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ORIGINAL PAPER

River flooding and landscape changes impact ecological conditions of a scour hole lake in the Rhine-Meuse delta, The Netherlands

**H. Cremer · F. P. M. Bunnik · T. H. Donders ·
W. Z. Hoek · M. Koolen-Eekhout ·
H. H. Koolmees · E. Lavooi**

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Abstract A 400-year sediment record from an 18 m deep scour hole lake (Haarsteegse Wiel) near the Meuse River in the Netherlands was investigated for past changes in water quality, flooding frequency and landscape change using geophysical, geochemical and micropaleontological information. The results are highly significant for determining long-term trends of water quality, the impact of atmospheric (as SCP, spheroidal carbonaceous particles) and industrial (chromium) pollution on the terrestrial and aquatic flora, and the impact of river floods. The studied sediment record was dated by combining ^{137}Cs activities, biostratigraphical ages, micro-tephra layers, and historically documented floods indicated by the magnetic susceptibility. The oldest flooding event is indicated at AD 1610 when the lake was created by water masses bursting through a dike. Large historical river floods are well documented in regional chronicles and thus may provide reliable age calibration points. Based on assumptions about the timing of flood events and constant rate of sedimentation, it appears that sedimentation rates in Haarsteegse Wiel declined after ca. AD 1880. This decline might be a result of a widespread change from wheat cultivation to pasture land from around AD 1875 as a direct result of falling wheat prices and intensified cattle farming linked to the agricultural crisis in the last quarter of the nineteenth century. Water quality changes and absolute phosphorus concentrations were reconstructed using a diatom-based transfer function. Results show that the currently nutrient-rich lake has mostly been in a mesotrophic state prior to ca. AD 1920, with the exception of several apparently sharp eutrophication events that were coeval with river floods. River flooding also impacted the vegetation composition by importing allochthonous components, and indirectly by the influx of nutrients which had a clear influence on the composition of the water plant communities and aquatic species diversity. Magnetic susceptibility changes and pollen data show that within the period AD 1610–1740, within the Little Ice Age period, several undocumented floods may have occurred. Thus, documentation of geophysical, geochemical, and biological flooding signals in a high-resolution archive present the possibility to detect flooding regimes further back in time.

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H. Cremer (✉) · F. P. M. Bunnik · T. H. Donders ·
M. Koolen-Eekhout · H. H. Koolmees
TNO Built Environment and Geosciences, Geological
Survey of the Netherlands, Princetonlaan 6, 3584 CB
Utrecht, The Netherlands
e-mail: holger.cremer@tno.nl

W. Z. Hoek · E. Lavooi
Department of Physical Geography, Faculty
of Geosciences, Utrecht University, Heidelberglaan 2,
3584 CS Utrecht, The Netherlands

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Introduction

Human impact on land use and ecology is a widespread and well-studied phenomenon. Worldwide, restoration projects seek to restore environmental conditions to the pre-impact natural situation and policies concerning vegetation diversity, water quality, and atmospheric pollution are developed to improve the milieu quality, often within international agreements (for example the European Water Framework Directive, EWFD). In the Netherlands, most water bodies are not natural and part of a centuries-long interaction between man and the environment. However, also for these lakes and streams 'natural' conditions need to be defined. Second, the interaction between human alteration of the landscape and natural dynamics needs better understanding since climate change is expected to alter important boundary conditions related to rainfall, flooding regime, and ecological turnover as a result of gradual global warming (IPCC 2007). These processes often act on decadal to centennial timescales that exceed instrumental measurement records. An alternative source of information is provided by sedimentary archives from lakes.

Scour holes (or kolks) in the Netherlands, formed by past dike breaches and extensive scouring of sediments from the river bed (Hesselink et al. 2003), provide excellent conditions for the accumulation of expanded sedimentary records of local lake water quality, regional environmental conditions and human activity, and river flooding. Because several of the scour holes are located inland of the embankments, river flooding events are clearly visible in sedimentary records as sandy layers within a fine-grained clayey matrix. The thickness of these layers can be measured and should be regarded as a single, 1-year event influencing the local average accumulation rate. The sandy layers produced by major, historically well-documented floods become evident by the magnetic susceptibility signature of the studied cores. The content of magnetic minerals in sediments has been shown to be a valuable proxy for monitoring variations in sedimentary and grain size composition (Nowaczyk 2001; Gilli et al. 2003; Wolfe et al. 2006; Dekkers 2007).

In this study, we aim to use biological and geochemical proxies to reconstruct past water quality and relate changes to regional environmental changes in the catchment area of a deep scour hole in the central Netherlands. The site, Haarsteegse Wiel, is located in the lowland Rhine-Meuse delta. We use information from historical sources (Buisman 2002, 2006; Driessen 1994) to determine the sedimentary expression and environmental impact of known regional river floods. The past water quality, and derived total phosphorous concentrations, are based on fossil diatom assemblage data (Kirilova et al. 2009). These reconstructions can subsequently be used to define water quality restoration targets in this and similar water bodies. Geochemical, pollen and fly-ash (Spheroidal Carbonaceous Particles, SCP) analyses provide independent information about recent land use, pollution levels and water quality changes (Middelkoop 1997; Rose 1996, 2001) and, hence, give insight into what regional changes are responsible for the currently eutrophic state of the lake (Van der Velde et al. 1976). Further, characterization of the flooding surfaces helps to constrain natural river dynamics in older sedimentary archives for which historical sources are lacking. This information is crucial for developing an understanding of river flooding in relation to long-term (decadal to centennial) natural cycles and climatic changes, and predicting future change in flooding regime.

Study area and environmental setting

Haarsteegse Wiel is a scour lake consisting of two basins as a result of two separate large dike bursts that occurred in AD 1610 and AD 1740 following ice damming of the river Meuse (Fig. 1). The floods causing the dike bursts came from the *Hedinkhuizensche Maas*, a now abandoned Meuse channel formed in AD 1474–1475 when the river was diverted upstream. Since the north–south oriented dike was restored after each burst and remained on the river side of the lake the basin did not fill up very rapidly by sediment input of annual floods. It remained a relatively deep body of open water that is rare in the Netherlands (Van Heusden 1945; Van der Velde et al. 1976), and only received significant

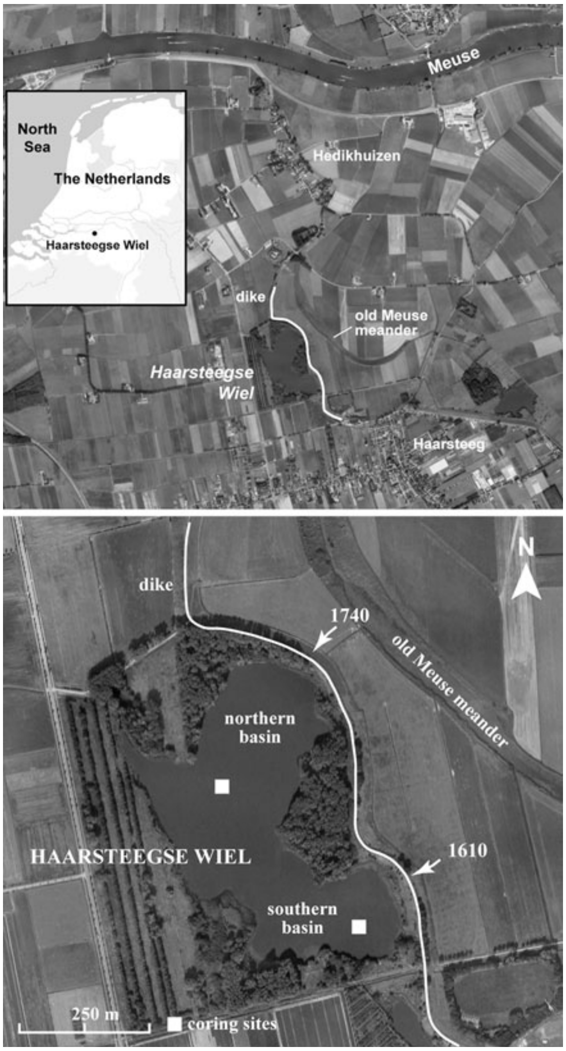

Fig. 1 Geographical setting of the scour hole Lake Haarsteegse Wiel

input from the river during a few large regional flooding events. These events preserve as well-recognizable layers in the lake sediment and thus, can serve to characterize the flooding signal.

The lake covers approximately 17.9 ha and reaches maximum depths of approximately 18 m and 8 m in the northern and southern basins, respectively. Van der Velde et al. (1976) characterized the lake as a eutrophic but non-polluted water with great biological richness. The lake is currently fringed by reed (*Phragmites australis* (Cav.) Trin. ex Steud.) and open woodland (predominantly *Populus*, *Alnus*, *Salix* and *Quercus*). The immediate surrounding is agricultural land, especially orchards with regional corn (*Zea mays* L.) cultivation and pastureland.

Materials and methods

Coring and sampling

In 2007 a coarse bathymetry map was constructed using an echo sounder, and the deepest point in both lake sub-basins were cored using a modified piston corer (UWITEC, Mondsee, Austria) deployed from a floating platform. Overlapping 3-m core sections recovered the complete lake sediment infill, reaching into coarse sand deposits at a depth of 3.40 and 4.80 m below the sediment–water interface in the northern and southern basin, respectively (Table 1). These 3-m core segments were partitioned into 1-m sections in the field and cut in 1-cm (the northern basin) and 2-cm slices (the southern basin) in the laboratory. Additional 80-cm gravity cores (HA07-03/04) were taken in the northern basin to retrieve the unconsolidated top sediments. All sediment cores consist of black, non-odorous and unconsolidated organic-rich clayey gyttja. No laminating or layering is visible, although flooding events are clearly visible as sandy or clayey layers. Sediments were sub-sampled for palynology and diatom analyses at 8-cm intervals, while 1-cm interval samples for geochemical measurements were taken from the northern basin cores (HA07-05/06). The older southern basin was sampled only for palynology for the interval

Table 1 Cores studied from Haarsteegse Wiel, The Netherlands

Core	Device	Water depth (m)	Penetration (cm)	Composite core depth (cm)
Northern basin (1740)				
HA07-03	GC	16.70	86	0–86
HA07-04	GC	16.70	88	0–88
HA07-05	PC	16.80	280	0–280
HA07-06	PC	16.80	280	208–488
Southern basin (1610)				
HA07-08	GC	7.40	77	0–77
HA07-09	PC	7.40	287	0–280
HA07-10	PC	7.40	300	205–495

Coring was carried out on 18 and 19 September 2007

GC Gravity corer, *PC* piston corer

2.7–4.8 m (HA07-10) to extend the main sequence retrieved from the northern basin.

Geochemical indicators

Carbon, nitrogen and sulfur contents were determined at Cologne University using a CNS elemental analyzer (VARIO Co.), and total organic carbon concentrations (TOC) with a Metalyt CS 1000S analyzer (ELTRA Co.). Concentrations of chromium (Cr) and other elements (As, Cd, Co, Hg, Ni, Pb, Zn, Ti) were detected with an inductively coupled plasma mass spectroscopy (ICP-MS) apparatus at Chemostrat Ltd (Welshpool, U.K.).

Spheroidal carbonaceous particle (SCP) analyses, indicative of past atmospheric pollution levels (Rose 1996, 2001), were performed on samples taken from core HA07-03. Freeze-dried weighted SCP samples were processed following Rose (2001). Organic material was digested with 65% HNO_3 for 4 h at 70°C, and siliciclastics were removed with 40% HF for 2 h. SCP concentrations (no. per gram dry weight) were calculated using *Lycopodium* tablets (Stockmarr 1971). The residues were mounted in glycerin on glass slides for light microscopic analysis.

Chronology

The age assessment of the drilled sediments is based on flood events as evidenced by magnetic susceptibility (MS) signatures, on micro-tephra shards that likely derive from an Iceland volcano outbreak, and on radiocesium activities in the upper part of the sediment column. The basal age of the sequence is determined by the well-documented formation of the scour hole in 1610 (south basin) and 1740 (north basin), and is recognizable as a sharp transition from gravelly sediment to organic lake sediment at the base of the sequence. Land use changes, derived from pollen analyses, provide further approximate age datings (e.g. from the regional introduction of corn cultivation) and support the age model.

Sediment characteristics, especially sand layers, were determined by magnetic susceptibility measurements using a GEOTEK Multi-logger at 5-mm resolution.

The age of the top sediment section was determined by measuring ^{137}Cs activity on 4-cm sub-samples from a gravity core (HA07-03). Cesium activity measurements of sediments in western Europe should indicate the atomic bomb tests in the 1960s and the Chernobyl reactor accident in AD 1986 (Appleby 2001) and contribute two more chronological control points. The measurements were carried out at the Kernfysisch Versneller Instituut (KVI) at Groningen with a HPGe-detector.

Micro-tephra analysis of a section of core HA07-05 was used to provide data independent of the flooding events that are recognizable in the sediments. Following the methods by Koren et al. (2008) and Pilcher and Hall (1992), 1 cm^3 samples were treated with 30% H_2O_2 to remove organic matter and 5% HCl to disaggregate the samples. Subsequent sieving over 31- and 75-μm mesh sizes removed fine and coarse fractions, respectively. The concentrates were mounted on glass slides and investigated for glass shards by light microscopy using polarized light.

Palynology

In order to calculate pollen concentrations, a known amount of exotic marker grains (*Lycopodium clavatum* L.) was added to the sample prior to processing. Palynological samples were treated with sodiumpyrophosphate (15 g l^{-1}), sieving (250- and 7-μm mesh sizes), HCl (30%), acetolysis (9:1 ratio of $[CH_3CO]_2O$:H_2SO_4) and flotation over heavy liquid (sodium-polytungstate SG 2.1 kg dm^{-3}) for the removal of mineral components. The residues were mounted in glycerin on glass slides for light microscopic analysis. Pollen percentages were calculated based on a pollen sum of trees, upland herbs, heath and crop plants.

Diatoms

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 dissolve carbonates and organic matter (Cremer et al. 2001). Evaporation trays (Battarbee 1973) and the highly refractive mountant Naphrax^{TM} were used to produce permanent slides. Diatom slides were analyzed at ×945 magnification with a Leica DM2500 microscope equipped with differential interference contrast.

Statistics

Diatom-based quantitative reconstructions of the total phosphorus concentration (TP) were performed using available training sets of the European Diatom Database Initiative (EDDI, http://craticula.ncl.ac.uk/EDDI/jsp). A combined diatom TP training set of EDDI (345 lakes; TP range 2–1,189 µg l^{-1}, mean 95 µg l^{-1}) and a Modern Analogue Technique (MAT) transfer function as implemented in the software package C2 Version 1.5 (Juggins 2007) were applied to calculate absolute TP concentrations in Haarsteegse Wiel since 1740. We used chi-squared distance as a dissimilarity coefficient and the weighted average of the ten closest analogues.

Pollen diagrams and cluster analysis were carried out using the *TGView* software package (Grimm 1987, 2004). Independent diversity indices for both upland vegetation and aquatic vegetation were determined using rarefaction analysis to normalize the number of different palynomorphs encountered in each sample (software RAREPOLL; Birks and Line 1992). This method calculates the diversity that would be expected if identical counting sums were used in every sample.

Results

Chronology

The transition from the coarse sands of the Kreftenheye Formation (Rijsdijk et al. 2005) to the lake sediment at the base of the sediment profiles is very distinct from the magnetic susceptibility signal (Fig. 2) and provides basal ages. The 1740 flood formed the northern basin but also deposited a well-discernable sand layer in the southern basin. These surfaces provide the initial age dating for the sediment sequences. Subsequent age control points are from well-known flooding events and summarized in Table 2 and Fig. 3.

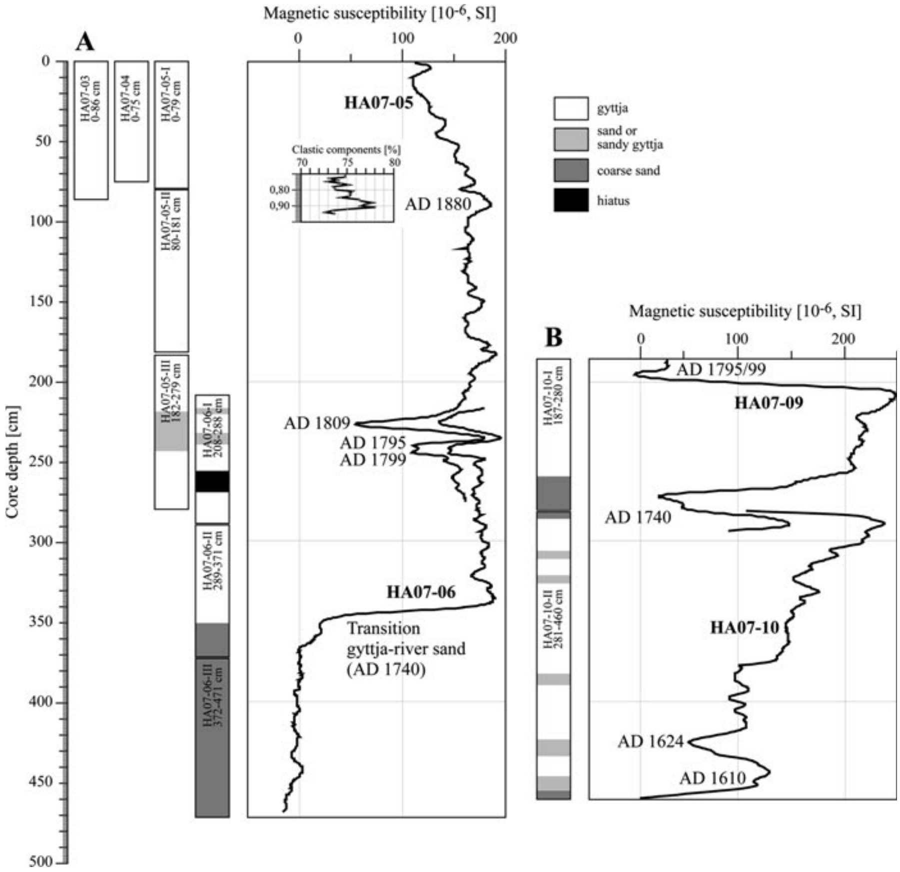

Fig. 2 Sediment cores and sedimentary magnetic susceptibility in the northern (**a**) and southern (**b**) basins of Haarsteegse Wiel. Estimated dates beside the magnetic susceptibility curves indicate historically documented flood events

Table 2 Chronological control points for the sediments cored in the northern and southern basins of Haarsteegse Wiel

Composite core depth (cm)	Year (AD)	Indicator	Event
Northern basin			
0	2007	Surface	Coring
20.6	1986	^{137}Cesium	Chernobyl reactor accident
34.5	1960	^{137}Cesium	Atomic bomb tests
81	1880	MS	Flood of ‘Nieuwkuijk’
226	1809	MS	Heusden flood
240	1799	MS	Heusden flood
245	1795	MS	Heusden flood
265	1783	Micro-tephra	Laki outbreak on Iceland
350	1740	MS	Flood, origin of northern basin
Southern basin			
280	1740	MS	Flood
425	1624	MS	Flood
451	1610	MS	Flood, origin of southern basin

MS Magnetic susceptibility

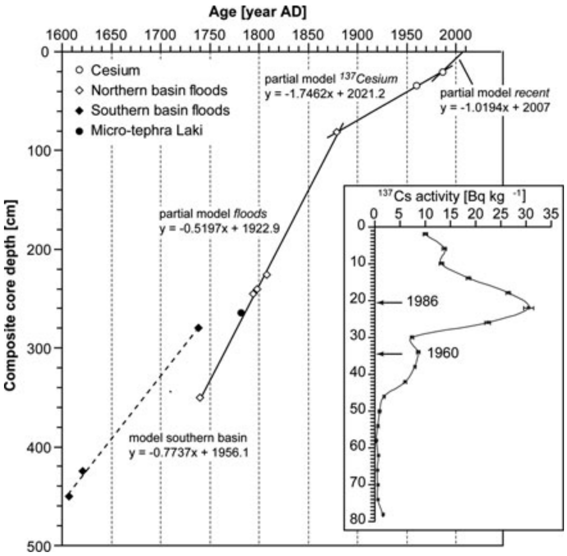

Fig. 3 Age-depth correlation of sediments in Haarsteegse Wiel (see also Table 2)

The magnetic susceptibility signatures of the sediments in both basins show distinct minima that correlate with sand layers in the sediment sequences (Fig. 2). These minima can be connected to historically documented flood events and form part of the age control points used to create the age model (Table 2). The last severe flooding, in AD 1880, is represented by a maximum in the magnetic susceptibility signature of sediments in the northern basin (Fig. 2). Loss-on-ignition (LOI) analysis around the presumable position of the date confirms this assumption. The LOI free fraction as measure for the proportion of clastic components in the samples shows enhanced values exactly at the same time when the magnetic susceptibility curve shows the positive excursion (Fig. 2).

^{137}Cs activities in core HA07-03 show two maxima, at 20.6 and 34.5 cm depth, that may be associated with the reactor accident at Chernobyl (AD 1986) and the atmospheric atomic bomb tests (AD ~ 1960) (Fig. 3; Appleby 2001).

The large AD 1783–1784 outbreak of the Laki (Skaftár Fires) volcano on Iceland erupted material equivalent to 0.4 km^3 dense rock and caused a dry sulphuric fog that was recorded across entire Europe (Thordarson and Self 1993). The sediment interval between 260 and 270 cm indeed contains abundant glass shards reaching a maximum at 265 cm. A fraction of the particles clearly represent the complex three-dimensional shape typical of micro-tephra (Van den Bogaard and Schmincke 2002). Based on the initial flooding chronology, the micro-tephra is most likely consistent with the AD 1783 Laki eruption but further geochemical testing is needed to confirm the origin.

Evident from the age-depth correlation is that the sedimentation rate distinctly lowered from ca. AD 1880 onward. This change is presumably caused by considerable changes in land use around that time and consequently lower terrestrial input from the catchment into the lake.

All age control points used for the sedimentary age models of the northern and southern basins are summarized in Table 2. We interpolated the flood-based chronological control points as point data since their thickness does not significantly alter the overall sedimentation rates. The resulting age-depth model consists of three linear interpolations or partial models for the northern basin of Haarsteegse Wiel and one for the southern basin (Fig. 3). The age control points lie on a straight line within each partial model, confirming the overall stability of the sedimentation rates. The age model is confirmed by various pollen-stratigraphical events as for example the decline of pollen of cereals and coeval increase of grass pollen (ca. AD 1875), the planting of pine (ca. AD 1860, 1880, 1930) and the deposition of corn pollen (*Zea mays* L.) from approximately AD 1970.

Geophysical and geochemical data

The origin of the lake is well-documented in the magnetic susceptibility record. Both the AD 1610 (southern basin) and AD 1740 (southern and northern basin) floods are reflected by negative excursions due to sand deposition (Figs. 2, 4). The southern basin shows an additional excursion at 420–430 cm, which is related to the AD 1624 flood that led to the formation of a scour lake in nearby Heusden (Driessen 1994). In the northern basin, between 215 and 245 cm core depth two prominent magnetic susceptibility excursions together with low CNS/TOC values are observed. These are most presumably connected to the AD 1795, 1799, and 1809 floods of the region (Driessen 1994). A small positive magnetic susceptibility excursion at 81 cm core depth most likely characterizes the most recent flood in AD 1880. This flood event is evident in the southern basin by sandy and in the northern basin by only clayey sediment. The event is further characterized by a SCP peak in the parallel core (HA07-03) above the regional background values for that period (Fig. 4), indicating allochthonous input from sources in the hinterland of Haarsteegse Wiel. In contrast to the other floods represented in the record which all came from a northern to north-eastern direction, the AD 1880 flood came from the south which explains the different magnetic susceptibility and lithological signatures of the sediment in the two basins (Figs. 2, 4; the post-1740 part of core HA07-09 from the southern basin is not shown).

Above 80 cm core depth, reflecting the period after AD 1880, TOC clearly started to increase toward the current maximum values. Sulphur values also increase after AD 1880, reaching a maximum between 72 and 60 cm core depth, corresponding with the period between ca. AD 1900 and AD 1910 (Fig. 4). SCP values show a single, isolated peak at 80 cm core depth (AD 1880), increase gradually above 70 cm core depth (ca. AD 1900) and reach a maximum at 38 cm core depth (approximately AD

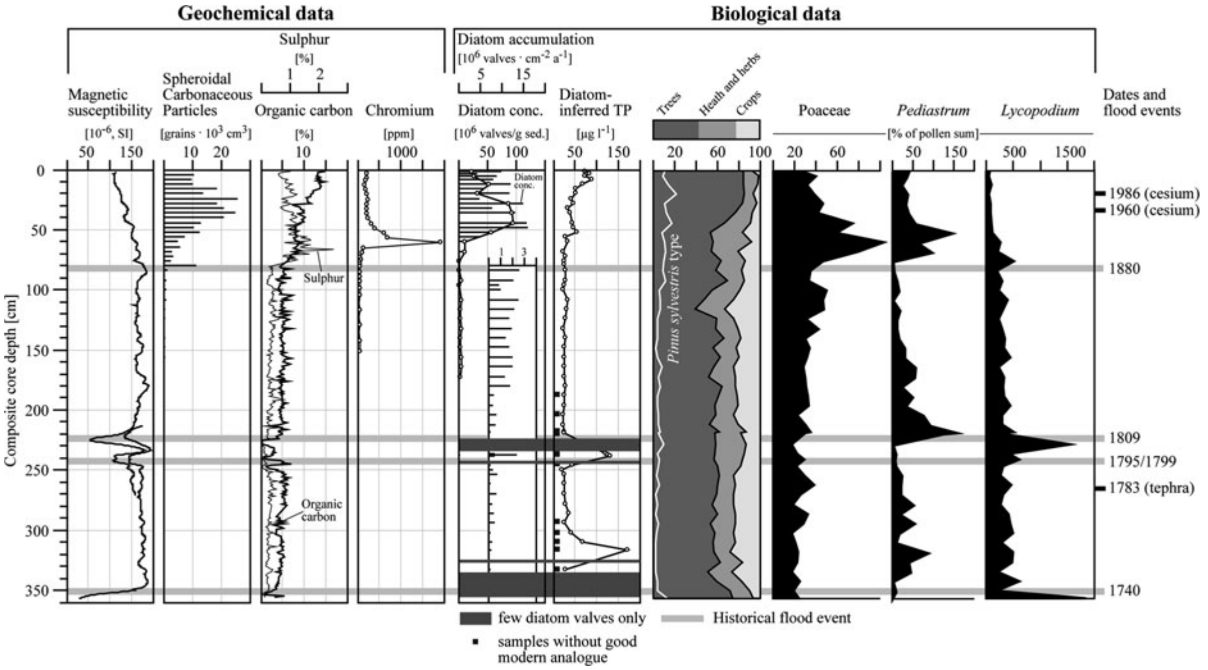

Fig. 4 Properties, SCP concentrations, reconstructed total phosphorus (TP) reconstruction, and microfossil content of sediments in Haarsteegse Wiel, northern basin, since AD 1740. Shaded areas indicate flood events. The composite sequence consists of two overlapping cores (see Fig. 2). In the first column, the magnetic susceptibility of both cores is shown

1960). SCP concentration subsequently decreased, interrupted by a conspicuous short peak at 25 cm core depth. Sulphur and chromium concentrations are clearly elevated between 70 and 60 cm core depth, approximately representing the period AD 1910–1930 and thus, indicating an only temporary external flux of these elements into Haarsteegse Wiel.

Biological indicators

Pollen preservation was excellent in both the southern and northern basin cores (Figs. 4, 5), while very few diatom valves were preserved in the southern basin and the lowermost intervals from the northern basin (prior to AD 1750; Fig. 4).

A diverse upland and aquatic flora is recorded, in which a few pollen assemblage zones have been distinguished (ESM Figs. 1, 2): HWK 1 and 2 in the southern basin, covering the period AD 1610–1740, and HWG 1-4 in the northern basin representing AD 1740–2007. The regional broadleaved woodland vegetation, dominated by *Alnus*, *Salix*, *Quercus*, *Betula* and *Corylus*, display a relatively stable abundance through time. Exceptions are the high *Pinus* abundance of up to 40% prior to ca. AD 1700, followed by low values (<10%) and a gradual stepwise increase to 20% after ca. AD 1880. *Populus* first appears at 180 cm core depth (approximately AD 1835) and increases to 10% at c. 60 cm core depth (around AD 1920) (ESM Fig. 2). Herbs are dominated by crop plants and associated taxa indicative of cultivated areas (ESM Figs. 1, 2) (*Rumex*, *Plantago lanceolata* L., *Ranunculus acris* L. *type* and, from ca. AD 1920, *Urtica*). Oat/wheat (*Avena*/*Triticum* type), rye (*Secale cereale* L.), buckwheat (*Fagopyrum esculentum* Moench), and hemp (*Cannabis*/*Humulus*) cultivation is dominant until ca. 1870. Afterward, buckwheat and hemp decrease and *Poaceae*, indicative of pastureland, strongly increase. Rye and wheat cultivation decrease from ca. AD 1920 onward and are replaced by corn (*Zea mays*) above 30 cm core depth or from around AD 1970.

Around most of the known flooding events (years AD 1610, 1624, 1740, 1795–1799, 1809) *Pinus* percentages show transient peaks that are indicative of river transport from the hinterland (Figs. 4, 5). The AD 1795/1799 and AD 1809 floods are represented by a single *Pinus* peak. In the northern basin, a period of high *Pediastrum* levels is attained after a flooding phase. Counts of the added exotic marker grain *Lycopodium* are indicative of the total pollen concentration. Clear *Lycopodium* peaks, indicating low

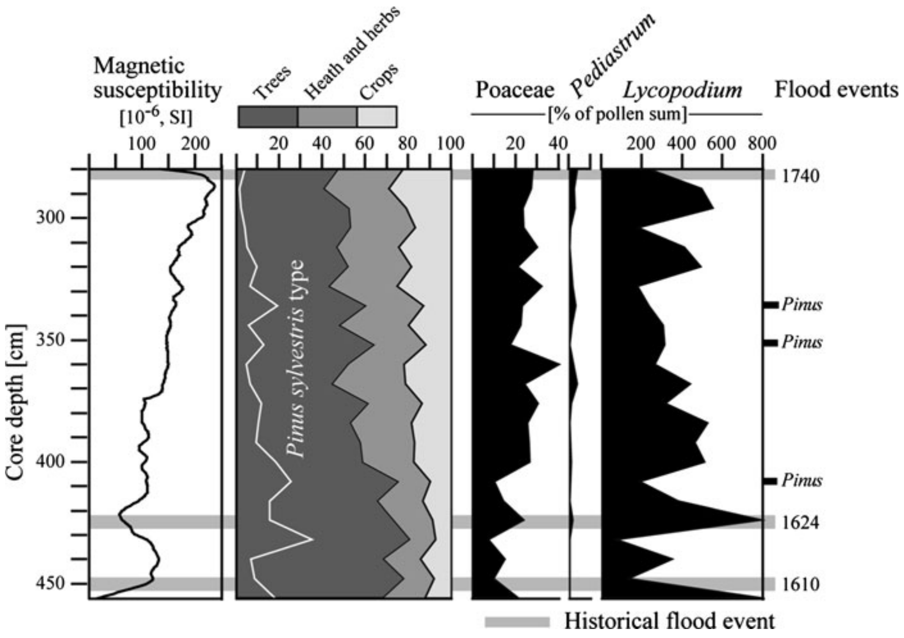

Fig. 5 Magnetic susceptibility and pollen data of sediments in Haarsteegse Wiel, southern basin, between AD 1600 and 1740. Shaded areas indicate flood events

pollen concentration, coincide with the elevated *Pinus* levels, although the ca. AD 1880 event is slightly offset.

Diatoms

The preservation of diatom valves in the sediments of the northern basin in Haarsteegse Wiel is very good in the upper 100 cm of the composite core but moderate to poor in the lower core parts (Fig. 4; ESM Fig. 3). Particularly, sediments representing the first years following the origin of the basin in 1740 (340–355 cm core depth) and the flood events around ca. AD 1800 (225–245 cm core depth) contain only single, moderately preserved diatom valves. Diatom concentration is generally low below 60 cm core depth, representing approximately AD 1920, and clearly higher above this depth (Fig. 4). Calculation of the diatom valve accumulation indicates that the increase of diatom valve numbers in the upper part of the sediment core is a consequence of augmented productivity and not abiotic factors as sediment compaction.

Diatom assemblages in sediments deposited between 330 and 70 cm core depth, corresponding to the period between ca. AD 1750 and 1820, are dominated by *Puncticulata praetermissa* (Lund) Håk. and *Fragilaria* spp. while after ca. AD 1820, related *P. radiosa* (Grun.) Håk. occurred in significant numbers. Valves of *Puncticulata praetermissa* were not identified after approximately 1890. The abundance of *P. radiosa* decreased above 55 cm core depth (after AD 1920) and diatom assemblages during the past centennium were mainly composed of *Asterionella formosa* Hassall, *Aulacoseira granulata* (Ehr.) Sim., *Cyclotella ocellata* Pantocsek, *Fragilaria crotonensis* Kitton, *Stephanodiscus medius* Håk., *S. hantzschii* Grun. and *S. parvus* Stoermer & Håk.

Paleoenvironmental implications

Landscape development

The recent vegetation composition represents a landscape strongly altered by human activities since the Late Holocene. Natural vegetation in the floodplain region is dominated by *Quercus*, *Tilia*, *Ulmus*, *Fraxinus* and *Corylus* woodland on elevated areas (levees), with transition from *Alnus*, *Salix* to *Phragmites* in the flood basins (Middelkoop 1997; Teunissen 1990). The open landscape documented by the pollen assemblage in the sediments of Haarsteegse Wiel represents the strongly cultural-dominated vegetation of the modern period, with cereal cultivation and allochthonous pine woodland in the cover sand areas of the province of Northern Brabant and Limburg. The known regional agricultural activities (Bieleman 1992) are well represented in the pollen data from Haarsteegse Wiel, only the well documented intensive hops cultivation in the region is represented by merely 10% *Humulus*/*Cannabis* type pollen (ESM Fig. 2). Since male plants were not allowed in the hop fields (only virginal female hop flowers were used in brewing), the majority of the *Humulus*/*Cannabis* type pollen may originate from the vast hemp fields existing in the area north of the river Meuse. Hemp combines high pollen productivity with excellent dispersing capacities; its pollen can be therefore transported over large distances. Results from a similar scour hole approximately 30 km northeast of Haarsteegse Wiel, near the village of Wamel, where cultivation was focused on hemp, document that *Humulus*/*Cannabis* type pollen reached over 50% in the pollen assemblage during the eighteenth century (Middelkoop 1997).

Regionally, crop cultivation decreased strongly from ca. AD 1875 due to foreign imports (Bieleman 1992), resulting in a large-scale conversion to grasslands, and stepwise increasing planting of pine in the adjacent cover sand district (in ca. AD 1860, 1880, 1930) and poplar at wetter sites in the vicinity of the lake (from c. 1830; ESM Fig. 2). This turnover is evident in the increased abundance of *Pinus*, Poaceae, and C_{org}, and the reduced sedimentation rate from approximately AD 1880 (Fig. 4), since permanent grasslands likely lead to much reduced clastic input compared to arable fields that are seasonally ploughed exposing bare soil. The most recent change is the introduction of corn cultivation (from 1970; ESM Fig. 2), for which high amounts of fertilizers are used.

Water quality

The development of the ecological quality of Haarsteegse Wiel strongly mirrors the vegetation and agricultural history in the region documented in the pollen data. The ecological quality is expressed as diatom-inferred total phosphorus (TP) concentration (Fig. 4). Between approximately AD 1770 and 1920 (240–60 cm core depth), the TP concentration was consistently below 30 μg l^{-1}, except for a short period around ca. AD 1800 (250–220 cm core depth), thus qualifying Haarsteegse Wiel in the eighteenth and nineteenth century as a mesotrophic lake, which is rare in a naturally nutrient-rich downstream river floodplain (Kirilova et al. 2009). The mesotrophic state of the lake may be a result of the fact that it is only sporadically flooded and, therefore, isolated from river input for most of the time. It is mainly fed by rain water and is in contact with nutrient-poor, calcium-rich groundwater seeping in from the sandy subsoil. As the organic rich sediment accumulates, sealing the sandy substrate, the water body in the lake may lose contact with the buffering groundwater in the course of time. The disappearance of species of oligo-to mesotrophic environments like *Littorela uniflora* (L.) Asch. (shoreweed) and *Menyanthes trifoliata* L. (bogbean) from the pollen assemblage in the course of the nineteenth century may be related to this process. Two total phosphorus peaks occur within this period: at around 320 and 240–230 cm core depths (corresponding with approximately AD 1760 and 1800, respectively). The reconstructed high TP values around ca. 1800 are certainly due to nutrient and diatom influx during the floods at the end of the eighteenth century, which obviously caused a strong growth and accumulation of the eutrophic diatom *Aulacoseira granulata* (ESM Fig. 3). However, we cannot offer a sound explanation for the TP peak around AD 1760. On the one hand, the diatom assemblages in the lowermost part of the core do not have good modern analogues in the used training set indicating that the reconstructed TP values are of limited reliability (Fig. 4). On the other hand, there might have been a short-term nutrient surplus or another lake-inherent factor which caused the growth of eutrophic indicator species as *Cyclostephanos dubius* (Fricke) Round and *A. granulata* (ESM Fig. 3). The peak could be possibly also due to the AD 1740 flood. A surplus of nutrients was certainly deposited on the lake floor during the flood event and these nutrients might have been released to the water column in subsequent years, causing eutrophication of the lake water and, hence, growth of eutrophic algae including diatoms.

After ca. AD 1920, elevated TP concentrations of around 40 μg l^{-1} were reconstructed (Fig. 4) indicating weakly eutrophic conditions in the lake, which marks a first eutrophication phase related to the changed and intensified land use and use of artificial fertilizers following the agricultural crisis from around AD 1875. A second step of increased algal growth is visible above 25 cm core depth, corresponding to ca. AD 1980, when TP values increased towards values of between 60 and 80 μg l^{-1}. This shows that Haarsteegse Wiel recently became clearly eutrophic, which is also documented in the few available biomonitoring reports (Bijkerk et al. 2002; Van der Velde et al. 1976), and is likely due to the recent excessive use of manure from regional pig farms on corn fields.

Locally, also chemical pollution levels likely rose after tanning (using chromium sulphate) and dairy industry developed in the direct vicinity of the lake (pers. commun. by B. van Opzeeland) in the beginning of the twentieth century. This temporary direct industrial impact on the lake is nicely documented in the sulphur and chromium records (Fig. 4) and witnesses drainage of industrial wastewater into the lake.

The TP reconstruction for Haarsteegse Wiel shows that the TP reference concentration was between 20 and 30 μg l^{-1} if accepting the early or middle nineteenth century as suitable dates for the reference conditions. This approach is supported by a literature survey of paleolimnological data showing that the first signs of eutrophication in most study sites are recognized in the middle and late nineteenth century (Battarbee et al. 2007).

Flooding signal and effects

The different proxies record the flooding signals in different ways. This is most evident in the consecutive flood events at ca. AD 1795/1799 and AD 1809 (grey bands in Fig. 6) that record as two distinct events in the magnetic susceptibility signal (Fig. 4; the AD 1795/1799 events shown as a single, protracted peak in the magnetic susceptibility signal). However, only the AD 1795/1799 event shows a clear signal in the data with high diatom-based TP and low pollen influx in the sandy sediment, immediately followed by a transient increase in recorded plant diversity and *Pinus* abundance in the clayey fraction

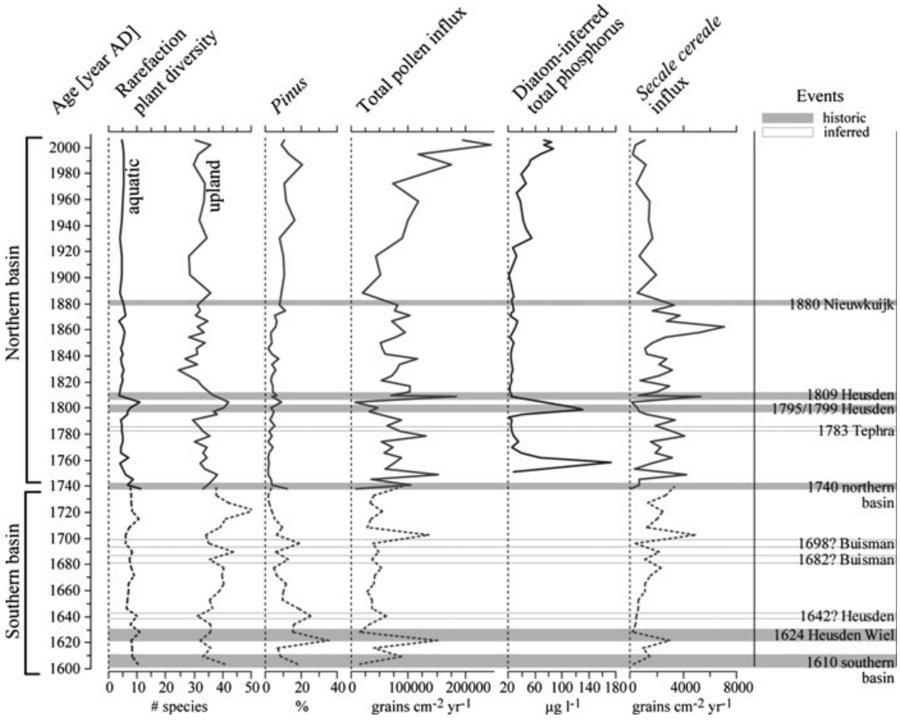

Fig. 6 Compilation of several individual proxy records (pollen diversity, total phosphorus (TP), and pollen influx) demonstrating a response to the basin flooding events since AD 1610. Records are plotted versus age following the age-depth model shown in Fig. 3 to allow for a correlation between influx values and flooding intervals

(Figs. 4, 6). The subsequent sandy flooding layer (ca. AD 1809) contains, contrary to the previous event, high organic carbon and an elevated pollen influx. Re-deposition and mixing of the sediment of such closely-spaced events might explain the contrasting signals, what makes detection in the sedimentary record complex.

Overall, the presumed flooding signals from the AD 1610, 1624, 1740 and AD 1795/1799 floods agree very well with the pollen indicators (Figs. 4, 5). Only very few diatoms were preserved in the AD 1740 and preceding flood layers, but the elevated aquatic plant diversity, *Pinus* abundance increased and reduced pollen influx due to the large clastic sediment load point to a similar response caused by a sudden sediment- and nutrient-rich influx of river water into the mesotrophic lake. Particularly, the *Secale cereale* pollen influx is lower during floods, possibly indicating failed crops of winter rye (a common practice was alternating summer and winter cereal growing) due to the floodings. The flood at AD 1880 is differently recorded in the sediment core since a sandy layer is only deposited in the southern basin. Lower pollen influx values and the SCP increase are evident, but the increase in *Pinus* abundance is rather low (Fig. 4). The flood was less extensive and came from a greater distance (approximately 3 km) from the south, while the other flooding followed dike bursts in a closer vicinity of the lake (Driessen 1994), resulting in a different expression of the flood signal.

Based on the signals discussed above, three additional intervals in the core from the southern basin were identified to likely represent flooding events (open bars in Fig. 6). They possibly relate to severe winter conditions in the years AD 1642, 1682, and 1698 listed in historical works (Buisman 2002, 2006). These events are not as clearly evidenced in the sedimentary record as the other floodings, but all show a peak in *Pinus* abundance and a decrease of *Secale cereale* influx. The increase in aquatic plant diversity, however, is less evident. A second clear difference between the southern (pre AD 1740) and northern basins (post AD 1740) are the phases of high *Pediastrum* abundance following flooding events in the latter (Fig. 4). Possibly the nutrient influx or washed-in seeds are not always sufficient to cause a clear change in plant communities. The diversity effect is clear for the known flood events and presents an interesting method to detect flood events since, due to the input of nutrients and allochthonous seeds, the signal lasts longer than the actual deposition of clastic material during flooding. Particularly the observed early presence of the hardy water lily (*Nymphea candida* C. Presl) (ESM Fig. 2), native to more continental climates and thought to be introduced recently in the Netherlands (Van der Velde et al. 1976), shows the potential of river floods for bringing in allochtonous species. The effect of floods on the diversity of the upland vegetation is present but not straightforward. Likely, nutrient enrichment and physical effects of floods cause opposite effects, resulting in a different balance following each flood.

The flooding signals documented in the high-resolution sedimentary archive of Haarsteegse Wiel provide an important calibration of flood events further back in time. Quantitative records of river floods in the Netherlands encompass maximally 150 year and are extrapolated to calculate the expected return time of, sometimes extreme, flood events. By ground truthing the extrapolated observational data with long-term records of river dynamics from natural archives such as oxbow lakes and abandoned river channels one can possibly reduce the uncertainties in the return times of floods and study the effect of long-term climate changes and human impact on the river catchment.

The demise of clear flooding signals after AD 1880, besides better water management and flood control, may be explained by the effect of decreased formation of ice dams known to have caused river flooding in the Netherlands during the Little Ice Age (Gottschalk 1975; Buisman 2002, 2006).

Conclusions

The detailed multi-proxy paleoecological analysis of the sediment record in Haarsteegse Wiel, located in the Meuse floodplain, demonstrates a tight relation between landscape, agricultural history and ecological water quality. The lake, formed by a dike burst, was initially a mesotrophic water body and eventually reached a highly eutrophic state around ca. AD 1980 due to the intensified land use. This original state can, hence, be used as a reference condition for water quality restoration as prescribed in the European Water Framework Directive (European Union 2000). Six documented regional flooding events between AD 1610 and AD 1880 demonstrate that river water influx caused temporary eutrophication of the lake, resulting in short-term changes of diatom and aquatic plant communities. Clear increases of pine abundance, reduction in cereal pollen, and the total pollen influx document the flooding levels in the studied sediment sequences. Combined with sedimentological data, these signals can be effectively used to detect unknown flood events in this and other sedimentary archives.

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References

Appleby PG (2001) Chronostratigraphic techniques in recent sediments. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments. Basin analysis, coring, and chronological techniques, vol 1. Kluwer Academic Publishers, Dordrecht, pp 171–203

Battarbee RW (1973) A new method for estimation of absolute microfossil numbers, with reference especially to diatoms. Limnol Oceanogr 18:647–653

Battarbee RW, Morley D, Bennion H, Simpson GL (2007) A meta-database for recent paleolimnological studies. PAGES News 15:23–24

Bieleman J (1992) Geschiedenis van de landbouw in Nederland 1500–1950. Boom, Meppel

Bijkerk R, Bulstra CA, Verweij GL (2002) Soortensamenstelling van epifytische kiezelalgen in wateren van het Waterschap De Maaskant, 2002, met een ecologische typering van de waterkwaliteit. Koeman en Bijkerk rapport 2002–2034, Haren, 92 pp

Birks HJB, Line JM (1992) The use of rarefaction analysis for estimating palynological richness from quaternary pollendanalytical data. Holocene 2:1–10

Buisman J (2002) Duizend jaar weer wind en water in de lage landen IV (1575–1675). Van Wijnen, Franeker

Buisman J (2006) Duizend jaar weer wind en water in de lage landen V (1675–1750). Van Wijnen, Franeker

Cremer H, Wagner B, Melles M (2001) Holocene climate changes reflected in a diatom succession from Basaltsø, East Greenland. Can J Bot 79:649–656

Dekkers MJ (2007) Magnetic proxy parameters. In: Gubbins D, Herrero-Bervera E (eds) Encyclopedia of geomagnetism and palaeomagnetism. Springer, Berlin, pp 525–534

Driessen AMAJ (1994) Watersnood tussen Maas en Waal: overstromingsrampen in het rivierengebied tussen 1780 en 1810. Walburg, Amsterdam

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. J Eur Comm L327:1–73

Gilli A, Anselmetti FS, Ariztegui D, McKenzie JÁ (2003) A 600-year sedimentary record of flood events from two sub-alpine lakes (Schwendiseen, Northeastern Switzerland). Eclogae Geol Helv 96:S49–S58

Gottschalk MKE (1975) Storm surges and river floods in the Netherlands I (the period 1400–1600). Van Gorcum, Assen

Grimm E (1987) CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Comput Geosci 13:13–15

Grimm E (2004) TGView v2.0.2 (Computer Software) Illinois State Museum, Research and Collections Center, Springfield

Hesselink AW, Weerts HJT, Berendsen HJA (2003) Alluvial architecture of the human-influenced river Rhine, The Netherlands. Sed Geol 161:229–248

IPCC (2007) In: Core Writing Team, Pachauri RK, Reisinger A (eds) Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, 104 pp

Juggins S (2007) C2 version 1.5 user guide. Software for ecological and palaeoecological data analysis and visualisation. Newcastle University, Newcastle upon Tyne

Kirilova EP, van Hardenbroek M, Heiri O, Cremer H, Lotter AF (2009) 500 years of trophic history of a hypertrophic Dutch dike-breach lake. J Paleolimnol. doi:10.1007/s10933-009-9371-2

Koren JH, Svendsen JI, Mangerud J, Furnes H (2008) The Dimna Ash—a 12.8 ^{14}C ka-old volcanic ash in Western Norway. Quat Sci Rev 27:85–94

Middelkoop H (1997) Embanked floodplains in the Netherlands. PhD thesis, Utrecht University, Department of Physical Geography, Utrecht

Nowaczyk NR (2001) Logging of magnetic susceptibility. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments. Basin analysis, coring, and chronological techniques, vol 1. Kluwer Academic Publishers, Dordrecht, pp 155–170

Pilcher JR, Hall VA (1992) Towards a tephrochronology for the Holocene of the north of Ireland. Holocene 2:255–259

Rijsdijk KF, Passchier S, Weerts HJT, Laban C, van Leeuwen RJW, Ebbing JHJ (2005) Revised upper cenozoic stratigraphy of the Dutch sector of the North Sea basin: towards an integrated lithostratigraphic, seismostratigraphic and allostratigraphic approach. Neth J Geosci 84:129–146

Rose NL (1996) Inorganic fly-ash spheres as pollution tracers. Environ Pollut 91:245–252

Rose NL (2001) Fly-ash particles. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments. Physical and geochemical methods, vol 2. Kluwer Academic Publishers, Dordrecht, pp 319–349

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. Pollen Spores 13:615–621

Teunissen D (1990) Palynologisch onderzoek in de omgeving van St. Odilienberg, Limburg. Mededelingen van de afdeling Biogeologie van de Discipline Biologie van de Katholieke Universiteit Nijmegen, p 16

Thordarson T, Self S (1993) The Laki (Skaftar Fires) and Grimsvotn eruptions in 1783–1785. Bull Volcanol 55:233–263

Van den Bogaard C, Schmincke HU (2002) Linking the North Atlantic to central Europe: a high-resolution Holocene tephrochronological record from northern Germany. J Quat Sci 17:3–20

Van der Velde G, Cuppen HPJJ, Roelofs JGM (1976) Een hydrobiologische waardering van het Haarsteegse Wiel (gemeente Vlijmen). Laboratorium voor Aquatische Oecologie, Nijmegen

Van Heusden GPH (1945) Waarnemingen in enige "wielen" in de Betuwe. Tijdschrift van het koninklijk Nederlandsch Aardrijkskundig Genootschap 62:118–141

Wolfe BB, Hall RI, Last WM, Edwards TWD, English MC, Karst-Riddoch TL, Paterson A, Palmini R (2006) Reconstruction of multi-century flood histories from oxbow lake sediments, Peace-Athabasca Delta, Canada. Hydrol Process 20:4131–4153