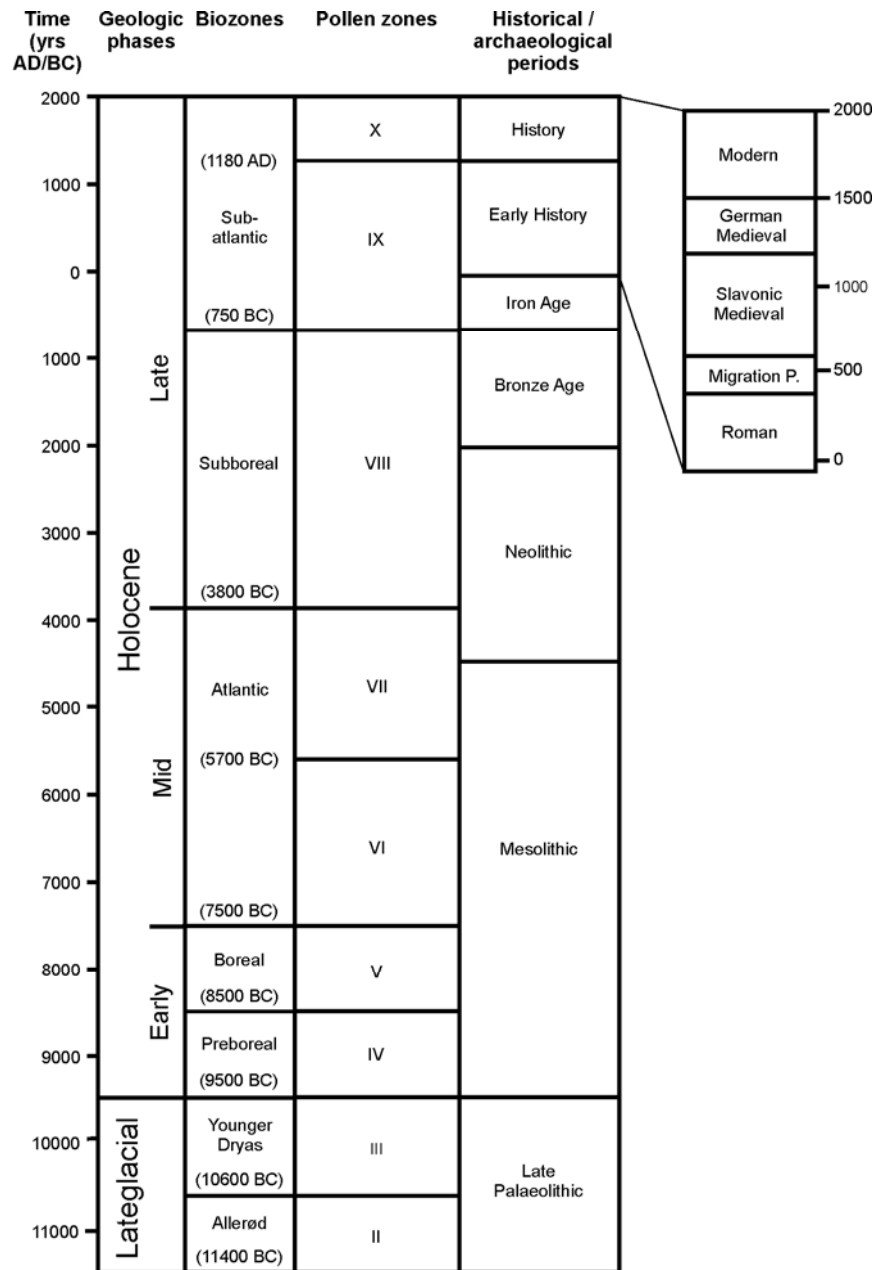
Site ID <sup>1</sup>	Section	Research context	Reference
1	Bollenfenn	Palynology	Brande, 1988
2	Heiligensee	Palynology	Brande, 1980
3	Teufelsbruch	Palynology	Brande, 1995
4	Burgwall Spandau 20/11	Archaeology	von Müller, 1987
4	Burgwall Spandau 26/12	Archaeology	this study
4	Burgwall Spandau 1838/I/2005	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
<sup>1</sup> see Figure 3			

Table II: Radiocarbon data of the sections investigated from river Havel. The calibrated  $^{14}\text{C}$  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.

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

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

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



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).

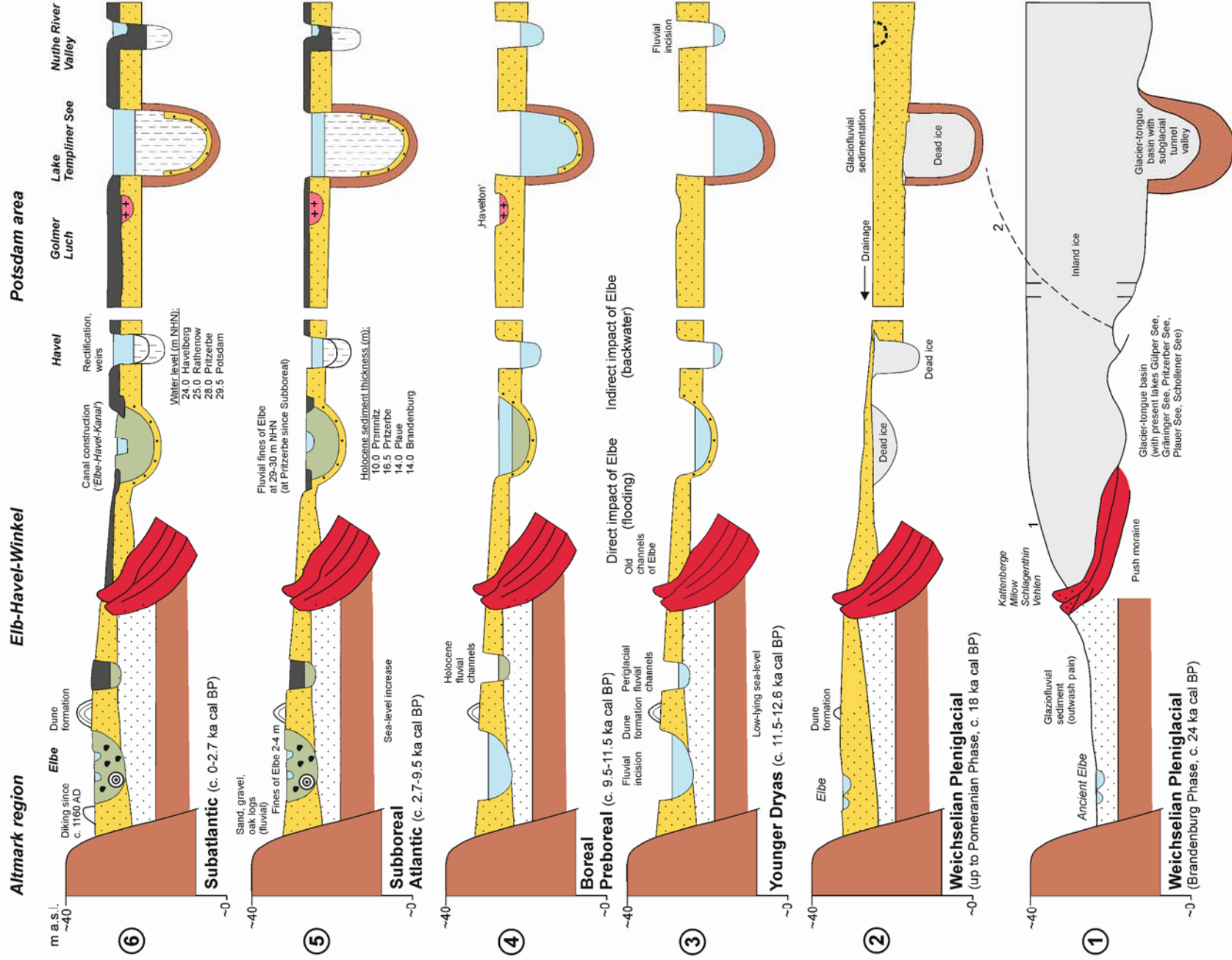
Source: Giesecke et al., 2012 (adapted)

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.

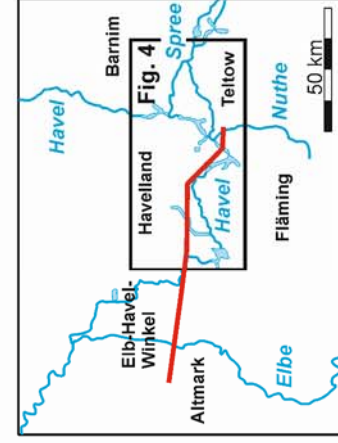
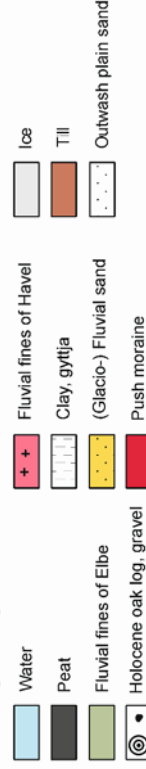
# Conceptual model of late Quaternary river valley and basin development in the Elbe-Havel region; geological cross-section (own compilation based on Weiße, 2003)

West

East

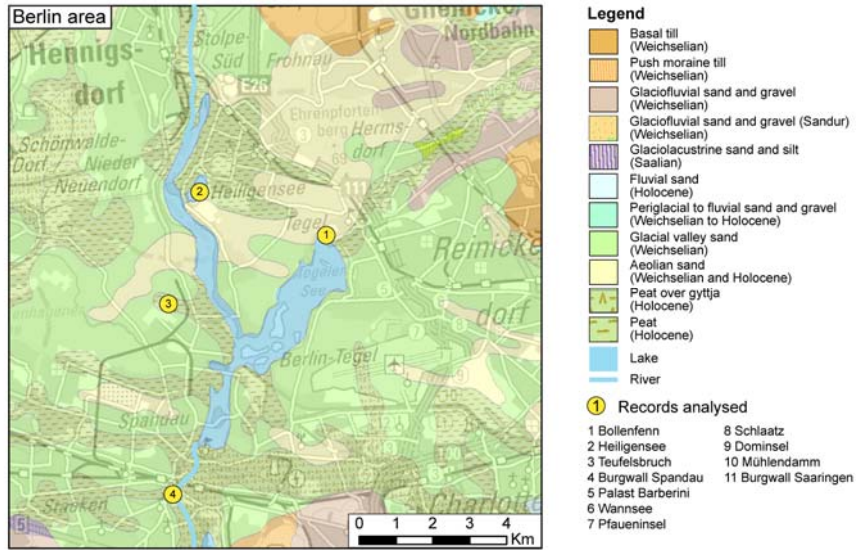


## Lithological legend

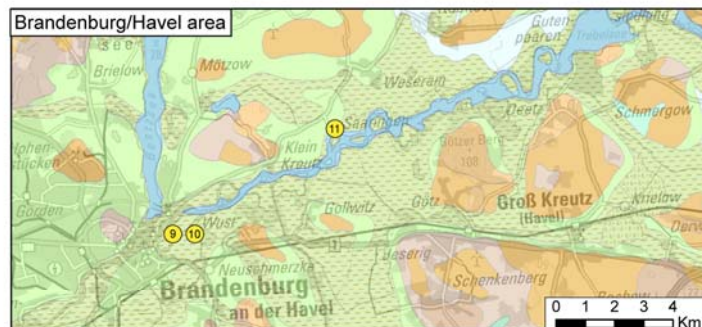
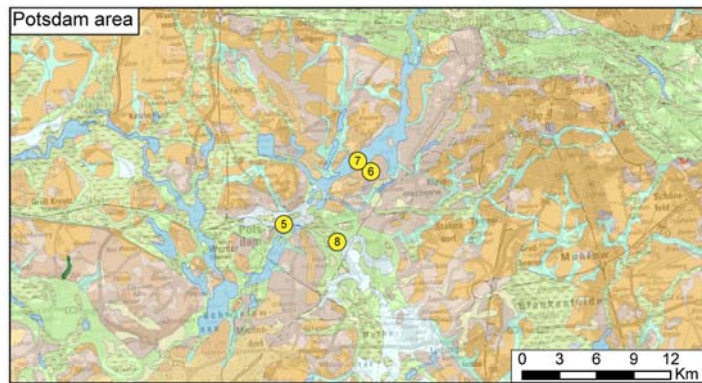


Geological cross-section displayed in the conceptual model

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

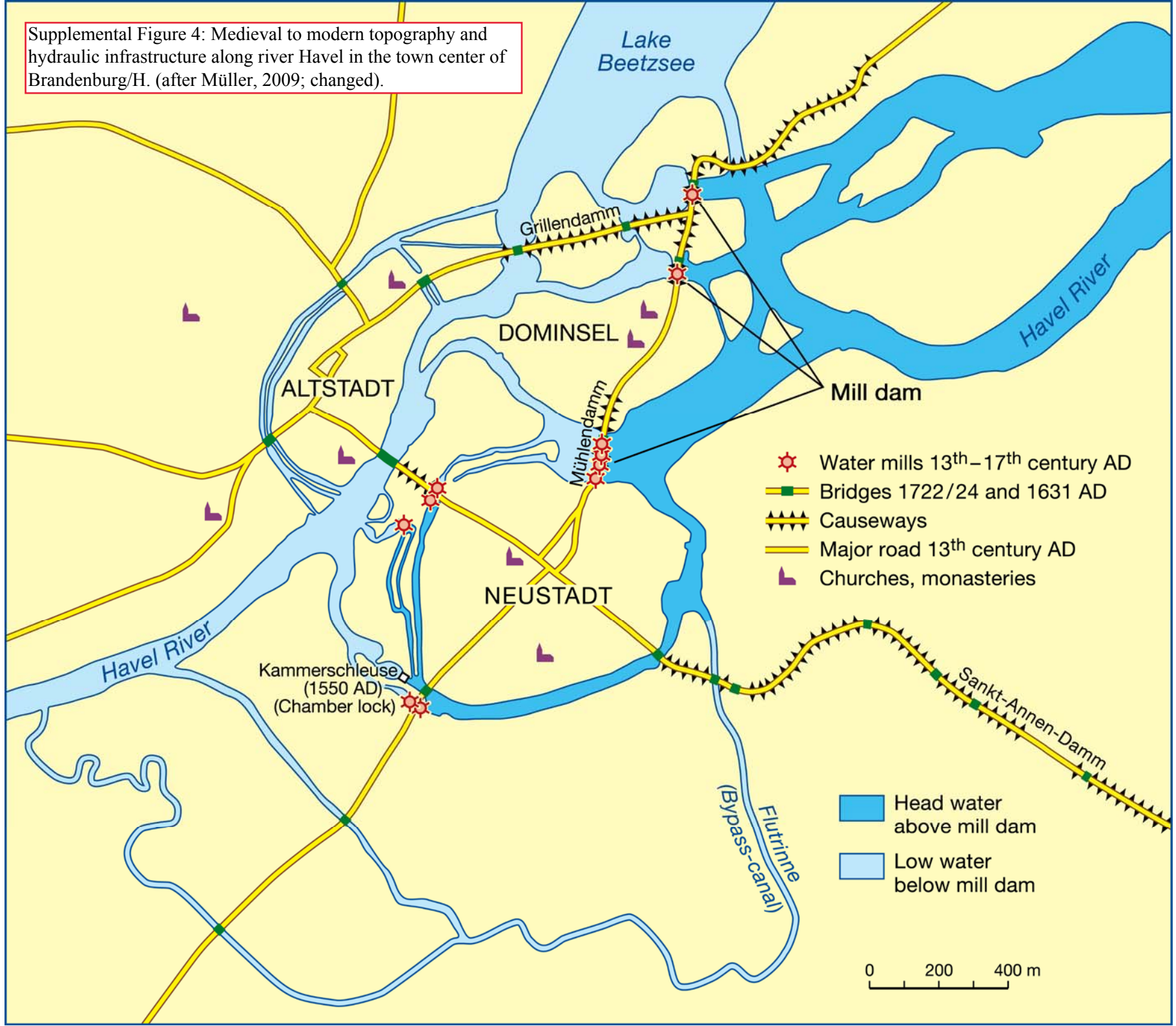


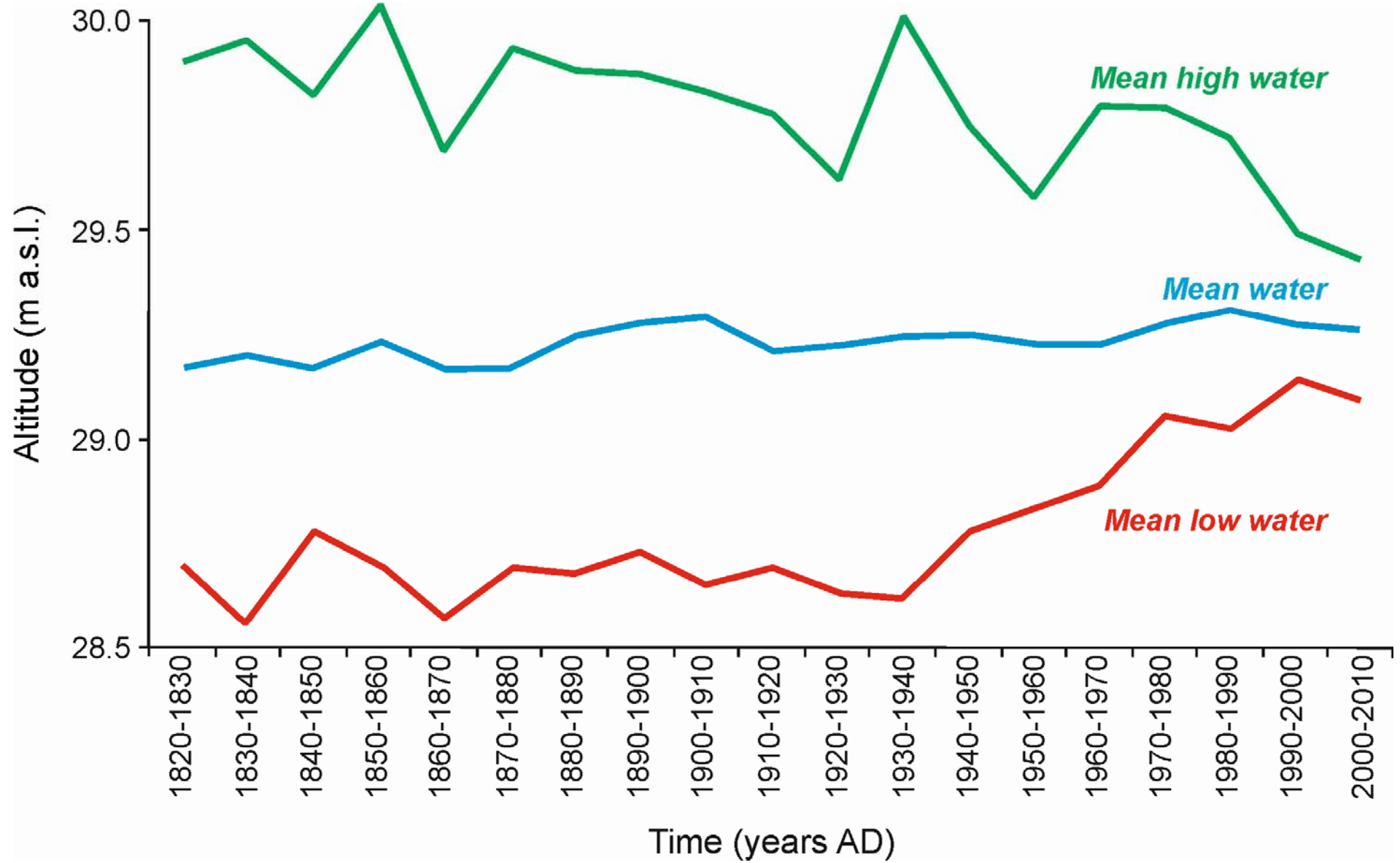
Supplemental Figure 3: Geology of the sites investigated (Geological Overview Map 1:300.000, Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg/LBGR).





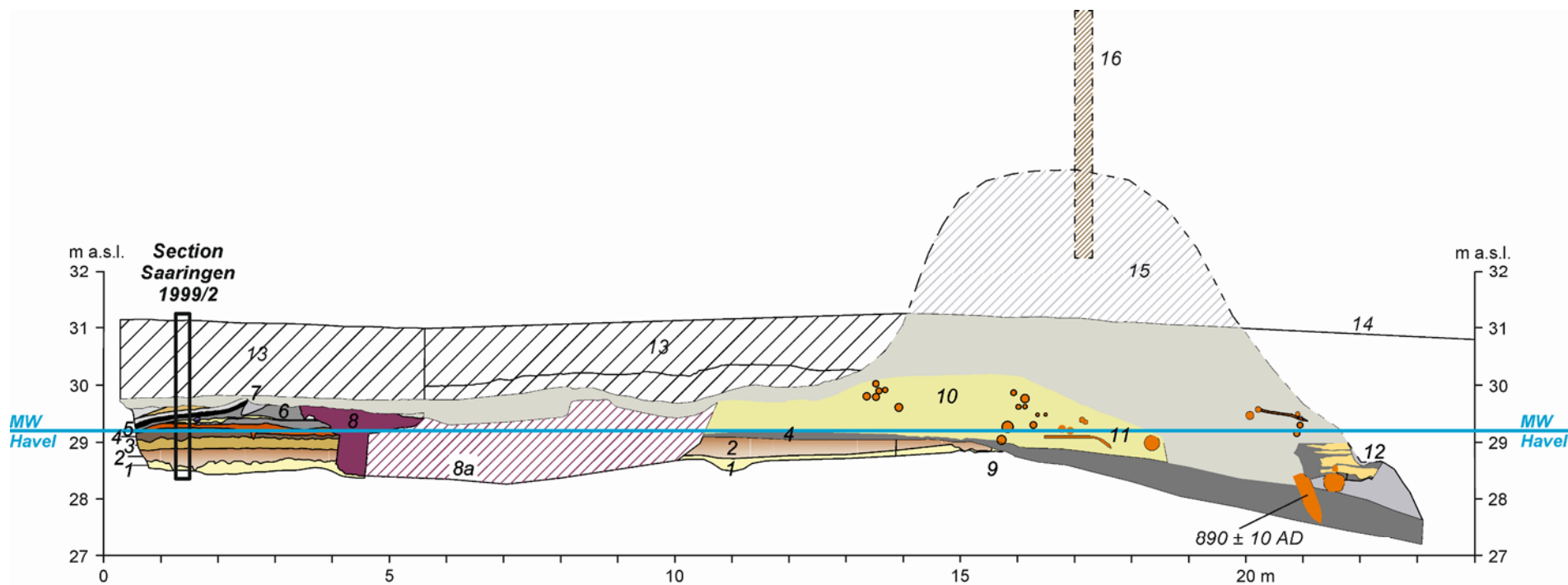
Supplemental Figure 4: Medieval to modern topography and hydraulic infrastructure along river Havel in the town center of Brandenburg/H. (after Müller, 2009; changed).





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.).





- 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

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.

Sampling	Sediment	Soil	Sample	Colour	Grain-size composition,		Grain-size composition,			Textural	Gravel	LOI	CaCO <sub>3</sub>	pH
depth	classification	horizon			total		sand fraction			class				
					Clay-Silt sum	Sand	Fine	Medium	Coarse					
					<0.002 mm - <0.063 mm	<2 mm	<0.2 mm	<0.63 mm	<2 mm		>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	2.5Yy4/2	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