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HOW DID THE NUTRIENT CONCENTRATIONS CHANGE IN NORTHEASTERN GERMAN LOWLAND RIVERS DURING THE LAST FOUR MILLENNIA? – A PALEOLIMNOLOGICAL STUDY OF FLOODPLAIN SEDIMENTS

Ilka Schönfelder[1,2], Christian E. W. Steinberg[2]

[1] Brandenburg Office for the Environment, Department of Ecology, Berliner Str. 21–25, D-14467 Potsdam, Germany, e-mail: schoenfelder@igb-berlin.de

[2] Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, D-12587 Berlin, Germany

Abstract

This study focuses on the feasibility of floodplain sediments and fluvial sediments in paleomeanders and ox-bows of two lowland rivers (River Havel, River Spree, Brandenburg State, Germany) as archives for quantitative paleolimnological reconstructions and potential basis of future river management strategies. The results presented provide a mean to differentiate between the natural and cultural eutrophication of rivers. Available transfer functions of littoral diatom assemblages in 84 Brandenburg lakes and river sites, and total phosphorus (TP) and total inorganic nitrogen (TN) were used to infer nutrient changes in the Rivers Havel and Spree since the last 4,000 years. In the River Spree near Platkow, fossil diatoms indicated moderate eutrophic TP- and TN-concentrations between 1300 and 1850 AD (TP: 36 $\mu g\ dm^{-3}$, TN: 1,000 $\mu g\ dm^{-3}$). During this time period, the human impact on the nutrient status of the River Spree was more or less indirect via increases of runoff from the catchment as a result of deforestation. In the second lowland river, the lower River Havel, diatom inferred TP-concentrations were 80 $\mu g\ dm^{-3}$ in the late Subboreal (2,000 to 500 BC). That means that the natural diatom flora of this river was eutrophic; mesotrophic conditions even in times without intensive land use did not occur. Furthermore, the fossil diatom flora revealed a potential nitrogen limitation during summer times (till 1400 AD: TN 1,600 to 1,700 $\mu g\ dm^{-3}$). Anthropogenic eutrophication impact on the River Havel can be detected since approximately 800 year ago. The diatom-inferred nitrogen/phosphorus-relation highlighted different trends in eutrophication history within the study area. Without human activities the ratio of both nutrient components was relatively constant. Anthropogenic changes in the catchment area led to a declining TN/TP ratio in the last 1,000 years with changes in algal communities, such as increases of nuisance cyanobacteria blooms in the last decades.

Key words: paleolimnology, littoral diatoms, floodplain sediments, river, total phosphorus, total nitrogen, quantitative reconstruction, natural eutrophic conditions

INTRODUCTION

Quantitative records of natural and pre-industrial nutrient concentrations of rivers and lakes are not available from direct measurements. To overcome this lack of information, modern paleolimnology has developed quantitative techniques for the reconstruction of freshwater environments, which are based on numerical transfer functions between microfossil assemblages in recent surface sediments and present-day measurements of environmental variables. The sediment record can easily be verified by consulting written sources, *e.g.* urbanization and cultivation that enables to decide whether past trophic changes are related to natural succession or reflect effects of human impact, respectively.

Recent studies have proven the advantage of diatom assemblages as biological indicators for chemical and physical factors, particularly in lacustrine ecosystems (*e.g.* Stoermer, Smol 1999, Schönfelder 2000). Total phosphorus (TP) concentration is not only the factor that controls epilimnetic chlorophyll *a* content, but usually has a major influence on the taxonomic composition of diatom assemblages. Hence, shifts in fossil diatom assemblages can be quantitatively related to past TP concentrations by transfer functions (*e.g.* Hall, Smol 1992, Fritz *et al.* 1993, Bennion 1994, Reavie *et al.* 1995, Wunsam, Schmidt 1995, Lotter *et al.* 1998). Another nutrient, total nitrogen, TN, may control the qualitative and quantitative algal development, and a number of diatom-based TN-transfer functions have been published (Christie, Smol 1993, Siver 1999, Reavie, Smol 2001, Rühland, Smol 2002, Schönfelder *et al.* 2002).

For paleolimnological approaches, the prerequisite are undisturbed and dated sediments. Isotopes dates or pollen stratification put the environmental inferences into a chronology. Stratified sediments from deep lakes are typical ob-

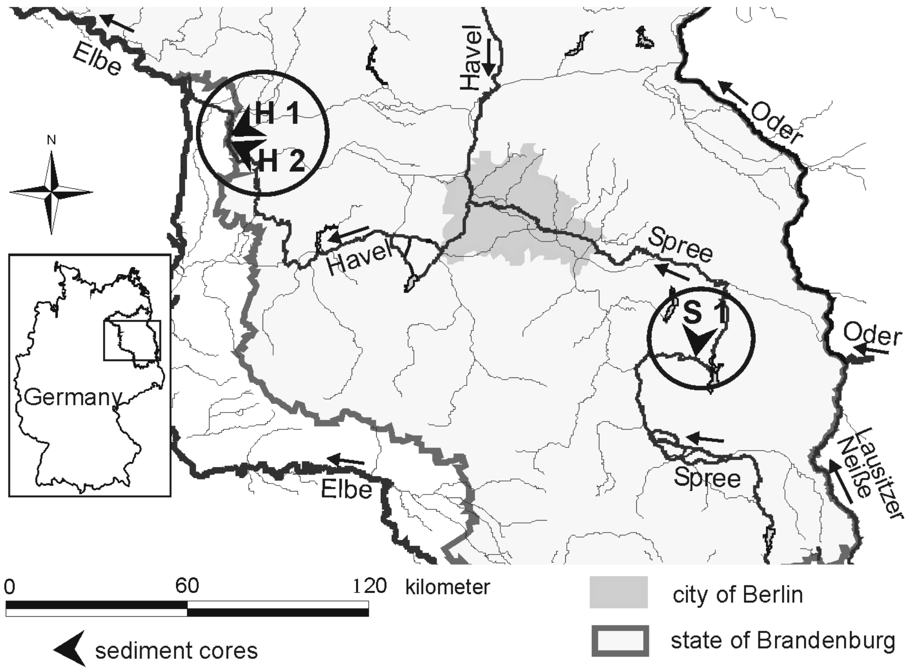

Fig. 1. Locations of the coring sites in Brandenburg, Germany.

jects for paleolimnological research (Battarbee 1986), and the cradle of paleolimnology stood beside deep, stratifying lakes, rather than rivers or shallow lakes. However, there is no general reason to assume that lenitic river habitats such ox-bows and paleomeanders in floodplains of lowland rivers, flushed lakes, or delta regions do not facilitate a continuous sedimentation of diatom frustules; but the paleolimnology of riverine systems is poorly understood (Serieyssol, Krier 1995, Hay *et al.* 1997, Reavie *et al.* 1998). The present study focuses on paleohydrological and geomorphologic features. By studying the lowland River Havel, Germany, Schönfelder (1997) showed the potential of fluvial sediments to even reconstruct past nutrient concentrations (TP, TN). However, quantitative records of nutrient conditions of rivers in the last 4,000 years, as presented in this study, have not been reported before.

To infer reference conditions for management purposes as well as to gain better understanding of the functioning of lowland river basin ecosystems, we surveyed riverine sediments of the lowland Rivers Havel and Spree, Germany. Well-preserved fossil diatom assemblages were found in paleomeander sediments of the lower River Havel floodplain and in ox-bows of the River Spree. We assume that transfer functions, based on diatom assemblages from the deepest points of stratifying lakes are inappropriate for floodplain habitats, since these diatom communities are dominated by littoral taxa. In particular, large benthic diatoms occupy all littoral substrates in high numbers, but are clearly underrepresented in profundal lake sediments (Hofmann 1994, Schönfelder 1997). Hence, littoral diatom assemblages provide a more appropriate tool for inferring paleo-environmental conditions in lotic freshwater systems.

In this paper we used quantitative weighted average (WA) inference models for annual mean TP concentration and annual mean total nitrogen (TN) concentration based on littoral diatom assemblages from 84 rivers and lakes in Germany (Schönfelder *et al.* 2002). The root-mean-square errors of prediction (RMSEP) of the models were estimated by jackknifing.

The goals of the study are:

1. The application of available transfer functions to pioneer quantitative reconstructions of the past trophic status of two lowland rivers up to 4,000 years ago;
2. To infer the pre-cultural (≈natural) trophic status of the lowland River Havel in order to derive realistic restoration targets;
3. To relate the fossil diatom records to long-term dynamics in the floodplain hydrology of the River Havel.

STUDY AREA, MATERIAL, AND METHODS

Study area

The study area is part of the central European lowland ecoregion (Illies 1978). The freshwaters of this region were formed by glaciation, deglaciation, and glacifluvial processes at the southern edge of the Weichselian ice shield between 20,000 and 14,000 years ago. The morphology of the Rivers Spree and Havel is characterized by numerous lake-like extensions, which serve as traps for seston and nutrients. All these riverine lakes within the courses of the Rivers Spree and Havel are shallow and at present highly eutrophic (TP > 60 $\mu g\ dm^{-3}$), or even polytrophic (TP > 100 $\mu g\ dm^{-3}$).

The floodplain of the lower River Havel is situated 80 km west of the city of Berlin (Fig. 1). Its catchment area is about 24,000 km^2. The predominant soil type is loamy sand, rich in calcium carbonate, thus the water of the River Havel is alkaline. More than 60% of the catchment area is arable land.

The forest in the catchment is dominated by pine (*Pinus sylvestris*) and oak (*Quercus robur*). The discharge of the slow-flowing river varies between 14 and 284 (mean 105) $m^3 s^{-1}$ (State Office for Environment and Nature Sachsen-Anhalt, pers. comm.). The study site is 23 m above sea level. Seven upstream lakes influence the algal communities of the lower River Havel. Paleomeanders in different stages of succession are preserved and function as sediment traps in the central part of the floodplain. The sediments in these paleomeanders consist of peat with pollen and well preserved fossil diatom assemblages resulting from both autochthonous algal growth and allochthonous ones washed in during flood events. Pollen records show a local dominance of natural wet to dry grassland vegetation in the floodplain without signs of anthropogenic influences during the Holocene (Schelski 1997).

The River Spree rises from the Lausitzer Bergland and flows within the city of Berlin into the Havel. The basin of the River Spree has a size of 10,104 km^2. Along its length of 403 km the Spree shows a downward gradient of 468 m. Our Study area, the lower Spree valley has even a weaker downward gradient of approximately 1 m per 10 km. The river is regulated and the current velocities range from 0.1 $m\ s^{-1}$ in summer to 0.6 $m\ s^{-1}$ in winter.

Sediment coring and dating

Two paleomeanders were cored in the floodplain of the River Havel, using a Russian chamber corer (Lang 1994, p.39). Four samples of peat from each core were dated by radiocarbon (^{14}C) and calibrated following Stuiver and Reimer (1993). Pollen analysis agreed well with the radiocarbon dating and gave evidence for an undisturbed sedimentation (Schelski 1997).

Core H 1 (Fig. 1) was retrieved from a paleomeander at Hünemörder Island approximately 300 m away from the two main river arms near Gülpe. The core length was 2.75 m. Pollen and radiocarbon dates indicate that this meander was separated from the main river during the late glacial. The habitat is regularly flooded and connected to the river in winter. The diatom flora preserved in the upper half of the core representing approximately the last 5,000 years. During summer, the paleomeander usually dries out. Core H 2 was 2.00 m long and taken in a paleochannel, 20 m away from the river. The diatom flora of this core reflects the situation of the river of the last 4,000 years. From the River Spree, we used fluvial sediments in an ox-bow near Platkow (S 1, Fig. 1).

Sub sampling, diatom preparation and identification

The cores were cut into 1 cm slices. Diatoms were studied at 5 cm intervals. Preparation procedures followed Krammer and Lange-Bertalot (1986), using hydrogen peroxide as oxidant and Naphrax (R.I. = 1.74, Northern Biological Supplies) as mountant. For counting, a Nikon FXA microscope was used with 60 x and 100 x objectives, Numerical Aperture = 1.40, and Normarski interference optics. Identification followed Krammer and Lange-Bertalot (1986–1991), Lange-Bertalot (1993), Lange-Bertalot and Metzeltin (1996). Between 800 and 1300 valves were counted per sample. The samples were checked for rare taxa after counting. Additional taxa were enumerated as 0.1 individuals per sample.

Table 1

Trophic classification of lake and river sites in Brandenburg, based on measured TP-concentrations in the euphotic zone. Logarithmically equidistant fixed limit values are appropriate for the phosphorus trophic classes as the base

Trophic classes	Mean value for ln TP	Gradient range TP, mg dm-3
Oligotrophic	2.2	7.0 - 11.6
Oligo- to mesotrophic	2.7	11.6 - 19.1
Mesotrophic	3.2	19.1 - 31.5
Meso- to eutrophic	3.7	31.5 - 51.9
Eutrophic	4.2	51.9 - 85.6
Eu- to polytrophic	4.7	85.6 - 141.2
Polytrophic	5.2	141.2 - 232.8
Poly- to hypertrophic	5.7	232.8 - 383.8
Hypertrophic	6.2	>383.8

Calibration data set, ordination, and inference models

Littoral diatom samples from stones and macrophytes of 69 lake and 15 river sites in Brandenburg State were used to establish diatom transfer function for TP and TN, which allow the inference of past trophic conditions (Schönfelder *et al.* 2002). The 84 study sites cover a range from 9 to 1,687 µg dm^{-3} TP and 320 to 6750 µg dm^{-3} TN. While the trophic classification of lakes, based on phosphorus concentrations, has a long international tradition (OECD 1982, LAWA 1999), a generally agreed trophic classification for running waters is not yet available. With this respect, Schönfelder (1997) used a logarithmic equidistant scale for TP (Table 1) and pooled both lenitic and lotic sites. A detailed description of the rivers and lakes of the recent calibration data set is given in Schönfelder *et al.* (2002).

304 out of 540 diatom taxa in the calibration data set fulfilled the following selection criteria: (1) present in samples from at least three sites and to be found in relative abundance of at least 0.5% in at least one sample; or (2) recorded at more than three sites. We are aware of the fact that the effect of one given TP concentration may be different in lenitic and in lotic systems; TP concentrations or trophic classification based on them do not equal the bioavailability of the TP concentrations. Hence, the use of trophic terms only refers to TP concentrations, rather than trophic effects or symptoms.

RESULTS

Diatom stratigraphy in the floodplain sediments of the River Havel

The most typical planktonic diatom taxa of the River Havel and associated riverine lakes have been *Aulacoseira granulata* (Ehrenberg) Simonsen and *A. ambigua* (Grunow) Simonsen (core H2, Fig. 2). The stratigraphy patterns of ben-

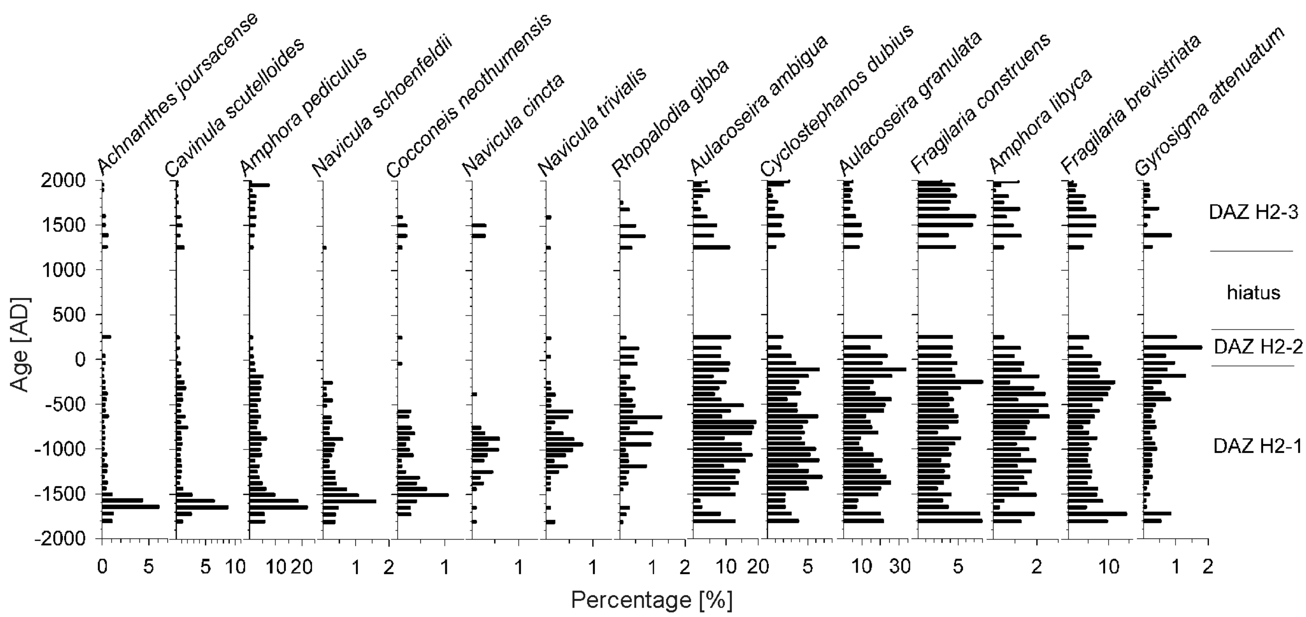

Fig. 2. Stratigraphy of selected diatom taxa from floodplain sediments of the River Havel (core H2).

thic diatoms indicate three ecological zones (Diatom Assemblage Zone = DAZ, Fig. 2). Zone DAZ H2–1 (200 cm to 80 cm) is identical with the Subboreal chronozone (Schelski 1997). At the beginning of the paleomeander succession (200 to 170 cm) at approximately 2,000 BC, a diatom flora typical of epipsammic or epilithic substrates was found. Some taxa peaked at a depth of 185 to 175 cm (Fig. 2), *e.g. Planothidium joursacense* (Heribaud) Lange-Bertalot, *Amphora pediculus* (Kützing) Grunow, *Cavinula scutelloides* W. Smith (D.G. Mann), *Geissleria schoenfeldii* (Hustedt) Lange-Bertalot & Metzeltin, and *Cocconeis neothumensis* Krammer. Apart from a slow decrease in the relative abundance of epipsammic taxa after 3,000 BP, which can be related to the progressing succession of the paleochannel, no significant floristic change occurred between 2,000 BC and 200 BC. Therefore, Subboreal diatom assemblages of the River Havel are considered to reflect the pristine but eutrophic fluvial environment.

The second zone (DAZ H2-2, 200 BC to 300 AD; 70 to 35 cm) is characterized by a peak development of some epiphytic eutraphent taxa. Special interest should be focused on the Epithemiaceae, *e.g. Epithemia adnata* (Kützing) Brébisson, *E. turgida* (Ehrenberg) Kützing (Fig. 3), *E. sorex* Kützing, and *Rhopalodia gibba* (Ehrenberg) O. Müller. Zone DAZ H2-2 reflects minor changes in the flora, chronologically related to the early German settling era before the peoples migration phase (after 300 AD). The period of 300 to 1200 AD, constitutes a hiatus, the record of this period does not exist in core H2. The third zone, beginning 35 cm below the floodplain surface (1200 AD), shows rapid floristic changes. One important fact is the occurrence of numerous *Pinnularia* species after 1200 AD. A large number of species reached peak relative abundances between 1650 and 1850 AD. These were *Fragilaria capucina* var. *vaucheriae* (Kützing) Lange-Bertalot, *Cocconeis pediculus* Ehrenberg, *Achnanthes minutissima* Kützing, *Meridion circulare* (Greville) Agardh, and *Gomphonema olivaceum* (Hornemann) Brébisson. Only two species, *Achnanthes lanceolata* (Brébisson) Grunow and *Fragilaria nitzschioides* Grunow, showed distinct peaks in development after 1850. One species emerges in the third zone as an exotic species: *Actinocyclus normanii* (Gregory) Hustedt. It appeared in the River Havel sediments at approximately 1900 AD and has not been found in any earlier sample (Fig. 3).

Quantitative TP and TN inferences

In Core H2, the quantitative inference indicates natural TP variations in the range of 55 to 95 μg dm^{-3} for the time 2,000 to 200 BC. Only minor changes in the inferred TP concentrations were reconstructed for the period 200 BC to 300 AD. At this time, TP ranged from 80 to 115 μg dm^{-3} (Fig. 4)

A significant increase of the TP concentration from 58 to 170 μg dm^{-3} was inferred for the time after 1200 AD. The most striking increase of TP was inferred for recent two hundred years. Inferred TN concentrations paralleled TP, but were less dynamic. During the period of 2000 to 200 BC, the TN concentrations can be considered natural, ranging from 1,400 to 1,900 μg dm^{-3}. A rapid increase of the TN concentration from 1,600 to 2,600 μg dm^{-3} was inferred for the time after 1200 AD. For the time after 1700, a clear decline of the TN/TP-ratio was observed.

Flood dynamics

The sum of the relative abundances of planktonic taxa in the fossil assemblages of central floodplain core H1 changed with time (Fig. 5). We interpret the occurrence of planktonic species in floodplain sediments as the result of flood events with flooded plains acting as shallow lakes, favoring some plankton diatom development. The diatom assemblages from the Preboreal chronozone (10,000 to 9,000 BP) and the

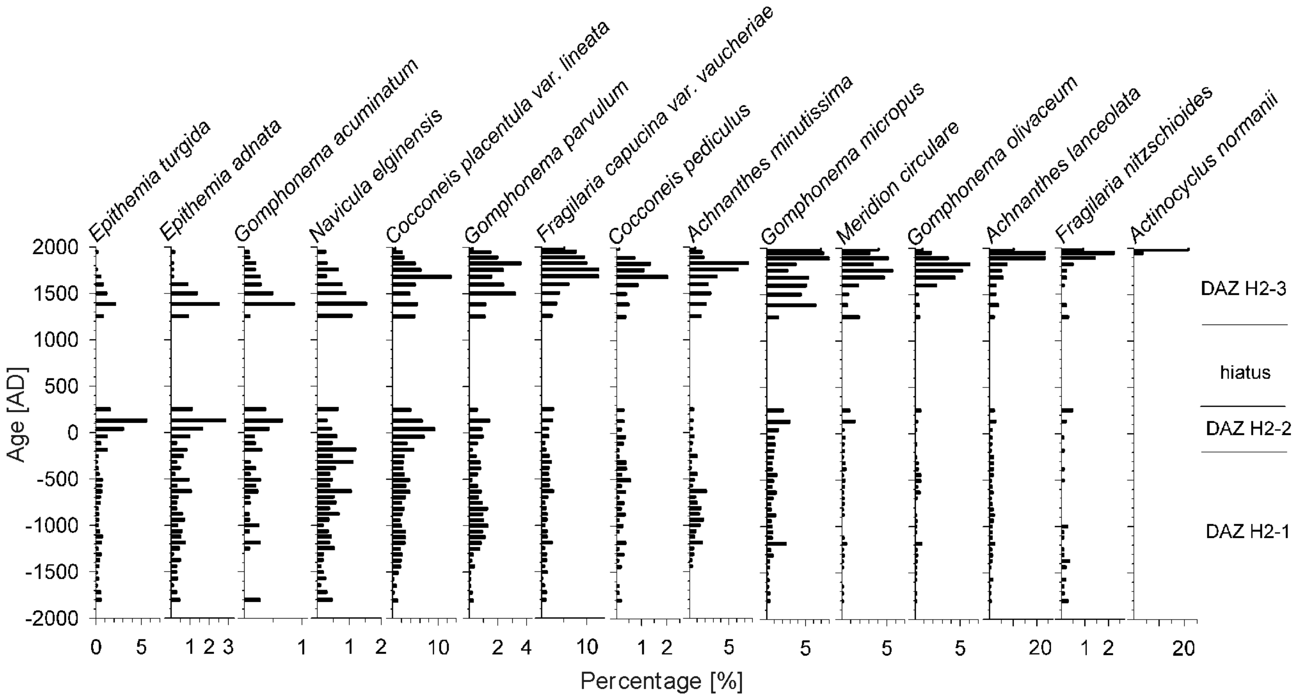

Fig. 3. Stratigraphy of selected diatom taxa from floodplain sediments of the River Havel (core H2).

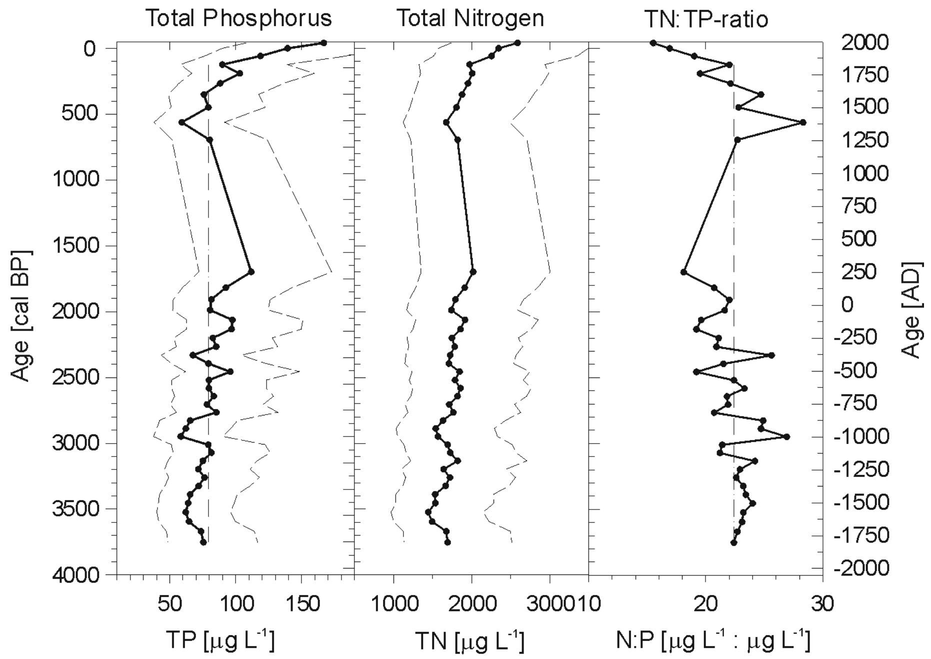

Fig. 4. Diatom-inferred TP and TN concentration and the TN/TP ratio of River Havel (core H2) in the last 4,000 years. The broken lines are the 95% confidence intervals

Boreal chronozone (9,000 to 8,000 BP) were poor in species with poorly preserved valves. The most abundant taxon between the fine sand grains was *Aulacoseira granulata* (Ehrenberg) Simonsen. The same situation was identified for the samples from the early Atlantic chronozone (8,000 to 7,000 BP). The Subboreal sediments of core H1 contained large proportions of silt and only low proportions of peat. These silty sediments contained high relative abundance of planktonic forms. Comparatively low was the loss on ignition in the Subatlantic sediment chronozone of core H1. The peat growth at the site of core H1 began at about 1000 AD.

Diatom stratifigraphy of the River Spree sediments

Changes in the benthic diatom assemblages allowed us dividing core S1 into three distinct zones (DAZ 1-3). The first zone (DAZ S1-1, 1350 to 1450 AD) is characterized by

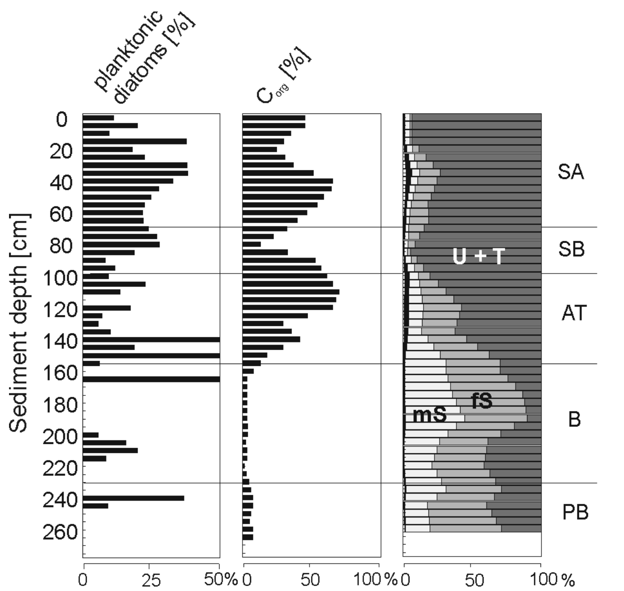

Fig. 5. The sum of the dominance values of planktonic taxa in floodplain sediments (core H1) and results of the sediment analysis reflects flood dynamics. particle size range: U+T = clay, fS = fine sand, mS = middle sand.

the occurrence of *Achnanthes delicatula* (Kützing) Grunow and *Navicula viridula* (Kützing) Ehrenberg (Fig. 6). *Cyclotella meneghiniana* Kützing showed its highest relative abundance in this early stage of the ox-bow development. The second zone (DAZ S1-2, 1450 to 1890 AD) is characterized by high percentages of *Cocconeis placentula* var. *lineata* (Ehrenberg) Van Heurck, *Tabellaria flocculosa* (Roth) Kützing, *Epithemia adnata*, *E. turgida*, and *Rhopalodia gibba*.

A few species, *e.g. Meridion circulare*, *Gomphonema micropus* Kützing, *Eunotia botuliformis* Wild, Nörpel & Lange-Bertalot, and *Stauroneis kriegerii* Patrick peaked after 1900 AD, indicating the beginning of the zone DAZ S1-3. *Achnanthes lanceolata* was the only species, which appeared for the first time in the sediment after 1950 AD.

Quantitative TP and TN inferences

The inferred TP concentrations in the River Spree at Platkow ranged from 30 to 57 µg dm^{-3} for the time before 1900 AD (Fig. 7). Only very minor alternations in the range from 30 to 40 µg dm^{-3} were inferred for the period 1400 to 1900 AD. A significant increase in the TP concentration was recorded for the time period after 1920, when TP peaked at approximately 80 µg dm^{-3}.

Similar to the TP concentrations, the inferred TN ones in the River Spree changed only very slightly from 1400 to 1900 AD within the range of 900 to 1,200 µg dm^{-3}. The TN/TP ratio showed striking fluctuations in the range from 20 to 33, but no clear trend was observed over the time.

DISCUSSION

Stratigraphy of the diatom flora

Our study is one of the first on paleolimnology of floodplains based on diatom analysis. The reason for the restricted use of floodplain sediments as environmental archives may be the fact that floodplain deposits are often destroyed by agriculture or settlement activities. Nevertheless, Serieyssol &

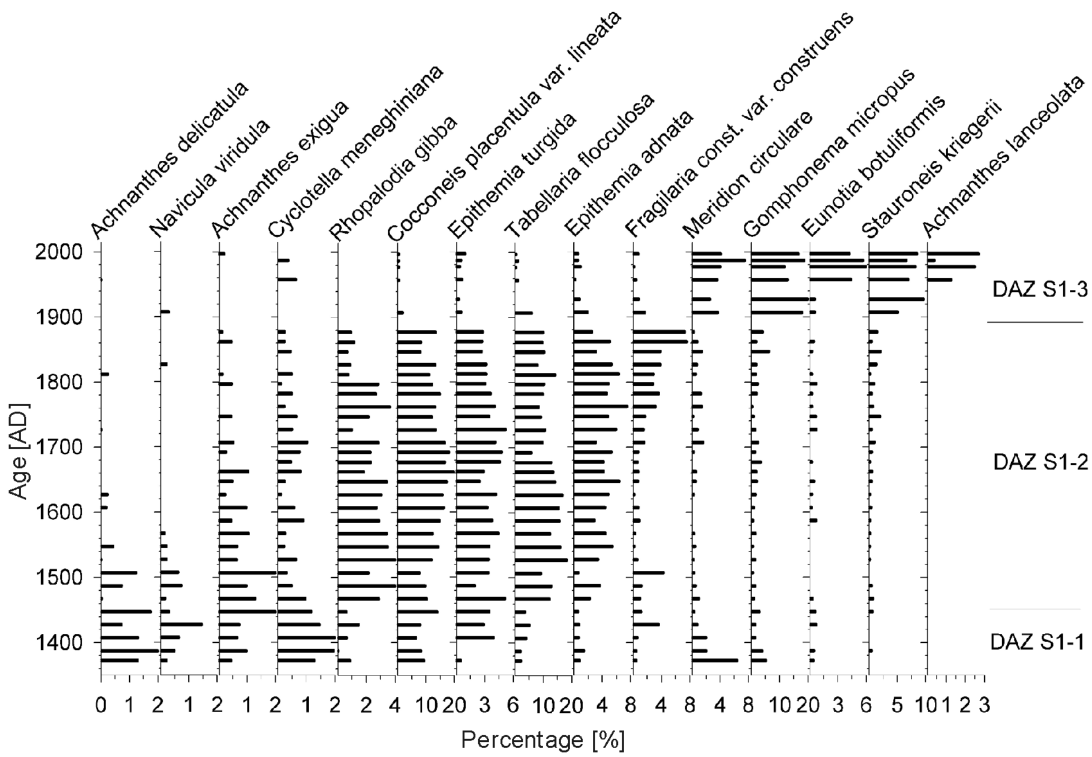

Fig. 6. Stratigraphy of selected diatom taxa from the River Spree ox-bow (core S1).

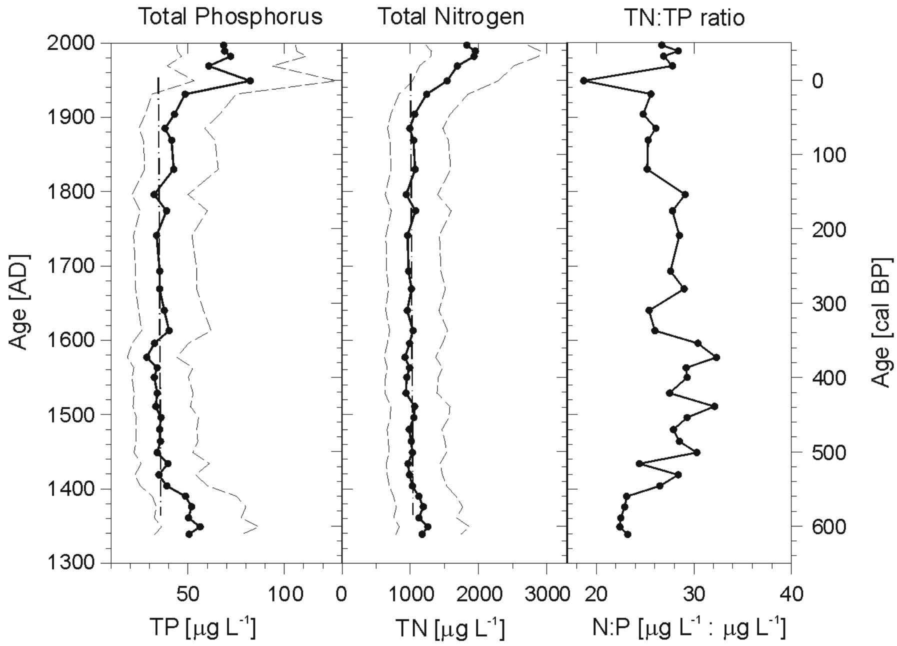

Fig. 7. Diatom-inferred TP and TN concentration and the TN/TP ratio of River Spree (core S1) in the last 700 years. The broken lines are the 95% confidence intervals.

Krier (1995) and our study show that floodplain sediments, including diatom remains, may be well preserved. Evidence for a relatively undisturbed stratification of the floodplain sediments of the Rivers Havel and Spree is provided by the radiocarbon dates, the pollen data (Schelski 1997), and the stratigraphy patterns of littoral diatoms, which are shown in Figs. 2, 3, and 6.

From the nutrient inferences for core H2 and S1, it is evident that the natural status of the Rivers Havel and Spree was more or less eutrophic, but never mesotrophic. Nevertheless, clear shifts in the fossil diatom assemblages were identified, beginning at approximately 1200 AD in the River Havel and at approximately 1900 AD in the River Spree. These shifts in the qualitative composition can be related to cultural eutrophication. Diatom assemblages from the River Havel and Spree floodplain sediments have had a clearly different composition as those from the River Oise, France (Serieyssol, Krier 1995). For example, the common mesotraphentic species *Cyclotella ocellata* Pantoćek is reported from some strata of the River Oise sediments, but was completely absent in the sediments of the Rivers Havel and Spree floodplains. The calibration data set of littoral diatom assemblages from lakes and rivers in Brandenburg State (Schönfelder *et al.* 2002) indicates that *C. ocellata* is a very frequent species in mesotrophic to slightly eutrophic (TP: 20 to 40 µg dm^{-3}) lakes, which corresponds well to results of a survey of planktonic diatoms in the Alpine region (Wunsam *et al.* 1995). The absence of this taxon and most other mesotrophic diatoms in the River Havel sediments confirms the results of the quantitative TP inferences provided by WA techniques. The appearance of some planktonic diatoms in the subrecent (younger than 200 years) diatom assemblages can directly be related to environmental changes. For instance, the first record of *Actinocyclus normanii* in the River Havel is given by Krieger 1911 (Jahn, Geissler 1993). This taxon prefers water bodies with higher conductivity (salinity). Also from the paleolimnological results, it is evident that *A. normanii* was absent before 1900 in the floodplain sediments. Hence, we assume that this centric species can be used as a biomarker for the beginning of industrial era in Berlin and Brandenburg, since only industrial and municipal wastewaters count as a major source for higher ion contents.

TP and TN reconstruction

Diatom assemblages can be used as a bioindicator of lake trophic status (Hofmann 1994, Schönfelder 1997, Schönfelder *et al.* 2002). In the lowland river floodplain, however, almost all planktonic forms of deep oligotrophic and mesotrophic lakes even of the same ecoregion were completely absent in the subfossil diatom assemblages. Instead, the diatom assemblages of the extremely shallow (0.1 to 1.0 m deep) floodplain waters were dominated by benthic and tychoplanktic forms. Consequently, a training set of littoral samples (Schönfelder *et al.* 2002) was preferred instead of a profundal training set to infer past fluvial environments.

The benthic diatom taxa showed marked succession patterns in the floodplain sediments of the River Havel (Figs. 2, 3); the indicative shift of the planktonic assemblage is restricted to the occurrence of one exotic species, *Actinocyclus normanii*. Therefore we conclude, that the indicative power of planktonic diatoms in rivers is weak. Furthermore, Fritz *et al.* (1993) argue that special caution is necessary when diatom assemblages dominated by planktonic forms are related to single environmental variables, *e.g.* TP. Some shifts in the species composition in sediment cores may be more strongly related to changes in the ratio of two variables, which may be highly interrelated in a recent calibration data set. For example, *Aulacoseira ambigua* is a taxon with a high TP optimum in the littoral diatom training set for lakes and rivers in Brandenburg State. We are unable to distinguish between the effects of soluble reactive silica (SRSi) and soluble reactive phosphorus (SRP) of this taxon, because the studied habitats of *A. ambigua* are supplied by drainage water from peatlands with high concentrations of both SRSi and SRP. Kilham *et al.* (1986) reported relatively high Si requirements for that species. Fritz *et al.* (1993) gave paleolimnological evidence for a high Si requirement of *A. ambigua* in Michigan lakes, where this species was present under subrecent oligo/mesotrophic conditions concerning TP. Taking into consideration that both *Aulacoseira granulata* and *A. ambigua* are the most abundant taxa in the subfossil floodplain sediments of the River Havel, the question arises as to whether some systematical error of the predictions for the fossil samples may result from the natural frequent occurrence of the *Aulacoseira* spp. alone. Suddenly, we were unable to include mesotrophic river sites in the recent autecological studies, because all large rivers of central Europe are heavily loaded with nutrients from both point and non-point sources (Gelbrecht *et al.* 1996). Pristine river sites are completely absent in the region. This shortcoming may have caused some systematic overestimations in the reconstruction of past TP for the River Havel. For all purposes the prediction errors should be respected. However, the comparison of diatom-inferred with measured TP values in the recent past indicate an underestimation of the diatom-inferred TP (see below). Nevertheless, the trend of the TP concentrations remains very indicative of precultural and cultural development of the landscape under discussion

The River Havel can be classified as naturally highly eutrophic long before the German eastward expansion (after 1000 AD). Deforestation, beginning around 1100 AD, and drainage of the large peatlands in the Havel region, culminating at 1718 AD (Fontane 1880), led to polytrophic conditions with annual mean TP concentrations exceeding the threshold of polytrophy at 150 μg dm^{-3} after 1900 AD. After 1950 AD, when the use of mineral fertilizers in agriculture and particularly the input of sewage and wastewater from the cities of Berlin and Potsdam heavily affected the river, the annual mean TP concentration may have reached or even exceeded 200 μg dm^{-3}.

From the diatom record, it is evident that the onset of the polytrophic phase must already be related to the extended peatland drainage in the early 18^{th} century. Nevertheless, the effects of mineral fertilizers and sewage are detectable from 1900 AD onwards according to changes in the fossil littoral diatom assemblages in the floodplain sediments.

Most Epithemiaceae, *e.g. Epithemia adnata*, *E. turgida*, *E. sorex*, and *Rhopalodia gibba* show peak relative abundance values in the middle parts of the cores. These taxa are reported to have high phosphorus and low nitrogen requirements (Fairchild, Lowe 1984). High phosphorus and low nitrogen conditions may occur in ox-bows during summer, when the water is stagnant and the small water body is disconnected to the river and denitrification processes at the sediment/water interface reduces the dissolved inorganic nitrogen pool.

Several taxa show clear maxima after 1200 AD (Fig. 3). This pattern is common for hypertraphentic taxa in relation to TP, but was not expected for *Achnanthes minutissima* Kützing var. *minutissima* with a TP optimum at the mesotrophic level. Without any doubt, the unexpected pattern of this very common taxon in sediments of the River Havel can not be taken as a signal of a mesotrophic phase. From lakes in Bavaria, southern Germany, *A. minutissima* var. *minutissima* is known as a littoral taxon with high tolerance to changing trophic states of the lake (Hofmann 1994). That means that TP is one major, but not the only key nutrient for *A. minutissima* var. *minutissima*. We interpret the distribution pattern of this taxon as a reaction to the strong decrease of the TN/TP ratio (Fig. 4). Our assumption is confirmed by a classical report of Carrick and Lowe (1989).

Floodplain hydrology

Before 7,000 BP, peat sediments and benthic diatom species were absent. We interpret this fact as the result of well-developed river dynamics. The onset of peat accumulation followed most likely a reduction in the slopes of the River Elbe and the River Havel due to an eustatic increase of the sea level at approximately 7,000 to 6,000 BP. Dry and presumably warm periods with peat growth in the paleomeander, but without flood events may have alternated with flood periods during the middle and late Atlantic (7,000 to 5,000 BP). The Subboreal sediments of core H1 contained large proportions of silt instead of peat. The silty sediments bear high percentages of planktonic forms, indicating that silt was distributed over the floodplain during long flood events from the catchment area. The forested catchment and the low precipitation rates of the subcontinental climate conditions in Brandenburg may have caused low summer discharges in River Havel during the time 300 to 1200 AD. Low water levels may have prevented a local peat growth during this period of time and this, in turn, affected the preservation of diatoms in the floodplain sediments.

Baseline conditions and restoration goals

Beside the increase of knowledge on the functioning of lowland river during the Holocene, the presented data allow some conclusions for river management practice. Integrated environmental conditions of large catchment areas stabilize the limnological situation of the lower parts of lowland rivers. Thus, long-term changes in floodplain algal communities may reflect more general tendencies of land use, climate, or impacts of emissions from point or non-point pollution sources than profundal sediments of small lakes can. For the River Havel, a eutrophic status can be inferred from diatoms long before the German eastern expansion. A general, but slow tendency of polytrophy was indicated from the beginning of the succession of the studied paleomeander onwards. Furthermore, the diatom based TP inferences paralleled the historical data for the region Havelland. Some smaller fluctuations, with peak diatom-inferred TP > 140 μg l^{-1}, occurred in the period between 1100 and 1600 AD, when the major part of the catchment was first cultivated by Germans. The ongoing increase of TP after 1800 is most probably caused by peatland drainage under the Prussian king Friedrich Wilhelm I, which started in 1718 AD in the Havelland (Fontane 1880). However, the most conspicuous TP increases occurred after 1950, due to phosphate in detergents, diversion of (purified) municipal wastewater, and the excessive use of mineral fertilizers and manure in agriculture. The onset of this hypertrophy period is not restricted to northeastern Germany; rather it appears to be almost a European problem. For instance, parallel results are reported from lakes, for instance, in Northern Ireland (Anderson 1997); primarily oligotrophic lakes in Austria and the pre- and subalpine Bavarian lakes, such as Lake Ammersee and Lake Walchensee, are reported to have been eutrophicated during the same period of time (Michler *et al.* 1978, Steinberg *et al.* 1981, Bennion *et al.* 1995, Alefs *et al.* 1996a, Alefs *et al.* 1996b).

Comparing diatom-inferred and measured TP values available since 1974, the inference underestimates the average annual TP records of 1974 to 1984. It must be taken into account that SRP is released from the sediments of the shallow lakes upstream of the floodplain mainly in summer, when the floodplain is dried out. Consequently, the summer peak TP concentrations in the river do not contribute to any diatom growth or sedimentation in the floodplain. The average winter TP in the River Havel for the period 1974 to 1984 (TP: 200 to 600 μg dm^{-3}) was considerably lower than the summer averages (TP: 400 to 800 μg dm^{-3}) for the same period. Thus, we assume that our TP reconstruction mainly reflects the winter nutrient situations during flood events of the lowland river.

The sedimentation rates in the floodplain depend on changes in the intensity and duration of the flood events. The human impacts on the river during the Subatlantic (2500 to 0 BP) resulted in forced flood dynamics before the river was straightened and widened from 1600 AD onwards. The peat accumulations of the last 2500 years include fine and middle grained sand. This feature can be related to more rapid flow velocities or to an elevated aeolic transportation. From about 1800 BP onwards the relative abundances of planktonic taxa decreased. For the recent past, this fact is a result of water management.

CONCLUSIONS

Our quantitative TP inference shows that the reconstruction of past fluvial environments is feasible using fossil floodplain diatom assemblages. As littoral diatoms are frequent forms in shallow floodplain waters, optima and tolerances obtained from littoral diatom assemblages and present-day chemical records can be used to infer past environmental changes in rivers. The application of paleolimnological methods is probably the only way to describe the ecological reference for river assessment according the directive 2000/60/EC. The subfossil diatom records from floodplain sediments of the lower River Havel demonstrate natural eutrophic conditions with a slow natural trend of increasing eutrophication. Heavy impacts on the diatom flora of the river were caused by human activities from the eighteenth century onwards. The main implication for water management is that a threshold of 100 μg TP dm^{-3} (Klose 1995) can be taken as a realistic target for the restoration of the lower parts of the river system and the flushed shallow Havel lakes.

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REFERENCES

Alefs J., Müller J., Lenhart B. 1996a. Die jährliche Änderung der Diatomeenvergesellschaftung seit 1958 in einem warvendatierten Sedimentkern aus dem Ammersee (Oberbayern). *Limnologica* 26, 39–48.

Alefs J., Müller J., Wunsam S. 1996b. Die Rekonstruktion der epilimnischen Phosphorkonzentration im Ammersee seit 1958. *gwf – Wasser und Abwasser* 137, 443–447.

Anderson N.J. 1997. Historical changes in epilimnic phosphorus concentrations in six rural lakes in Northern Ireland. *Freshwater Biology* 38, 427–440.

Battarbee R.W. 1986. Diatom analysis. In Berglund B.E. (ed.), *Handbook of holocene palaeoecology and palaeohydrology*, 527–569. John Wiley & Sons, Chichester, New York, Toronto, Singapore.

Bennion H. 1994. A diatom-phosphorus transfer function for shallow, eutrophic ponds in southeast England. *Hydrobiologia* 275/276, 391–410.

Carrick H.H., Lowe R.L. 1989. Benthic algal response to N and P enrichment along a pH gradient. *Hydrobiologia* 179, 119–127.

Christie C.E., Smol J.P. 1993. Diatom assemblages as indicators of lake trophic status in southeastern Ontario lakes. *Journal of Phycology* 29, 575–586.

European Union 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. PE-CONS 3639/1/00, REV 1, ENV 221, CODEC 513, 1–152.

Fairchild F.W., Lowe R.L. 1984. Algal substrates which release nutrients: Effects on periphyton and invertebrate succession. *Hydrobiologia* 114, 29–37.

Fritz S.C., Kingston J.C., Engstrom D.R. 1993. Quantitative trophic reconstruction from sedimentary diatom assemblages: a cautionary tale. *Freshwater Biology* 30, 1–23.

Fontane T. 1880. *Wanderungen durch die Mark Brandenburg. Part 3, Havelland.* Wiener Verlag, 1991.

Gelbrecht J., Driescher E., Lademann H., Schönfelder J., Exner H.-J. 1996. Diffuse nutrient impact on surface water bodies and its abatement by restoration measures in a small catchment area in North-East Germany. *Water Science and Technology* 33, 167–174.

Hall R.I., Smol J.P. 1992. A weighted-averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. *Freshwater Biology* 27, 417–434.

Hay M.B., Smol J.P., Pipke K.J., Lesack L.F.W. 1997. A diatom-based paleohydrological model for the Mackenzie Delta, Northwest Territories, Canada. *Arctic and Alpine Research* 29, 430–444.

Hofmann G. 1994. Aufwuchs-Diatomeen in Seen und ihre Eignung als Indikatoren der Trophie. *Bibliotheca Diatomologica* 30, 241 pp, J. Cramer, Berlin.

Illies J. 1978. *Limnofauna Europaea.* Eine Zusammenstellung aller die europäischen Binnengewässer bewohnenden mehrzelligen Tierarten mit Angaben über ihre Verbreitung und Ökologie. 532 pp, Fischer, Stuttgart.

Jahn R., Geissler U. 1993. Zur Bedeutung von Proben-Sammlungen mikroskopischer Organismen anhand von Diatomeen-Beispielen. *Festschrift für Prof. W. Krutzsch, Museum für Naturkunde Berlin*, 19–26.

Kilham P., Kilham S.S., Hecky R.E. 1986. Hypothesized resource relationships among African planktonic diatoms. *Limnology and Oceanography* 31, 1169–1181.

Klose H. 1995. Die Eutrophierung der Havel und ihr bestimmender Einfluss auf Ökosystem und Nutzungen. Die Havel. *Studien und Tagungsberichte, Schriftenreihe des Landesumweltamtes Brandenburg* 8, 16–32.

Krammer K., Lange-Bertalot H. 1986–1991. *Süßwasserflora von Mitteleuropa, Bacillariophyceae*. Band 2/1: *Naviculaceae*, 1–876; Band 2/2: *Bacillariaceae, Epithemiaceae, Surirellaceae*, 1–596; Band 2/3: *Centrales, Fragilariaceae, Eunotiaceae*, 1–576; Band 2/4: *Achnanthaceae*, 1–437. Fischer, Stuttgart.

Lang G. 1994. *Quartäre Vegetationsgeschichte Europas*. Gustav Fischer Verlag, Jena, 608 pp.

Lange-Bertalot H. 1993. 85 neue Taxa und über 100 weitere neu definierte Taxa ergänzend zur Süßwasserflora von Mitteleuropa. *Bibliotheca Diatomologica* 27, Verlag J. Cramer, 456 pp, Berlin.

Lange-Bertalot H., Metzeltin D. 1996. Indicators of Oligotrophy. 800 taxa representative of three ecologically distinct lake types. *Iconographia Diatomologica* 2, Koeltz Scientific Books, 390 pp.

LAWA 1999. Gewässerbewertung – stehende Gewässer. *Richtlinie für die Bewertung nach trophischen Kriterien. Länderarbeitsgemeinschaft Wasser, Empfehlungen*, 1–48.

Lotter A., Birks H.J.B., Hofmann W., Marchetto A. 1998. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. *Journal of Paleolimnology* 19, 443–463.

Michler G., Simon K., Wilhelm F., Steinberg C. 1980. Vertikale Verteilung von Metallen im Sediment eines Alpenvorlandsees als Zivilisationsindikatoren. *Archiv für Hydrobiologie* 88, 24–44.

Organisation for Economic Co-operation and Development (OECD), 1982. *Eutrophication of waters – monitoring, assessment and control.* Paris, 155 pp.

Reavie E.D., Hall R.I., Smol J.P. 1995. An expanded weighted-averaging model for inferring past total phosphorus concentrations from diatom assemblages in eutrophic British Columbia (Canada) lakes. *Journal of Paleolimnology* 14, 49–67.

Reavie E.D., Smol J.P. 2001. Diatom-environmental relationships in 64 alkaline southeastern Ontario (Canada) lakes: a diatom-based model for water quality reconstructions. *Journal of Paleolimnology* 25, 25–42.

Reavie E.D., Smol J.P., Carignan R., Lorrain S. 1998. Diatom paleolimnology of two fluvial lakes in the St. Lawrence River: A reconstruction of environmental changes during the last century. *Journal of Phycology* 34, 446–456.

Rühland K.M., Smol J.P. 2002. Freshwater diatoms from the Canadian Arctic treeline and development of paleolimnological inference models. *Journal of Phycology* 38, 249–264.

Schelski A. 1997. Zur Vegetationsgeschichte der unteren Havelniederung bei Gülpe. *Doctoral Dissertation, University of Potsdam*.

Schönfelder I. 1997. Eine Phosphor-Diatomeen-Relation für alkalische Seen und Flüsse Brandenburgs und ihre Anwendung für die paläolimnologische Analyse von Auensedimenten der unteren Havel. *Dissertationes Botanicae* 283, 148 pp. Verlag J. Cramer, Berlin.

Schönfelder I. 2000. Indikation der Gewässerbeschaffenheit durch Diatomeen. In Steinberg C.E.W., Calmano W., Klapper H., Wilken R.-D. (eds.) *Handbuch der Angewandten Limnologie*. ecomed-Verlag, Landsberg/Lech, 9. Ergänzungslieferung, 1–62.

Schönfelder I., Gelbrecht J., Schönfelder J., Steinberg C.E.W. 2002. Relationships between littoral diatoms and their chemical environment in northeastern German lakes and rivers. *Journal of Phycology* 38, 66–82.

Serieyssol K.K., Krier V. 1995. Diatoms from the archeological site, "Le grand Marais", Champagne-Sur Oise, France. *Vie Milieu 45*, 243–248.

Siver P.A. 1999. Development of paleolimnological inference models for pH, total nitrogen and specific conductivity based on planktonic diatoms. *Journal of Paleolimnology* 21, 45–59.

Steinberg C., Wöhlecke C., Hämmerle E. 1981. Die Belastung des Walchensees und ihre Auswirkung auf den Seezustand. *Vom Wasser* 57, 37–58.

Stoermer E.F., Smol J.P. 1999. *The Diatoms. Applications for the Environmental and Earth Sciences.* 469 pp, Cambridge University Press.

Stuiver M., Reimer P.J. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35, 215–230.

Wunsam S., Schmidt R. 1995. A diatom-phosphorus transfer function for Alpine and pre-alpine lakes. *Memorie dell'Istituto Italiano di Idrobiologia* 53, 85–99.