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Maximum Holocene groundwater levels and associated extension of peat in the border zone of 'Het Gooi' (the Netherlands): a reconstruction based on the study of soil transects

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Original Article

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Abstract

The area 'Het Gooi' in the Netherlands is part of a Pleistocene ice-pushed ridge system that partially drowned during the Holocene upon sea level and associated groundwater rise. As a result, the ridge system was gradually encroached by peat. From the late Middle Ages onward, man reclaimed the peatlands surrounding Het Gooi, heavily reducing their extension and lowering the regional groundwater level by increasingly intensive drainage. Based on historical and archaeological arguments, several authors assume that the Holocene peat cover in the border zones of 'Het Gooi' formed the extension of large raised peat bogs that formed further to the west and east, respectively. They presume that in the late Middle Ages these extensions reached 'upslope' to a maximum altitude of 3 m + NAP (Dutch Ordnance Datum – approximating mean sea level). However, the original extension is difficult to reconstruct, as this peat has disappeared as a result of its exploitation and oxidation, if having been present at all.

In this study, the maximum extension of the Holocene peat cover on the ice-pushed ridge system was reconstructed based on soil characteristics. Used soil characteristics concerned the presence of iron coatings around sand grains and the upper boundary of gleyic features, because these are indicators for the mean highest groundwater level (MHG). For peat to form, this MHG needs to be at or just above the ground surface for most of the year. Based on study of a number of soil transects, we reconstructed to what maximum altitude peat encroachment may have occurred. This 'maximum extension' can alternatively be described as the maximum altitude of the bottom of the peat onlapping the ridge system.

In the western border zone, this peat cover was found to have reached to *c.* NAP or just above, near Hilversum. No indications were found for the occurrence of raised bogs. We conclude that the phreatic groundwater level in this zone was controlled by the sea level and associated lake levels (Naardermeer and Horstermeer), a dominant role being played by the shallow presence of Pleistocene formations with a high hydraulic conductivity. In the eastern border zone, altitudes were more variable and in places reached 2 m + NAP. Peat at this higher elevation probably formed under the influence of a higher phreatic groundwater level, induced by the presence of a clayey Eemian fill with low hydraulic conductivity in the adjacent glacial basin (the Eem valley).

This study demonstrates the value of detailed soil transect studies for palaeogeographical reconstructions of the former Holocene peat cover in Pleistocene landscapes of NW Europe. It also provides independent data for validation of geohydrological models for such landscapes.

Introduction

In the Netherlands, Holocene sea-level rise induced a gradual groundwater level rise and drowning of a Pleistocene landscape. In the western and central parts of the country, Holocene sediments and peats relate to the coeval sea level and phreatic groundwater in the coastal prism, allowing for a detailed spatiotemporal reconstruction of the drowning of the Pleistocene landscape (e.g. Cohen, 2003; Hijma & Cohen, 2011; Stouthamer et al., 2011; Koster et al., 2017). For peats the situation is more complex since groundwater-fed fen peat regionally developed into rainwater-fed bog peat. The resulting raised bogs (or peat domes) are supposed to have reached to 4–5 m above the contemporary regional groundwater level, although physical evidence supporting these claims is lacking (Pons, 1992; De Bont, 2008; Van Loon et al., 2009). The assumable high elevation of raised bogs in the western part of the Netherlands is probably the main reason that several authors (e.g. De Bont, 1991; Wimmers & Van Zweden, 1992) assume that in 'Het Gooi' peat reached to *c.*3 m + NAP (Dutch Ordnance Datum, approximating mean sea level). Altitudes in this area, which basically consists of a Saalian ice-pushed ridge complex with associated fluvio-glacial deposits, partially overlain by Weichselian coversands, range from

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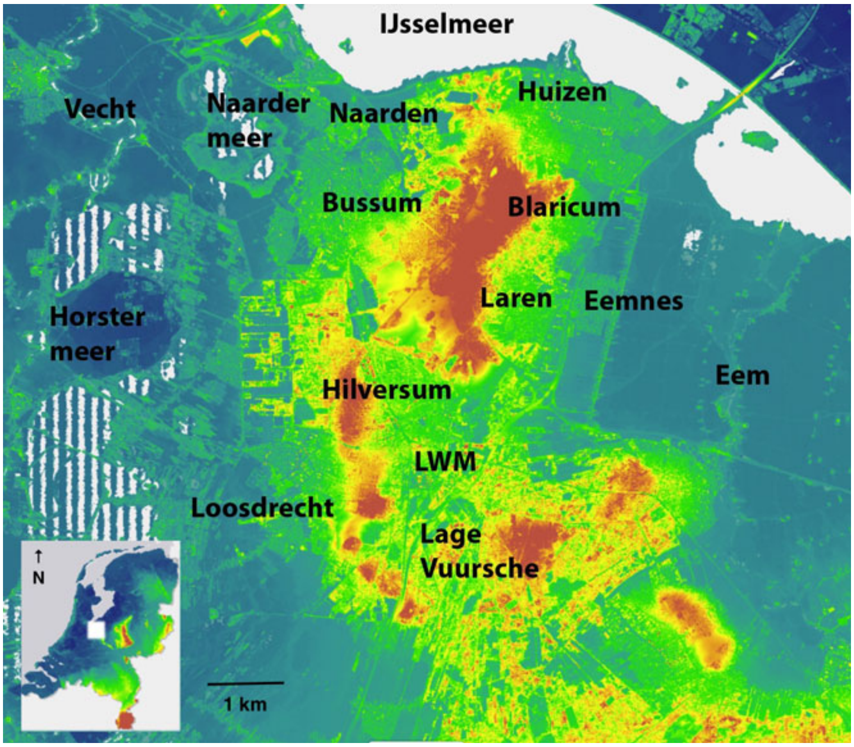

Fig. 1. Location of the study area (AHN-2 model: blue = below NAP; green/yellow/brown = above NAP: brown = >10 m + NAP). LWM = Laarder Wasmeren.

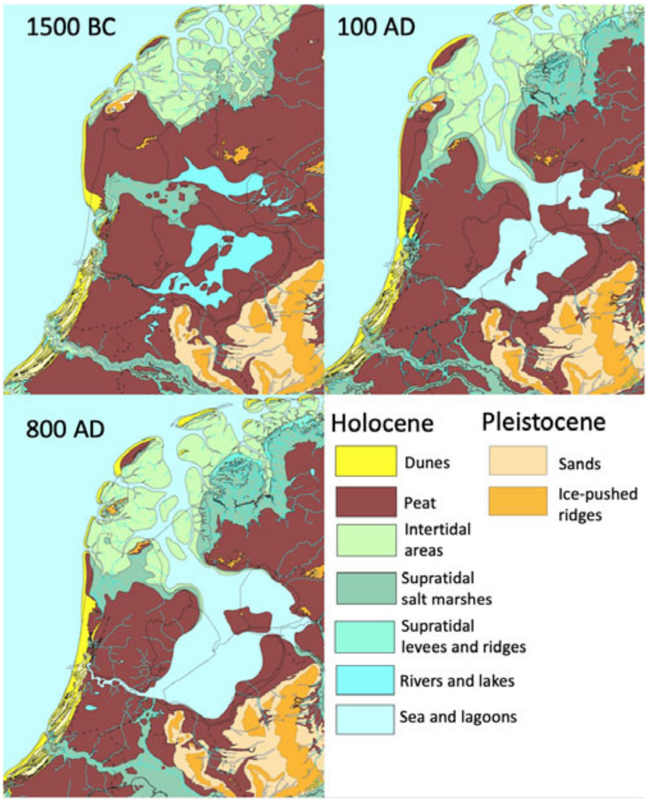

Fig. 2. Palaeogeographical maps for the years 1500 BC, 100 AD and 800 AD. Source: Vos and De Vries (2013).

c. NAP to *c.*40 m + NAP (Fig. 1). Background information on the history of peat distribution in the form of palaeogeographical maps is given in Fig 2, while the overall present-day geohydrological situation is depicted in Fig 3.

From the late Middle Ages onward, in the western part of the Netherlands, reclamation of peat areas for agriculture and their accompanying artificial drainage set off a process of peat compaction and its massive oxidation, which continues till today (Hoogland et al., 2012; Koster et al., 2018). Peat areas were additionally reduced by peat extraction for fuel and salt production (e.g. Borger, 1992). These processes were accompanied by a gradual fall in the regional phreatic groundwater levels, which never again reached the altitude of the late medieval levels. For Het Gooi, De Bont (2008) concluded that the current absence of peat in higher parts of its border zones is a result of drainage and oxidation. That study claims that the peat would have reached to 7 m + NAP, although field studies evidencing the former occurrence of such peat in these zones do not exist. Moreover, data presented by Van Loon et al. (2009) and Koster et al. (2017) point against such high cover.

In none of the studies mentioned is field-based evidence presented for the former presence of peat in the border zone of Het Gooi in the form of coring data evidencing occurrences of peat at higher elevations. The same holds for other coring data from which information on the former presence of peat or on the maximum altitude of the phreatic groundwater level can be derived. As to the latter, for peat to form, i.e. for non- to poorly decomposed organic matter to accumulate, the soil needs to be seasonally saturated with water over a prolonged period of time. The requirements have been extensively described in the literature (see e.g. Joosten et al., 2017) and also depend on such factors as nutrient content, pH, etc., but the main and basic criterion is prolonged water saturation. A soil parameter that is indicative for such prolonged saturation is the MHG (mean highest groundwater level), which corresponds to the upper boundary of the layer with gleyic properties (IUSS Working Group WRB, 2015). In other words, the altitude of the upper boundary of the MHG, as established in soils in the border zone, represents the local altitudinal limit for the maximum extension of the peat cover.

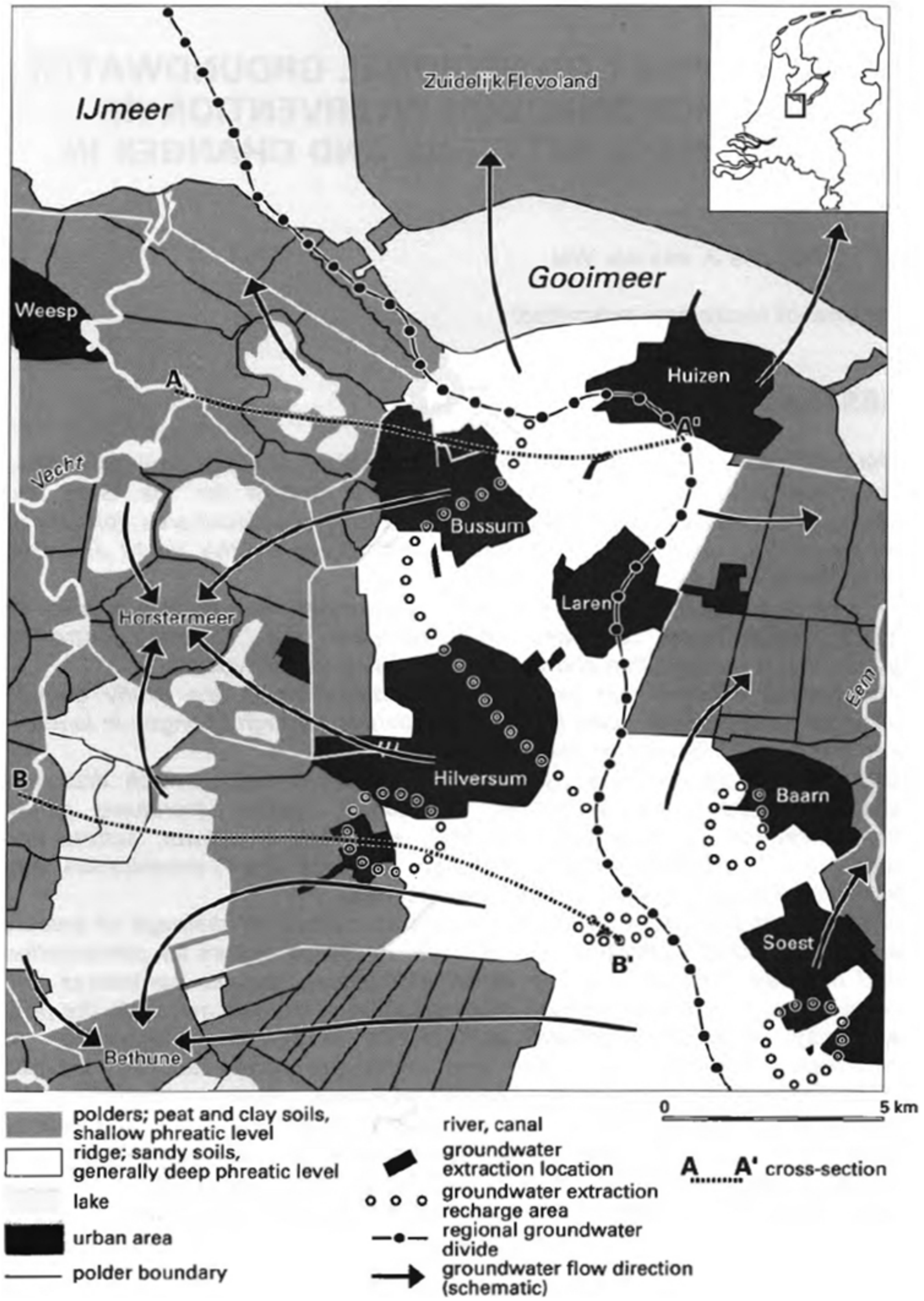

Fig. 3. Geohydrology of Het Gooi and adjacent areas. From Schot and Van der Wal (1992).

Soil transects in the border zone of Het Gooi were systematically studied to establish the local MHG and these data were used to reconstruct the maximum regional extension of the peat cover. This was checked by also coring in the lower extension of these transects to assess the occurrence of (residual) peat layers and thus the reliability of our soil-based method. The backgrounds of this approach are described in more detail below in the section 'Soil indicators for past groundwater level'. Our second aim was to confront these results with the results from model-based reconstructions (e.g. Van Loon et al., 2009; Koster et al., 2017) and with the reconstructions, based on early maps, archival data and other sources, by historical geographers and historians. As regards the latter, the aim also was to solve a long-lasting controversy about this extension of peat in the border zone.

Regional geological and hydrological setting

Traditionally, Het Gooi was defined as the area covered by the (former) municipalities Blaricum, Bussum, 's Graveland, Hilversum, Huizen, Laren and Naarden. To the west and east, the boundaries with the Vechtstreek and Eemland roughly coincide with the 0 m NAP isohypse, but its southern and eastern boundaries are administrative (boundary between the provinces Utrecht and Noord-Holland).

The regional history of the Vecht–Gooi–Eem region has been extensively studied, with emphasis on the Vecht–Gooi region. The geology and history of the western side of Het Gooi differ considerably from its eastern side. These are therefore dealt with separately, focusing on aspects relevant for our study. Additionally, some attention is paid to the northern coastal zone of Het Gooi, which has not been included in our study, for specific reasons that we briefly discuss.

The western border zone

Though 8th-century settlements existed, significant land reclamation is supposed to have started in the 11th century (e.g. Loosdrecht, Kortenhoef and Ankeveen), as for example described in Verhoeven (2013). Evidently, this reclamation induced a lowering of the regional phreatic groundwater level and ended further build-up of any peat dome that may have existed at that time, implying that the reconstructed MHG will reflect the maximum MHG shortly before or during the onset of this large-scale reclamation.

By the end of the 12th century, the river Vecht became a tidal river that connected the river Rhine with the former inland sea, the Zuiderzee. Earlier, the river Vecht was connected to the IJ-estuary, a system that stopped functioning between 200 and 100 BC (Bos et al., 2009; Kranendonk et al., 2015). This river had previously deeply cut through the Holocene deposits into the Pleistocene subsoil, which is composed of ice-pushed older Pleistocene deposits, a massive cover of overall coarse-textured fluvio-glacial deposits and, lastly, a complex of Weichselian coversands (Bos et al., 2009).

In the Middle Ages, to the west of Het Gooi, several lakes existed that had their shallow basis in these Pleistocene deposits (the Naardermeer and Horstermeer, respectively). De Gans et al. (2010) provided an overview of their history and stressed that wind and wave erosion led to a gradual eastward expansion of smaller lakes that were connected to the river Vecht from the late Roman period onward. Whereas nearer to the Vecht river Sphagnum peat seems to have dominated, the thin peat cover into which the Naardermeer and Horstermeer expanded probably largely consisted of relatively eutrophic types of peat, such as forest and sedge peats (see e.g. Verhoeven, 2013). The prevalence of such peats closer to Het Gooi can be linked to seepage of groundwater from the higher grounds. The rare occurrences of moss peat, and thus potential peat domes, were apparently limited to a narrow zone between the river Vecht and the seepage zone to the west of Het Gooi, as is tentatively suggested by Verhoeven (2013).

Conclusions by De Gans et al. (2010) are (i) the Naardermeer already started to form during the late Roman period (*c.* 500 AD) and (ii) lake sediments from that early period hold marine diatoms, which they explain by far earlier marine or brackish phases in the predecessors of the Zuiderzee than earlier assumed (e.g. Bos et al., 2009). Finally, they state that in that late Roman period sea level still stood at 1 m − NAP, with probably only slightly higher water levels in the Flevomeer (0.50 m) and later on the early Zuiderzee.

The eastern border zone

Large-scale reclamation in this border zone and the ensuing fall in the regional groundwater level also took place in the late Middle Ages, in the villages Laren, Blaricum and Eemnes dating from the 11th–12th century. However, the geological structure of this area deviated from that of the western border zone. During the Eemian, the former deep glacial basin to the east of Het Gooi was filled in with clayey sediments with low hydraulic conductivity (Bosch et al., 2000; Wesselingh et al., 2010). These sediments reach to *c.*10 m below ground surface and are overlain by Weichselian coversands and Holocene peat. Except for some general studies on the soils of the Eem valley and on the nature of the major peat deposits encountered (Pleijter and Beekman, 1979; Vervloet and Van den Bergh, 2007), relevant detailed studies on the Holocene from the western Eem valley are non-existent. Van Westrienen et al. (1991) describe the geohydrology of this eastern border zone in quite some detail but focus on the current situation and the ecological aspects of drinking-water extraction.

The northern coastal area of Het Gooi

Several excavations in Naarden (unpublished reports: e.g. by T.N. Krol & J. Schoneveld, 2014; A. Pels-Ouweneel & E. Mol, 2017) and some corings within the built-up area of Huizen (Dutch Geological Service website Geotop) point to the occurrence of Holocene marine to estuarine clays on top of Pleistocene coversands, eventually with intercalated peats. This coastal zone has been seriously affected by inundations from the Zuiderzee, following its embankment that started in the 12th century (Henderikx, 1995) and the ensuing repeated flooding as a result of dike breaches during storm floods. Altitudes reached by floods will have been considerably higher than in the pre-embankment period, a phenomenon that has been extensively described by Vos & Zeiler (2008), De Gans et al. (2010) and Vos (2015). It is ascribed to a major reduction in the accommodation space of the southern Zuiderzee basin and adjacent lowlands upon the embankment of these lowlands. This and the fragmentary nature of the data presented in the archaeological reports prevented us from reliably reconstructing the pre-embankment situation.

Soil indicators for past groundwater level

In the Netherlands, grains of well-drained Pleistocene sands, such as coversands and fluvio-periglacial deposits, are covered by thin coatings composed of ferric iron hydroxides and clay, giving these sands a yellowish to brownish 'blonde' tinge. The coatings have been described as iron coatings (Van der Veer, 2006; De Bakker, 2013) and form the main primary source of iron and clay in these sands. In the topsoil of a well-drained podzol, ferric iron is leached by complexation, while deeper in the soil the original coatings are preserved and leached iron compounds precipitate. Still deeper in the soil, near the groundwater table, anoxic conditions occur and gleyic properties develop (IUSS Working Group WRB, 2015).

The processes give rise to the characteristic sequence of soil horizons in such podzols, described as the Ah and E horizon (leached), the Bh horizon (h= humus: with illuviated organic matter), the Bs horizon (s = sesquioxides: with illuviated iron and often also organic matter – Bhs) and deeper horizons, including the Bg or Cg horizon (g = gley: with gleyic properties). The upper boundary of these gleyic properties corresponds to the mean highest groundwater level (MHG). The most prominent characteristics are Fe-mottling and accumulation of iron by depletion of the underlying reduced zone in which iron coatings completely disappear. Extensive descriptions of the phenomenon can be found in publications on soil formation in the humid temperate zone (e.g. Schlichting & Schwertmann, 1973; De Bakker & Schelling, 1989; Duchaufour. 2012; De Bakker, 2013).

Iron coatings can be used as indicator for the occurrence of anoxic conditions brought about by prolonged saturation with water, more precisely as indicator for the MHG. Since these coatings, once removed by gleying, do not form again, they also are indicators for past hydrological conditions, i.e. for the highest altitude the MHG ever reached. Their identification is hampered by the fact that illuviated organic material often forms coatings around sand grains (organans) and may visually resemble iron coatings (see e.g. De Coninck, 1980). Such organans are particularly abundant in podzols that form under poorly drained conditions (hydropodzols), but most of these soils are currently well-drained. A distinction between 'true iron coatings' and cutans composed of illuviated yellowish-brown organic matter can be made by heating soil material in a furnace to oxidize all organic matter and transforming iron compounds into red iron oxide. This method has been widely employed in Dutch soil surveys and is used as a criterion to distinguish between hydro- and xeropodzol soils (De Bakker & Schelling, 1989; De Bakker, 2013).

Criteria for hydromorphic characteristics of podzols (hydropodzols) are thus described as: a peaty topsoil, or an intermediate peaty layer, and/or no iron coatings on the sand grains below the B2 horizon (De Bakker & Schelling, 1989). Similarly, for sandy vague soils (soils with very limited soil formation and thus without distinct B horizon) they define hydromorphic properties (hydrovague soils) as with 'no iron coatings on the sand grains below the A horizon'. The method of 'turning red upon ignition' is used to assess whether coatings are indeed 'iron coatings', but no strict analytical procedure and criteria for this method have been developed.

Since the later Middle Ages, when reclamation of the peatlands started, the overall impact of land use has been that phreatic groundwater levels were lowered throughout the region concerned. Particularly in modern times, massive groundwater extraction for drinking water production even led to local reversal of groundwater flows, and in the border zones exfiltrating areas were often converted into infiltration areas (see e.g. Van Westrienen et al., 1991). Altitudes of current MHG levels are distinctly lower than those in late medieval times, but these altitudes cannot be established by the indicator described above, i.e. the presence of iron coatings around sand grains. The reason is that once 'destroyed' by reduction, they do not form again upon improved drainage and oxidation of formerly reduced soil material, as already stated above.

Methods

A systematic study was performed of soil transects (Fig. 4). These start with distinct xeropodzols, generally at several metres above NAP, and gradually descend towards less well-drained soils. The maximum altitude of the MHG was estimated, based on the occurrence of iron coatings and gleyic features. Features such as a residual peaty topsoil or intermediate peaty layer were also recorded. Where the altitude of the MHG was not truly evident from the field observations, relevant soil profiles were sampled and checked for the presumed occurrence of iron coatings by the 'turning red upon ignition' method (for details see below).

Transects were selected using the 1:50,000 soil maps of the region to identify suitable areas with undisturbed soils, and the AHN-2 (Current Dutch Elevation of the Netherlands – a digital elevation map with x, y and z precision of 0.5 m, 0.5 m and *c.*0.05 m, respectively). Soils were cored using an Edelman corer and described for their colour, texture, lithology and soil horizon sequence (Jahn et al., 2006). Special attention was given to the potential occurrence of stagnative layers and occurrence of a perched groundwater table. Examples are in the Wasmeren (LWM) to the east of Hilversum (see also 'lakes' in Fig. 4).

The samples were dried and subsequently ignited to *c.*1000°C in a furnace. Afterwards, they were visually classified for their redness using a qualitative scale of 1–8, from 1 = white (free of iron) to 8 = maximum redness. For a selection of samples, representing this redness range, iron contents were established by means of a handheld X-ray fluorescence meter (XRF) to check whether redness values obtained could be correlated with iron contents. For calibration, a series of standard samples with known iron content was used. In the XRF-examined samples, iron is present in the form of grains, such as magnetite and other iron-bearing minerals, and, eventually, as coatings around grains. Values obtained by XRF thus pertain to total iron (both as minerals and as coatings).

Results

Field observations focused on reconstruction of the MHG. Results from the lab analyses were used, if the MHG could not easily be established by the occurrence of a distinct Bs horizon or distinct iron coatings around sand grains,. These lab results will be described and discussed first, followed by a description by transect. Transects and corings are indicated in Fig 4.

Iron coatings and ignition method

In total, 127 samples were ignited, of which only a few were found to be free of iron coatings, but still holding some iron in the form of primary minerals. Samples were classified in a range from 1 to 7. The reddest sample (8) was omitted, since only one sample with such relatively high Fe content (1.1% Fe) and strong red colour upon ignition was found. Fig 5 shows the statistical relation between the iron content (XRF) and relative redness (see also Fig. 6). The results illustrate that most samples hold in the order of 0.10–0.15% Fe and fall in the 3–6 redness class. However, they also illustrate that the correlation between the redness value and measured iron content is certainly not optimal. The explanation is that the measured iron content represents both mineral grains and coatings, and in sands with a low contribution from coatings very much depends on the content of iron-containing mineral grains. The latter content may vary considerably (e.g. Huisman & Kiden, 1997; Schüttenhelm & Laban, 2005) and thus samples with a low redness value still may hold a relatively large amount of Fe (by XRF), as strongly suggested by Fig 5.

Median Fe values for Dutch coversands are reported to be 0.15% by Van der Veer (2006), who also described the iron coatings as characteristic for these sands. This value is well in line with the values observed and indicates that the boundary with sands without such iron coatings can be put at <0.10% Fe and at ≤2 for our redness classes. Evidently, from the relatively poor correlation between the XRF-measured Fe content and the redness value it had to be concluded that it is only this redness value that forms a reliable indication for the presence or absence of iron coatings, which therefore has been used to check the field observations on the depth of the MHG in the soil profiles studied. To elucidate how MHG values were established from the observations, first examples are given in the form of soil profiles and transects from the western and eastern border zone, respectively. This is followed by a description of the results for the two border zones.

Estimation of the MHG: examples

In Fig 7 two examples are presented of transects and studied soil profiles. Altitudes are based on the z-coordinate values for sections and corings from the AHN-2 (see Methods). Part of transect IV is

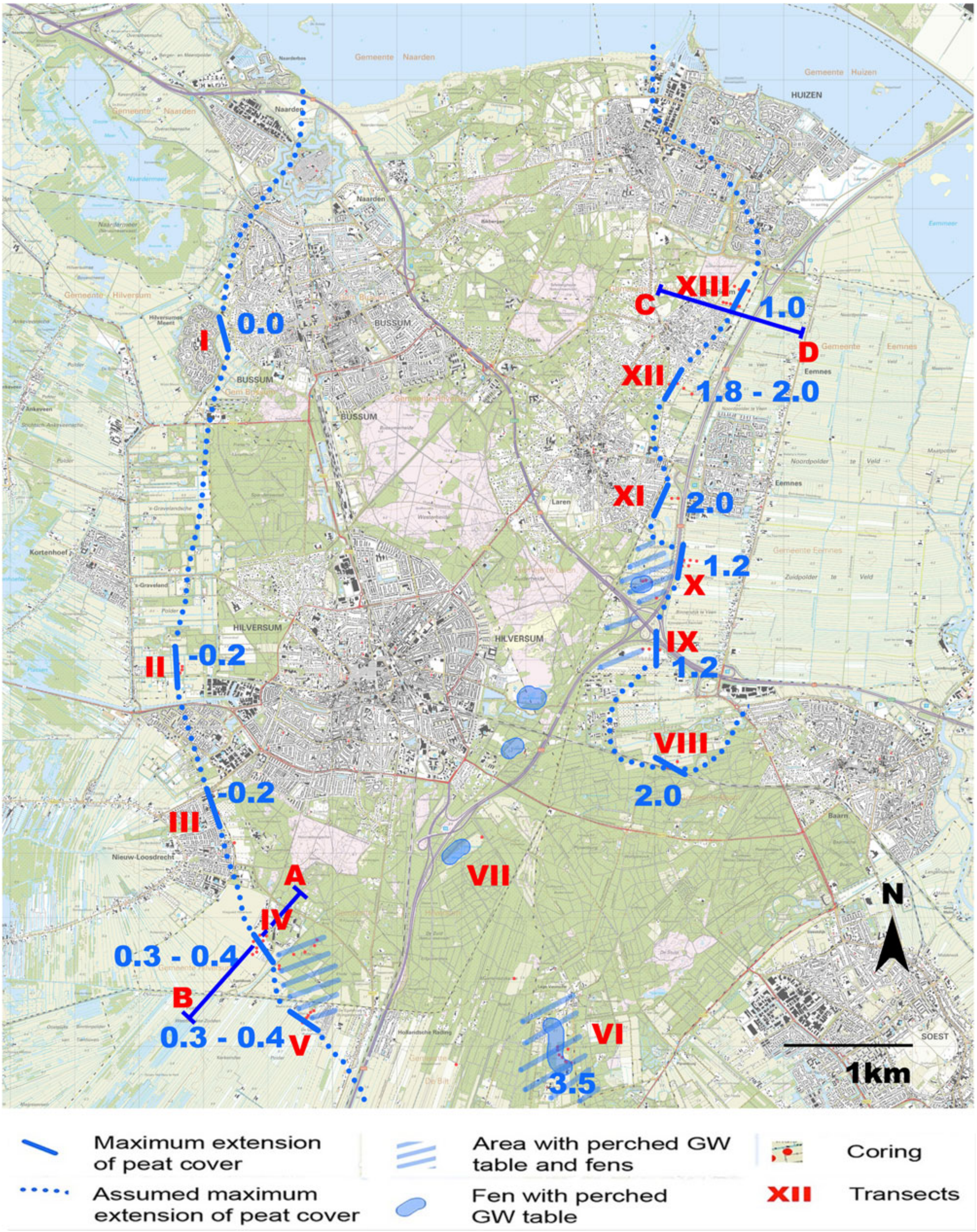

Fig. 4. Location of transects and corings, and maximum altitudes of the GHG in m NAP (in blue). GHG = mean highest groundwater level; GW = groundwater.

depicted in Fig 7a, while the location of the transect within a wider, more regional context is given in Fig 7b. In transect IV, the Saalian deposits do not contain till, in contrast to those in transect XIII, where till is an important component. Their location within the regional groundwater flow system can be seen in Fig 3. In coring 9, the MHG could be identified by the absence

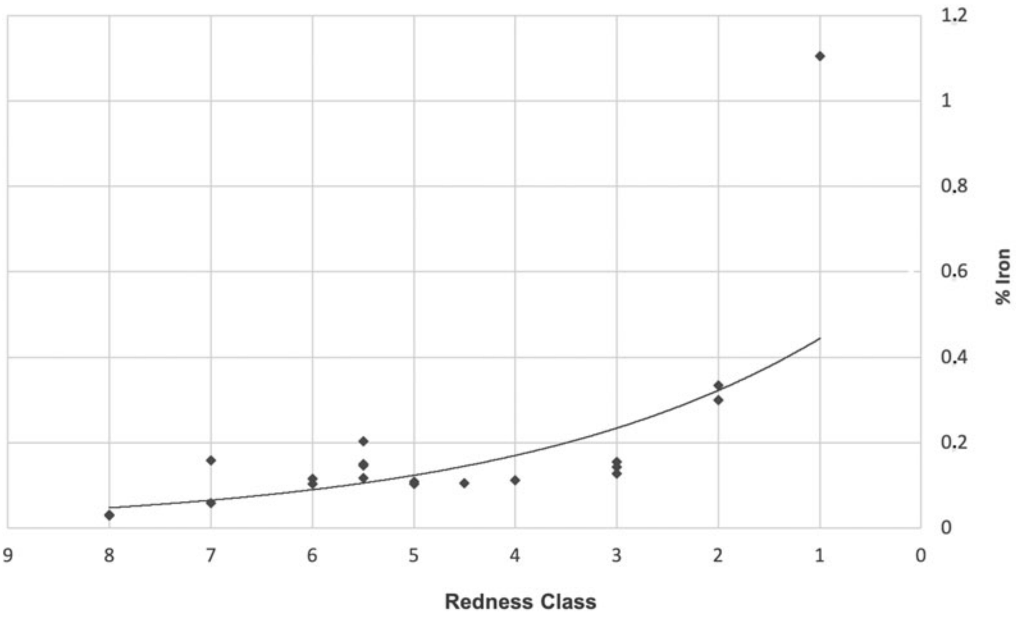

Fig. 5. Fe content in % (y-axis) versus relative redness class (x-axis) for a representative series of samples.

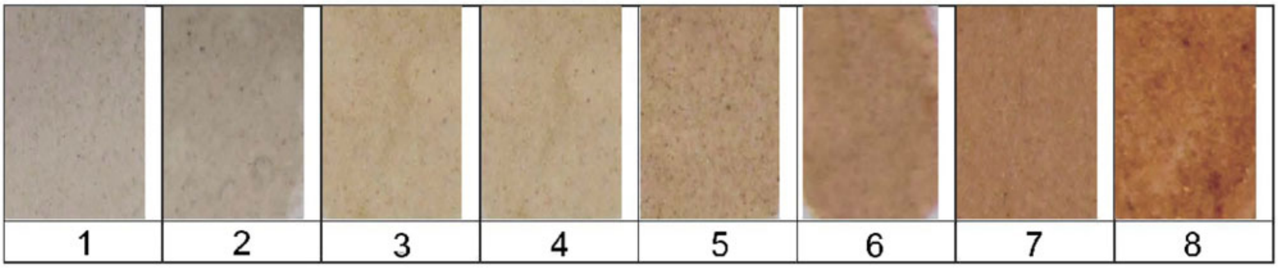

Fig. 6. The redness classes distinguished in this study, based on the full set of samples ($n = 127$).

of iron coatings below *c.*0.6 m + NAP, while in the corings further down the gentle slope the altitude of this MHG declines to *c.*0.2 m + NAP. In coring 6, this MHG cannot be established with certainty, since the upper part of this profile (Ap horizon) has been ploughed. However, it is clearly still somewhat lower than the value observed in coring 8, where both field observations and redness test point to a MHG at *c.*0.50 m depth (i.e. 0.4 + NAP).

The second section (section XIII, see Fig. 7c) covers part of transect XIII and shows the irregular longitudinal profile of this slope, which overall is steeper than transect IV. The depth of the MHG ranges from nearly 1.4 m + NAP (based on field observations: gleying), down to less than 1 m in the east (corings 102 and 103). This illustrates the inclination of the phreatic level along this slope. Coring 102 very clearly demonstrates that on the lower slope the MHG was at *c.*1.0 m + NAP or slightly lower, since this profile had a distinct Bhs horizon and transition towards a gleyic subsoil, very clearly showing up in the field and in the lab (redness test). Also here, in the lowest coring (103) the depth of the MHG could not be established with certainty, being located in the Ap horizon. In corings further down the slope (not shown), topsoils were peaty.

The western border zone

The first transect at Gijzenveen, transect I, was previously studied by Den Haan & Sevink (2010), later followed by Koopman & Sevink (2015) and Van Geel et al. (2016). In a thin layer of coversand over diamictic, coarse-textured deposits, a well-developed xeropodzol is present with distinct E and Bh horizons, and a Bs horizon that is developed in the diamictic material. The soil was exposed over a large area, allowing for a very precise estimation of the MHG: below the Bs horizon iron coatings were observed to *c.*0 m NAP, *c.*0.55 m below ground level; below that level the soil exhibited gleyic mottling.

Recently, evidence was found very nearby (Van Geel et al., 2016) for a high perched groundwater table (to at least 0.3 m − NAP) that formed around 4000 BC and led to the development of ombrotrophic peat. Millennia later, the area drowned and again peat accumulated, culminating in inundation during the later Middle Ages by seawater, causing pyrite to accumulate in the upper peat layers (Van Geel et al., 2016). Clear evidence was found that before, during and after this inundation phase the MHG did not reach to >0 m NAP: the younger peat thinly wedged out against a drift sand dune complex to the east and its top remained below that altitude.

Transect II at Corversbos (six corings) started in coarse-textured gravelly sands with a plaggic topsoil over a xeropodzol with distinct Bh and Bs horizons, and prominent iron coatings below the Bs. To the west it gradually changed into hydropodzols with a distinct Bh horizon and lacked such iron coatings, and subsequently hydropodzols with relatively well-preserved peaty topsoils. The top of the Cg horizons was found to be at *c.*0.2 m − NAP, *c.*0.5 m below ground level.

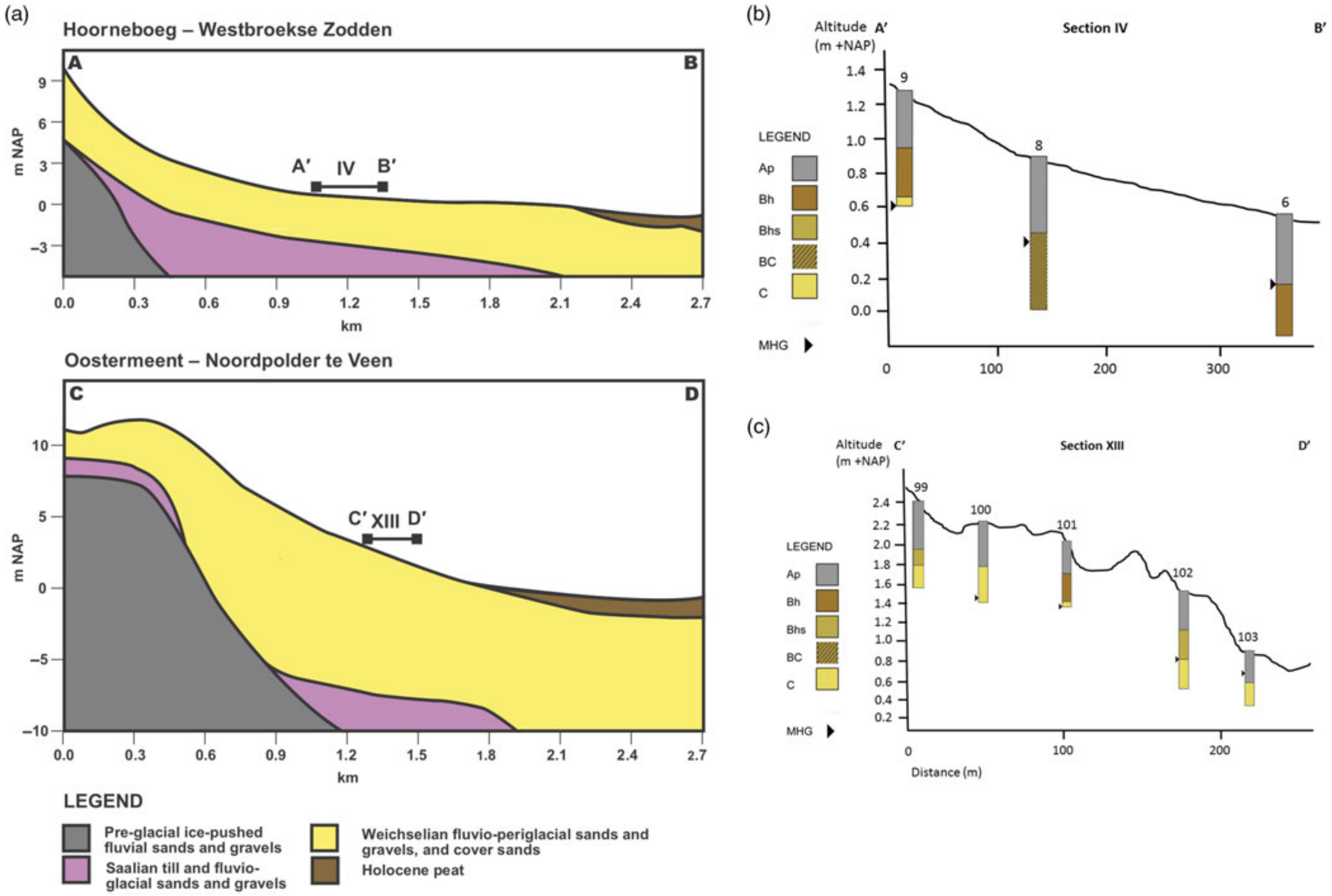

Fig. 7. (a) Lithostratigraphy of transects IV and XIII; (b, c) parts of (b) Transect IV and (c) transect XIII with altitudes (in m NAP), major soil horizons and MHG.

Transect III at Loosdrecht (four corings) started with plaggen soils with a rather thick plaggic topsoil (up to 0.60 m) over a well-conserved xeropodzol with a Bh/Bs horizon sequence developed in coarse-textured gravelly sands. The lower boundary of the Aan horizon was at 0.50 m + NAP. To the NW these soils gradually changed into a hydropodzol with a Cg, starting at *c.*0.70 m depth, and subsequently into a hydropodzol with a peaty topsoil. Throughout the sequence, the upper boundary of the Cg horizon was at *c.*0.2 m − NAP, and peaty topsoils occurred in soils of which the top was at approximately that altitude.

Transect IV at Vliegveld Hilversum (eight corings) was in an area with a low undulating coversand relief. In the transect, a transition was observed from xeropodzols with gley deeper than 0.90 m to distinct hydropodzols with peaty topsoil and gley at <0.5 m. The MHG reached to 0.3–0.4 m + NAP.

Transect V at the Einde Gooi/Egelshoek (10 corings at Einde Gooi) was also in an undulating coversand area with similar podzols, like transect IV. In the first corings (coming from the north) soils have been deeply worked, and only near the provincial border (Graaf Floris V road) were less disturbed soils found (but with severely truncated topsoils) with hydromorphic properties starting slightly above NAP (depth below ground level between 0.7 and 0.9 m). In the southern extension of this transect (12 corings, near Egelshoek), soils had a deep plaggic horizon (>0.5 m) over a podzol with a Bs horizon. The upper boundary of the Cg horizon in these soils is at 0.3–0.4 m + NAP (depth below ground level ranging between 0.4 and 0.9 m) and soils had iron coatings to that depth.

The central southern part of Het Gooi

In transect VI near the Lage Vuursche area (18 corings), podzols in coversands with peaty topsoils were encountered. These soils had a perched groundwater table and were confined to an area underlain by a humuspodzol with a stagnant, strongly developed podzol Bh horizon. Below this horizon, sand grains had distinct iron coatings, evidencing that the regional phreatic level was never that high. The altitude of the top of the stagnant podzol B horizon ranged between 3.0 and 3.5 m + NAP. Further north, corings along transect VII (near the Hilversumse Wasmeer: five corings), next to a fen on a stagnant humuspodzol, showed that here the upper boundary of the horizon with gleyic features was at *c.*1.8 m below ground surface, which lies at *c.*3.10 m + NAP. Thus, the highest MHG was at *c.*1.3 m + NAP, while between the peaty podzol in the top and this Cg horizon was an aerated zone, which was *c.*1 m thick in most corings. The present-day phreatic groundwater was not reached in these corings (>2.20 m below ground level). This evidently proves that the lake has a perched groundwater table. Finally, Sevink et al. (2013) showed in the Laarder Wasmeren area that the former MHG was at *c.*2.1 m + NAP. That high groundwater level existed around 3000 BC, while today it is at *c.*1.9–2.0 m + NAP. For details, reference is made to that paper.

Fig. 8. Xeropodzol with plaggic horizon over Bh/Bhs horizon sequence. Characteristic dark/black humic fibres and 'blonde' C horizon at the Oostermeent (transect XIII).

The eastern border zone

In the eastern border zone the situation differs from the west, with overall higher MHG altitudes. In the coversands of transect VIII (Groeneveld: nine corings), the boundary between xeropodzols and hydropodzols was fairly sharp. In the xeropodzols, the upper boundary of the Cg horizon was found at 0.40–0.50 m depth below ground level or deeper, at an altitude of *c.*2 m + NAP. Further down, at altitudes less than 2 m + NAP, the hydropodzols had a peaty topsoil.

Transect IX (Klaverblad: 11 corings) ran from a slightly higher (*c.*2 m + NAP) coversand area with xeropodzols towards a depression with peaty soils. The reconstructed MHG was at *c.*1.2 m + NAP, based on the distinct presence of iron coatings in soils at altitudes above 1.2 m + NAP. Its depth below ground level ranged from *c.*0.8 m to 0 m. The presence of these coatings was evidenced by the redness after ignition of samples from these soils, and in the field the upper boundary of the Cg horizons encountered was clearly visible.

Transect X (Kwekerij Gooi en Eemlust: seven corings) was more complex because of the local presence of a perched groundwater table on a stagnative podzol. In a first coring, humified peat was found at 0.45–0.50 m depth over a hydropodzol, with a ground surface at 2.3 m + NAP. However, in adjacent corings no peat was observed, and hydromorphic features were not observed at altitudes above 1.2 m + NAP, confirmed by tests for redness after ignition. Depths below ground level of these features were 1 m or more. Subsequent coring showed that the hydropodzol, which today is excessively drained, indeed had a perched groundwater table over a stagnant Bh horizon. Hence, the MHG was estimated to be 1.2 m + NAP.

In transect XI (Laren: four corings) peat was encountered in topsoils to altitudes of up to 2 m + NAP. The soils exhibited prominent rusty mottles (redness class 8). In the subsoil no stagnant layers were found, but fully reduced sediment, testifying that the MHG must have been at least at *c.*2 m + NAP. This was confirmed by corings in slightly higher parts of the transect where iron coatings were observed above that altitude (*c.*50 cm below ground level).

Soils in transect XII, further north (Schapendrift: four corings in total), also exhibited distinct rusty mottles. Where the ground surface was below *c.*1.8 m + NAP they had a peaty topsoil. Two corings in xeropodzols at higher altitude showed that the upper boundary of the Cg horizons was at 1.8–2.0 m + NAP (at *c.*1 m below ground level).

The last transects, XIII (Blaricumse Meent: 10 corings and 12 corings respectively), were cored from the higher terrain with xeropodzols (gleyic features >1.2 m below ground level), to the lower terrain in the east with hydropodzols having peaty topsoils. Here the upper boundary of the Cg horizon was at *c.*1.0 m + NAP or even somewhat lower, confirmed by the presence of iron coatings (redness upon ignition) to that depth. In Fig 8, an example is presented of the xeropodzols encountered in this transect. It exhibits the characteristic 'blonde' subsoil and very dark to black humic fibres below the podzol B horizon. The weak expression of this 'blonde' colour illustrates the subtleties in the identification of these grain coatings, which under magnification (loupe or microscope) are commonly clearly visible.

Discussion

Crucial for the identification of the MHG is its recognition in the field, which is primarily based on the occurrence of iron coatings around the sand grains. Their field identification was often problematic. Therefore, in many transects the reconstruction of the MHG rested on the outcome of the 'redness upon ignition method'. First, some attention is paid to the reliability of this method as indicated by the XRF analyses. This is followed by a more extensive discussion of the reconstructed MHG in the various transects and their implications for the maximum extension of the peat in the border zones of Het Gooi.

As described above in 'Iron coatings and ignition method', the correlation between the visually established redness class and measured Fe content (XRF) is rather weak, which can be explained by the fact that the XRF-measured Fe content represents the total iron content, including Fe in mineral grains and not only Fe present in the form of iron coatings, whereas the redness class is typically linked to the presence of iron coatings. For that reason, only the redness class was used to check the reliability of the MHG, as based on the field observations. In none of the studied transects did results from this 'redness upon ignition method' conflict with the field observations or point to major local variation in the altitude of the MHG. Moreover, altitudes at which peaty topsoils were encountered in lower soil profiles in several transects corresponded to the reconstructed MHG. This strongly suggests that iron coatings are indeed reliable indicators for the maximum altitude (or depth below the ground surface) at which prolonged water saturation occurred.

In Fig 4, locations of transects, reconstructed altitudes of the MHG, and the maximum extension of the peat cover based on these MHG altitudes are plotted. Altitudes of the MHG in the western border zone are consistent and only reach to slightly above NAP in the south. In the east, altitudes are higher, but also more variable. Maximum altitudes reached are *c.*2 m + NAP near Laren, in which case also distinct seepage phenomena were observed.

Because of the major differences between the two border zones, results are discussed by zone.

Western border zone

Lateral extension of raised bogs is described as paludification (Crawford et al., 2003; Schaffhauser et al., 2017) and is associated with the development and gradual extension of a stagnative podzol. The phenomenon is well known from the Dutch coversand landscapes (Van Wirdum et al., 1992; De Bakker, 2013). However, such a stagnative podzol is absent throughout the western border zone, where the surficial Pleistocene sediments (Boxtel Formation) mainly consist of moderately fine sandy aeolian deposits, locally with intercalated coarse sandy-gravelly layers of fluvio-periglacial origin (Koopman & Sevink, 2016). In places, the thickness of the Boxtel Formation is more limited and the underlying coarse-textured fluvio-glacial deposits (Schaarsbergen Member of the Drenthe Formation) may be close to the surface (e.g. Corversbos and Loosdrecht, transects II and III). All these sediments are highly permeable. This implies that the altitude of the MHG in this border zone of Het Gooi was directly related to the regional phreatic groundwater level and no perched groundwater levels occurred.

Prior to the late medieval drainage of the peats and the resulting subsidence, the regional phreatic groundwater level in the west was most likely controlled by the level of a proximal inland lake (Flevolake) that transformed into the Zuiderzee at a later stage (De Gans et al., 2010; Vos, 2015). The river Vecht and associated lakes, all with highly permeable Pleistocene deposits at their base, were in open connection with this interior lake and later on the Zuiderzee. Given this geohydrological situation – open connection to the sea and highly permeable subsoil – the altitude of the coeval regional groundwater level and thus the regional MHG will have been roughly equal to today's sea level or was even lower (see 'Estimation of the MHG: examples', above). In local raised bogs that were further away from these lakes, the river Vecht, and the drier border zone of Het Gooi, higher groundwater levels may have occurred (see De Bont, 2008, 2015). However, it is unlikely that significant raised bogs and associated high regional groundwater levels existed at that time in the direct vicinity of the drier western border zone, fully in line with our observations. Such a conclusion is also in accordance with the results of Koster et al. (2017), who state that in the area concerned the mean MHG reached *c.*0 NAP around that time.

Van Loon et al. (2009) assumed an important role for peat domes. In their southern transect, which runs considerably further south (near Bilthoven), the modelled phreatic groundwater level would have been >2 m + NAP around 800 AD. However, in their northern transect, which runs E–W through the Horstermeer, this level would have been roughly at sea level at that time (see 'Estimation of the MHG: examples', above). This illustrates that there was quite a steep gradient in this phreatic level, going north, as also suggested by our observations in the border zone to the SW of Hilversum, where the MHG never was >0.5 m + NAP. Furthermore, it is in full agreement with the conclusions of De Gans et al. (2010) for the Horstermeer, of which the history and link with the river Vecht would have been very similar to that of the Naardermeer.

Eastern border zone

Our observed MHG values are distinctly higher than in the west, particularly in the transects near Laren and further south. For transect VIII (near Groeneveld), the observed MHG is quite in line with the earlier study of the nearby Laarder Wasmeren area (Sevink et al., 2013), where a highest phreatic groundwater level was found at 2.3 m + NAP (around 3000 BC), while later on it reached to *c.*2 m + NAP. Additional indications for such local higher groundwater level are the paludification observed near Laren, and the reported occurrence of peat domes in the Eem valley. Nevertheless, maximum altitudes reached in the border zone are distinctly lower than suggested in the literature: at maximum *c.*2 m + NAP, instead of an assumed maximum altitude of 7 m + NAP (see De Bont, 2008).

An explanation for the overall higher MHG and associated peat extension may be readily found in the geohydrology of the Eem valley, in which the presence of a stagnative, thick stratum of Eemian clays, starting at *c.*10 m – NAP, plays an important role. Van Westrienen et al. (1991) ascribe the local higher groundwater level and significant lateral seepage to this specific situation. Clear indications for such seepage are found in the form of the rather massive iron hydroxide accumulations in several profiles from the Laren area (XI and XII, described as abundant rust mottles. These are also known as 'bog iron' and characteristic for seepage zones (Joosten et al., 1998)).

Interestingly, the spatial pattern in maximum MHG that we observed is virtually identical to that of the mean MLG (summer level) published by Van Westrienen et al. (1991). Evidently, absolute values cannot be compared since current groundwater levels have been lowered in recent times, notably by deep drainage caused by the reclamation of the Flevopolders and by extraction of groundwater for consumption.

General

In the earlier palaeogeographical studies no distinction was made between fen peats that originally were groundwater-fed, but developed into rainwater-fed bogs, and peats in local bogs that formed on stagnative podzols and had a perched groundwater table. Such perched groundwater tables and associated local bogs were particularly encountered in the southern part of Het Gooi (see Fig. 4) and were extensively described by Sevink et al. (2013), Van Geel et al. (2016) and Sevink & Van Geel (2017). They are a local phenomenon inside Het Gooi and their altitude bears no relation to the maximum MHG of the phreatic groundwater in its border zones.

The differences in maximum altitude of the MHG between the western and eastern border zones illustrate the crucial role played by the hydraulic conductivity of the subsoil. In the west, this zone is underlain by overall coarse-textured deposits with high permeability (like most of the ice-pushed ridges in the central part of the Netherlands). Paludification, in the sense of the extension of a peat cover through the development of a stagnative soil (Klinger, 1996; Schaffhauser et al., 2017), plays a very minor role. In this type of area, the altitude of the MHG is directly linked to the regional phreatic groundwater level and varies little at the regional scale. Small areas with perched groundwater and peat may occur, but their formation is driven by the classic successional development of podzols in depressions, as often encountered in coversand landscapes (De Bakker, 2013). The origin of such peat can be easily established by soil surveys, though such surveys have been rarely performed to support the parcellation and toponym-based palaeogeographical reconstructions.

In the east, larger spatial variation occurs in the altitude of the regional phreatic groundwater level, which is ascribed to the occurrence of deeper strata with low hydraulic conductivity. Here, the altitude of the MHG can less readily be established and truly systematic detailed soil studies were needed to distinguish between peat formed in connection with the local phreatic groundwater level and peat connected with perched groundwater. However, distinction was possible, and the maximum extension of phreatic groundwater-based peat could be established. Examples of detailed studies of similar areas are those for the Beezerveld (Sevink et al., 2019) and for the Dwingelderveld (Verschoor et al., 2003). Van Beek et al. (2015) give examples from Twente in the east of the Netherlands and place these in the wider context of the long-term development of raised bogs.

In areas with near-surface impervious strata (e.g. tills and Tertiary clays in the north and east of the Netherlands), perched groundwater becomes dominant and paludification is the major process, ultimately leading to the nearly complete coverage of the Pleistocene land surface by bog peat (Verhoeven, 2013). Our approach – establishment of the maximum MHG on the basis of iron coatings /gley – may be used to identify local drier areas, which were not covered by this bog peat. However, it is expected that information may be gathered on the maximum regional groundwater level only coincidentally.

Conclusions

Using soil data, we try to reconstruct the highest altitude of the mean highest level of the phreatic groundwater level and assume that this altitude was reached during the late Middle Ages. This is because large-scale reclamation and drainage of the peatlands started in the 11th–12th century and led to the fall in regional groundwater levels. Our reconstruction shows that in the western border zone of Het Gooi its maximum altitude was at *c.*0 m NAP, which sets the upper altitudinal limit for the extension of the peat cover in this zone. Our values are consistent and fully in line with results from recent geological and geohydrological studies (Van Loon et al., 2009; De Gans et al., 2010; Koster et al., 2017). It is unlikely that significant domes reaching altitudes of several metres above 0 m NAP ever existed in the peat area immediately west of this border zone, where eutrophic to mesotrophic forest and sedge peats dominate. Drainage by the Naardermeer and Horstermeer, with their Pleistocene base and sea-level-controlled lake levels, will have prevented a serious build-up of peat domes.

The situation in the eastern border zone is distinctly different, with maximum MHG values locally reaching to 2 m + NAP. Van Westrienen et al. (1991) described the impact of the geological structure of the Amersfoort basin on the hydrological functioning of this border zone and the resulting spatial variation in the phreatic level. The basin holds overall fine-textured Eemian deposits with relatively low hydraulic conductivity, filling in a deep glacial basin and having a limited burden of younger, Weichselian and Holocene deposits. We conclude that the variations in the altitude of the late medieval MGH must have the same background. Though peats expanded further and to higher altitudes than in the west, altitudes reached are still rather limited, particularly towards Huizen, close to the Zuiderzee, and certainly were not in the range mentioned by various historical geographers, i.e. to 3 m + NAP and even higher.

Results from our study can be considered as independent data suited for validation of the geohydrological models for the Vecht region and adjacent border zone of Het Gooi (Van Loon et al., 2009; Koster et al., 2017), since the latter studies did not include soil-based reconstructions of former groundwater levels and peat covers. For the Eem valley such model studies have not yet been published, but here too the soil-based data can be useful. The strong agreement between the results from the models and our results is remarkable and underscores the reliability of these models and our reconstruction of the extension of the peat cover.

The soil-based approach is potentially suited for application in other parts of the Netherlands where peat encroached Pleistocene reliefs. It is most appropriate for areas underlain by sediments with high hydraulic conductivity, where the maximum extension of peat is controlled by the maximum regional phreatic groundwater level. In areas with shallow slowly permeable strata, paludification and the associated development of perched groundwater levels play a dominant role in the genesis of peat covers, and the approach is only suited for identification of peat borders on truly higher grounds.

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