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Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact – an overview

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Abstract: Knowledge of regional palaeohydrology is essential for understanding current environmental issues, such as the causes of recent hydrologic changes, impacts of land use strategies and effectiveness of wetland restoration measures. Even the interpretation of model results on future impacts of climatic and land-cover changes may be improved using (pre-)historic analogies. An overview of palaeohydrologic findings of the last c. 20,000 years is given for northeast Germany with its glacial landscapes of different age. River development is examined with a focus on valley(-floor) formation and depositional changes, river course and channel changes, and palaeodischarge/-floods. Major genetic differences exist among 'old morainic' (Elsterian, Saalian) and 'young morainic' (Weichselian) areas, and among topographically high- and low-lying valleys, the latter of which are strongly influenced by water-level changes in the North and Baltic Seas. Lake development was analysed with respect to lake formation, which was predominantly driven by late Pleistocene to early Holocene dead-ice dynamics, and with respect to depositional changes. Furthermore, lake-level changes have been in the focus, showing highly variable local records with some conformity. The overview on peatland development concentrated on phases of mire formation and on long-term groundwater dynamics. Close relationships between the development of rivers, lakes and peatlands existed particularly during the late Holocene by complex paludification processes in large river valleys. Until the late Holocene, regional hydrology was predominantly driven by climatic, geomorphic and non-anthropogenic biotic factors. Since the late Medieval times, human activities have strongly influenced the drainage pattern and the water cycle, for instance, by damming of rivers and lakes, construction of channels and dikes, and peatland cultivation. Indeed, the natural changes caused by long-term climatic and geomorphic processes have been exceeded by impacts resulting from short-term human actions in the last c. 50 years as discharge regulation, hydromelioration and formation of artificial lakes.

Die spätquartäre Entwicklung von Flüssen, Seen und Mooren in Nordostdeutschland als Spiegel klimatischer und anthropogener Einflüsse – eine Übersicht

Kurzfassung: Die Kenntnis der regionalen Paläohydrologie ist eine wesentliche Grundlage für das Verständnis aktueller Umweltfragen, wie zum Beispiel nach den Gründen von hydrologischen Veränderungen, dem Einfluss von Landnutzungsstrategien und der Wirksamkeit von Renaturierungsvorhaben in Feuchtgebieten. Auch die Interpretation von Modellierungsergebnissen zu den künftigen Einflüssen des Klima- und Landnutzungswandels auf das Gewässersystem kann durch die Einbeziehung (prä-) historischer Analogien verbessert werden. Für das glazial geprägte nordostdeutsche Tiefland wurde eine Übersicht der vorliegenden paläohydrologischen Befunde für den Zeitraum der letzten etwa 20.000 Jahre erarbeitet. Die Entwicklung der Flüsse wurde mit Blick auf die Tal-/Auengenese und das Ablagerungsmilieu, die Veränderung des Tal- und Gerinneverlaufs sowie den Paläoabfluss bzw. das Paläohochwasser betrachtet. Wesentliche genetische Unterschiede bestehen zwischen Alt- (Elster- und Saalekaltzeit) und Jungmoränengebieten (Weichselkaltzeit) sowie zwischen hoch und tief gelegenen Tälern. Letztere sind stark durch Wasserspiegelveränderungen in der Nord- und Ostsee beeinflusst worden. Die Entwicklung der Seen wurde hinsichtlich der Seebildung, die überwiegend eine Folge der spätpleistozänen bis frühholozänen Toteistieftau-Dynamik ist, und der Veränderungen im Ablagerungsmilieu analysiert. Weiterhin standen Seespiegelveränderungen im Fokus, wobei sich hoch variable lokale Befunde mit einigen Übereinstimmungen zeigten. Der Überblick zur Moorentwicklung konzentrierte sich auf hydrogenetische Moorentwicklungsphasen und auf die langfristige Entwicklung des Grundwasserspiegels. Enge Beziehungen zwischen der Entwicklung der Flüsse, Seen und Moore bestanden insbesondere im Spätholozän durch komplexe Vermoorungsprozesse in den großen Flusstälern. Bis in das Spätholozän wurde die regionale Hydrologie überwiegend durch klimatische, geomorphologische und nicht-anthropogene biologische Faktoren gesteuert. Seit dem Spätmittelalter wurde in der Region das Gewässernetz und der Wasserkreislauf im starken Maß durch anthropogene Interventionen beeinflusst (z.B. Aufstau von Flüssen und Seen, Bau von Kanälen und Deichen, Moorkultivierung). In den letzten etwa 50 Jahren haben dann sogar die kurzfristigen anthropogenen Eingriffe, z.B. in Form von Abflussregulierung, Hydromelioration und künstlicher Seebildung, die Wirksamkeit langfristiger klimatischer und geomorphologischer Prozesse übertroffen.

Keywords: *palaeohydrology, valley formation, depositional change, lake- and groundwater-level fluctuation, mire, late Pleistocene, Holocene*

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1 Introduction

Global climate change causes regional and local variations in the terrestrial water balance (e.g. Tao et al. 2003, IPCC 2007, Bates et al. 2008, Gerten et al. 2008, Kundzewicz et al. 2008, Huang et al. 2010), influencing the hydrologic, geomorphic and ecologic properties of the regional drainage system comprised of flowing (rivers, streams) and stagnant waters (lakes, ponds) as well as peatlands of varying dimension. An aridification trend, for example, will inevitably cause a reduction (1) in the discharge of rivers by diminishing supply, (2) in the size of lakes by level lowering and (3) in the extension of peatlands by groundwater lowering.

As hydrologic and climatic research in Europe shows, there are currently distinct changes in water balances with regionally differing trends (e.g. Lehner et al. 2006, BACC Author Team 2008, EEA 2009, Merz et al. 2012). In northeast Germany widely a 'drying' trend prevails, resulting in decreasing groundwater and lake levels as well as river discharges (e.g. Gerstengarbe et al. 2003, Kaiser et al. 2010, 2012a, Germer et al. 2011). If this trend continues, a negative influence on ecosystem services, such as the provision of water for human use and wetland conservation, is to be feared.

Undoubtedly, the knowledge of both historic hydrologic (last c. 1000 years) and palaeohydrologic developments can help us to understand the hydrologic system dynamics at present and even in the future (e.g. Branson et al. 1996, Gregory & Benito 2003, Brázdil et al., 2006, Gregory et al. 2006, Czymzik et al. 2010). In particular, the frequency and magnitude of short-term events, such as river floods and droughts, as well as long-term processes, such as lake-level fluctuations, changes in the river's mean annual discharge and its hydromorphologic status can be detected retrospectively (e.g. Petts et al. 1989, Berglund et al. 1996a, Harrison et al. 1998, Brown 2002, Starkel 2005, Baker 2008, Battarbee 2010). Insights gained through such historic analogies can be used to improve the interpretation of modelled future impacts of climatic and land-cover changes and, hence, to develop and optimise adaptation strategies. Furthermore, information on the pre-modern ecologic status of aquatic landscapes is a precondition for developing restoration measures in accordance with the European Union Water Framework Directive (CEC 2000, Bennion & Battarbee 2007, Zerbe & Wiegleb 2009).

In theory, palaeohydrology is concerned with all components of the hydrologic cycle. But in practice most research focuses on specific compartments, such as river channels and discharge, lake- and groundwater-level fluctuations, isotope chemistry, or on proxy indicators of past precipitation characteristics (Anthony & Wohl 1998, Gregory & Benito 2003). Such knowledge on the palaeohydrology of temperate regions in the world is well-established. Particularly western and central Europe have a long-standing research tradition (e.g. Starkel et al. 1991, Gregory 1995, Hagedorn 1995, Vandenberghe 1995a, Starkel 2003, Macklin et al. 2006, Hoffmann et al. 2008). However, stronger integration between the regional findings as well as with related disciplines is necessary.

In northeast Germany, there are well-structured scientific communities dealing with both present-day and future hydrologic changes (investigated by hydrologists and climate impact researchers) as well as with palaeohydrology (investigated by geoscientists and palaeoecologists). Unfortunately joint investigations by both communities are lacking. In addition, existing palaeohydrologic knowledge is not sufficiently being considered in the interpretation of (pre-)recent hydrologic trends and prospective (modelling) purposes. Obstacles to the exploitation of hydrologic palaeo-data are the multitude of local case studies, and their prevailing publication in German periodicals and monographs with a regional or national focus. Publications synthesising regional paleohydrologic results are rare.

This overview offers access on the results of regional palaeohydrologic research over the last c. two decades. The consolidation of findings into one paper will hopefully foster the consideration of (pre-)historic hydrologic changes into the respective discussions, increasing the interpretational power for modelling results. This paper primarily focuses on the evolution of drainage systems during the last c. 20,000 years, spanning the late Pleistocene and the Holocene epochs. The long-term and partly interdependent development of the region's main aquatic *inland* environments – rivers, lakes and peatlands – will be outlined. For several specific issues (e.g. river valley formation, palaeodischarge characteristics, dead-ice dynamics, lake- and groundwater-level changes, peatland formation), the state-of-the-art will be reported.

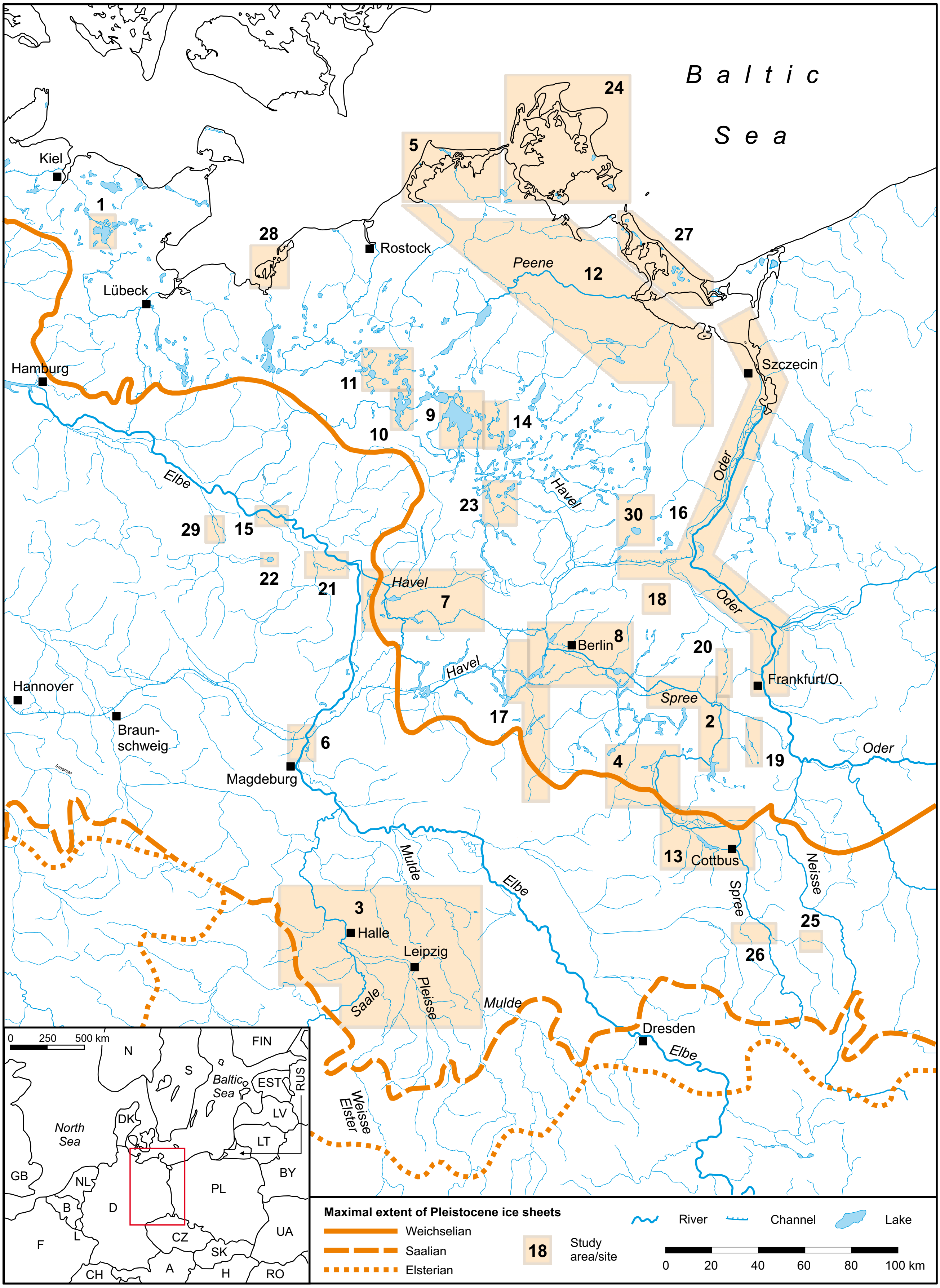

Fig. 1: Hydrography, main glacial structures and study areas/sites with palaeohydrologic findings in northeast Germany (map after BMUNR 2003, adapted). The numbers refer to the study areas/sites presented (see Tab. 1).

Abb. 1: Hydrografie, glaziale Hauptstrukturen (Marginalzonen) und Arbeitsgebiete/-orte mit paläohydrologischen Befunden in Nordostdeutschland (Karte nach BMUNR 2003, verändert). Die Zahlen beziehen sich auf die vorgestellten Arbeitsgebiete/-orte (siehe Tab. 1).

Tab. 1: Study areas and sites with palaeohydrologic findings in northeast Germany (see Fig. 1).

Tab. 1: Arbeitsgebiete und -orte mit paläohydrologischen Befunden in Nordostdeutschland (siehe Abb. 1).

No.	Study area / site	Research field[1]	References
1	Lake Plöner See	LB, LL, NT, GA, PL, PE	Sirocko et al. 2002, Dörfler 2009
2	Lower Spree River	FM, PD, PE	Schulz & Strahl 1997, Schulz 2000, Schönfelder & Steinberg 2004, Hilt et al. 2008
3	Leipzig-Halle area	LB, LL, GA, PL, FM, PE, GG, HI	Hiller et al. 1991, Mania et al. 1993, Wolf et al. 1994, Mol 1995, Böttger et al. 1998, Fuhrmann 1999, Tinapp et al. 2000, 2008, Eissmann 2002, Wennrich et al. 2005, Czegka et al. 2008
4	Lower Spree River, lower Spreewald area and Dahme River	FM, LB, PE, GG	Böttner 1999, Juschus 2002, 2003
5	Darss peninsula, Barthe River and Endinger Bruch basin	LB, LL, GA, PL, FM, PT, CE, PE	Kaiser 2001, 2004a, de Klerk 2002, Kaiser et al. 2000, 2006, 2007, Lampe 2002, Lane et al. 2012
6	Elbe River N of Magdeburg	FM, HI	Rommel 1998
7	Lower Havel River, Elb-Havel-Winkel and Rhinluch/Havelländisches Luch areas	PT, GG, PE, GA, LL, GW, PL, HI	Mundel et al. 1983, Kloss 1987a, 1987b, Mundel 1995, 1996, 2002, Schelski 1997, Küster & Pötsch 1998, Rowinsky & Rutter 1999, Gudermann 2000, Mathews 2000, Zeitz 2001, Gramsch 2000, Kaffke 2002, Weisse 2003, Schönfelder & Steinberg 2004
8	Berlin area	LB, LL, GW, GA, PL, FM, PE, GG, PT, HI	Böse & Brande 1986, 2009, Pachur & Röper 1987, Brande 1986, 1988, 1996, Gärtner 1993, Schich 1994, Uhlemann 1994, Varlemann 2002, Grünert 2003, Kossler 2010, Neugebauer et al. 2012
9	Lake Müritz	LL, PL, PE, HI	Kaiser 1998, Kaiser et al. 2002, Ruchhöft 2002, Lampe et al. 2009
10	Lake Plauer See	LL, GA, HI	Ruchhöft 2002, Bleile et al. 2006, Bleile 2008
11	Nossentiner/Schwinzer Heide area	LB, LL, PE, PL, FM, HI	Schmidtchen et al. 2003, Lorenz 2003, Rother 2003, Hübener & Dörfler 2004, Lorenz & Schult 2004, Kaiser et al. 2007, Lorenz 2007, 2008, Lorenz et al. 2010
12	Low-lying river valleys of Vorpommern (e.g. Recknitz, Peene and Uecker River)	FM, LB, LL, GW, PE, GG, CE, PT, GA, HI	Kaiser & Janke 1998, Helbig 1999, Kaiser et al. 2000, 2003, Michaelis 2000, Schatz 2000, Helbig & de Klerk 2002, Janke 2002, 2004, de Klerk 2004, Kaiser 2004b, Berg 2005, Krienke et al. 2006, Michaelis & Joosten 2010, Jantzen et al. 2011, Küster et al. 2011
13	Upper Spreewald and Cottbus areas	FM, GA, GG, PE, PT, HI	Kühner et al. 1999, Neubauer-Saurer 1999, Rolland & Arnold 2002, Woithe 2003, Poppschötz & Strahl 2004, Brande et al. 2007
14	Headwaters of Havel River	LB, LL, PE, PL, FM, HI	Kaiser & Zimmermann 1994, Küster 2009, Küster & Kaiser 2010, Küster et al. 2012
15	Lower Elbe River at Lenzen	FM, HI, GA	Schwartz 1999, Schatz 2011
16	Lower Oder River, Oderbruch area, Stettiner Haff (Szczecin Lagoon), Eberswalder Urstromtal (spillway)	FM, GG, PL, PE, CE, PT, PD, HI	Dobracka 1983, Brose 1994, 1998, Schlaak et al. 2003, Borówka et al. 2005, Carls 2005, Dalchow & Kiesel 2005, Schlaak 2005, Lutze et al. 2006, Börner 2007
17	Potsdam area, Havel and Nuthe Rivers	LB, GW, PL, FM, PE, GG, PT, HI	Rowinsky 1995, Weisse et al. 2001, Wolters 2002, 2005, Hickisch 2004, Hickisch & Päzolt 2005, Lüder et al. 2006, Kirilova et al. 2009, Enters et al. 2010
18	Biesenthal Basin, upper Finow Stream	LB, PE, GG	Chrobok & Nitz 1987, 1995, Nitz et al. 1995
19	Schlaube Stream	PL, LB, PE	Schönfelder et al. 1999, Brose 2000, Giesecke 2000
20	Kersdorfer Rinne (tunnel valley)	LB, GG, PE	Schulz & Brose 2000, Schulz & Strahl 2001
21	Wische area (lower Elbe River)	FM	Caspers 2000
22	Lake Arendsee	PL, PE, HI	Scharf 1998, Scharf et al. 2009
23	Lake Stechlinsee, Upper Rhin River	LB, FM, PL, PE	Gärtner 2007, Brande 2003, Kaiser et al. 2007
24	Rügen Island and adjacent coastal and land areas	LB, GW, NT, GA, PL, PE, GG, PE, GG, CE, PT	Kliewe 1989, Strahl & Keding 1996, Helbig 1999, de Klerk et al. 2001, Krienke 2003, Verse 2003, Hoffmann & Barnasch 2005, Hoffmann et al. 2005, de Klerk et al. 2008a, 2008b, Kossler & Strahl 2011
25	Weisser Schöps River (Reichwalde area)	FM, PT, GW, GA, PE	Friedrich et al. 2001, van der Kroft et al. 2002
26	Upper Spree River (Nochten/Scheibe area)	FM, GG	Mol 1997, Mol et al. 2000, Hiller et al. 2004
27	Usedom Island	LB, NT, PL, PE, GG, CE	Helbig 1999, Hoffmann et al. 2005
28	Poel Island and adjacent coastal and land areas	CE, NT, PE, GA, CE	Lampe et al. 2005, 2010
29	Jeetzel River	FM, PE, GA	Turner 2012
30	Schorfheide area	LB, PE, PT	Schlaak 1997, Stegmann 2005, van der Linden et al. 2008

[1]LB = Lake-basin formation, LL = Lake level, GW = Groundwater level, NT = Neotectonic, GA = Geoarchaeology, PL = Palaeolimnology, FM = Fluvial geomorphology / valley formation, PD = Palaeodischarge, PE = Palaeoecology, GG = Glacial geomorphology / geology, CE = Coastal evolution, PT = Peatland evolution, HI = Human impact on inland waters

Chronology	**Phases of river valley genesis** [Marcinek & Brose 1972]	**Phases of (lake-) basin genesis** [Nitz 1984]
Late Holocene [0-4 kyrs BP]	**Holocene phase influenced by man** *[‘Anthropogen beeinflusste, holozäne Phase’]* • strong human influence on the drainage system by channels, weirs, hydro amelioration and agriculture	**Colluvial phase** *[‘Kolluviumsphase’]* • man-induced filling up of smaller depressions by colluvial sediments [hillwash]
Mid-Holocene [4-8 kyrs BP]	**Natural Holocene phase** *[‘Natürlich holozäne Phase’]* • weak fluvial erosion and accumulation	**Aggradation phase** *[‘Verlandungsphase’]* • filling up of lake basins by sedimentation of gyttja and peat
Early Holocene, Lateglacial [8-13 kyrs BP]	**Lateglacial-Early Holocene transitional phase** *[‘Spätglazial-altholozäne Übergangsphase’]* • reversals of flow direction • partly formation of interior drainage • melting of stagnant ice / lake formation • decay of permafrost	**Deep melting phase** *[‘Tieftauphase’]* • melting of stagnant ice, formation of [lake] basins • decay of permafrost
Late Pleniglacial [20-13 kyrs BP]	**Fluvial periglacial phase** *[‘Fluvioperiglaziäre Phase’]* • formation of a hierarchic river system on permafrost	**Conservation phase** *[‘Konservierungsphase’]* • conservation of stagnant ice by permafrost • sedimentation of periglacial lacustrine, fluvial and aeolian deposits
Late Pleniglacial [>20-14 kyrs BP]	**Fluvioglacial Phase** *[‘Fluvioglaziäre Phase’]* • initial ice-marginal drainage, later ice-radial drainage • outwash plain formation	**Ice-melting phase** *[‘Niedertauphase’]* • inclusion / burial of stagnant ice by sediments **Formation phase** *[‘Anlagephase’]* • formation of depressions by ice exaration and glaciofluvial erosion

Tab. 2: Conceptual models of late Quaternary river valley and lake basin development in northeast Germany. Adapted and modified from Marcinek & Brose (1972) and Nitz (1984).

Tab. 2: Konzeptionelle Modelle der spätquartären Flusstal- und Seebeckenentwicklung in Nordostdeutschland (nach Marcinek & Brose 1972 und Brose 1984, verändert).

2 Regional settings

The region northeast Germany is part of the North European Plain, which is bounded by the coasts of the North Sea and Baltic Sea to the north and the German Central Uplands to the south. The surface relief (<200 m a.s.l.) varies from flat to undulating. Several Quaternary glaciations of Scandinavian ice sheets, subsequent periglacial shaping and interglacial processes have formed this area. A multitude of ice terminal zones of the Saalian and Weichselian glaciations traverse the region and reflect the glaciation/deglaciation (Fig. 1). The complex glacial and interglacial processes produced a mosaic of glacial, fluvial, lacustrine, colluvial, marine and aeolian landforms and sediments.

The Weichselian glacial belt (‘young morainic area’) covers the northern area and comprises landscapes with an immature *river* system that developed following the last deglaciation (c. 24,000–17,000 cal yrs BP; Böse 2005, Lüthgens & Böse 2011). River valleys in that belt are characterised by frequently alternating degradational (erosion) and aggradational (accumulation) river stretches, by frequent shifts in direction, by the common presence of lake basins (partly within the valley floors) and by frequent areas with interior drainage. By contrast, the river system of the Elsterian (c. >330 kyrs) and Saalian belts (c. >125 kyrs; ‘old morainic areas’) is maturated. Major rivers in the region are the Elbe and Oder which drain northeast Germany into the North Sea and the Baltic Sea, respectively. These rivers are character-

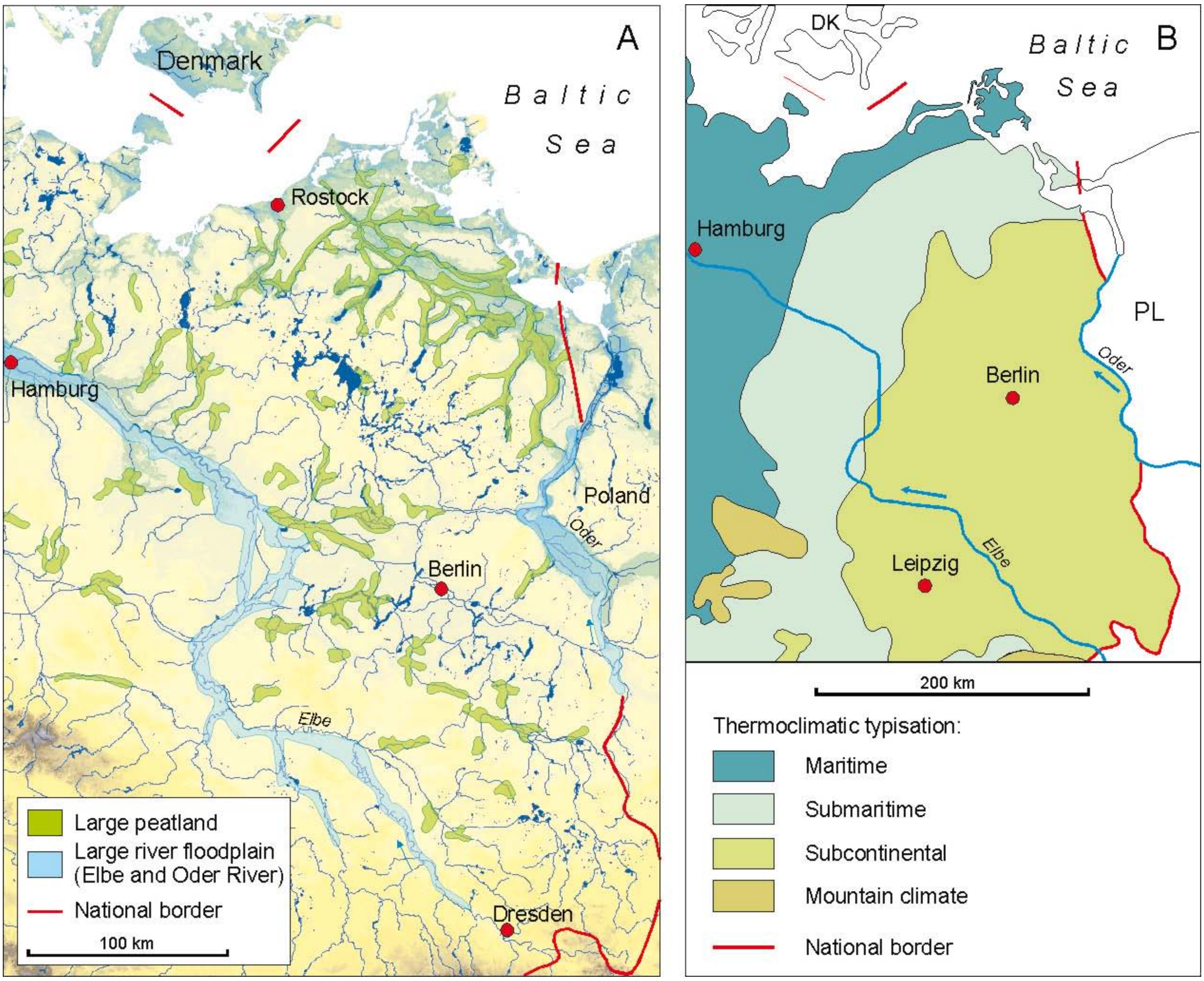

Fig. 2: Distribution of large peatlands and large river floodplains (A) as well of thermoclimatic zones (B) in northeast Germany (after BGR 2007, IfL 2008, adapted).

Abb. 2: Verbreitung großer Moorgebiete und großer Flussauen (A) sowie thermoklimatischer Zonen (B) in Nordostdeutschland (nach BGR 2007, IfL 2008, verändert).

ised by present-day mean annual discharges in a range of 500–700 $m^3 s^{-1}$. Several tributaries exist; the most important are the Saale, Havel, Mulde, Spree and Peene (20–120 $m^3 s^{-1}$; BMUNR 2003). A mainly east-west-oriented network of canals used for inland navigation connects the rivers.

The Weichselian belt is characterised by the occurrence of numerous *lakes* of different size and of different genetic, hydrologic and ecologic type. According to estimations from the adjacent Polish young morainic area, only one-third to half of the former lakes from the late Pleistocene to early Holocene have remained due to aggradation caused by natural and anthropogenic processes (Starkel 2003). By contrast, only a few natural lakes in the Saalian belt occur, but several artificial lakes originating from river damming and lignite opencast mining exist. In northeast Germany the total area of natural lakes amounts to c. 1300 km^2 (Korczynski et al. 2005). In general, the region's natural lakes largely represent 'hollows' located in the first unconfined aquifer. Thus groundwater and lake hydrology are closely connected.

In addition, a large area of the region (c. 5800 km^2) is covered by *peatlands*. This term refers to all kinds of drained or undrained areas with a minimal thickness of peat of at least several decimetres (Joosten 2008). Peatlands primarily occur in river valleys and large basins in the Federal States of Mecklenburg-Vorpommern (2930 km^2) and Brandenburg/Berlin (2220 km^2; Fig. 2A). Smaller areas are distributed in the lowland parts of Sachsen-Anhalt (580 km^2) and Sachsen (70 km^2). Groundwater-fed peatlands dominate with c. 99 % versus only 1 % rain-fed peatlands (Couwenberg & Joosten 2001).

The present-day climate of the region (Hendl 1994) is classified as temperate humid with mean annual air temperatures around 8–9 °C and mean annual precipitation ranging from 773 mm a^{-1} (Hamburg) to 565 mm a^{-1} (Cottbus). A distinct thermoclimatic gradient exists from northwest to southeast, dividing the region into maritime, sub-maritime and sub-continental parts with decreasing precipitation (Fig. 2B). The driest sites are located at the Saale (Halle/S.) and Oder Rivers (Frankfurt/O.) with a mean annual precipitation of about 450 mm a^{-1}.

3 Principle research questions, concepts and methods used in regional studies

The main disciplines providing regional palaeohydrologic knowledge (Fig. 1, Tab. 1) are geomorphology, Quaternary geology, palaeobotany and historical sciences. The prin-

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Tab. 3: Facies areas of Holocene river valley development in northeast Germany considering geographic location, river valley dimension and valley history (Brose & Präger 1983, adapted).

Tab. 3: Faziesgebiete der holozänen Flusstalentwicklung in Nordostdeutschland unter Berücksichtigung der Lage, der Flusstaldimension und der Talgeschichte (nach Brose & Präger 1983, verändert).

<table>
<tr><th>Zone</th><th>Facies area</th><th>Example (river)</th><th>Selected genetic properties</th><th>Comparing conclusions (cross-zonal)</th></tr>
<tr><td>I</td><td>periglacial valley bottoms in the German Uplands</td><td>Saale, Mulde (middle reaches)</td><td>▪ state of equilibrium between erosion and aggradation in the early Holocene
▪ deposition of gravel during Atlantic frequently burying oak stems
▪ late Holocene deposition of flood loams and/or erosion</td><td rowspan="7">▪ as most river valleys (facies zones) are only initially investigated, comparing conclusions are partly of preliminary status
▪ after the retreat of the Weichselian ice sheet an erosional phase took place (Lateglacial) affecting the large river valleys up to the uplands
▪ erosion / aggradation in northern valleys is mainly controlled by water-level changes in the Baltic Sea and North Sea basins, whereas southern valleys are controlled by climatic and (in the late Holocene) by human impact
▪ widespread deposition of organic sediments (peat, gyttja) and soil formation characterises the Atlantic and Subboreal
▪ areal deposition of human-induced flood loams is a characteristic of the late Holocene except in low-lying valleys of zone IVb</td></tr>
<tr><td>II</td><td>valley bottoms in the loess belt</td><td>Elster, Unstrut</td><td>▪ erosional phase in the early Holocene with subsequent deposition of gravel, sand and topping overbank fines
▪ mid-Holocene hiatus (soil formation)
▪ late Holocene deposition mainly of flood loams</td></tr>
<tr><td>IIIa</td><td>valley bottoms in the old morainic area between Weichselian maximum and loess belt</td><td>Spree, Neiße (middle reaches)</td><td>▪ similar depositional history as in zone II</td></tr>
<tr><td>IIIb</td><td>valley bottoms in the young morainic area between Weichselian maximum and Pomeranian stage</td><td>Havel, Dosse, Spree (lower reaches)</td><td>▪ frequent occurrence of fluvial connections of basins (river-lake-structures)
▪ erosion / aggradation depending from river bed changes of Elbe and Oder (zone IVa)</td></tr>
<tr><td>IVa</td><td>valley bottoms of large transzonal rivers occupying several facies areas</td><td>Elbe, Oder</td><td>▪ erosional phases during (Pre-?)Bølling (lower Oder) and early Holocene (Elbe)
▪ early to mid-Holocene deposition of gravels and sands (Elbe) and mainly of peat (lower Oder)
▪ late Holocene deposition of overbank fines</td></tr>
<tr><td>IVb</td><td>valley bottoms of tributaries of the Baltic Sea north of the Weichselian Pomeranian stage</td><td>Peene, Warnow</td><td>▪ erosional phases during (Pre-?)Bølling, Preboreal and late Boreal
▪ flattening of the river bed gradient by organic sedimentation in the Atlantic/Subboreal caused by marine influence (Littorina transgression)
▪ dominating deposition of peat and gyttja instead of overbank fines in the late Holocene</td></tr>
</table>

ciple research questions – some of which have been posed periodically for more than 100 years (e.g. Woldstedt 1956, Marcinek 1987, Kaiser 2002) – concern (1) the structure and formation of the natural drainage system, (2) its anthropogenic use and historic reshaping, and (3) the (palaeo-) ecologic status and change. More specific research questions in relation to the single aquatic environments investigated – rivers, lakes and peatlands – are given in chapters 4.1, 4.2 and 4.3.

Corresponding to different thematic approaches, the research concepts used come from different disciplines. Both geosciences and palaeoecology use climatologic- and biostratigraphic concepts and units. They are defined for dividing and explaining stages of deposition, relief formation and biotic changes, respectively. More specifically, the general model for the regional late Quaternary relief formation with emphasis on fluvial geomorphology, proposed by Marcinek & Brose (1972) and extended to incorporate the development of lake basins (Nitz 1984), has been adapted for use in this overview (Tab. 2). Additionally, the conceptualised regional facies areas of Holocene river development by Brose & Präger (1983) will be outlined (Tab. 3). These models and schemes provided the thematic framework for most of the later geomorphic and palaeohydrologic research. However, they base on relatively few local field studies only and generally lack sufficient numeric age control.

Archaeology, as a discipline of the historic sciences, has concentrated on the settlement and human use of aquatic landscapes in pre-Medieval (i.e. 'pre-German') times, thought to be a period with little human impact on the aquatic environment (e.g. Bleile 2012). History and historic geography have dealt with strong human impact on the regional drainage system since Medieval times (e.g. Schich 1994, Driescher 2003, Blackbourn 2006).

Corresponding to the disciplines involved, the results presented are based upon a broad range of geoscientific (including geochronology), biological (palaeoecology) and historic methods. The basic geoscientific methods used include the analysis of thousands of sedimentary profiles from corings as well as open sections, geomorphic mapping of fluvial and lacustrine structures, sedimentologic analyses and geophysics. Geochronology provides absolute chronologic control

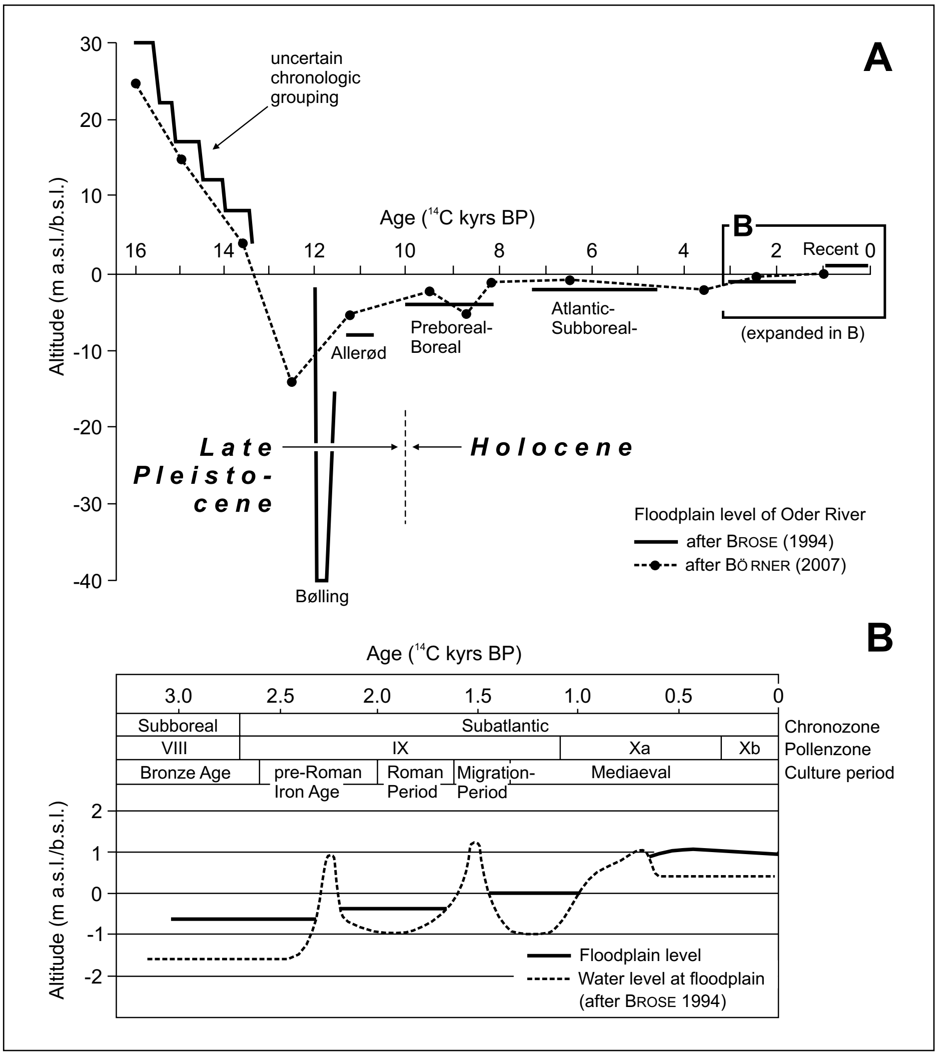

Fig. 3: Changes in the floodplain level of the lower Oder River. A: General development during the late Pleistocene and Holocene (after Brose 1994, Börner 2007, adapted). B: Detailed development during the late Holocene (after Brose 1994, adapted).

Abb. 3: Veränderungen des Auenniveaus der unteren Oder. A: Generelle Entwicklung während des Spätpleistozäns und Holozäns (nach Brose 1994, Börner 2007, verändert). B: Detaillierte Entwicklung während des Spätholozäns (nach Brose 1994, verändert).

comprising radiocarbon dating and, at a progressive rate, luminescence dating (mostly OSL). Normally, the chronology in this overview is based on calibrated radiocarbon ages (cal yrs BP). But, depending on the context, some other chronologic systems were also used (e.g. yrs BC, yrs AD, ^{14}C yrs BP, varve yrs BP). The most important biological method applied is pollen analysis providing both stratigraphic (thus to a certain degree even chronologic) information and palaeoecologic data (e.g. on vegetation structure, groundwater situation, human impact). Regional knowledge of the historic sciences is mainly based on archaeological excavations including find matter analysis, and interpretation of historic public records (documents) and maps. The latter are not available earlier than the 16th century AD.

4 Results and discussion
4.1 Rivers

In general, subjects of research on regional river evolution have been mainly (glacio-) fluvial geology and geomorphology (e.g. change of river course, river bottom incision/aggradation, valley mire formation), and palaeoecology, particularly analysing sedimentary archives in river valleys for vegetation and water trophic level reconstruction. It is only in recent years that quantitative estimations of palaeodischarge were attempted for some rivers (Elbe, Oder and Spree), using palaeoecologic, climatic and hydraulic data. The following overview on river and valley development concentrates on the aspects (1) river valley formation and depositional changes, (2) changes in the river courses and channels, and (3) palaeodischarge and palaeofloods.

4.1.1 River valley formation and depositional changes

The backbone of the regional river network has been a system of glacial spillways (ice-marginal valleys). These spillways worked as southeast-northwest oriented drainage following the retreat of the Weichselian ice sheet, except for the southernmost spillways, which originated from the previous Saalian glaciation. The valleys were operating from c. 26,000 to 17,000 cal yrs BP, partly initiated by the glacier blocking of northwards, i.e. to the North Sea and Baltic Sea basins, flowing rivers (Marcinek & Seifert 1995). The general subglacial and subaerial drainage of the ice sheet to the south led to connections of these spillways via lower-scale valleys. After glaciers decay, unblocking of the terrain often has initiated flow reversals (e.g. Kaiser et al. 2007, Lorenz 2008). In parallel, several short-lived ice-dammed (proglacial) lakes of different dimension developed; some of them of vast extent (see chapter 4.2.1.2)

A striking geomorphic property of the young morainic area is the existence of numerous so-called (*open*) 'tunnel valleys' (glacial channels), containing rivers and streams as well as lakes and peatlands. Additionally, *buried* tunnel valleys of similar dimension occur both in the young and old morainic area (Eissmann 2002). The valleys were mainly eroded by meltwater supposed to have drained from subglacial lakes. Their water was most likely released in repeated outburst floods (so-called 'jökulhlaups') and flowed in relatively small channels on the floors of the tunnel valleys (Piotrowski 1997, Jørgensen & Sandersen 2006).

Knowledge on late Quaternary river development is very irregularly available in the region (Fig. 1, Tab. 1). The region's main river, the Elbe, has been recently only marginally in the (geo-) historic focus (e.g. Rommel 1998, Caspers 2000, Thieke, 2002, Turner 2012), in further contrast to other large central European rivers, such as Vistula and Rhine (Schirmer et al. 2005, Starkel et al. 2006).

A characteristic of low-lying valleys in the northern part of the study area, comprising the lower sections of the Elbe and Oder Rivers as well as the Vorpommern rivers (e.g. Uecker, Peene, Trebel, Recknitz; Fig. 1), is the hydraulic dependency of valley bottom processes from water-level changes in the North Sea and Baltic Sea basins and from isostatic movements. In general, a rise in the water level in the sea basins causes a lower hydraulic river bed gradient, whereas a water level fall leads to the opposite. This strongly influences several processes in the river and its floodplain (e.g. transport, flooding, sedimentation/erosion, vegetation). The Oder River and some Vorpommern rivers were extensively investigated in this respect. In the Lateglacial and early Holocene marked valley bottom changes were caused by lake-level changes of ice-dammed lakes in the Baltic Sea basin (Fig. 3). The mid- to late Holocene sea-level rise (Lampe 2005, Behre 2007, Lampe et al. 2010) triggered a large-scale formation of peatlands (mostly of percolation mires), temporally even the drowning of lower valley sections (e.g. Brose 1994, Janke 2002, Börner 2007, Michaelis & Joosten 2010). Thus, in contrast to river valleys of the higher-lying glacial landscape and the German Uplands, which are mainly filled by minerogenic deposits (gravels, sands, flood loams), peat widely fills the present valleys (Fig. 4).

Most regional studies have noticed that Holocene river bottom development up to the late Atlantic/early Subboreal is exclusively controlled by climatic and (natural-) geomorphic as well as biotic processes, such as fluvial erosion/aggradation and beaver damming. By contrast, Neolithic and subsequent economies, regionally starting in the south c. 7300 cal yrs BP (Tinapp et al. 2008) and in the north c. 6100 cal yrs BP (Latałowa 1992), considerably changed the vegetation structure, water budget and geomorphic processes of the catchments. Erosional processes, following forest clearing and accompanying agricultural use, increased the suspended load of rivers causing deposition of flood loams (overbank fines, 'Auelehm' in German) during flood events. Accordingly, a larger number of flood loams date from the late Atlantic (e.g. Hiller et al. 1991, Mundel 1996, Caspers 2000). Moreover, there is a multitude of flood loam records dating from the Subboreal and Subatlantic (e.g. Fuhrmann 1999, Börner 2007, Brande et al. 2007, Kaiser et al. 2007, Tinapp et al. 2008).

As shown by palaeo-flood indicators, human-induced changes in the catchment hydrology led to an increase in the frequency and magnitude of floods in the late Holocene (see chapter 4.1.3). The river valley bottoms shifted from quasi-stable to unstable conditions (Schirmer 1995, Kalicki 1996, Starkel et al. 2006, Hoffmann et al. 2008). More frequent and heavy floods caused both an intensification of river bed erosion and an aggradation of the valley bottom and levelling of its relief differences.

4.1.2 Changes in river courses and channels

In general, rivers can change their *course* by leaving their old valley or by formation of a new channel within their hitherto existing valley. Rivers can be forced to leave old valleys through tectonics, retrograde erosion or glacier damming. The accordant timescale mostly is a few to hundreds thousands of years (in phase with climatic *evolution*). Smaller changes in the *channel* pattern ('fluvial style') lead to new river beds within existing valleys, which are predominantly initiated by climate-driven changes of drainage (frequency, magnitude), erosion and bedload. This spans a timescale of tens to hundreds of years (in phase with climatic *changes*; Vandenberghe 1995b).

Of the regional rivers, only the Elbe has been investigated for changes in its course. In the Tertiary to mid-Pleistocene, *large-scale* river course changes (lateral river bed deviation of max. c. 150 km) occurred due to tectonic processes and to river damming triggered by glaciations. It was not until the end of the Saalian that its present course was substantially formed (e.g. Thieke 2002). *Small-scale* river course changes (max. c. 25 km) occurred in the Elbe-Havel River region ('Elb-Havel-Winkel' in German) still in historic times (early 18th century AD), when the river, caused by strong floods, was following older courses in the deeper lying Havel River valley (Schmidt 2000). Finally, evidence for river channel changes (max. c. 5 km) is available for the river section between Magdeburg and Wittenberge, showing that the present-day single channel river was a Holocene anastomosing system in this section up to the mid-18th century AD (Rommel 1998, Caspers 2000).

A few records are available on channel pattern changes in the region (Fig. 5). The mean *present-day* annual discharge of accordant rivers, however, varies extremely (0.3 to 550 m^3 s^{-1}). Six types of channel patterns were identified (braiding, meandering with large and small meanders, anastomosing, V-shape valleys/straight course, and inundation/valley mire formation). The type formed depends on several hydraulic parameters (bed gradient, load, flow velocity, discharge volume and temporal distribution; Miall 1996). In the late Pleniglacial and early Lateglacial all rivers investigated were braided systems caused by high load and strongly episodic discharge after heavy snow melting under periglacial conditions (e.g. Mol 1997). An incision phase took place in the early Lateglacial, when the regional erosion base in the Baltic Sea and North Sea basins was low or when the local erosion base was lowered by dead-ice melting. The (early) Lateglacial is characterised by the formation of so-called large meanders, which are attributed to short-term high discharges following extreme snow melting (Vandenberghe 1995a). For the Spree River, a distinct radius downsizing of sequenced meander generations was postulated (large meanders: 900–1000 m, small meanders: 600–900 m, recent me-

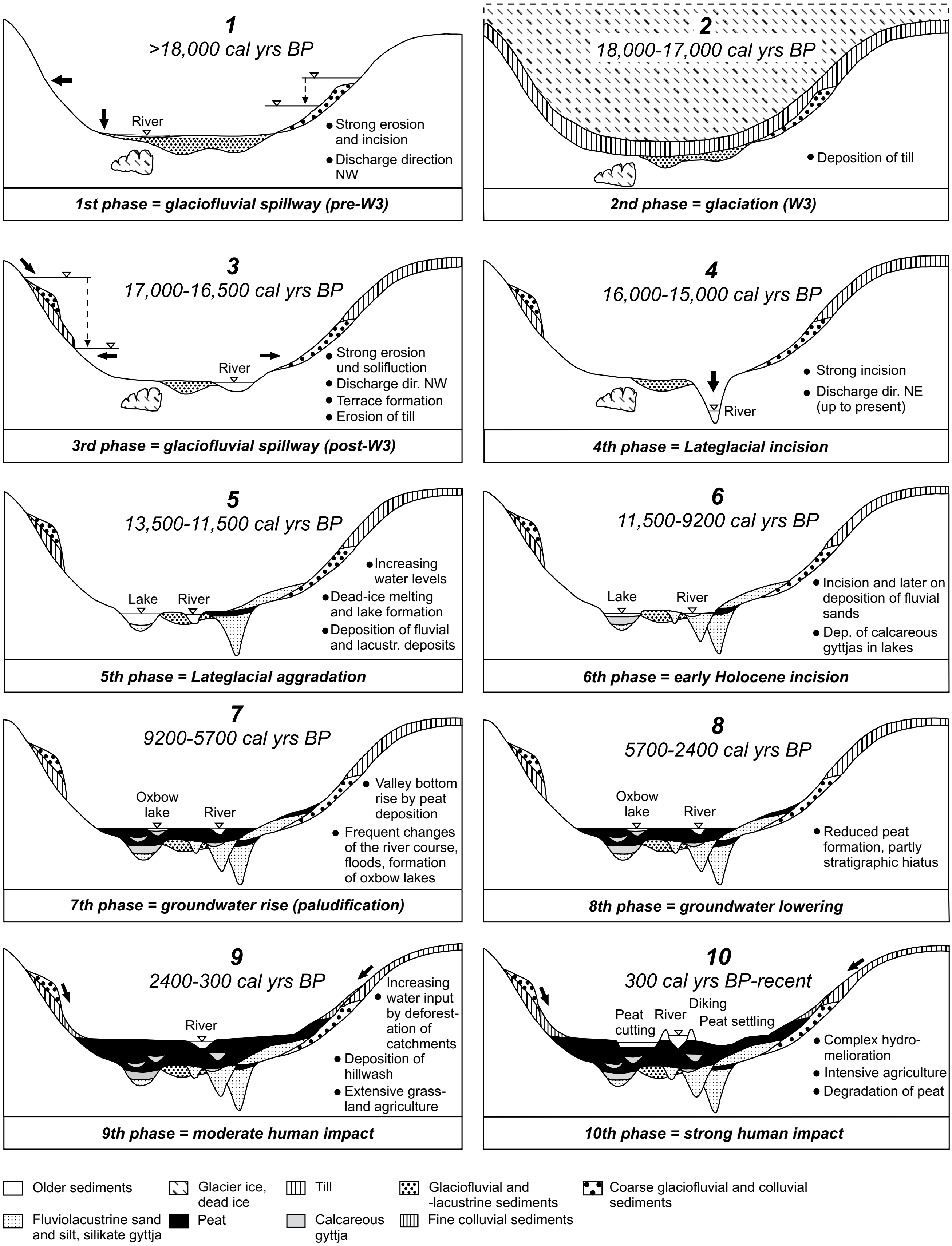

Fig. 4: Model of the geomorphic development of low-lying river valleys in Vorpommern (after Kaiser 2001, Janke 2002, adapted); a schematic geologic cross-section through a river valley is depicted. The term 'W3' used for phases 1–3 refers to the late Pleniglacial inland-ice advance of the Mecklenburgian Phase (Weichselian3/W3)', which is approximately dated by radiocarbon data from the Pomeranian Bay, southern Baltic Sea (Görsdorf & Kaiser 2001).

Abb. 4: Modell der geologisch-geomorphologischen Entwicklung tiefliegender Flusstäler in Vorpommern (nach Kaiser 2001, Janke 2002, verändert). Dargestellt ist ein schematischer geologischer Schnitt durch ein Flusstal. Der Begriff „W3", genutzt für die Talentwicklungsphasen 1–3, bezieht sich auf den spätpleniglazialen Inlandeisvorstoß der Mecklenburger Phase (Weichsel3/W3). Dieser Eisvorstoß ist näherungsweise durch Radiokohlenstoffdaten aus der Pommerschen Bucht/südliche Ostsee datiert (Görsdorf & Kaiser 2001).

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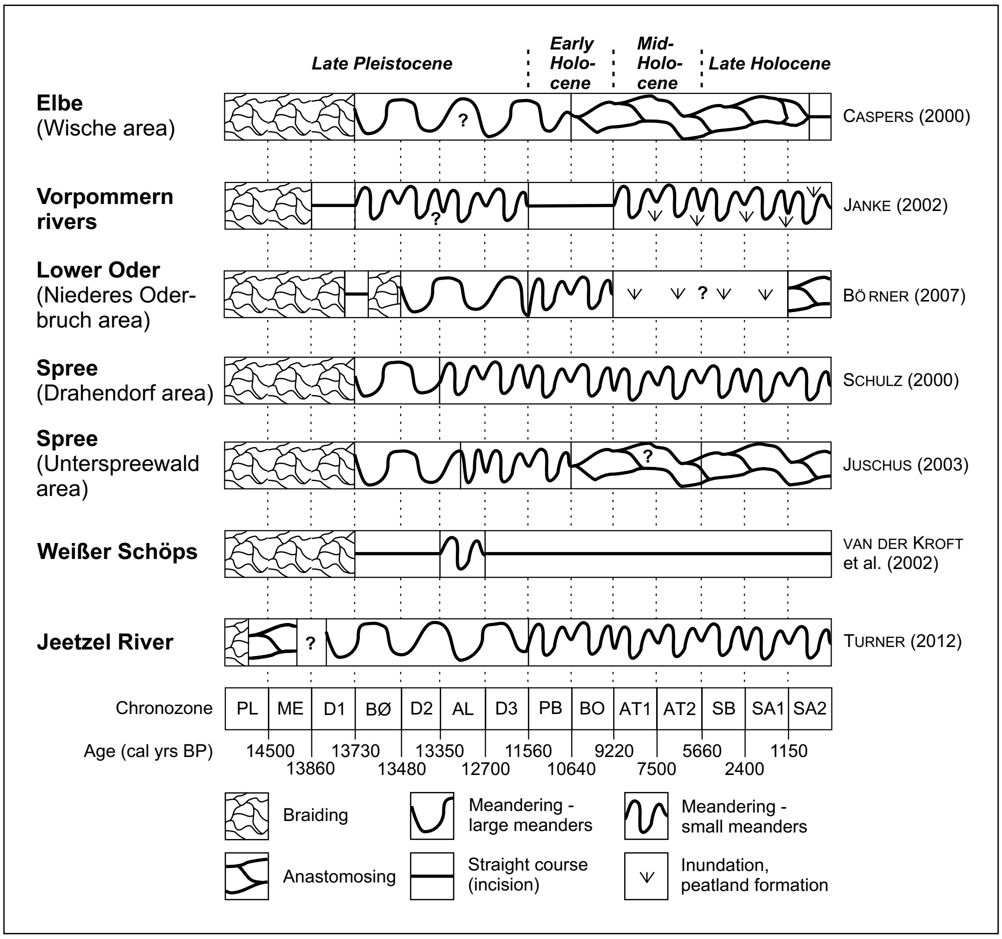

Fig. 5: Late Pleistocene and Holocene channel pattern changes in river valleys in northeast Germany (after various authors, adapted). Note missing data or questionable records are indicated by question marks.

Abb. 5: Spätpleistozäne und holozäne Veränderungen der Gerinnebettmuster in Flusstälern Nordostdeutschlands (nach verschiedenen Autoren, verändert). Fehlende Daten oder fragliche Befunde sind mit Fragezeichen gekennzeichnet.

anders: 150–300 m; Schulz 2000), which generally indicates decreasing (seasonal) discharge volumes. Beginning in the late mid-Holocene but strengthened in the late Holocene, some low-lying river sections were temporarily inundated and were generally transformed into peatlands (e.g. lower Oder River and some Vorpommern rivers).

In the last c. 800 years, human impact has considerably changed both the floodplain structures and courses of regional rivers by deforestation, artificial river-bed removing and strengthening as well as dyking, settlement and infrastructure construction (e.g. Schich 1994, Schmidt 2000, Driescher 2003). For example, a dense network of canals for inland navigation has been built, beginning in the 16th century AD and culminating in the late 19th to early 20th century AD (Uhlemann 1994, Eckoldt 1998), in addition to the construction of innumerable drainage ditches.

4.1.3 Palaeodischarge and palaeoflood characteristics

Quantitative estimations of palaeohydrologic parameters for rivers usually aim at describing palaeodischarge (mean annual discharge, bankfull discharge) and palaeoflood characteristics (magnitude, frequency, risk; e.g. Gregory & Benito 2003, Benito & Thorndycraft 2005). Whereas in the adjacent Polish territory, palaeodischarge and palaeoflood studies were performed quite early (e.g. Rotnicki 1991, Starkel 2003), corresponding studies for northeast Germany are generally rare and of more recent status.

One recent study of the Elbe River mouth (German Bight, North Sea) produced a high resolution 800-year-long proxy record of palaeodischarge, based on a $\delta^{18}O$-salinity-discharge relationship (Scheurle et al. 2005; Tab. 4). The reconstructed variance of mean annual discharge (MAD), revealing a minimum-maximum span of 100–1375 $m^3 s^{-1}$, is linked to long-term changes in precipitation. Four main periods of palaeodischarge/palaeoprecipitation become apparent, with higher and lower values than at present.

For the lower Oder River, a coupled climatic-hydrologic model estimated MADs for the early and mid-Holocene similar to those of today (Ward et al. 2007; Tab. 4). These modelling results coincide with local palaeohydrologic data from the Prosna River (a tributary of the Oder via the Warta in Poland; Rotnicki 1991), which show that discharges there in the early and mid-Holocene were broadly similar to those in the period 1750–2000 AD.

For the Spree River, late Holocene palaeomeanders were investigated (Hilt et al. 2008). Reconstructions show narrower and shallower channels for the undisturbed lower Spree as compared to recent conditions, which are strongly influenced by mining drainage water input (Grünewald 2008). Flow velocities and discharge at bankfull stage (Tab. 4) were smaller in palaeochannels and flow variability was higher. Furthermore, the increase in bankfull discharge was attributed to deforestation and drainage of the catchment as well as channelisation, bank protection and river regulation measures.

For the joint area of Vorpommern and northeast Brandenburg, Bork et al. (1998) estimated a regional water balance

Tab. 4: Holocene palaeodischarge estimations for Elbe, Oder and Spree Rivers after Scheurle *et al. (2005),* Ward *et al. (2007) and* Hilt *et al. (2008), respectively.*

*Tab. 4: Abschätzungen der holozänen Paläoabflüsse für die Elbe (*Scheurle *et al. 2005), die Oder (*Ward *et al. 2007) und die Spree (*Hilt *et al. 2008).*

River	**Elbe**	**Oder**	**Spree**
Gauging site	Neu Darchau (upstream of Hamburg)	Gozdowice (downstream of Frankfurt/Oder)	Neubrück (downstream of Cottbus)
Recent discharge ($m^3 s^{-1}$)	720 (100 %)[1]	527 (100 %)[1]	52 (100 %)[2]
Gauging period	1900-1995	1901-1986	present
Approach used	proxy record of palaeodischarge using a $\delta^{18}O$-salinity-discharge relationship	coupled climatic-hydrologic model	proxy record of bankfull palaeo-discharge using hydraulic properties of palaeomeanders
Palaeodischarge ($m^3 s^{-1}$)	1300 AD: 800 (111 %)[1] 1400 AD: 900 (125 %)[1] 1500 AD: 700 (97 %)[1] 1600 AD: 500 (69 %)[1] 1700 AD: 1000 (139 %)[1] 1800 AD: 900 (125 %)[1] 1900 AD: 500 (69 %)[1] Max. c. 1580 AD: 1375 (191 %)[1] Min. c. 1260 AD: 100 (14 %)[1]	early Holocene (9000-8650 cal yrs BP): 522 (99 %)[1] mid-Holocene (6200-5850 cal yrs BP): 538 (102 %)[1]	late Subboreal-early Subatlantic (3200-2500 cal yrs BP): 8 (15 %)[2]
Reference	Scheurle et al. (2005)	Ward et al. (2007)	Hilt et al. (2008)

[1]mean annual discharge
[2]bankfull discharge

for the time steps 650 AD, 1310 AD and today, which shows a maximum discharge value for the late Medieval period. This was caused by the lowest amount of forested areas (thus relatively low amounts of evapotranspiration and interception) during the late Holocene (Tab. 5).

Data on palaeoflood characteristics in the region are primarily available for the Elbe (Brázdil et al. 1999, Glaser 2001, Mudelsee et al. 2003), Oder (Glaser 2001, Mudelsee et al. 2003) and Spree Rivers (Rolland & Arnold 2002). Sporadic historical records start in the 11th century AD, while more continuous records are not available until the 16th century AD. As an example, for the Elbe River Mudelsee et al. (2003) detected significant long-term changes in flood occurrence rates from the 16th to the 19th century AD. A first maximum in the flooding rate was reached in the mid-16th century AD. At this time, rivers in central and southwest Europe experienced a similar increase in floods, which has been attributed to higher precipitation (Brázdil et al. 1999). Later on winter floods reached an absolute maximum (around 1850 AD) and then finally decreased. Mudelsee et al. (2003) concluded by means of statistical correlations for the Elbe and Oder Rivers that reductions in river length, construction of reservoirs and deforestation have had only minor effects on flood frequency. Furthermore, they arrived at the conclusion that there is no evidence from both historic data and modern gauging for a recent upward trend in the flood occurrence rate (in this context see Petrow & Merz 2009). This represents an important *regional* finding with respect to the current debate on regional hydrologic changes initiated by global climate change, emphasising the importance of temporally long hydrologic data series.

4.2 Lakes

In general, lake basins ubiquitously provide sedimentary archives from which both the local and to a certain extent even the regional landscape development can be reconstructed.

The lake basins in the northern part of the region (Mecklenburg-Vorpommern) were formerly classified by size as 'large glaciolacustrine basins' (former proglacial lakes, >100 km²), 'medium-sized lakes' (0.03–100 km²), and 'kettle holes' (<0.03 km²; Kaiser 2001, Terberger et al. 2004). Although designed for a specific area, this classification by size can also be applied for the whole morainic area, additionally taking into account some local characteristics. Regional research on lake genesis performed so far mainly concentrated on (1) lake basin development (e.g. dead-ice dynamics and depositional changes) and on (2) palaeohydrology (lake-level and lake-area changes). Both aspects will be presented in the following.

4.2.1 Lake basin development
4.2.1.1 Dead-ice dynamics

Most of the medium- and small-sized lake basins in the Weichselian glacial belt originated from melting of buried stagnant ice, usually called 'dead ice' (e.g. Nitz et al. 1995, Böse 1995, Juschus 2003, Niewiarowski 2003, Kaiser 2004a, Lorenz 2007, Błaszkiewicz 2010, 2011). This term refers to the temporary *local* conservation/incorporation of ice in depressions and/or in sedimentary sequences; either coming from the freezing of pre-existing water bodies (e.g. shallow lakes) before being overridden by glacier ice or as a direct remnant from the glacier. Glacially- and melt water-driven

Tab. 5: Estimation of the water balance for the northern part of northeast Germany considering the Vorpommern and Uckermark areas (after Bork et al. 1998, adapted).

Tab. 5: Abschätzung der Wasserbilanz für den nördlichen Teil von Nordostdeutschland (Vorpommern und Uckermark; nach Bork et al. 1998, verändert).

Time step	**650 AD**		**1310 AD**		**Present**	
Land cover parameter	km^2	%	km^2	%	km^2	%
Total area	10000	100	10000	100	10000	100
Arable land and grassland	100	1	7900	79	6800	68
Forest (including uncultivated land)	9400	94	1500	15	2400	24
Surface waters	500	5	500	5	500	5
Other areas	<100	<1	100	1	300	3
Hydrological parameter	$mm\ a^{-1}$	%	$mm\ a^{-1}$	%	$mm\ a^{-1}$	%
Mean annual precipitation	595[1]	100	595[1]	100	595	100
Total runoff	40	7	140	24	120	20
Surface runoff	<1	0	10	2	3	<1
Subterraneous runoff	2	<1	5	1	4	<1
Mean evapotranspiration and interception	555	93	455	76	475	80

[1]assumed as today

erosive processes produced variously formed depressions (wide basins, channels, kettle holes), which were filled by dead ice during the glacier's decay. After the melting of these ice 'plombs', water-filled basins of varying size could appear, depending on the local hydrologic situation. Between dead-ice formation/burial and dead-ice melting, thousands of years, occasionally tens of thousands of years passed by. In contrast, the rare *present-day* natural lakes in the Saalian belt owe their existence mainly to local endogenic processes triggered by the dynamics of Zechstein salt deposits in the deep underground.

Dead-ice dynamics can be sedimentologically detected either by dislocation of sediment layers or by unusual succession of certain sediments. In the region, the first was repeatedly demonstrated by the record of heavily tilted peats and gyttjas (e.g. Kopczynska-Lamparska et al. 1984, Nitz et al. 1995, Strahl & Keding 1996, Kaiser 2001). The latter is normally attributed to the occurrence of basal peats below gyttjas, partly below a present-day water body of several decametres thickness (e.g. Kaiser 2001, Błaszkiewicz 2010, 2011).

Subsequent to the melting of dead ice in the basins and valleys, swamps/mires and lakes began to occupy the depressions. For parts of the study area, overviews on this onset of lacustrine sedimentation in medium-sized lakes and kettle holes are available (Kaiser 2001, 2004b, Brande 2003, de Klerk 2008). According to Kaiser (2001), in about 90 % of the lake basins compiled for Mecklenburg-Vorpommern and northern Brandenburg (total profile number analysed = 99) the process of sedimentation began in the Lateglacial, 38 % alone in the Allerød (Fig. 6).

In general, basin-forming dead-ice melting processes occurred from the Pleniglacial up to the early Holocene, with a concentration in the Allerød. Final dead-ice melting was assumed or reported for the Preboreal (e.g. Böse 1995, Niewiarowski 2003, Błaszkiewicz 2010, 2011). Over a third of the profiles analysed for Figure 6 include basal peats mainly from the Allerød, which ended regularly in a secondary position due to settling as the result of dead-ice melting.

4.2.1.2 Depositional changes

The deposition of fine silicate clastic gyttjas is characteristic for the cold Lateglacial stages. Peats and gyttja deposits rich in carbonates and organic matter mainly originate from the relatively warm Allerød. The dominant minerogenous input during the Lateglacial is caused by a very thin vegetation cover and an unstable overall relief (ablation, deflation, gully erosion, dead-ice melting, braiding). Besides basal peats from the Allerød, higher-lying peats of the same age buried by lacustrine and fluvial sands occur. They indicate a significant intensification of lacustrine and fluvial deposition during the subsequent Younger Dryas, which has been recognised throughout northeast Germany, triggered by renewed cold-climate conditions (e.g. Helbig & de Klerk 2002, Kaiser 2004b, de Klerk 2008). Although the increase in fluvial and erosional dynamics during the Pleistocene-Holocene transition constitutes a more general trend throughout the region, on an individual basis, some sedimentary records show that changes occurred rapidly and were often triggered by local relief instabilities and small scale catastrophic drainage events (e.g. Kaiser 2004a).

Sedimentation of organic and calcareous gyttja as well as peat generally characterises the Holocene. This is mainly due to a reduction in clastic input following a dense veg-

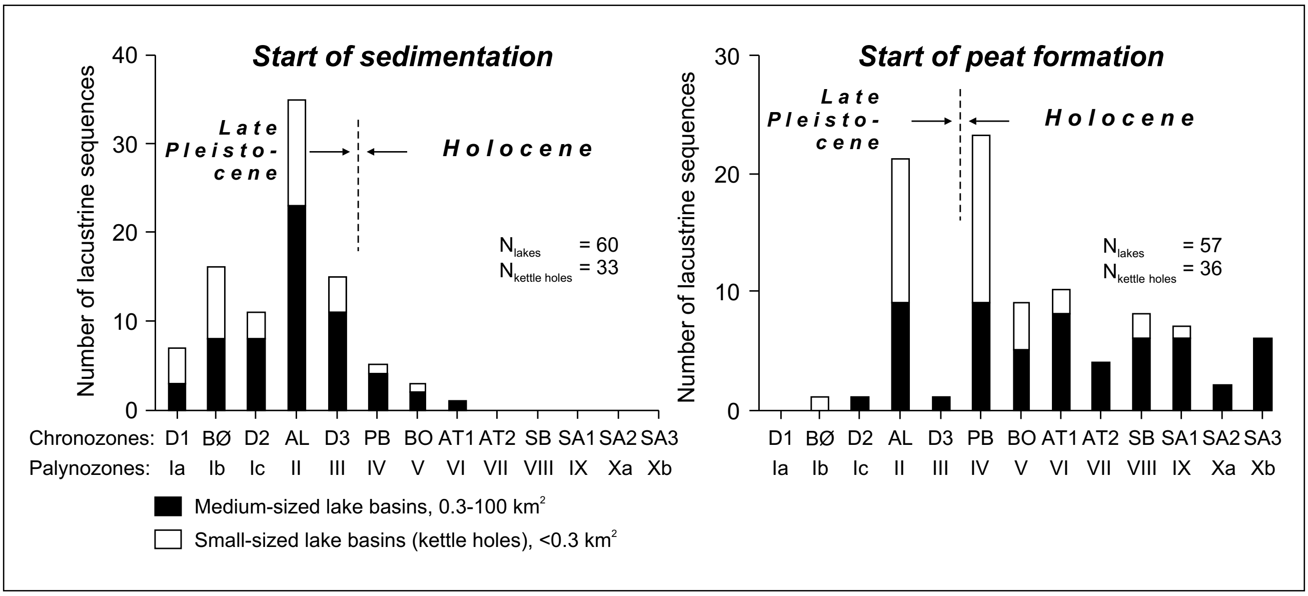

Fig. 6: Onset of lacustrine sedimentation (left) and peat formation (right) in lake basins of northeast Germany (areas of Mecklenburg-Vorpommern and northern Brandenburg; after Kaiser *2001, adapted).*

Abb. 6: Beginn der limnischen Sedimentation (links) und der Torfbildung (rechts) in Seebecken in Nordostdeutschland (Mecklenburg-Vorpommern und nördliches Brandenburg; nach Kaiser *2001, verändert).*

etation cover and a reduced geomorphic activity. In parallel the lake bioproduction increased. Deposition of gyttjas and, to a lesser degree, of fluvio-deltaic sequences filled shallow lacustrine basins. The common occurrence of fluvio-deltaic sequences, called (palaeo-) fan-deltas or Gilbert-type deltas (Postma 1990), in dead-ice depressions represents a previously undescribed geomorphic feature in the Weichselian glacial belt of northeast Germany (Kaiser et al. 2007), which corresponds to fan-deltas described from northwest Poland (Błaszkiewicz 2010).

Peat accumulation causing (natural) aggradation of lakes became a widespread regional phenomenon during the mid- to late Holocene. Commencing in the Subboreal and increasingly during the Subatlantic, human impact led to noticeable effects on the lake development. Increases in lacustrine sedimentation rates and clastic matter influxes since c. 1250 AD are evidence of erosion following forest clearing and systematic land use including anthropogenic lake-level changes and lake drainages (e.g. Brande 2003, Lorenz 2007, Selig et al. 2007, Enters et al. 2010). In the late 19th century AD, but enormously strengthened in the mid-20th century, human induced eutrophication by nutrient loading through agriculture, industry, sewage release, and soil erosion became a major threat to regional lakes (e.g. Scharf 1998, Mathes et al. 2003, Lüder et al. 2006). This eutrophication, partly in conjunction with human- and climate-driven hydrologic processes (e.g. Germer et al. 2011, Kaiser et al. 2012b), caused both depositional and hydrographic changes (increasing deposition rates, formation of anoxic sediments, partly shrinkage of lakes by aggradation).

The former vast ice-dammed (proglacial) lakes at the Baltic Sea coast underwent, in comparison to the medium- and small-sized inland lakes described above, a different development during the late Pleistocene and Holocene (Fig. 1). These late Pleniglacial lakes received water both from the melting inland-ice in the north and the stagnant (non-buried) ice in the immediate lake surroundings as well as from the ice-free area in the south. The largest lakes reconstructed are the 'Haffstausee' (c. 1200 km²; Janke 2002, Borówka et al. 2005) in the vicinity of Szczecin and the 'Rostocker Heide-Altdarss-Barther Heide-Becken' (>700 km²; Kaiser 2001) in the vicinity of Rostock. During deglaciation around 17,000 cal yrs BP, up to 25 m-thick glaciolacustrine sediments (clays, silts, sands) were accumulated. Local littoral gyttjas and aeolian sands dated to the Lateglacial have been found, indicating the end of the *large*-lake phase still within the Pleniglacial due to the decay of the basin margins consisting of ice (Kaiser 2001). For the Allerød and the early Younger Dryas, soils, peats, littoral gyttjas and Final Palaeolithic archaeological sites indicate widely dry conditions in these basins, in which only local lakes and ponds existed. In the late Younger Dryas, over large areas the basin sands were re-deposited by wind. The Holocene, on the one hand, is terrestrial, or locally also lacustrine, fluvial and boggy in form (e.g. Bogen et al. 2003, Terberger et al. 2004, Borówka et al. 2005, Kaiser et al. 2006, Börner et al. 2011). On the other hand, the lower parts of the glaciolacustrine basins came under marine influence, thereby becoming integrated into the Baltic Sea or the coastal lagoons (Lampe 2005, Borówka et al. 2005, Lampe et al. 2010)

4.2.2 Palaeohydrology

4.2.2.1 Lake-level changes

In general, lake-level records offer an important palaeohydrologic proxy as they can document past changes in the local to regional water budget in relation to climatic oscillations. Lake levels are influenced by climatic parameters affecting both evaporation and precipitation. But they can also be influenced by a variety of local, non-climatic factors such as local damming of the outflow by geomorphic processes and vegetation, animals (beaver) and man, or by land-

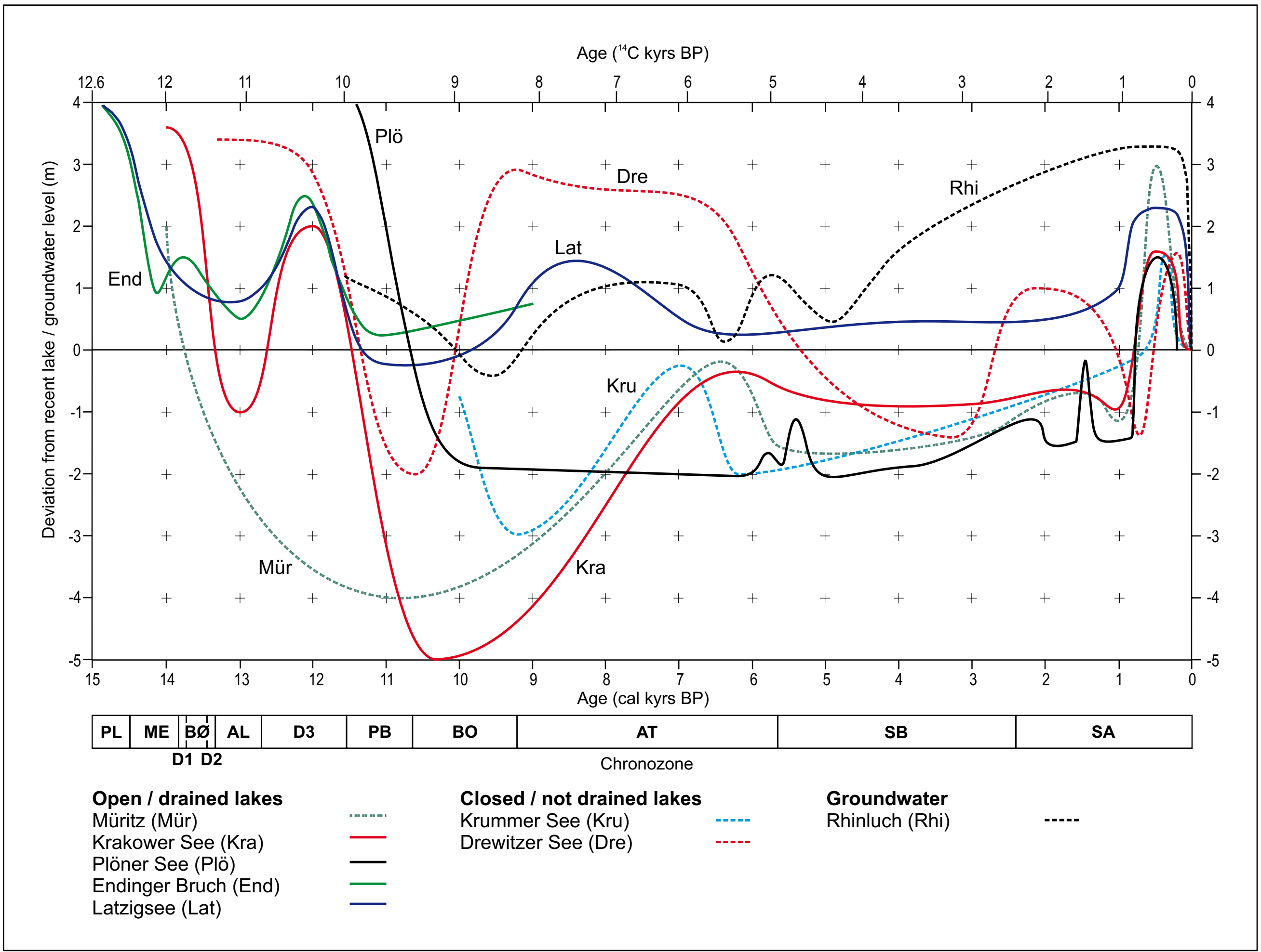

Fig. 7: Reconstruction of late Quaternary lake levels from northeast Germany (Lake Müritz: Kaiser et al. 2002, Lampe et al. 2009; Lake Endinger Bruch: Kaiser 2004a; Lake Latzigsee: Kaiser et al. 2003, Kaiser 2004b; Lake Krakower See: Lorenz 2007; Lake Großer Plöner See: Dörfler 2009; Lake Krummer See: Küster 2009). Additionally the reconstruction of the groundwater level in the Rhinluch peatland is shown (Gramsch 2002). All curves are adapted.

Abb. 7: Rekonstruktion spätquartärer Seespiegel in Nordostdeutschland (Müritz: Kaiser et al. 2002, Lampe et al. 2009; Endinger Bruch: Kaiser 2004a; Latzigsee: Kaiser et al. 2003, Kaiser 2004b; Krakower See: Lorenz 2007; Großer Plöner See: Dörfler 2009; Krummer See: Küster 2009). Ergänzend wird die Rekonstruktion des Grundwasserspiegels für das Rhinluch abgebildet (Gramsch 2002). Alle Kurven sind verändert.

cover changes in the catchment area influencing runoff and groundwater recharge (e.g. Gaillard & Digerfeldt 1990, Digerfeldt 1998, Duck et al. 1998, Harrison et al. 1998, Magny 2004).

Long-term ('continuous') records on the regional lake-level dynamics are available almost exclusively for the young morainic area north of Berlin. These records have been synthesised and are shown in Figure 7. Some further lake-level records that exist for the region have several constraints (e.g. coarse resolution, comparative only, temporally very fragmented, very synthetic/tentative; e.g. Brande 1996, Böttger et al. 1998, van der Kroft et al. 2002, Wennrich et al. 2005).

The records shown in Figure 7 span different time segments (i.e. chronozones) over the last 15,000 years. The manner of reconstructing past lake levels varied in the investigations (e.g. using subaquatic peats, lacustrine terraces and beach ridges, subaquatic wood remains and archaeological sites, historic documents), so the levels are based on data with different precision. The original records are referenced to absolute topographic levels (m a.s.l.), whereas the synoptic presentation in Figure 7 uses the (relative) deviation from the recent lake level for better comparison. Generally, the records available have a relatively low resolution, comprising often only one data point per chronozone. Thus the lake-level *curves* actually represent links of discrete data *points*, not continuous records. Consequently, far more (short-term) lake-level fluctuations can be expected than suggested by these curves. Despite these constraints, however, some *general trends* can be derived:

In the Pleniglacial and in parts of the Lateglacial, all lakes investigated had distinctly higher levels than at present. This was initially caused by deglaciation processes occurring at higher terrain levels, and later on caused by several geomorphic processes specific to the Pleistocene-Holocene transition, such as dead-ice melting, phased initiation of fluvial runoff and permafrost dynamics. After a distinct lowering in the early Holocene, lake-levels in one portion of lakes remained below present levels until the late Holocene, accompanied by fluctuations. Another portion of lakes shows temporally higher Holocene lake levels than at present. Common to all lakes, however, are the sudden and large changes in levels, initially positive, later on negative, that occurred in the late Holocene, after c. 1250 AD.

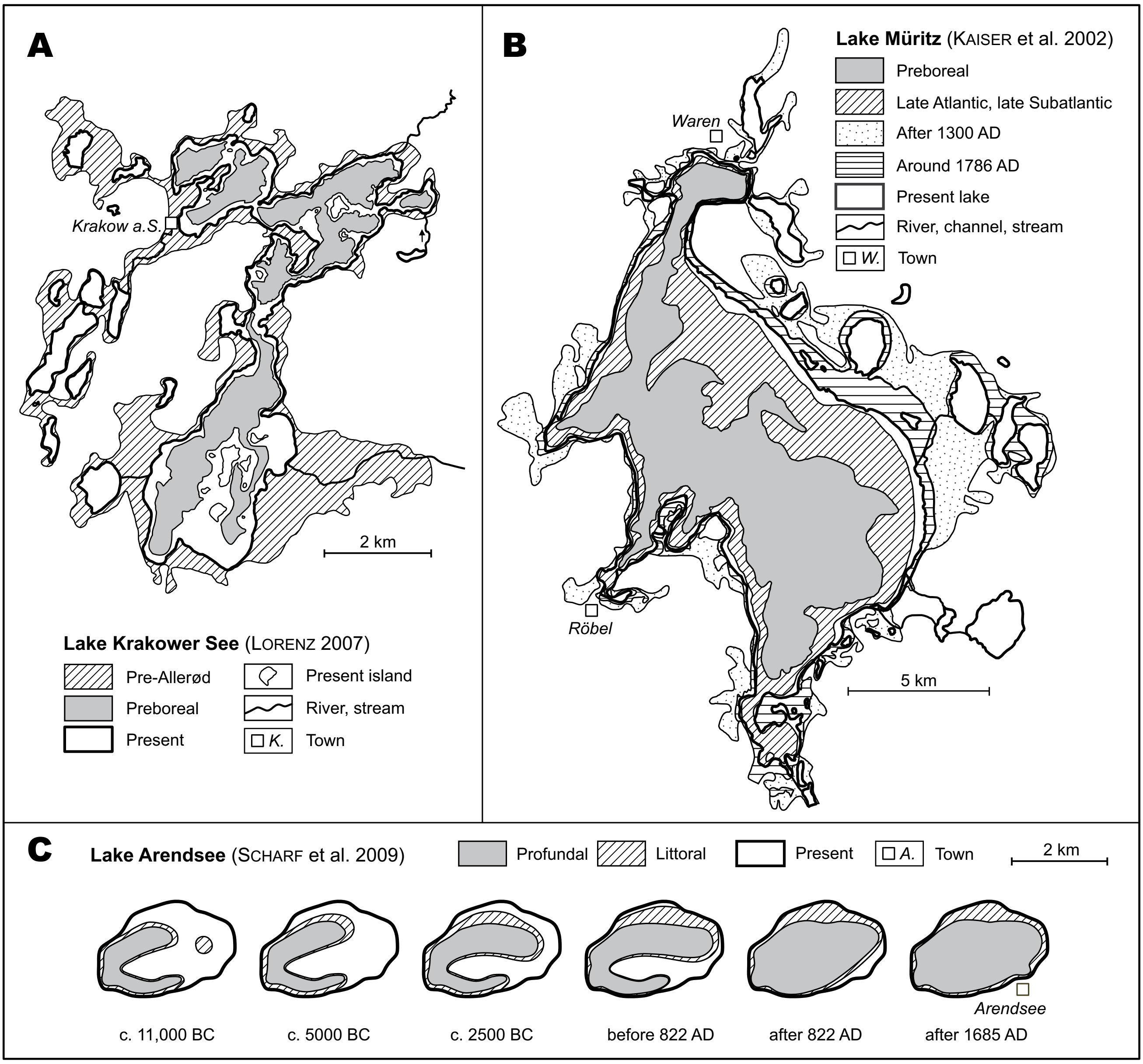

Fig. 8: Reconstruction of late Pleistocene and Holocene lake contours from northeast Germany. A: Lake Krakower See (Lorenz 2007). B: Lake Müritz (Kaiser et al. 2002). C: Lake Arendsee (Scharf et al. 2009). All subfigures are adapted.

Abb. 8: Rekonstruktion spätpleistozäner und holozäner Seeflächen in Nordostdeutschland. A: Krakower See (Lorenz 2007). B: Müritz (Kaiser et al. 2002). C: Arendsee (Scharf et al. 2009).

More specific, distinct phases of relatively low and relatively high lake levels can be deduced for the young morainic area (Fig. 7). Low lake levels in the Allerød and high lake levels in parts of the Younger Dryas were repeatedly detected (e.g. Helbig & de Klerk 2002, Kaiser 2004a, Lorenz 2007), which can be explained by climatic and geomorphic changes in that time. During the Allerød a moderate warm climate, forest vegetation and dominant dead-ice melting prevailed. The Younger Dryas, in contrast, was characterised by a cold climate with regional reestablishment of permafrost conditions, tundra vegetation and enhancement of surficial drainage. Similar observations have been made for the Baltic Sea near-coastal regions of Poland and Sweden (Berglund et al. 1996b, Ralska-Jasiewiczowa & Latałowa 1996). The early Holocene (Preboreal, Boreal) is widely characterised by low lake levels that can be ascribed to climatic warming and a fully forested landscape, as well as final dead-ice melting and intensification of erosive fluvial processes. In that time all lakes presented reached their Holocene minimum, partly lying 5–7 m below the present lake level (e.g. Lorenz 2007). In the mid-Holocene warm-wet Atlantic period the lakes initially rose, despite the fact that forests had their Holocene maximum extent and vigour (Lang 1994), potentially leading to high evapotranspiration rates in the lake catchments. This is in contrast to north Polish findings where predominantly low lake levels during the Atlantic have been detected (Starkel 2003). After the decreases in levels during the late Atlantic and Subboreal, some, partly strong, undulations took place in the Subatlantic (e.g. Kaiser et al. 2002, Lampe et al. 2009). The last c. 800 years saw almost identical dynamics, with increases in lake levels in the 13th–14th century AD (partly up to the 17th–18th century AD) and decreases in the

18th–19th century AD. These changes are primarily caused by man, who became a major factor in lake hydrology due to the construction of mill and fish weirs, drainage improvement, canal construction and forest clearing (e.g. Jeschke 1990, Schich 1994, Kaiser 1996, Bork et al. 1998, Driescher 2003, Lorenz 2007, Küster & Kaiser 2010).

4.2.2.2 Lake-area and lake-contour changes

The late Quaternary lake-level changes caused to some extent drastic changes in the lake topography (volume, area, contour). However, only a few areal calculations and topographic (map) reconstructions exists for the region so far, showing that the lake areas and contours varied substantially (Fig. 8). For example, Lake Müritz, with a current area of 117 km² (100 %), varied from a minimum area of c. 74 km² (63 %) in the Preboreal to a maximum area of c. 188 km² (161 %) in the beginning of the 14th century AD (Kaiser et al. 2002).

4.3 Peatlands

Analogously to rivers and lakes, peatlands can also act as late Quaternary palaeohydrologic archives primarily indicating groundwater dynamics (e.g. Chambers 1996). Knowledge on their contribution, function, stratigraphy and development in northeast Germany is well-developed with an increasing number of studies and publications in the last c. 20 years (Succow & Joosten 2001). The following overview offers (1) a presentation of generalised phases of regional peatland formation and information on long-term groundwater dynamics, (2) the identification of genetic relationships between rivers, lakes and peatlands, and (3) an outline of the impact of historic mill stowage on peatlands and lakes.

4.3.1 Peatland formation and groundwater-level changes
4.3.1.1 General development

In central Europe, eight hydrogenetic mire types – mires are undrained virgin peatlands (Koster & Favier 2005, Joosten 2008) – can be distinguished (Succow & Joosten 2001). They are defined by the topographic situation, the hydrologic conditions (water input) and the processes by which the peat is formed. This hydrogenetic setting is of great importance in deciphering (palaeo-) hydrologic information.

A statistical analysis of 168 palynostratigraphically investigated profiles from peatlands in northeast Germany reveals distinct periods of specific hydrogenetic mire formation (Couwenberg et al. 2001; Fig. 9). With a maximum age of c. 12,400 ^{14}C yrs BP (c. 14,600 cal yrs BP), swamp mires are the oldest peat-forming systems in the region. The first lake mires developed still in the Lateglacial at c. 11,500 ^{14}C yrs BP (c. 13,400 cal yrs BP), whereas first kettle-hole and percolation mires did not develop until the early Holocene. The first rain-fed mire development started as recently as in the mid-Holocene at c. 7500 ^{14}C yrs BP (c. 8300 cal yrs BP). Partly, this temporal sequence reflects a stratigraphic succession of different mire types at the same location. The comparatively late increase and onset of percolation mire and rain-fed mire formation could reflect the mid- to late Holocene increase of regional humidity. Furthermore, there is a conspicuous peaking for the formation of some mire types in Figure 9, partly followed by a rapid decline. Between c. 1000–500 yrs BP, swamp mires show a maximum formation period, which was attributed to strong anthropogenic deforestation (e.g. Brande 1986, Jeschke 1990, Bork et al. 1998, Wolters 2005). The declining number of kettle-hole, percolation and rain-fed mires in the last 1000 to 2000 yrs, on the other hand, reflects direct human impact in the form of hydro-melioration measures and peat cutting. This caused the cessation of peat formation and the disappearance of older peat layers.

In contrast to the numerous pollen diagrams from peatlands and accordant estimations of the local *relative* groundwater dynamics, only two curves of *absolute* groundwater levels exist so far for northeast Germany. For the Reichwalde lignite open cast mine (Niederlausitz area), a short-term curve covers the Lateglacial Bølling to Allerød chronozones, i.e. a total of c. 1400 years, showing the development from a relatively stable low to an instable high groundwater level (van der Kroft et al. 2002). The Holocene groundwater dynamics derived from the c. 11,500 years-long synthetic Rhinluch peatland record (west of Berlin) reveal a low level at the end of the early Holocene, an increasing level accompanied by fluctuations during the mid-Holocene and a maximum level in the late Subatlantic (Gramsch 2002; Fig. 7). A marked decrease of the groundwater level of c. 3 m occurred in the very late Subatlantic (18th-19th century AD), which was caused by local hydro-melioration measures (e.g. Zeitz 2001).

4.3.1.2 Peatlands in large river valleys

Close relationships between the development of rivers, lakes and peatlands existed particularly during the late Holocene complex paludification processes in large river valleys of the region. They are caused, on the one hand, by natural climatic and hydraulic changes and, on the other hand, by direct anthropogenic impact in the form of mill stowage (for the second see chapter 4.3.2).

The largest peatlands in the region are located in former ice marginal spillways of Brandenburg and Mecklenburg-Vorpommern. Beside local lake mires and widely-stretched (but typically small) floodplain mires accompanying the abundant rivers, vast swamp (paludification) mires occur.

The Havelländisches Luch (c. 300 km²) and Rhinluch (c. 230 km²) peatlands, for instance, form wide elongated depressions which were formed by glaciofluvial and glacial erosional processes during the Weichselian glaciation and by (glacio-) fluvial processes during deglaciation and afterwards (Weisse 2003). After a Pleniglacial fluvio-lacustrine phase leading to the deposition of vast amounts of sands ('Beckensand' in German), a number of small shallow lakes developed following dead-ice melting in the Lateglacial. During the early Holocene most lakes aggraded by both sedimentary infill and groundwater lowering (Fig. 7), forming local lake mires (Succow 2001a). Dated palaeosols in peat, fluvial and lacustrine sequences (8770 ± 160 to 4170 ± 150 cal yrs BP; Mundel 1996, Kaffke 2002) form a stratigraphic hiatus, which indicates regional groundwater lowering and reduced fluvial activity in the mid-Holocene to the early phase of the late Holocene. The former vegetation of the Havelländisches Luch peatland with dominating sedges and reed was largely

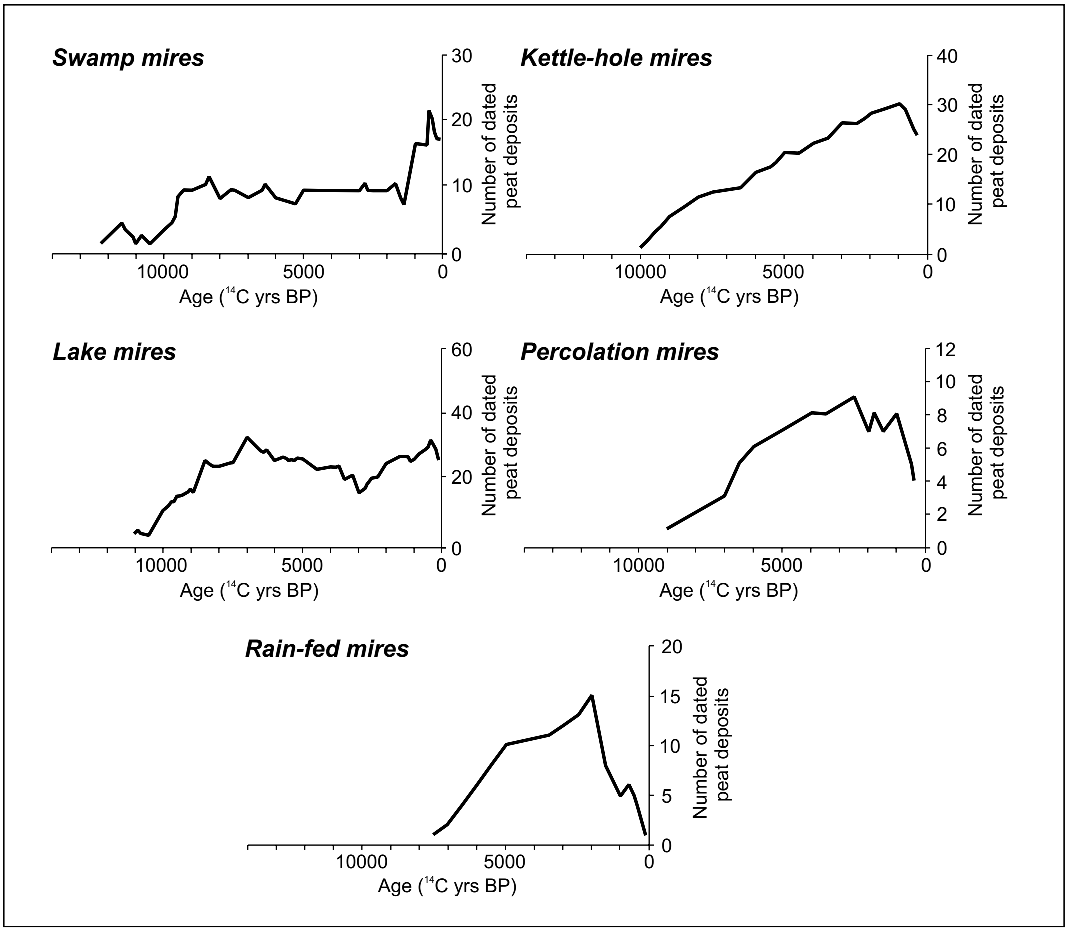

Fig. 9: Temporal distribution of palynologically dated peat and gyttja deposits of selected hydrogenetic mire types in northeast Germany (Couwenberg et al. 2001, adapted).

Abb. 9: Zeitliche Verteilung palynologisch datierter Torf- und Seeablagerungen ausgewählter hydrogenetischer Moortypen in Nordostdeutschland (Couwenberg et al. 2001, verändert).

replaced by wet forests consisting of oaks and alders (Kloss 1987a). In general, although local mire development in northeast Germany varies considerably, many peat sequences are characterised by this mid- to early late Holocene stratigraphic hiatus (e.g. Brande 1996, Succow 2001a, Wolters 2002, Janke 2004, Brande et al. 2007) reflecting the regional dry climatic conditions in that time. Looking at this from a wider perspective, this northeast German peatland-palaeosol (and hiatus) is apparently comparable with the so-called 'Black Floodplain Soil', a polygenetic buried humic soil horizon (Boreal-Atlantic) found in river valleys and basins of central and southern Germany (Rittweger 2000). Between c. 3800 cal yrs BP (Mundel 1996) and c. 2600 cal yrs BP (Kaffke 2002) an increase in groundwater occurred, causing regional paludification and local lake levels to rise. The vegetation shifted back from wet forests to reeds. Basically in that time vast swamp mires were formed transgrading onto former areas without peats. Two possibly superimposing reasons have been identified for this, namely a supra-regional late Holocene climatic shift to relatively wet-cool conditions (Mundel 1996; see more general: e.g. Zolitschka et al. 2003) and a regional damming-effect of the rising Elbe River bed, which was driven by the eustatic rise of the North Sea (Mundel 1996, Küster & Pötsch 1998; see more general: e.g. Behre 2007). This damming effect was linked to relatively high aggradation rates in the Elbe valley versus low rates in the Havel valley. The abundant lake basins in the Havel course serve even now as effective traps for river load (Weisse 2003). Thus the drainage of the Havel and its tributaries was impeded, causing a rise in the regional groundwater. No later than the mid-18th to early 19th century AD, regional peat growth stopped again, this time caused by hydro-melioration measures for agricultural use and peat cutting.

Close relationships between fluvial-lacustrine processes and mire development are also a characteristic of several low-lying river valleys of Vorpommern close to the Baltic Sea coast, which were strongly forced by marine influence (Janke 2002, Michaelis & Joosten 2010; see chapter 4.1.1).

4.3.2 Human impact on peatlands and lakes by mill stowage

In general, until the late 12th to early 13th century AD landscape hydrology in northeast Germany was dominantly driven by climatic (e.g. wet and dry phases), geomorphic (e.g. fluvial aggradation and incision) and non-anthropogenic biotic (e.g. beaver activity) factors. However, since the Neolithic, localised and phased hydrologic changes in catchments due to land-cover changes can be assumed.

During the German Medieval colonisation, the water mill technology was introduced by the west German and Flemish/Dutch settlers in eastern central Europe. For water mill

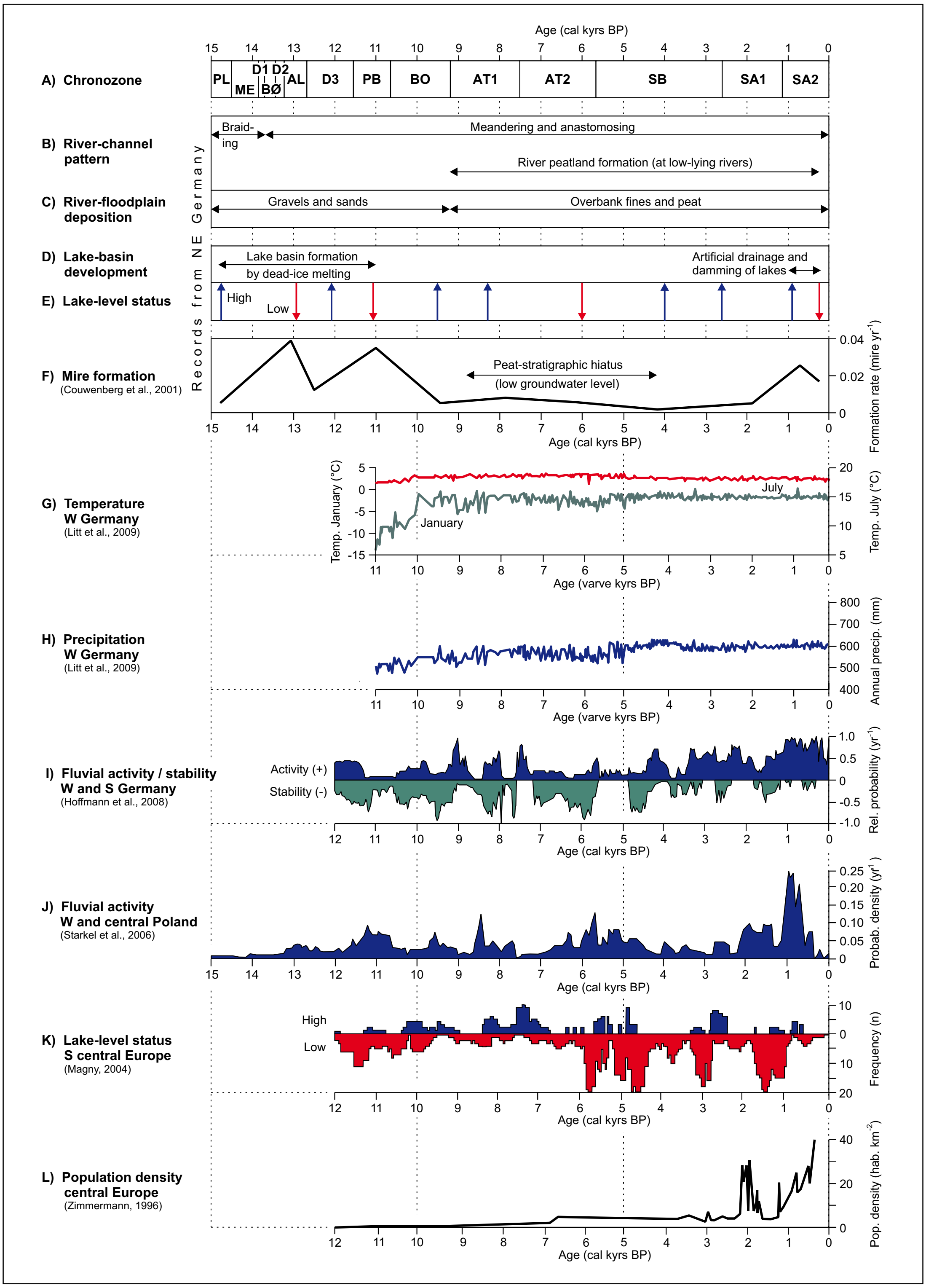

Fig. 10: Late Quaternary hydrologic changes in northeast Germany (B-F) plotted alongside further palaeoclimatic and palaeohydrologic proxy records (G-K) as well as population data (L) from central Europe. G-H: January and July temperatures and annual precipitation reconstructed from pollen data from annually laminated (varved) sediments of Lake Meerfelder Maar (Eifel region, west Germany), using pollen-transfer functions (Litt et al., 2009; adapted). I: Geomorphic activity (positive probability values) and stability (negative probability vales) based on CDPF analysis of west and south German fluvial deposits (Hoffmann et al. 2008, adapted). J: Geomorphic activity based on CDPF analysis of west and central Polish fluvial deposits (Starkel et al. 2006, adapted). K: Lake-level status reconstructed from lakes of southern central Europe (Jura, French Pre-Alps and Swiss Plateau; Magny 2004, adapted). L: population density of central Europe reconstructed from archaeological evidence (Zimmermann 1996, adapted).

Abb. 10: Spätquartäre hydrologische Veränderungen in Nordostdeutschland (B-F) dargestellt mit weiteren paläoklimatischen und paläohydrologischen Proxydaten (G-K) sowie paläodemografischen Daten (L) aus Mitteleuropa. G-H: Januar- und Juli-Temperaturen sowie Jahresniederschlag rekonstruiert anhand von Pollendaten (mittels Pollen-Transferfunktionen) aus den jahreszeitlich geschichteten (warvierten) Sedimenten des Meerfelder Maars (Eifel, Westdeutschland; Litt et al., 2009, verändert). I: Geomorphodynamische Aktivität (positive Wahrscheinlichkeitswerte) und Stabilität (negative Wahrscheinlichkeitswerte) basierend auf der CDPF-Analyse west- und süddeutscher fluvialer Ablagerungen (Hoffmann et al. 2008, verändert). J: Geomorphodynamische Aktivität basierend auf der CDPF-Analyse west- und mittelpolnischer fluvialer Ablagerungen (Starkel et al. 2006, verändert). K: Seespiegelstatus rekonstruiert für das südliche Mitteleuropa (Jura, französische Voralpen, Schweizer Mittelland; Magny 2004, verändert). L: Bevölkerungsdichte in Mitteleuropa rekonstruiert anhand archäologischer Befunde (Zimmermann 1996, verändert).

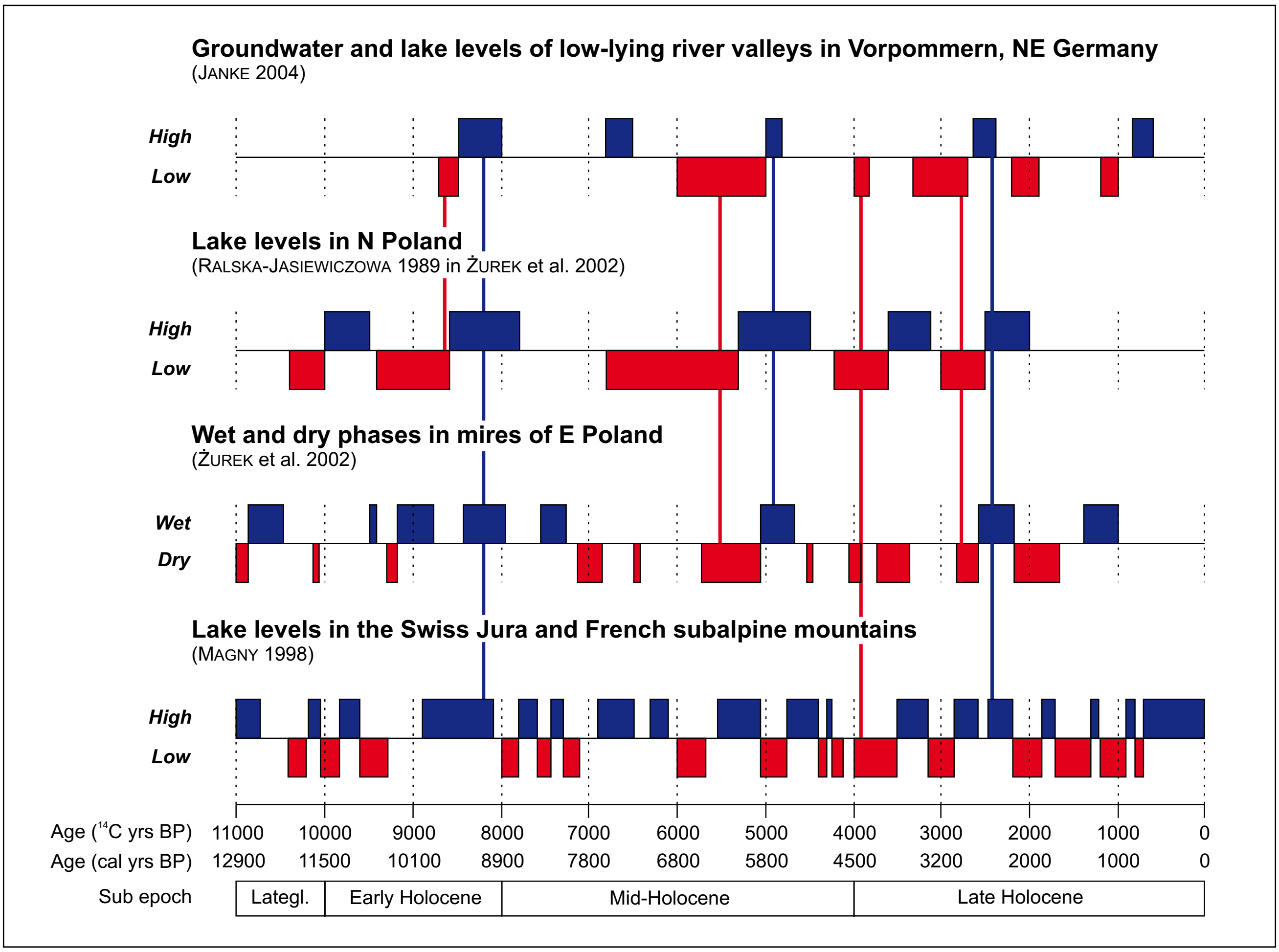

Fig. 11: Lateglacial and Holocene lake- and groundwater-level data from northern and southern central Europe (after various authors, adapted). Vertical bars mark synchronicity of wet (in blue) or dry (in red) phases.

Abb. 11: Spätglaziale und holozäne Seespiegel- und Grundwasserspiegeldynamik im nördlichen und südlichen Mitteleuropa (nach verschiedenen Autoren; verändert). Die vertikalen Linien markieren Synchronität feuchter (in blau) oder trockener (in rot) Phasen.

operation, a local water level difference of c. 1 m at minimum is required. This led to the construction of a multitude of mill dams and, accordingly, of dammed (mostly originally natural) lakes and of rising groundwater levels upstream (e.g. Schich 1994, Kaiser 1996, Driescher 2003, Bleile 2004, Nützmann et al. 2011). The operation of hundreds of water mills (together with fish weirs) drastically changed the Medieval hydrology in the region.

The phenomenon of 'mill stowage' ('Mühlenstau' in German) and its implications for settlement, economy and landscape was first systematically investigated by Beschoren (1935) and Herrmann (1959) particularly for the Spree and Havel Rivers, and later on extended by Driescher (2003) in the form of a multitude of local case studies in the wider region. The impacts of mill stowage on groundwater and lake levels, mire development and sedimentary processes are particularly well-investigated in the Berlin region. For the time-span 12th–14th century AD dated sequences from peatlands typically show a sudden change from highly to weakly decomposed peats or an inversion of the aggradation sequence (lake deposits overlying peats). These records were interpreted in terms of an intensification of mire formation and rising lake levels, respectively, by mill stowage (Brande 1986, 1996, Böse & Brande 1986, 2009, Küster & Kaiser 2010). Medium-scale rivers and their riparian zones, such as the Havel and Spree, were in part drastically influenced by these processes, whereas the large-scale Elbe River had no damming constructions but boat mills (Gräf 2006). Along the low-gradient middle Havel course, mill weirs in the cities of (Berlin-) Spandau and Brandenburg/Havel, which were constructed in the late 12th/early 13th century AD (Schich 1994), caused large-scale lake enlargements and paludifications (Kaiser et al. 2012b). Some smaller rivers and streams had a multitude of water mills ('mill staircases'). For instance, along a 20 km section of the upper Dahme River (Brandenburg) 14 mills were operated, some since the 13th/14th century AD (Juschus 2002), strongly changing the river gradient, the discharge process and the local groundwater level.

5 Synopsis

The temporal focus of this overview is the Late Quaternary comprising here the last c. 20,000 years and using a millennial scale. Accordingly, this synopsis will concentrate on this time span, comparing the regional results with those from other parts in central Europe and adding information (e.g. on climatic evolution), which is important for the understanding of the results presented. However, as the regional drainage system is influenced, on the one hand, by very long-term endogenic processes, and, on the other hand, has experienced a historically unprecedented strong change during the last c. 300 years (e.g. Blackbourn 2006, Kaiser et al. 2012b), these both time perspectives shall be touched at least by a glimpse.

5.1 Impact of neotectonic processes

As outlined in chapter 2, successive Pleistocene glaciations have formed the main relief and sedimentary settings in the North European Plain. However, the river system shows several conspicuous patterns – e.g. the asymmetric (right-skewed) catchments of the Elbe and Oder Rivers, a west oriented turn of the Havel and Spree Rivers, the nearly orthogonal valley grid of Vorpommern (Fig. 1) – which suggests the impact of neotectonic processes. Accordingly, several authors (e.g. Schirrmeister 1998, Reicherter et al. 2005, Sirocko et al. 2008) have asked to what extent does the present-day topography of the so-called 'North German Basin' mirror the heterogeneous structure of the basement? They stated that several river valleys (including spillways) and terminal moraines in northern Germany apparently run parallel to the major tectonic lineaments and block boundaries. Moreover, the drainage pattern and the distribution of lakes in north Germany exactly follow block boundaries and, hence, mark zones of present-day subsidence. The Tertiary morphology in that area was apparently draped by Quaternary glacial deposits, but rivers and lakes that dominate the topography of the modern landscape still reflect the geodynamic centres of Tertiary tectonism and halokinesis (Sirocko et al. 2002).

5.2 Climate impact

The synoptic Figure 10A-F shows a selection of results on Late Quaternary river, lake and peatland formation, which represent the regionally typical processes discussed in the previous sections. The temporal resolution of those results is quite coarse mostly covering a chronozone or representing, in general, a millennial scale. By contrast, comparing climatic, hydrologic, geomorphic and historic data from central Europe partly represent centennial- up to decadal-scale records (Fig. 10G-L). It should be borne in mind that the statistical basis for certain evidence in northeast Germany partly is still small (e.g. on the lake-level status).

In this region, climate was the dominant driver for geomorphic and hydrologic changes up to the late Holocene intensification of land use by man. With the exception of neotectonic processes of yet inadequately known impact even the partly considerably effective sea level rise of the North and Baltic Seas is ultimately climate-driven. Within this climate-controlled setting local geomorphic and biotic processes operated (e.g. dead-ice melting, fluvial aggradation/incision, mire formation).

However, there is no specific (high-resolution) Late Quaternary *climate record* from northeast Germany available so far except those that cover relatively short periods (e.g. Büntgen et al. 2011). Hence the pollen-based high-resolution record from Lake Maarfelder Maar (Eifel region, west Germany; Litt et al. 2009) can be used to characterise some climatic trends at least for the Holocene, which, in general, can be assumed even for northeast Germany. In particular for the relatively dry-warm early Holocene and the wet-warm mid-Holocene ('Holocene optimum' between c. 8000–5000 varve yrs BP; Wanner et al. 2009) some simultaneous hydrologic phenomena of northeast Germany (e.g. early Holocene lake-level lowstands, mid-Holocene groundwater lowering in peatlands) can be presumably ascribed to direct climatic impact. Geochronological data from river catchments of west and south Germany as well as west and central Poland allow some general assumptions on *palaeodischarge and palaeoflood dynamics*, which can be hypothesised even for the region under study. Large datasets of ^{14}C ages obtained from late Quaternary fluvial units were analysed using cumulative probability density functions (CPDFs) in order to identify phases of fluvial activity (floods) and stability (Starkel et al. 2006, Koślacz et al. 2007, Hoffmann et al. 2008; Fig. 10I, J). In the west and south German record (Fig. 10I), several periods of fluvial activity were identified and compared to climatic, palaeohydrologic and human impact proxy data. Until c. 4250 cal yrs BP, events of fluvial activity are mainly coupled to wetter and/or cooler climatic phases. Due to growing population and intensive agricultural activities during the Bronze Age the increased fluvial activity between c. 3300 and 2820 cal yrs BP cannot unequivocally be related to climate. Since 875 AD the growing population density (Fig. 10L) is via landcover changes in the catchments (increasing arable land and pastures, decreasing forests) considered as the major external forcing (Hoffmann et al. 2008). Similar curve characteristics of CPDFs from ^{14}C data on fluvial units show records from west and central Poland (Starkel et al. 2006; Fig. 10J), allowing corresponding conclusions.

From southern central Europe a data set of 180 radiocarbon, tree-ring and archaeological dates obtained from sediment sequences of 26 lakes was used by Magny (2004) to construct a regional Holocene lake-level record (Fig. 10K). The dates form clusters suggesting an alternation of lower and higher, climatically driven lake-level phases. The comparison of *relative* Holocene lake- and groundwater-level data from north and south central Europe reveals some distinct synchronicities of wet and dry phases, but also some distinct disparities (Ralska-Jasiewiczowa 1989, Kaiser 1996, Magny 1998, Wojciechowski 1999, Kleinmann et al. 2000, Żurek et al. 2002, Janke 2004; Fig. 11). In general, synchronic correlation of identical phases works far better within nearby German and Polish sites of northern central Europe. In comparison to the southern central European record, however, these records appear to be somewhat 'monolithic', which probably is caused by a low temporal resolution. For the early Holocene, the lake-level record in northeast Germany and north Poland shows a clear tendency towards low levels. This is not reflected in the mire record of east Poland that widely indicates a wet phase. The late Boreal and partly the early Atlantic is characterised by increasing lake and groundwater levels followed by a decrease in the late Atlantic. The beginning and mid-late Holocene (c. 2500 cal yrs BP) reveals wet phases, whereas a dry phase lies in between. The general wet-dry pattern inferred correlates well with major Holocene climatic episodes (e.g. Harrison et al. 1993, Magny 2004, Litt et al. 2009, Wanner et al. 2009).

A synoptic view on the northeast German results (Fig.

Tab. 6: Examples of new and promising palaeohydrologic research topics for northeast Germany.

Tab. 6: Beispiele für neue, vielversprechende Forschungsthemen zur Paläohydrologie/Historischen Hydrologie in Nordostdeutschland.

Research field	Remarks
Exploration and combination of proxies	Using new proxies and new combinations of proxies for deciphering and validating of palaeohydrologic information (e.g. tree ring data, near-shore and shoreline sediments of lakes, palaeosols of wetlands)
Human induced lake drainage	Exploring the occurrence and the rewetting potential of lake basins drained by historic anthropogenic hydromelioration
Human induced lake formation	Exploring the properties and genesis of lakes and ponds formed in Medieval times and afterwards; deciphering historic hydrologic information from young deposits / geoarchives
Long hydrologic time series	Linking instrumental records of specific hydrologic parameters (observations e.g. by gauging) with proxy records from geoarchives
Quantitative palaeohydrology	Combining palaeohydrologic field records with hydrologic modelling at different areal and temporal scales
Reference status of wetlands	Reconstructing the (near-) natural status of wetlands; i.e. before human impact has sustainably changed the aquatic environments

10B-F) and on evidence from other central European regions (Fig. 10G-L) reveals some concordances. But even discrepancies become apparent, partly within a type of proxy. Reasons for this might be, on the one hand, real differences in the regional hydrologic evolution, which are partly caused by different (pre-)historic human impact. On the other hand, a partly drastically different statistical base for the parameters presented is to consider. For example, a few data on the lake-level status in northeast Germany contrast a large database in southern central Europe. Thus future research possibly will modify the regional information available.

5.3 Pre-modern and modern human impact

First *intended* changes of the regional hydrography date from late Medieval times (since the late 12th century AD). In parallel the regional forests were widely cleared (Bork et al. 1998; Tab. 5), causing several *unintended* hydrologic changes such as rising groundwater and lakes followed by increasing fluvial discharge. In the period 18th to first half of the 20th century AD most of the peatlands were transformed by hydromelioration into *extensive* grasslands (Schultz-Sternberg et al. 2000). In parallel a dense network of channels for inland navigation was formed and most channels of large rivers were modified by hydraulic engineering.

The most intensive changes, however, did not occur until the last c. 50–60 years. The peatlands were nearly totally transformed into *intensive* grassland and arable land by complex melioration measures (e.g. Succow 2001b); only 2 % of the original mires remained in a near-natural status (Couwenberg & Joosten 2001). In Mecklenburg-Vorpommern, for instance, for the period 1965–1995 a total loss of c. 290 km^2 peatlands by peat decomposition was calculated, which accounts for c. 13 % of the state's pre-modern peatland area (Lenschow 2001). Even as a consequence of hydro-melioration measures in parallel with climatic and land-cover changes, the groundwater level of the first aquifer significantly dropped (1–2 m) at a regional scale, particular in Brandenburg, causing in many cases lake-level lowerings (e.g. Germer et al. 2011, Kaiser et al. 2012b).

Furthermore, lignite open cast mining has drastically changed vast areas in some regions. In the Niederlausitz region a total of c. 800 km^2 was required for mining activity so far. A large number of artificial lakes and connective canals were formed by flooding of disused open-cast mines, forming the 'Lausitzer Seenland' (Grünewald 2008). In the near future the lake area here amounts to a total of c. 250 km^2. In the Leipzig-Halle-Bitterfeld area the total area of anthropogenic lakes in the mid-21st century AD will result in c. 70 km^2, forming the 'Neue Mitteldeutsche Seenlandschaft' (Czegka et al. 2008). If the total area of natural lakes in northeast Germany is considered (c. 1300 km^2; Korczynski et al. 2005), artificially dug 'new lakes' (c. 320 km^2) will form a portion of c. 20 % of the total lake area soon of c. 1620 km^2.

Thus in modern times, man became by several impacts a very important geomorphic and hydrologic factor in the region. With respect on the pace and magnitude his influence exceeds natural changes by climate and natural geomorphic processes.

5.4 Final remarks and research perspectives

The results presented here on the partly interdependent development of the main aquatic (inland) environments in northeast Germany hold treasures for those seeking to understand the long-term hydrologic dynamics of these ecosystems. Many modern day issues, such as understanding the causes of present hydrologic changes, re-evaluation of land use strategies and implementation of restoration measures, can profit from being looked at from a longer temporal perspective. Periodic hydrologic change is the 'normal status' of the environments discussed. But even if the current regional hydrologic change, probably strongly triggered by man-made global climate change, should be exceptional with respect to its pace and magnitude, historic analogies may help to understand or even foresee complex future landscape dynamics.

As shown above, a number of principle questions on regional palaeohydrology have been posed periodically – gaining in significance each time they resurface. Research over the last c. 20 years has generally made progress in terms of expanding the regional thematic knowledge base. What is new for the region is the growth in well-documented *local* field findings with a broad range of accompanying lab analyses, particularly of geochronological and palaeoecological data. These have been complemented with (semi-) quantitative data on the development of specific hydrologic parameters (e.g. on river-channel patterns or lake-level status) as well as summaries of certain processes (e.g. on peatland formation) in several studies. Even some specific geomorphic and sedimentary-pedologic features were newly discovered for the region (e.g. fluvio-deltaic sequences / fan-deltas in lake basins, palaeosols / hiatuses in peatlands).

New research is needed to refine knowledge on the long-term development of the regional drainage system and its specific aquatic environments. This includes the establishment of hydrologic records with high temporal resolution, which are widely missing in the region so far. In addition, new and particularly promising regional research aspects still abound; some examples are listed in Table 6.

6 Conclusions

(1) Regional research performed on late Quaternary palaeohydrology has largely concentrated on single aquatic environments and single hydrologic parameters so far. But the drainage pattern evolution as a system was rarely in focus. This first comprehensive overview on drainage system evolution in northeast Germany has shown in detail how rivers, lakes and peatlands developed partly interdependently during the last c. 20,000 years.

(2) Until the late Holocene (c. 12th/13th century AD), landscape hydrology in northeast Germany was predominantly driven by climate, including geomorphic and non-anthropogenic biotic factors. Furthermore, initial structural geologic findings suggest that tectonic and halokinetic influence played a more pronounced role on late Quaternary hydrographic evolution than previously assumed. The first *indented* anthropogenic changes of the regional hydrography date from the late Medieval. Strong human impacts on a regional scale occurred from the 18th century AD onwards. In modern times, man's impact exceeds the natural changes caused by natural climatic and geomorphic processes.

(3) Although certain aspects of regional drainage network evolution have attracted considerable interest, the general state of thematic knowledge can be characterised as 'moderate' at best. For example, (a) the late Quaternary development of the large rivers (Elbe, Oder) and most of the medium-scale rivers (e.g. Havel, Spree) is only initially known; (b) high-resolution lake-level records are not yet available; (c) estimations of palaeodischarge and palaeoflood characteristics are widely lacking; (d) the aspect of climatic versus human forcing of past hydrologic processes has rarely been pursued so far; and (e) the role of beavers as effective 'engineers' forming Holocene aquatic landscapes has not yet been approached in the region.

(4) To overcome these deficiencies new research is necessary. Several current and planned projects on river valley and peatland restoration in the region open promising opportunities for the regular integration of palaeohydrologic work into present issues. Future research, more than previously, should aim at developing and integrating multiproxy records from a variety of scientific perspectives. Close links to high resolution records of climate and human impact, which regionally are still to be established, must be encouraged and fostered.

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