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PALAEOLIMNOLOGY

Diatom-inferred trophic history of IJsselmeer (The Netherlands)

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Abstract IJsselmeer was formed in 1932 through the closure of the Afsluitdijk that separated the artificial lake from the former Zuiderzee estuary. The palaeoecology of IJsselmeer was studied on a 63-cm-long sediment core. Lithology and microfossil data, particularly the diatom flora, clearly show the transition from the marine Zuiderzee into the freshwater IJsselmeer. Trophic conditions in IJsselmeer since 1932 have been inferred by qualitative and quantitative diatom-based approaches: by plotting the distribution of trophic categories based on published trophic indicator values, by a canonical correspondence analysis (CCA) yielding relative total phosphorus (TP) changes and by applying a transfer function in order to calculate TP concentrations. All three approaches indicate that IJsselmeer initially was meso- to eutrophic. A first hypertrophic period is indicated for the mid-1940s, likely due to internal loading. After 1960, the phosphorus load steadily increased and TP in IJsselmeer reached highest concentrations (ca. 150 $\mu g\ l^{-1}$) in the 1980s as confirmed by monitoring data since 1975. The monitored data show that the TP concentration continuously decreased after 1985 due to successful environmental protection measures. This trend is not (or not yet) evidenced by the diatom data and thus, the diatom-inferred TP concentration.

Keywords Palaeolimnology · Lake sediments · Diatoms · Phosphorus · Eutrophication

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Palaeolimnological Proxies as Tools of Environmental Reconstruction in Fresh Water

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Introduction

Lake IJsselmeer is a main target area for the implementation of the European Union's (EU's) Water Framework Directive (WFD) in the Netherlands. As an artificial, so-called heavily modified water body (HMWB), the lake is exposed to various man-made pressures including shoreline regulation, high nutrient loads and overexploitation of fish (Lammens et al., 2008). The WFD requires that all European Union member states determine reference conditions for their aquatic ecosystems to provide a baseline against which the effects of past and present activities should be measured. EU member states are obliged to undertake measures to achieve the formulated goals before 2015 (European Union, 2000). Reference conditions are subsequently used to classify the ecological status of an aquatic ecosystem which is defined by the (widely accepted) deviation from the reference conditions and ranges from 'good' through 'moderate' and 'poor' to 'bad'. Palaeolimnology is able to assists the implementation of the WFD through the determination of reference conditions for aquatic ecosystems (Bennion & Battarbee, 2007). Through deciphering the natural histories of ecosystems, reference conditions are indicated by the apparent 'natural state' of a water body, which prevailed in periods when human pressures were less drastic than today. Several studies (i.e. Taylor et al., 2006 and references therein) have demonstrated the value of palaeolimnology for WFD related issues.

Here, we describe the environmental history of the past 75 years of IJsselmeer based on a multiproxy palaeolimnological study with emphasis on the development of the trophic state. Various microfossils were initially used to document the transition from the former marine Zuiderzee towards the fresh IJsselmeer in 1932. Changes in trophic state of the past 75 years are reconstructed using diatoms and three different approaches. These analyses should reveal distinct changes of the total phosphorus concentration in IJsselmeer during the relatively short time span of its existence. The article also attempts to clarify the possibilities and limitations of using algae, particularly diatoms, for paleoenvironmental reconstructions in young and artificial water bodies that, in addition, are strongly affected by human activities.

Study area

IJsselmeer was created in 1932 by the separation of the former Zuiderzee estuary from the North Sea through the construction of a dam, the Afsluitdijk (Fig. 1). After its formation, IJsselmeer changed within a few years into a freshwater lake. In the years subsequent to completion, the size of the lake was reduced by land reclamation projects through which a number of border lakes were created. The construction of another dam, the Houtribdijk, in 1975 divided IJsselmeer into two lakes: IJsselmeer (ca. 1125 km^2) to the north and Markermeer (ca. 650 km^2) to the south of the newly formed dam (Fig. 1). The IJssel River, a tributary of the Rhine River, is the main freshwater source of IJsselmeer. Today, the IJsselmeer region is a strongly regulated, multifunctional area with various recreational, industrial, natural, nautical and agricultural interests.

IJsselmeer is a large, buffered and still eutrophic to hypertrophic lake with moderate chlorinity. The average and maximum water depths of IJsselmeer are 4.5 and 7 m, respectively. Regular measurements of the phosphorus concentration started in the mid-1970s when the lake was already hypertrophic (total phosphorus (TP) concentration of 200–300 μg l^{-1}; Lammens et al., 2008). Since 1985, the phosphorus load constantly decreased to present-day concentration of ca. 100 μg l^{-1} (De Leeuw et al., 2006). Improvements over the past two decades are also indicated by changes in total nitrogen and chlorophyll *a* (De Leeuw et al., 2006).

Materials and methods

Sediment core IJ6 (Length: 63 cm) was recovered with a UWITEC gravity corer in spring 2006 in the western part of IJsselmeer (Fig. 1) at 420 cm water depth. A total of 45 samples from this core were analyzed for diatoms and palynological indicators (dinoflagellates, foraminifera, green algae and pollen).

Sediment samples for diatom analysis were freeze-dried and 0.5–2 g of this material was treated consecutively with HCl (30%) and H_2O_2 (35%) in order to remove the carbonates and organic matter. Sedimentation trays (Battarbee, 1973) and the highly refractive mountant Naphrax ($RI = 1.74$) were used to produce permanent slides. Diatom slides were analyzed at 945× magnification with a Leica DM2500 microscope equipped with differential interference contrast.

Palynological slides were prepared by treating the samples consecutively with sodium pyrophosphate (15 g/l), HCl (30%) and acetolysis in order to disperse the samples and to dissolve carbonates and organic matter. In a final step, the samples were centrifuged with heavy liquid to eliminate sand and silt particles and to concentrate pollen and other microfossils. Palynological slides were mounted using glycerin.

Diatom-based reconstructions of the trophic history of IJsselmeer were carried out with a qualitative,

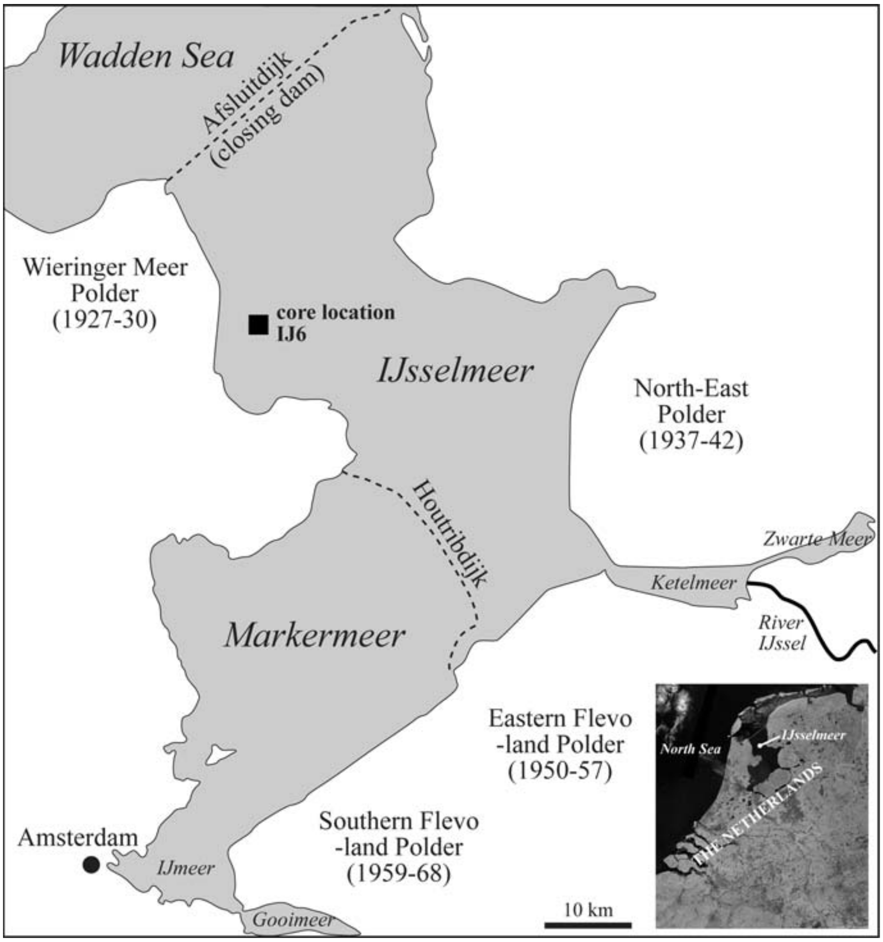

Fig. 1 Lakes and dams in the IJsselmeer area. The location of core IJ6 is indicated by a *black square*

semiquantitative and quantitative method. First, an estimation of the trophic state was performed by calculating the frequency of diatom-based trophic state categories. For this approach, trophic indicator values for diatom species according to the classification of Van Dam et al. (1994) were used. Second, a canonical correspondence analysis (CCA; Ter Braak, 1986) was performed with a modern diatom training set and TP as the only constraining environmental variable. The 28 fossil diatom assemblages of core IJ6 were used as passive samples in the CCA. The available European diatom TP datasets (the Combined TP dataset was used) of European Diatom Database Initiative (EDDI; http://craticula.ncl.ac.uk/EDDI/jsp) were used as modern training set (345 lakes; TP range 2–1,189 µg l^{-1}, mean 95 µg l^{-1}). The CCA, performed with the program CANOCO 4.52 (Ter Braak & Šmilauer, 1998), resulted in first CCA axis scores of the passive fossil samples that represent relative total phosphorus (TP) concentrations. Thirdly, a diatom-based quantitative TP reconstruction was performed using the available European diatom TP training sets of EDDI and a Modern Analogue Technique (MAT) transfer function as implemented in the software package C2 Version 1.5 (Juggins, 2007) to calculate absolute TP concentrations in IJsselmeer for the past 70 years. We used chi-squared distance as a dissimilarity coefficient and the weighted average of the 10 closest analogues.

Results

Zuiderzee to IJsselmeer transition

The transition from marine conditions of the Zuiderzee to the freshwater lake IJsselmeer is indicated by both the lithology and micropaleontology in core IJ6 (Fig. 2). The transition is indicated by a change from

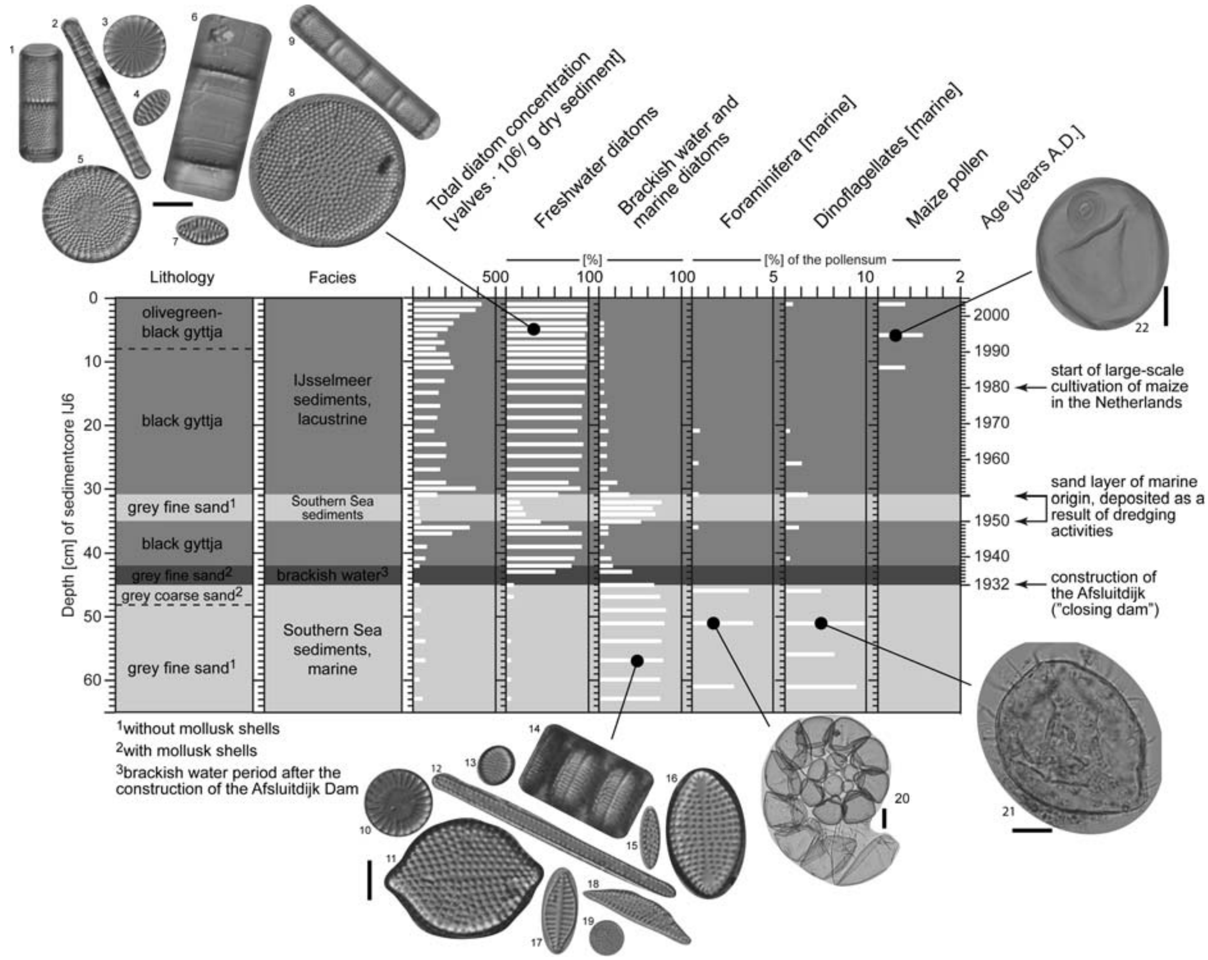

Fig. 2 Lithology, facies and abundance of diatoms, foraminifera, dinoflagellates and maize pollen in sediment core IJ6 from IJsselmeer. Micrographs. *Freshwater diatoms*: 1. *Aulacoseira ambigua* (Grunow) Simonsen. 2. *Diatoma tenuis* Agardh. 3. *Stephanodiscus hantzschii* Grunow. 4. *Staurosirella pinnata* (Ehrenberg) Williams et Round. 5. *Stephanodiscus medius* Håkansson 6. *Stephanodiscus binderanus* (Kützing) Krieger. 7. *Staurosira venter* (Ehrenberg) Cleve et Möller. 8. *Actinocyclus normanii* (Gregory) Hustedt. 9. *Aulacoseira subarctica* (O. Müller) Simonsen. *Marine and brackish water diatoms*: 10. *Cyclotella meneghiniana* Kützing. 11. *Raphoneis amphiceros* (Ehrenberg) Ehrenberg. 12. *Thalassionema nitzschioides* (Grunow) Mereschkowski. 13. *Delphineis minutissima* (Hustedt) Simonsen. 14. *Paralia sulcata* (Ehrenberg) Cleve. 15. *Cymatosira belgica* Grunow. 16. *Delphineis surirella* (Ehrenberg) Andrews. 17. *Planothidium delicatulum* (Kützing) Round et Bukhtiyarova. 18. *Campylosira cymbelliformis* (A. Schmidt) Grunow. 19. *Thalassiosira proshkinae* Makarova. *Foraminifera*: 20. Chitinous inner linings. *Marine dinoflagellates*: 21. *Operculodinium centrocarpum* (Deflandre et Cookson) Wall. *Pollen*: 22. *Zea mays* (maize). Scale bars: 10 μm

coarse sand with mollusk shells through fine sand without mollusk shells to a black gyttja. The grey fine sand layer at 45–42 cm core depth represents the brackish water period following the closure of the Afsluitdijk. The transition is also documented by the occurrence of marine diatoms, foraminifera and dinoflagellates. Shells of these protists are common below 45 cm core depth and disappear in the gyttja where freshwater diatoms constitute the main microfossil group (Fig. 2). Marine diatoms are also predominant in a sand layer at 35–31 cm core depth suggesting that this layer is of marine origin. The sand was assumingly deposited during dredging activities, which are common in IJsselmeer.

Chronology

The chronology of core IJ6 is based on the marine–freshwater transition in 1932 following the construction of the Afsluitdijk. The post-1932 period is represented in this core by the upper 45 cm of sediment, which indicates a mean sedimentation rate of 5.6 mm/year. This estimate is supported by the occurrence of *Zea mais* (maize) pollen in the sediment. In the Netherlands, large scale maize cultivation started in the 1980s. The first maize pollen in core IJ6 was found in 11 cm core depth. Applying a mean sedimentation rate of 5.6 mm/year this would correspond to the year 1986. Accordingly, the marine sand layer at 35–31 cm core depth was deposited in 1950.

Zuiderzee and IJsselmeer diatom flora

Figure 3 shows the most frequent marine and freshwater diatoms documenting the Zuiderzee and IJsselmeer diatom floras, respectively (Cremer & Bunnik, 2006). The Zuiderzee sediments were mainly characterized by *Cymatosira belgica* Grunow and *Delphineis minutissima* (Hustedt) Simonsen. *Planothidium delicatulum* (Kützing) Round et Bukhtiyarova, *Thalassiosira levanderi* Van Goor, *T. proschkinae* Makarova and several other marine to brackish diatoms were present in smaller numbers. Following the closure of the connection with the North Sea, the newly formed IJsselmeer became less saline within a few years, which is clearly visible in the completely changed diatom flora. The dominating diatom in the upper 42 cm of core IJ6 is *Staurosirella pinnata* (Ehrenberg) Williams et Round together with *Staurosira construens* Ehrenberg s.l. (Fig. 3). Other frequently occurring planktonic or tychoplanktonic diatoms include several taxa of the genera *Aulacoseira* and *Stephanodiscus*, *Cyclostephanos dubius* (Fricke) Round, *Diatoma tenuis* Agardh, *Nitzschia angustatula* Lange-Bertalot and *Nitzschia palea* (Kützing) W. Smith.

Trophic history of IJsselmeer

Trophic state indicator values

The downcore distribution of the most prominent diatom species (Fig. 3) is reproduced in Fig. 4 as trophic state categories, the compilation of which is based on species' trophic state indicator values according to Van Dam et al. (1994). The major part of the diatom assemblages throughout core IJ6 consists of *Staurosirella pinnata*, which is known to be indifferent to changes of a lake's nutrient load

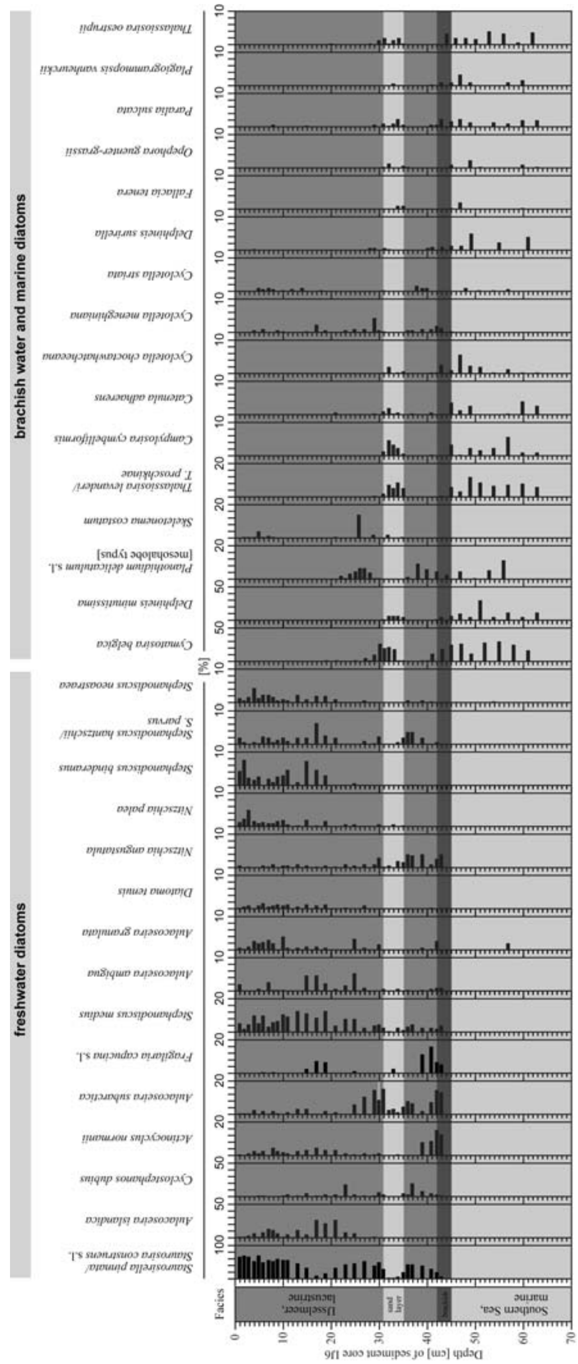

Fig. 3 Percentages of the most frequent freshwater and marine diatoms in core IJ6 from IJsselmeer

(Van Dam et al., 1994). Diatoms with eutrophic affinities are also very common throughout the past 70 years. However, Fig. 4 shows that the oligo-mesotrophic diatom *Aulacoseira subarctica* (O. Müller)

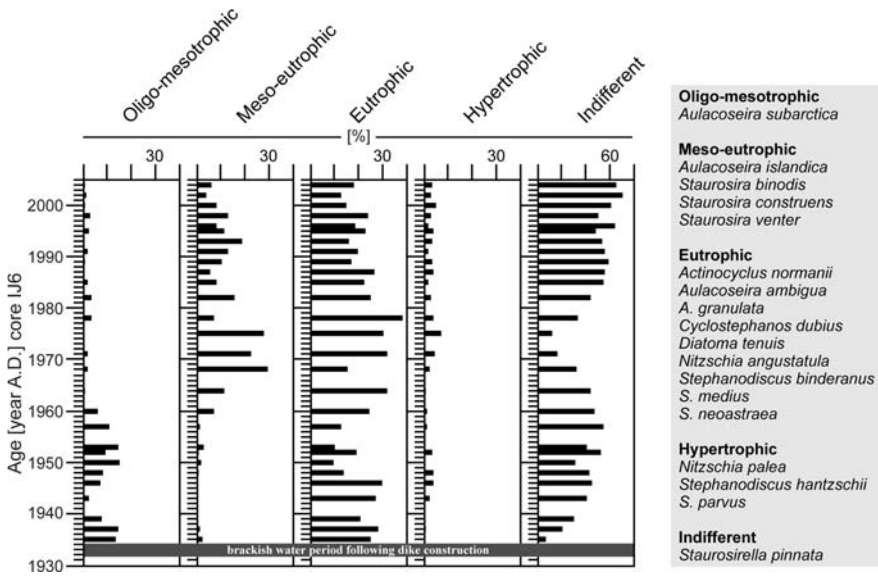

Fig. 4 Trophic history of IJsselmeer based on trophic indicator values (van Dam et al., 1994) of the most frequent diatoms

Haworth was mainly deposited during the intervals 1935–1939 and 1946–1960, which might indicate comparably lower nutrient concentrations, notably phosphorus, in IJsselmeer during these periods. On the other hand, diatoms of the meso-eutrophic category occur mainly in the assemblages deposited after 1960 and show highest frequencies in the period 1968–1975. This supports the assumption that the trophic state of IJsselmeer was already eutrophic in the 1960s and 1970s and even higher (hypertrophic) during the past 25 years.

Canonical correspondence analysis

Figure 5 shows the result of the partial CCA with TP as the sole constraining variable. The sample scores of the fossil diatom assemblages on the first CCA axis represent relative TP concentrations. The sample scores are comparably low in the earliest part of the record, representing the period 1935–1940 after which they increase considerably and generally remain with some fluctuations on a high level. Comparably lower sample scores and therefore lower TP concentrations are indicated for the periods 1948–1950, 1953 and 1960–1968. High sample scores, representing higher TP concentrations, are indicated for the period 1970–1978. Since the end-1970s, the high sample scores show a slightly declining, but fluctuating trend.

TP transfer function

The quantitative TP reconstruction in IJsselmeer since 1935 using the EDDI European training sets and a weighted MAT transfer function is shown in Fig. 6. The applied transfer function has a bootstrapped r^2 of 0.74 and a root mean squared error of prediction of 0.2955 log TP. Good modern analogues were defined as modern diatom samples having a chi-squared distance of less than the 5th percentile (Jones & Juggins, 1995). In the first years of the newly formed lake TP concentration increased rapidly towards the first maximum at ca. 100 μg l^{-1} in the early 1940s. Following this eutrophic period, the diatom-inferred TP concentration decreased to a value of ca. 60 μg l^{-1} in 1950, which was the lowest TP concentration ever calculated for IJsselmeer. Between 1950 and 1970 TP concentrations ranged between 60 and 100 μg l^{-1}. From the early 1970s, the onset of strong eutrophication is indicated by TP concentrations distinctly over 100 μg l^{-1}. The highest diatom-inferred TP concentration (156 μg l^{-1}) is calculated for 1987 indicating hypertrophic conditions in IJsselmeer at that time. A slight downward trend of the TP concentration in IJsselmeer is indicated since the 1990s but the diatom-inferred trophic state remains still in the eutrophic–hypertrophic range. Figure 6 also shows water column TP in IJsselmeer, which has been monitored since 1975.

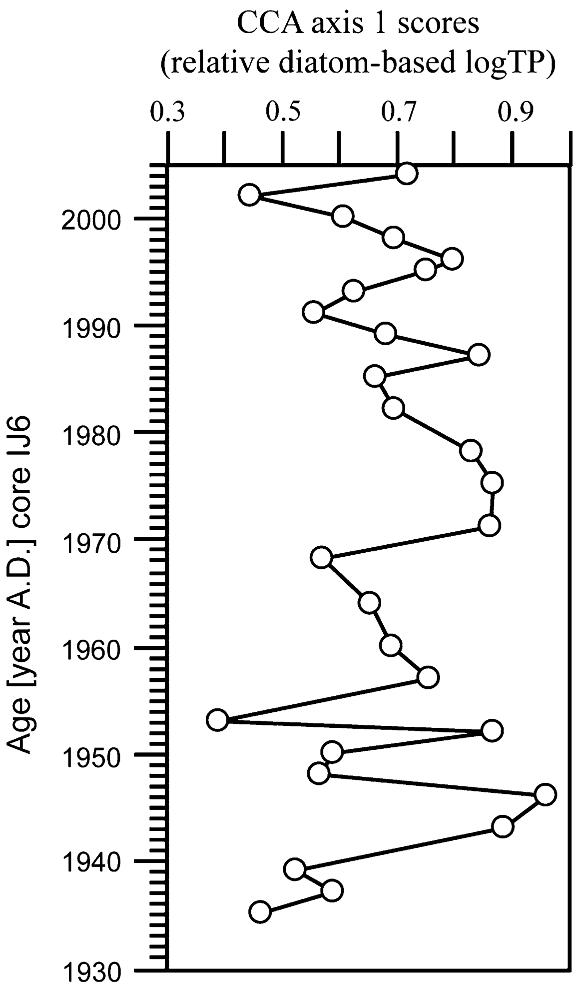

Fig. 5 Sample scores of the first CCA axis for core IJ6 from IJsselmeer. The scores on the ordination axis represent relative TP concentrations

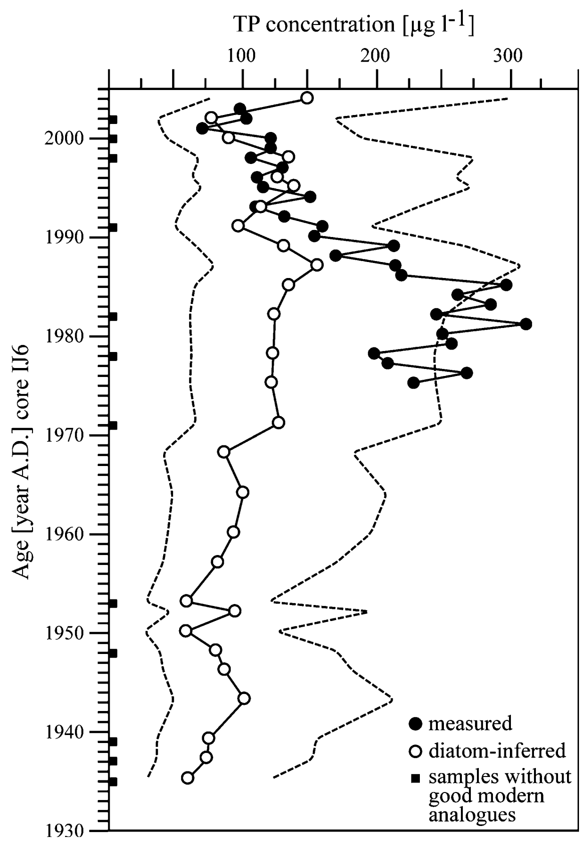

Fig. 6 Diatom-inferred (since 1935) and measured (since 1970) summer mean TP concentrations in IJsselmeer. The *dotted lines* represent the sample-specific standard errors of prediction and the *squares* represent samples without good modern analogues. The diatom-inferred TP reconstruction is based on the weighted Modern Analogue Technique using the EDDI TP diatom training set. Measured data from De Leeuw et al., (2006)

The recordings document highest TP concentrations between 1980 and 1985 (200–300 µg l^{-1}; Lammens et al., 2008). As a consequence of reduced nutrient load into IJsselmeer the measured TP concentrations decreased steadily since the mid-1980s and have reached present-day concentrations of slightly below 100 µg l^{-1}. This trend, however, is not as conspicuous in the diatom-based reconstruction (Fig. 6).

Discussion

The compilation of diatom-based trophic state classes provides first evidence of the development of the trophic history of IJsselmeer during the past 70 years. However, this qualitative approach only documents relative trends of trophic state changes. The multivariate approach using a direct gradient analysis (CCA) assumes a unimodal distribution of species (Ter Braak, 1986) along environmental gradients (here TP). As the CCA is constrained uniquely to TP, the CCA scores of the IJsselmeer samples (Fig. 5) show relative changes in TP concentration, and thus, represent a semiquantitative method. This approach is strongly recommended, if the general parameters of the studied fossil environment largely differ from those of the lakes contained in the modern training set (e.g. Bohncke et al., 2008). In this case, we are using several regional TP training sets that are based on diatom assemblages from surficial sediments from small lakes to infer past TP values in the artificially formed, large lake IJsselmeer. It is assumed here that the reconstructed TP curve reflects a realistic history of the trophic state of IJsselmeer for the past few decades. The curve (Fig. 6) basically shows the same trends as the CCA-based reconstruction (Fig. 5) of relative TP changes.

As 93.3% of the fossil diatom flora of IJsselmeer is represented in the EDDI training set, we feel confident that a transfer function approach such as MAT can be applied. However, in situ measurements made during the period of highest TP concentration show that diatom-inferred TP concentrations may underestimate actual TP values. Between 1975 and 1990, the average diatom-inferred TP concentration is distinctly lower than the measured average summer values of the same period (Fig. 6). The phenomenon of over- or underestimation of diatom-inferred compared to measured TP concentrations has been reported and discussed many times in the literature (e.g. Bennion et al., 1995; Lotter, 1998; Bradshaw & Anderson, 2001; Sayer, 2001). The reasons that might lead to such differences include training set- and model-inherent problems, e.g. the presence and number of low, medium and high TP sites in the training set or the fact that TP measurements document the situation during a single season (often summer), whereas the sedimentary diatom sample represents a larger period (one or several years). Another important factor might be the dominance of small, often benthic fragilarioid diatoms (*Staurosirella pinnata, Staurosira construens*; Figs. 3 and 4) in the sediment assemblages. These taxa have been described to react more sensitive to habitat availability than to TP concentration and therefore may have a distorting influence on TP reconstructions (Sayer, 2001). Furthermore, the variability of factors other than TP, including climate, light conditions, zooplankton grazing and competition between algal groups and genera, may also have a significant impact on the composition of fossil diatom assemblages and thus, indirectly have an influence on reconstructed TP concentrations. Spatial and temporal variabilities in the deposition of inorganic sediment and biogenic components, including microfossil remains, particularly in large lakes, may have an indirect influence on past TP estimates (Blom & Winkels, 1998). Taking all these factors, as well as the sample-specific standard errors of prediction into account, the reconstructed TP concentrations for IJsselmeer are within the measured TP ranges and therefore, can be regarded as reliable.

The diatom-inferred reconstruction of absolute TP concentrations shows two noticeable trends: first, the eutrophic maximum in the early 1940s, and second, the weakly declining TP concentrations since 1985 compared to the clearly reduced measured values (Fig. 6).

The true reasons for the first eutrophic period in IJsselmeer remain unexplained at the moment. It can be speculated that the construction of the Afsluitdijk caused hydrological, hydromorphological, geochemical and sedimentological conditions in the initial IJsselmeer that led to a massive release of phosphorus from the ancient sea bottom. Possible, even probable, triggers include changes in the redox potential and pH and/or increasing algal blooms (e.g. cyanobacteria) in the meanwhile freshened lake. These processes have been intensely studied and discussed in recent literature (e.g. Christophoridis & Fytianos, 2006; Xie et al., 2003 and references therein). Decrease of the TP concentration after 1945 might then be interpreted as a consequence of using up- and rebinding of phosphorus and reaching a more or less stable phosphorus budget in IJsselmeer.

There are also some possible reasons for the consistently relatively high reconstructed TP concentrations in the 1990s (TP 100–150 $\mu g\ l^{-1}$) compared to the previous interval. In contrast, the monitored measurements show a clear downward trend after 1985 (Fig. 6). The recovery of IJsselmeer from extreme phosphorus loads is seemingly not (or not yet) evident from the diatom data. A probable reason for this observation is that at hypertrophic conditions (TP $\geq$100 $\mu g\ l^{-1}$) phosphorus is not the limiting factor for diatom growth and particularly the composition of the diatom flora. Such overestimation of diatom-inferred TP concentrations has been also reported in other studies (e.g. Bradshaw & Anderson, 2001) and indicates that the decreased input of a single nutrient (e.g. phosphorus) does not necessarily lead directly to observable changes of the algal community, which might be a reflection of hysteresis effects. Moreover, model-inherent factors, such as the length of the phosphorus gradient covered by the calibration dataset, have also an effect on the reconstructed TP. The application of datasets that are not designed for the region in which it is used in many cases yields reconstructions that tend to either over- or underestimate the monitored phosphorus data (Bradshaw & Anderson, 2001). This does not necessarily mean, however, that such reconstructions cannot reveal valuable information on the trophic history of lakes.

The present study demonstrates the value of palaeolimnological approaches for assessing trophic histories of artificial lakes. As evidenced by diatom analysis, IJsselmeer was already meso-trophic within a few years of its formation in the early 1930s and underwent the initial eutrophic period in the early 1940s. Since the late 1950s, conditions in IJsselmeer were strongly eutrophic and increased to hypertrophy in the early 1970s. The continuous improvement in the trophic state since 1985 is not yet reflected in the diatom assemblages and the diatom-inferred TP values. This suggests that diatom-inferred nutrient reconstructions should preferably be validated by long-term monitoring data to reduce misinterpretations.

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