

Late Weichselian and Holocene fluvial palaeogeography of the southern Rhine-Meuse delta (the Netherlands)

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Abstract

During the Late Weichselian, climatic changes induced the formation of a two-fold terraced braided-river plain that was formed by precursors of the rivers Rhine and Meuse in the central Netherlands. The older (and higher) terrace is Pleniglacial. It is partly covered by river dunes and coversand of Younger Dryas age. The younger (and lower) terrace originated during the Younger Dryas. Sea-level rise during the Holocene forced the rivers to aggrade since the Early Atlantic. Since then, avulsions have led to a complicated palaeo-channel pattern in which Rhine and Meuse precursors still can be distinguished. River avulsions occurred predominantly during three periods; between 5000 and 4000 BP, around 3000 BP, and around 1800 BP. These periods of increased avulsion frequency have also been found in the northern and central parts of the delta. Rivers were essentially meandering, but in the western part of the area anastomosing rivers existed before 3000–4000 BP. Some Meuse distributaries also have an anastomosing pattern around circa 2000 BP, although they show lateral accretion, and have a rather high width/thickness ratio (40–60). Meander wavelength increased considerably in the Middle Ages. This reflects an increase in peak discharge.

Introduction

The Late Weichselian and Holocene Rhine-Meuse delta in the Netherlands has been studied and mapped extensively over the past decades (e.g. Pons 1957, Verbraeck 1970, 1984, Berendsen 1982, 1986, Törnqvist 1993a, b). The presence of two buried river terraces in the subsoil of the Rhine-Meuse delta and river plain was already noticed by Pons (1954). The thickness of the Holocene deposits covering these terraces increases from less than 1.5 m near the German border to approximately 20 m near Rotterdam. Törnqvist (1993a) presented a sedimentation model for the Holocene Rhine-Meuse delta. He found that a combination of rapid vertical aggradation (> 1.5 mm/yr) caused by sea-level rise and thick (at least 3–4 m) cohesive banks caused river anastomosis. If one (or both) of these two conditions was not met, rivers were meandering (Törnqvist 1993a).

Former channels of meandering and anastomosing rivers consist of sandy channel deposits, sometimes

containing some gravel. Natural-levee deposits typically are about 1–2 m thick and consist of silty clay. Crevasse-splay deposits show a large variety of grain-sizes. Floodbasin deposits are made up of alternating layers of clay and peat. The clastic fluvial sediments are incorporated in the Betuwe Formation, the peat is assigned to the Broek Formation (Fig. 1; Berendsen 1982, 1984).

In the central part of the delta the Holocene sequence is underlain by Late Weichselian, sandy and gravelly, braided-river deposits of the Kreftenheye Formation (Doppert et al. 1975), which are topped by a thin clay bed (Pons 1957, Berendsen et al. 1994) that represents the Wijchen Member of the same formation (Törnqvist et al. 1994). Near the northern and southern margins of the delta, fine-grained aeolian coversands (150–210 μm) of Late Weichselian age (Twente Formation) form the subsoil. Locally Late Weichselian river dunes, consisting of medium sand (210–300 μm), crop out. The dunes are incorporated in the Delwij-

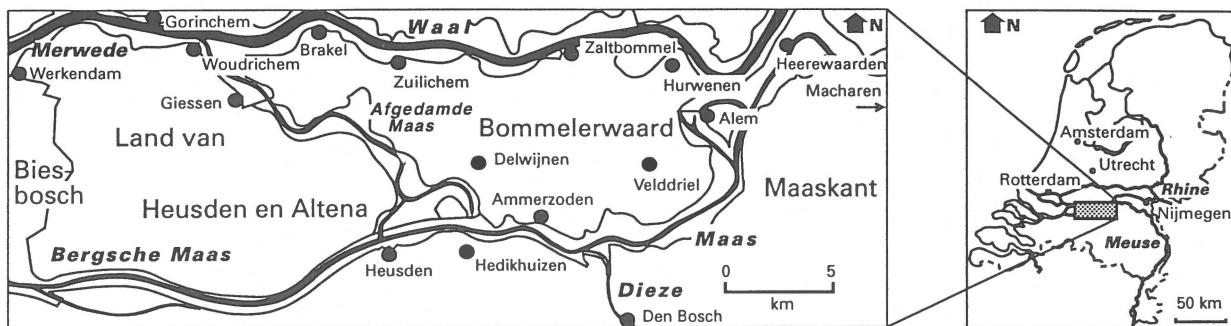


Fig. 2. The research area. Thin black lines indicate river dikes (cf. Fig. 7e).

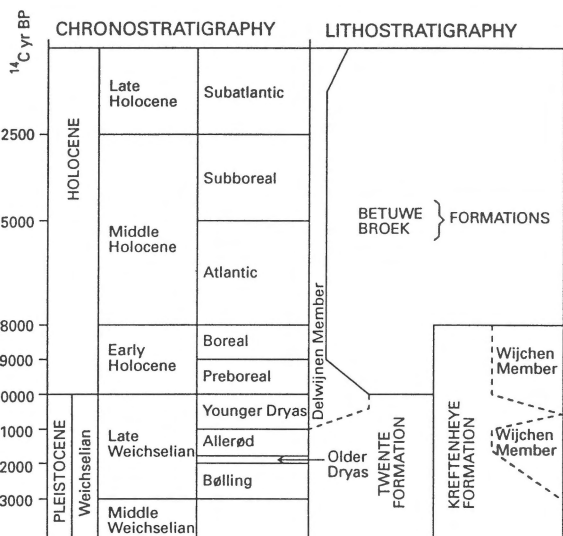


Fig. 1. Stratigraphy of the Late Weichselian and Holocene in the fluvial Rhine-Meuse delta (after Törnqvist et al. 1994). Chronostratigraphy according to Mangerud et al. (1974).

nen Member of the Twente Formation (Törnqvist et al. 1994).

So far, relatively little was known of the Late Weichselian and Holocene geology and palaeogeographic development of the southern part of the Rhine-Meuse delta. For this part of the delta no geological data had been published, with the exceptions of Berendsen (ed. 1986) and Berendsen & Cortenraad (1988). In the present article, a detailed palaeogeographic reconstruction of the Late Weichselian and the Holocene is presented for this area, based on detailed mapping and 25 radiocarbon dates. The palaeogeographic reconstruction is discussed in the context of changes in fluvial

style and periods of increased avulsion frequency that have been found in the central and northern part of the Rhine-Meuse delta by Törnqvist (1993a, 1994). The study area (Maaskant, Bommelerwaard and Land van Heusden en Altena regions) is indicated in Fig. 2.

Methods

Over 15000 handborings were carried out in the research area by students of Physical Geography at Utrecht University in 1984, 1985, 1986 and 1994. About 15% of these borings reach the Late Weichselian formations. After mapping former river channel belts, some of these channels were radiocarbon-dated, using the methods described by Berendsen (1982) and Törnqvist & Van Dijk (1993). This involves essentially the dating of tops and bases of peat layers, intercalated in fluvial overbank deposits, and the dating of peat layers in residual channels. All ages are expressed in conventional radiocarbon years (Table 1).

Relative dates were obtained from cross sections, by comparing the levels of overbank deposits formed by different palaeo-rivers. Indirect dates were also inferred from cross-cutting relationships. A ¹⁴C-dated channel that is crossed by a younger distributary gives a terminus post quem for the beginning of sedimentation of the younger channel. Similarly, a ¹⁴C-dated channel that crosses an older channel gives a terminus ante quem for the ending of sedimentation of the older channel.

Table 1. Radiocarbon dates (cf. Fig. 5).

No.	Laboratory number	¹⁴ C age (years BP)	Coordinates x / y / z* surface	Sample depth (cm)	Sample name	Material	Published by
1	GrN-6993	1815 ± 50	158.475/428.170/+3.7	85-87	Dreumel	Vegetation horizon	Verbrack 1984: 211
2	GrN-6994	2560 ± 50	158.475/428.170/+3.7	132-134	Dreumel	Vegetation horizon	Verbrack 1984: 211
3	GrN-12456	1795 ± 30	132.900/425.000/+1.2	150-160	Waal I	Top of humic clay layer	Berendsen 1986: 54
4	GrN-12461	4160 ± 60	135.715/423.815/+1.0	300-310	Zijving I	Base of clayey peat layer	Berendsen & Cortenraad 1988: 225
5	GrN-12462	4820 ± 70	135.715/423.815/+1.0	410-420	Zijving II	Top of clayey peat layer	Berendsen & Cortenraad 1988: 225
6	GrN-12463	1760 ± 45	142.600/420.275/+2.0	150-160	Bruchem Bansloot	Clayey peat, base of residual channel fill	Berendsen & Cortenraad 1988: 225
7	GrN-12465	2190 ± 60	150.416/429.817/+2.80	125-130	Est II	Strongly clayey <i>Phragmites</i> peat, base of residual channel	Törnqvist 1990: 225
8	GrN-12466	2310 ± 60	150.531/429.814/+2.70	182-188	Est III	Strongly humic clay, base of residual channel fill	Törnqvist 1990: 225
9	GrN-18098	3180 ± 40	137.865/423.760/+1.7	236-251	Zuilichem	Sandy peat, base of residual channel fill	this paper
10	GrN-18099	6040 ± 60	147.820/421.180/+2.46	630-650	De Vliert	Sandy peat overlying coversand of Twente Form.	this paper
11	GrN-18100	3210 ± 40	147.455/420.310/+2.07	140-153	De Hoevens I	Top of clayey peat layer	this paper
12	GrN-18101	3090 ± 40	147.455/420.310/+2.07	163-170	De Hoevens II	Base of clayey peat layer	this paper
13	GrN-18102	4020 ± 35	147.455/420.310/+2.07	230-234	De Hoevens III	Base of clayey peat layer	this paper
14	GrN-18103	5660 ± 50	147.430/420.500/+2.03	443-453	De Hoevens IV	Base of clayey peat layer overlying Wijchen Member	this paper
15	GrN-18104	2560 ± 40	147.990/422.500/+2.57	149-157	Geenweide	Top of layer of humic clay	this paper
16	GrN-18105	10800 ± 60	147.330/421.275/+1.83	473-483	Veilingweg I	Thin peat layer underneath river dune sand	this paper
17	GrN-18108	2340 ± 30	129.145/421.220/+0.03	135-145	Alm I	Top of clayey peat layer	this paper
18	GrN-18109	11140 ± 90	127.250/419.090/-0.5	760-770	Den Duyl	Thin layer of sandy peat underneath river dune sand	this paper
19	GrN-18919	7350 ± 70	129.100/432.600/-0.3	748-753	Arkel I-3a	<i>Alnus-Phragmites</i> peat (alk. residu) on Wijchen Member	Törnqvist 1993b: 137
20	GrN-18927	6515 ± 50	129.960/427.360/-0.10	655-661	Dalem I-2	Strongly clayey <i>Alnus</i> peat	Törnqvist 1993b: 140
21	GrN-18933	6680 ± 50	128.030/432.620/-1.20	581-585	Bazeldijk II-1	Slightly clayey <i>Alnus</i> peat	Törnqvist 1993b: 137
22	UtC-1604	1760 ± 50	148.844/419.745/+2.71	195-205	Velddriel	Twig of cf. <i>Alnus</i> wood at base of residual channel fill	Berendsen 1990: 247
23	UtC-1896	2810 ± 190	130.015/426.315/+0.1	210-213	Dalem II-2	1 <i>Sparanium</i> sp. fruit	Törnqvist 1993b: 138
24	UtC-1899	1600 ± 50	130.015/426.315/+0.10	157-160	Dalem II-1	Fragment of cf. <i>Salix</i> wood in top of thin peat layer	Törnqvist 1993b: 141
25	UtC-3626	890 ± 40	129.015/421360/+0.23	210-212	Alm II	2 <i>Rumex congl.</i> fruits at base of residual channel fill	this paper

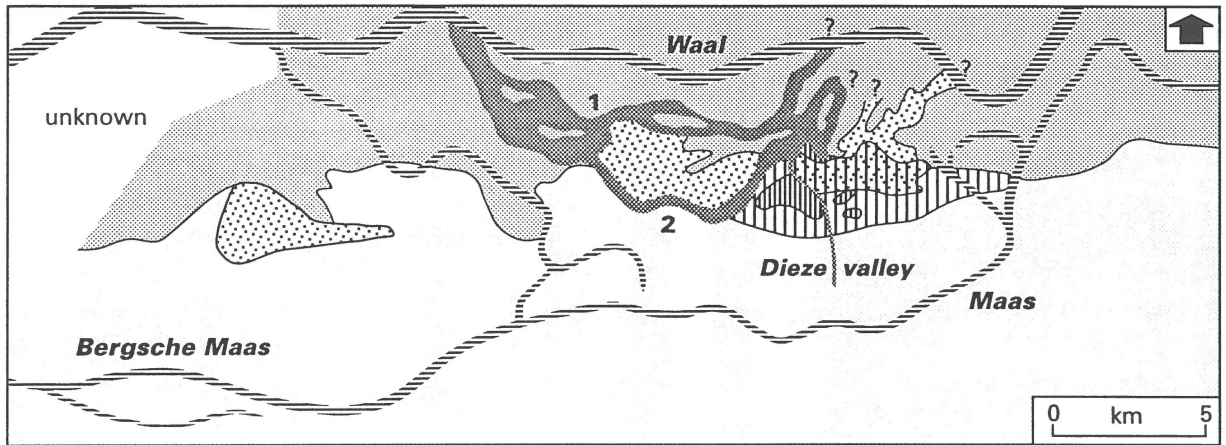
* x, y = position in Dutch Coordinate System (km), z = surface elevation relative to NAP (Dutch Ordnance Datum) in m.

Late Weichselian river terraces

In the northern half of the study area, the Late Weichselian subsoil consists of sandy and gravelly deposits of braided rivers (Kreftenheye Formation; Fig. 3). These deposits are covered by an approximately 30 cm-thick layer of sandy clay (Wijchen Member) that was deposited by incipient meandering rivers (Verbrack 1970, Törnqvist et al. 1994). This sequence was also found by Pons (1957) and Berendsen et al. (1994) in the Land van Maas en Waal, just upstream of the study area, where the Wijchen Member is 0.5–1.0 m thick.

The Wijchen Member is absent in the southernmost part of the study area. Here, the Holocene deposits are directly underlain by coversand of the Twente Formation. This coversand may reach a thickness of over 5 m in coversand ridges. The Late Weichselian fluvial subsoil actually consists of two terrace levels that are 0.9 m apart (Fig. 4). The range of elevation within each terrace may vary by about 1.4 m. Still, the elevations of the terraces are different if statistically tested. The approximately 200 borings that reached the Pleistocene subsoil are divided into a southern and a northern population along a terrace-step in the sub-

10000 - 9000 BP



Kreftenheye Formation



Pleiglacial Terrace



Younger Dryas Terrace

Pleiglacial Terrace
underneath coversand

Twente Formation



River dunes



Coversand

Pleiglacial Terrace
underneath river dunes

Early Holocene incision

1 Brakel system

2 Broek system



Present rivers

Fig. 3. Palaeogeographic map of the top of the Late Weichselian deposits in the southern Rhine-Meuse delta around the Younger Dryas - Preboreal transition.

soil, that is present in cross sections. After de-trending both populations by correcting the absolute height of the top of the terrace deposits for their mean gradient (25.5 cm/km) a Student's *t*-test was used to test if both populations have a different mean elevation. The use of this test is allowed because both populations have a Gaussian distribution and the same variances. Even at a significance level of $\alpha = 0.001$ the means of both populations are different; the populations therefore do represent two distinct levels.

Further upstream, in the Land van Maas en Waal, also two terraces were found; here the levels are 1.5 m apart (Berendsen et al. 1994). Extrapolation of gradient lines shows, that our upper level can be correlated with the Pleiglacial Terrace mapped by Pons (1957: Lower Terrace or 'Laagterras'), while our lower level correlates with the Younger Dryas Terrace (Pons' 'Terrace X'). A peat layer within the Wijchen Member that covers the upper terrace revealed an age of 10800 ± 60 BP (Table 1 no. 16), indicating that this terrace is older than Younger Dryas. This confirms that the higher terrace level must indeed be correlated with the Pleiglacial 'Lower Terrace' described by Pons (1957).

River dunes

The two terraces indicated in Fig. 3 are partly covered by aeolian sediments. The Pleiglacial Terrace is partly covered by a thin layer (up to 2 m thick) of Twente Formation coversand (median grain size 150–210 μm). Near the southern margin of the Younger Dryas Terrace, three river dune complexes occur which have an irregular topography (Fig. 3). Sand dunes of 5–6 m height are frequently found. Their median grain size is 210–300 μm . The areal extent of the aeolian deposits in the subsoil is far greater than indicated by Törnqvist et al. (1986: 22). The eastern river dune complex overlies the Wijchen Member of the Younger Dryas Terrace as well as the Pleiglacial Terrace, while the western river dune complex overlies coversands. The central complex mostly overlies the Younger Dryas Terrace. Up till now, virtually no river dunes had been found on this terrace. Since a braided river was present here at the time of dune formation during the Younger Dryas, the preservation potential of aeolian deposits on this terrace has always been considered low. However, they obviously do occur. Preserved river dunes on active

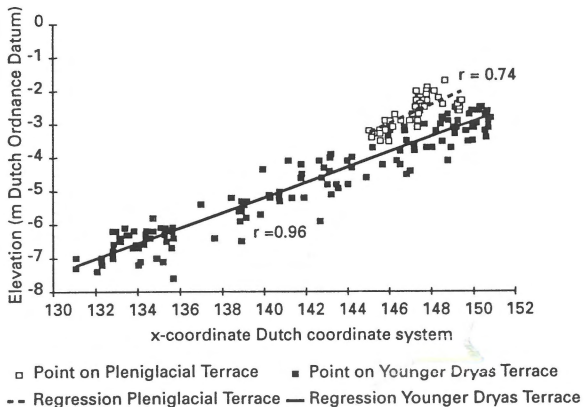


Fig. 4. Elevations of the top of the Wijchen Member on the Pleniglacial Terrace and the Younger Dryas Terrace. The gradient on top of the Pleniglacial Terrace is 27.9 cm/km (correlation coefficient $r = 0.74$). The gradient has been determined using linear regression, with a total of 50 measurements over a distance of 5 km. The gradient on the Younger Dryas Terrace is 22.8 cm/km ($r = 0.96$). Here the precision is much greater due to a larger number of measurements (139) and a greater distance (20 km).

braidplains also occur in Medano Creek, Colorado, and Mojave River, California (Langford, 1989).

A ^{14}C date from a peat layer underneath the eastern river dune complex gave an age of 10800 ± 60 BP (Table 1 no. 16). A layer of sandy peat underneath the western river dune complex was dated at 11140 ± 90 BP (Table 1 no. 18). This indicates a Younger Dryas age of the river dunes. In other parts of the Netherlands comparable ages were found (Berendsen 1988, Bohncke et al. 1993, De Jong 1981). Vandenberghe (1987: 735) states that especially the second half of the Younger Dryas was a cold and dry period with strong aeolian activity. Aeolian redeposition of the river dune sands in the research area took place in the Holocene, as is evidenced by interfingering of aeolian sand with fluvial overbank deposits. The SW-NE oriented aeolian deposits just north of the eastern dune complex (Fig. 3) must also be the result of Holocene aeolian redeposition; they overlie early Holocene clay (Wijchen Member) on the Younger Dryas Terrace.

Holocene fluvial palaeogeography

During the early Holocene, meandering rivers incised the Younger Dryas Terrace. The incision was caused by the changing climate, resulting in an increase in the discharge/sediment load ratio (Berendsen et al. 1994).

Remnants of early Holocene valleys (now filled with clay) occur along the courses of the Brakel system, Broek system and the former Dieze valley (Fig. 3). Incision took place at least 2.5 m below the Pleniglacial Terrace level in the study area. Total incision may have been deeper. Berendsen et al. (1994) observed incisions of down to 7 m in the Land van Maas en Waal; De Groot & De Gans (in press) mention incisions of 15 m near Rotterdam.

From the Early Atlantic on, aggradation started as a result of a groundwater table rise that was linked to sea-level rise (Van Dijk et al. 1991). Sedimentation on the Younger Dryas Terrace most likely started first, because of its lower position. Sedimentation on the Pleistocene subsoil in the west of the study area began around 7000 BP. Törnqvist (1993b: 137) gives dates of 7350 ± 70 and 6680 ± 50 (Table 1 nos 19, 21) for the onset of Holocene sedimentation on the Pleistocene subsoil a few kilometres to the northwest of the research area. Two ^{14}C dates of peat overlying the Pleniglacial Terrace in the eastern Bommelerwaard show that peat formation here started between 6040 ± 60 and 5660 ± 50 BP (Table 1 nos 10, 14). If the depth and location of these two radiocarbon dates are plotted in the diagram of isochrones of basal peat formation given by Van Dijk et al. (1991: fig. 8), both samples plot 1.5–2.0 m lower than expected. This may be due to tectonic movements along the Peel Boundary Fault, an active fault of the Roer Valley Graben (Van Eck & Davenport 1994, Geluk et al. 1994). Van den Berg et al. (1994: 162) observed recent movements along this fault of up to 6 cm per century in the southern Netherlands. Dijkstra & Willemstein (1990) found indications of Holocene activity of the fault in the Rhine-Meuse delta.

As a result of increasing sedimentation, the incised meandering rivers filled up the valleys they had cut during the early Holocene and avulsions became possible. This gave rise to a complicated pattern of channel belts and floodbasins (Fig. 5a). The thickness of the Holocene fluvial and organic deposits in the research area varies from 10 m in the northwest to 6 m in the northeast (Figs 6a, b). Rhine and Meuse distributaries are discriminated in Fig. 5 as far as possible, based on geographic position. Discrimination on other grounds is difficult, because no significant differences in grain size and heavy mineral composition exist between these distributaries. Pons (1957) observed a difference in carbonate content between Holocene natural levees of the Rhine and Meuse in the Land van Maas en Waal. However, this difference does not exist downstream of

Heerewaarden, where Rhine and Meuse used to join. Also, reworking of underlying sediments may obscure differences found further upstream. The description of the avulsion history that follows below is restricted to the distributaries that were ^{14}C -dated. Periods of activity of the other distributaries indicated in Fig. 5 were inferred from their stratigraphic position.

Holocene avulsions of the Meuse

This section reviews the channel belt systems of the Meuse, numbered and named as shown in Figs 5a and b. The oldest Holocene distributary in the research area is the *Brakel system (1)* (Figs 5, 7a). Channel deposits of this system so far were found only in the Bommelerwaard. Overbank deposits of the system directly overlie the Wijchen Member at the top of the Kreftenheye Formation on the Younger Dryas Terrace (Fig. 6b). The top of a peat layer, directly overlying the overbank deposits of the system 3 km north of the channel, gave an age of 6515 ± 50 BP (Table 1 no. 20), which indicates that sedimentation of the Brakel system at that location must have stopped earlier. The terminus ante quem for the end of activity of the next oldest and nearby *Broek system (2)* is given by a ^{14}C date of a peat layer overlying the overbank deposits: 4020 ± 35 BP (Table 1, Fig. 6b, no. 13). Whether the Brakel and Broek systems are Meuse distributaries remains uncertain, because no upstream connections with the Meuse have been found.

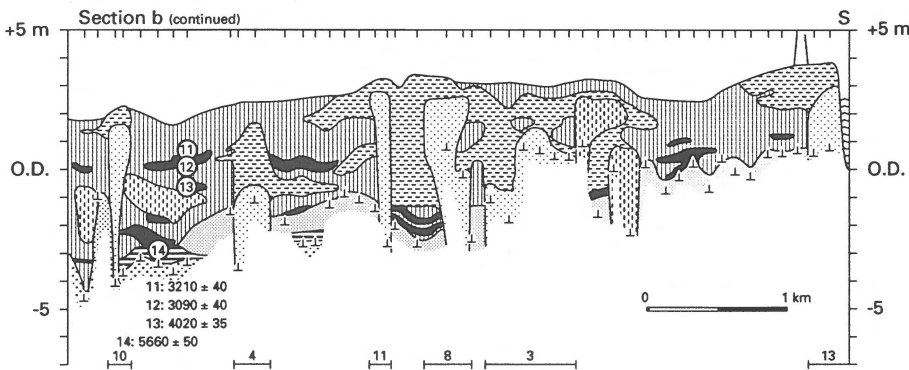
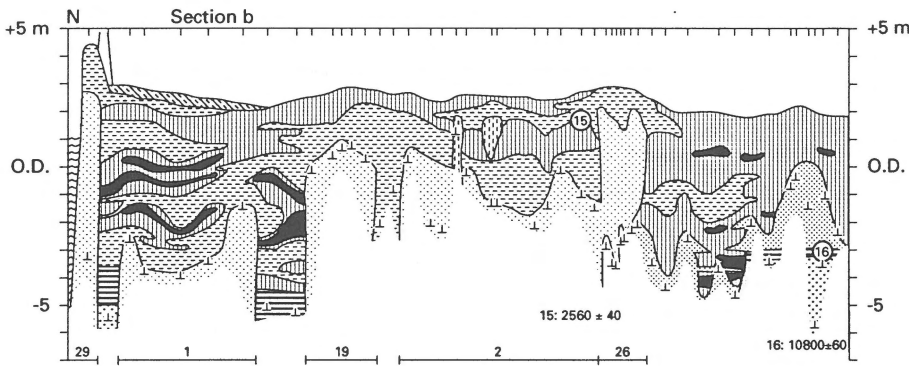
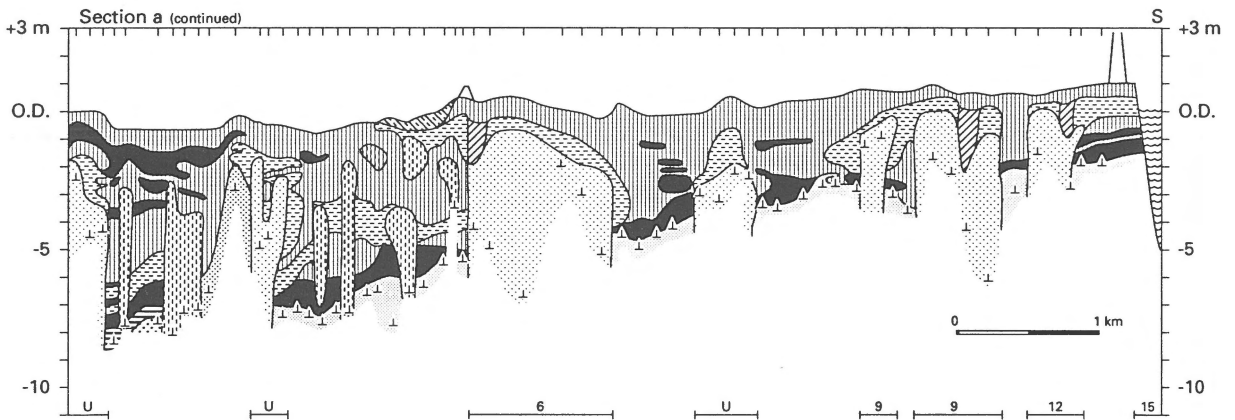
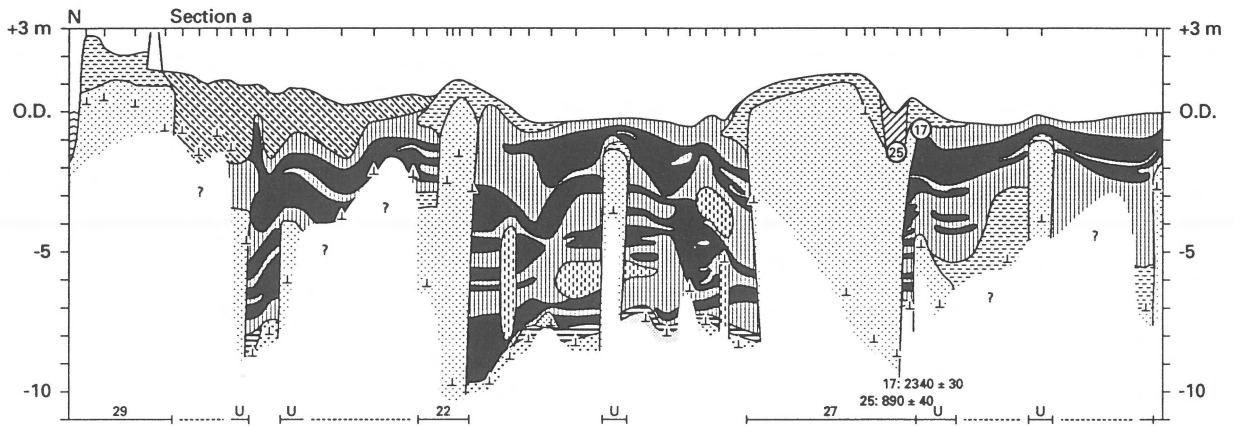
The next generation of Meuse distributaries includes the *Hoorzik (3)*, *Hedel (4)*, *Wordragen (5)* and *Biesheuvel (6)* systems (Figs 5, 7b). The onset of sedimentation of the Hedel system was radiocarbon-dated at 4020 ± 35 BP (Table 1, Fig. 6b, no. 13). A peat bed overlying its overbank deposits revealed ages of 3210 ± 40 and 3090 ± 40 BP (Table 1 nos 11, 12).

The large *Lith (7)*, *Velddriel (8)* and *Dussen (9)* systems represent the next younger generation (Figs 5, 7c). The beginning of sedimentation of the Velddriel system was indirectly dated at 3090 ± 40 BP (Table 1, Fig. 6b, no. 12). This presumably also dates the beginning of sedimentation of two small distributaries of this system, the *Beemden (10)* and *Achterdijk (11)* systems. The end of activity of the Velddriel system and its distributaries was ^{14}C -dated at 1760 ± 50 BP (Table 1 no. 22; Berendsen 1990). The upstream and downstream continuations of the Velddriel system are the Lith and Dussen systems respectively. The Lith system may be the upstream part of all Meuse distributaries found fur-

ther downstream, including the systems 3–6. The Lith system still contained water during Roman times, as is evidenced by the remains of a Roman vessel in a residual channel of the system near Macharen (Van Diepen 1952: 116). Figure 7c shows that the Meuse distributaries of the Velddriel generation have an anastomosed pattern. However, the width/thickness ratios of their channels are between 40 and 60, which is generally considered too high for anastomosing rivers (Törnqvist 1993a, Nadon 1994). Furthermore, complex overbank deposits typical for anastomosing rivers in other parts of the Rhine-Meuse delta (Törnqvist 1993a, Weerts & Bierkens 1993) are lacking here.

The present *Meuse (= Maas, 13)* river in the Bommelerwaard has a maximum age of 1760 ± 50 BP (Table 1 no. 22). It crosses the residual channel of the Velddriel-Lith system at Alem and at Macharen. Downstream of Ammerzoden, several avulsions of the Meuse occurred in historical time. The *Oude Maasje (12)* was dammed at Hedikhuizen (a few km SW of Ammerzoden) between 1230 AD (Fockema Andreae 1950) and 1270 AD (Ramaer 1899). Downstream of Hedikhuizen, the Meuse followed a new course along the present-day *Afgedamde Maas (14)*, Fig. 7d). This new course presumably originated during the Early Middle Ages (Sonneveld 1958). According to Hardenberg (1953) the Afgedamde Maas was connected to the Rhine branches Alm and Werken. During the 12th century a new course north of Giessen was formed, and the Meuse flowed into the Waal near Woudrichem forming the Merwede river. This is confirmed by a ^{14}C sample (Table 1 no. 25), which gives an age of 890 ± 40 BP for the beginning of the silting up of the Alm system.

Around 1230 AD the construction of river dikes around the Land van Heusden en Altena was completed (Fockema Andreae 1950). Embankment of the Bommelerwaard was completed in 1327 AD (Edelman et al. 1950) and that of the Maaskant between 1309 and 1331 AD (Van Diepen 1952). From then on, sedimentation was essentially restricted to the embanked floodplains, although dike breaches and floods were common until the beginning of the 20th century. The most disastrous was the St. Elisabeth's flood of 1421 AD (Fockema Andreae 1950). Soon after this marine flood, the southern Merwede dikes collapsed and the Merwede was diverted into the tidal inlet that had formed at the location of the present Biesbosch and the western part of the Land van Heusden en Altena (Sonneveld 1954). In 1461 most of the Land van Heusden en Altena was reclaimed (Fockema Andreae 1950). Due to the flood,



- BETUWE FORMATION**
- Channel deposits
 - Residual channel deposits
 - Natural levee deposits
 - Crevasse-splay deposits
 - Flood basin deposits
 - Dike breach deposits and Estuarine deposits
- BROEK FORMATION**
- Organic deposits
- KREFTENHEYE FORMATION**
- Overbank deposits
 - Other fluvial deposits
- TWENTE FORMATION**
- River dune deposits
 - Other eolian deposits
- Water
 - Dike
 - Borehole
 - Max. depth of borehole
 - ¹⁴C sample and number in table 1
 - Number of fluvial system in fig. 5 (U = unnamed)

←

Fig. 6. Cross sections through Late Weichselian and Holocene deposits in the southern Rhine-Meuse delta. Numbers of channel belt systems and ^{14}C samples correspond to those in Fig. 5. See Fig. 1 for overall age relationships. Section (a) Land van Heusden en Altena. Note the thick organic beds compared to section (b). The top of the Kreftenheye Formation corresponds to the top of the Younger Dryas Terrace. Section (b) Bommelerwaard. North of channel belt system 19, the top of the Kreftenheye Formation corresponds to the top of the Younger Dryas Terrace; South of channel belt system 26, it corresponds to the top of the Pleniglacial Terrace.

the westernmost part of the research area is covered by a 1–2 m thick layer of estuarine sandy clay (Fig. 7e). Between the Rijswijk system and the Waal-Merwede the estuarine deposits consist of sand.

Many meanders of the Meuse were cut off between 1400 and 1930. The *Bergsche Maas* (15) was dug between 1887 and 1904. At the same time the Afgedamde Maas was dammed, thus diverting the Meuse into an entirely new course (see Stein 1986, for a detailed description of historical river adjustments).

Holocene avulsions of the Rhine

The oldest of the fifteen Rhine distributaries recognized in the area are the *Spelwerd* (16), *Molenveld* (17), *Nederhemert* (18) and *Zaltbommel* (19) systems (Figs 5, 7b). The Molenveld system was radiocarbon-dated with a sample taken from the top of peat underneath its overbank deposits at 4820 ± 70 BP and with a sample taken from the base of an organic layer on top of its overbank deposits at 4160 ± 60 BP (Table 1 nos 5, 4). Berendsen & Cortenraad (1988: 225) assume that these dates refer also to the activity of the Nederhemert system. Upstream, the Nederhemert system is probably connected with the Zaltbommel system. In the Land van Heusden en Altena, several narrow interconnected channel belts with channel width/thickness ratios of less than 20 and with complex overbank deposits were found at a similar stratigraphic level as the Molenveld system.

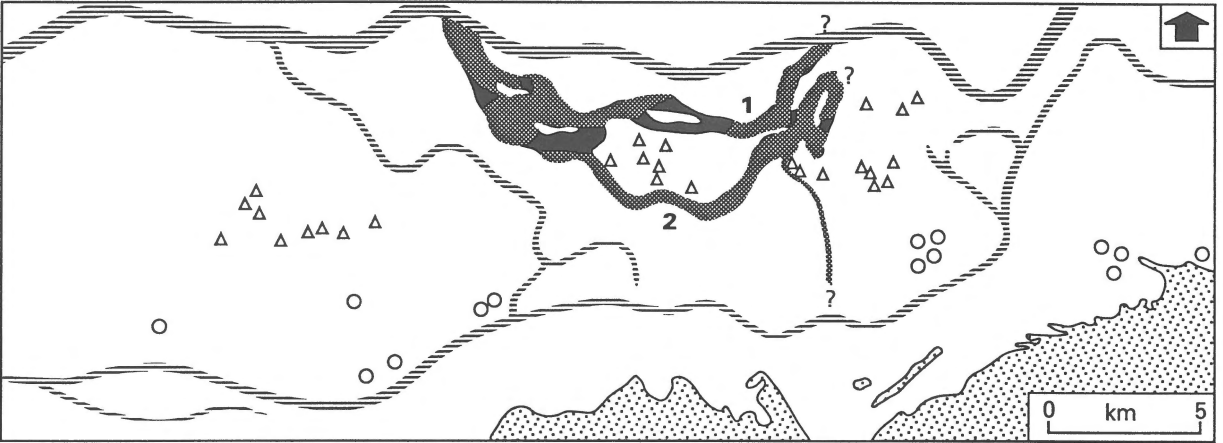
The next generation of Rhine distributaries comprises the *Oensel* (20), *Gameren* (21), *Rijswijk* (22), *Munnikenland* (23), *Leuven* (24), *Verdriet* (25), *Bruchem* (26), *Alm* (27) and *Werken* (28) systems (Figs 5, 7c). The Gameren-Rijswijk and the Oensel-Bruchem distributaries came into existence after 4160 ± 60 BP (Table 1 no. 4). The beginning of sedimentation of the Bruchem system east of the confluence with the Oensel system was dated at 2560 ± 40 BP (Table 1, Fig 6b, no. 15). The continuation of the Bruchem system upstream of Hurwenen is probably situated at the location of the present Waal. This is suggested by a radiocarbon sample underneath overbank deposits of an unknown system in a cross section published by

Verbraeck (1984: 211), that was dated at 2560 ± 50 BP (Table 1 no. 2). The end of the Bruchem-Oensel system was dated at 1760 ± 45 BP in the residual channel (Table 1 no. 6; Berendsen & Cortenraad 1988). This is exactly the same age as the final stage of the Velddriel system of the Meuse. The Alm and Werken channel belts are the downstream continuation of the Oensel-Bruchem system. Remains of Roman occupation were found on the natural levees of the Alm and Werken distributaries (Sonneveld 1958), indicating a pre-Roman age of these distributaries. This is confirmed by a radiocarbon age of 2340 ± 30 BP for a sample taken from a peat layer underneath overbank deposits of the Alm (Table 1, Fig. 6a, no. 17). The Alm system was later rejuvenated by the Meuse and was active until 890 ± 40 BP (Table 1, Fig. 6a, no. 25). Channels of the systems 20–28 have width/thickness ratios ranging from 20 (Rijswijk system) to 100 (Alm system). Complex overbank deposits are lacking.

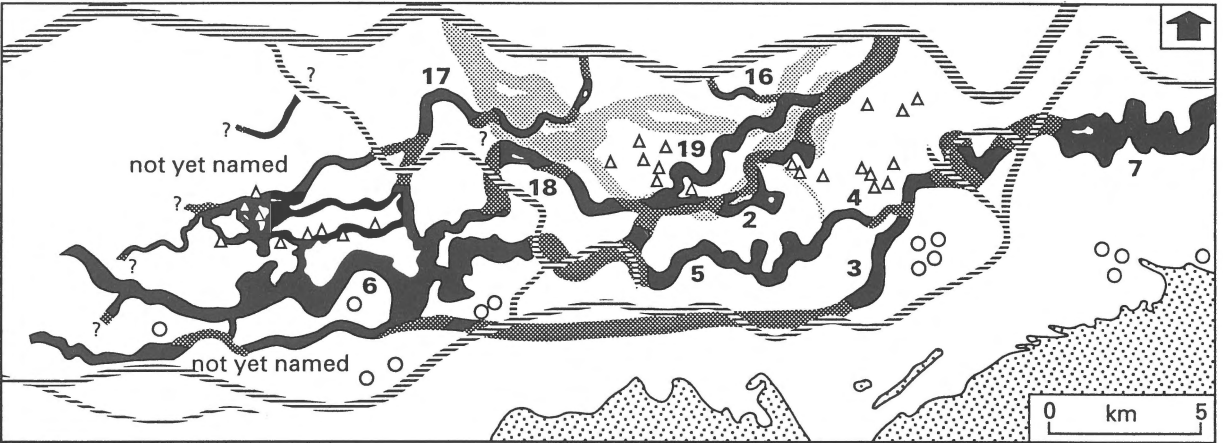
Dating results of the Gameren system are ambiguous. A ^{14}C sample taken from the base of peat in what seemed to be a small residual channel near Zuilichem gave an age of 3180 ± 80 BP (Table 1 no. 9). This date, however, is far too old and has to be rejected. The Gameren system is considered to be the downstream continuation of the Est system (Berendsen 1990), which is located northeast of Zaltbommel. Radiocarbon dates from a residual channel in the Est system gave ages of 2190 ± 60 and 2310 ± 60 BP (Table 1 nos 7, 8; Törnqvist 1990). A terminus post quem of 2810 ± 190 BP was found for the beginning of sedimentation of the Gameren system (Table 1 no. 23; Törnqvist 1993b: 140). Edelman et al. (1950) mention that Roman settlements were found on either side of the residual channel near Gameren, suggesting that the channel still contained water around 200 AD. Berendsen (1986: 54) placed the main period of sedimentation of the Gameren system between 300 BC and 300 AD.

The youngest Rhine distributary in the southern Rhine-Meuse delta is the present-day river *Waal* (29) that came into existence after a complex avulsion. This involved the partial abandonment of the river Linge near Tiel, north of the study area, and the silting up

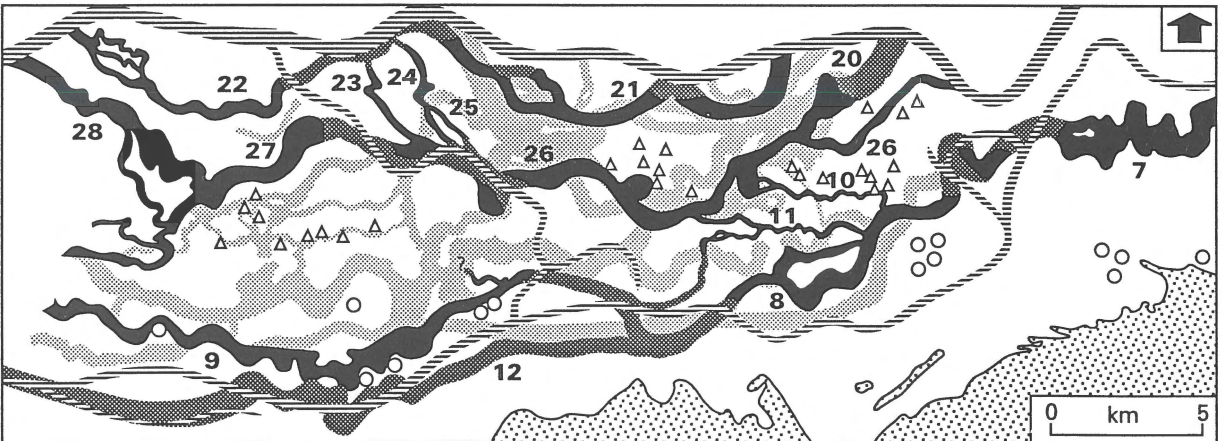
a ca. 7000 - 6500 BP



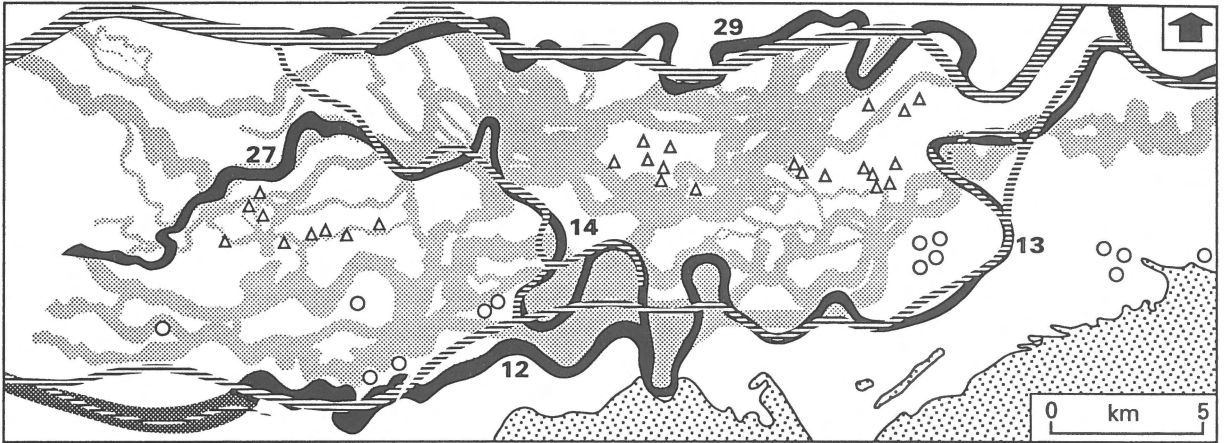
b ca. 4500 BP



c 2000 BP



d 1000 AD



e present situation

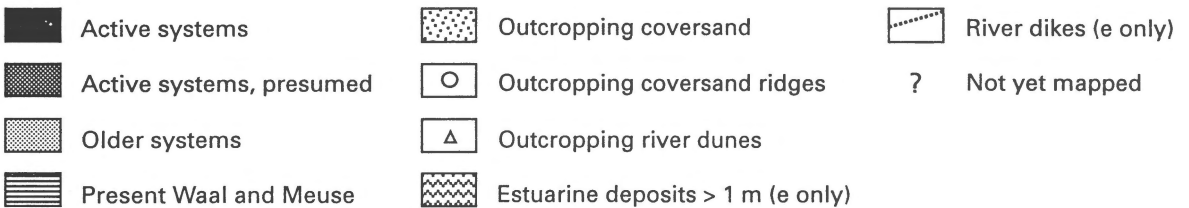
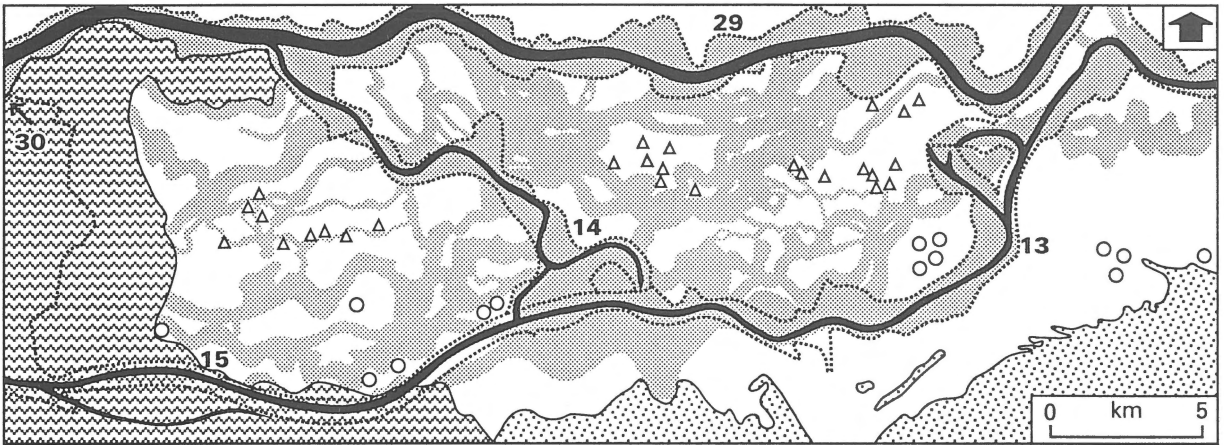


Fig. 7. Palaeogeographic maps of the southern Rhine-Meuse delta. Numbers of channel belt systems correspond to those in Fig. 5. (a) Atlantic (ca. 7000–6500 BP), (b) Early Subboreal (ca. 4500 BP), (c) Early Subatlantic (2000 BP), (d) Middle Ages (1000 AD), (e) Present situation.

of the Est-Gameren-Rijswijk system. A subsequent avulsion occurred near Hurwenen, which resulted in the new course of the Waal and the silting up of the Bruchem system downstream of the avulsion point (Figs 7c, d). The beginning of Waal sedimentation was dated between Tiel and Hurwenen at 1815 ± 50 BP (Table 1 no. 1; Verbraeck 1984: 211) and near

Brakel at 1795 ± 35 BP (Table 1 no. 3; Berendsen 1986: 54). Törnqvist (1993b: 140) dated macrofossils near Woudrichem and obtained a slightly younger date: 1600 ± 50 BP (Table 1 no. 24). Since the embankment of the river Waal, several meanders were cut off near Zaltbommel between 1600 and 1700 AD. Between 1851 and 1860 the *Nieuwe Merwede* (30) was dug, in

order to enhance Waal drainage to the sea (Beekman 1948). Near Heerwaarden, the confluence of Maas and Waal was dammed in 1904 (Stein 1986).

Fluvial style

Figure 5 shows that three periods of increased avulsion frequency occurred, namely 5000–4000 BP, around 3000 BP, and around 1800 BP. The period between 4000 and 3000 BP is characterized by a lack of avulsions. This remarkable feature was also found in the northern and central part of the delta (Törnqvist 1994). The high avulsion frequencies prior to 4000 BP and around 3000 BP correspond with the widely recognized large-scale transgressive tendencies in the coastal areas along the southern North Sea, embodied in the clastic tidal Calais and Dunkirk deposits (Törnqvist 1994). The period between 4000 and 3000 BP corresponds roughly to the intervening regressive period. The increased avulsion frequency around 1800 BP has also been found in other parts of the delta (Berendsen 1990, Törnqvist 1994).

The Holocene channel belts of the Rhine that were formed in the western part of the research area before approximately 4000 BP, appear to form a network of anastomosing rivers with low-sinuosity channels (Fig. 7b). In cross sections they are characterized by a large number of crevasse splays, and a width/thickness ratio of less than 20. These are characteristics typical of anastomosing rivers (Törnqvist 1993a, Weerts & Bierkens 1993, Nadon 1994). The younger channel belts of the Rhine clearly are formed by meandering rivers, each with a single, relatively high-sinuosity channel (Fig. 7c). Width/thickness ratios of 20–100 have been found for these recent Bruchem-Alm-Werken and Gameren-Rijswijk systems. These channel belts also have a point-bar-and-swale topography, which is typical for meandering rivers.

In the southernmost part of the research area the situation seems to be slightly different. Here the easily erodible, sandy Pleistocene subsoil is at shallow depth. The Meuse channel belts of the Veldriel generation show lateral accretion (point-bar-and-swale-topography), while crevasse splays are rare and width/thickness ratios are relatively high (40–60). These generally are characteristics of meandering channels. At the same time they also seem to have bifurcating and rejoining channels (Fig. 7c), a characteristic of anastomosing rivers. Although more ^{14}C dates are necessary to prove that some of these channels indeed

existed simultaneously, their map view locally is of the anastomosing type. Apparently, the Meuse channel belts of the Veldriel generation take an intermediate position between meandering and anastomosing. An explanation may be found in different discharge characteristics: for the present Rhine the ratio between maximum and minimum discharge is 15, for the Meuse it is 100. This factor, which is not incorporated in Törnqvist's (1993a) model, may well be responsible for the observed behaviour of some of the Meuse river systems.

Comparison of Figs 7c and d shows that a marked increase of meander wavelength occurred after 2000 BP, suggesting a strong increase of peak discharge. This is probably related to the changes in land use, especially deforestation, in the Rhine and Meuse catchments, resulting in higher peak discharges and increased sediment loads. The changes in meander wavelength observed between 1000 AD and the present (Figs 7d, e) are largely induced by man: cutting off of meanders, construction of dams and groynes, digging of new courses.

Summary and conclusions

During the Late Weichselian, climatic changes gave rise to the formation of two river terraces in the research area. The older level is of Pleniglacial age. During the Younger Dryas Stadial a second river terrace, the Younger Dryas Terrace, was formed by lateral erosion at 0.9 m below the Pleniglacial Terrace level. The remaining part of the Pleniglacial Terrace became largely covered by aeolian coversands and river dunes during the Younger Dryas. Some river dunes on the Younger Dryas Terrace were also preserved.

During the early Holocene the Rhine and the Meuse were meandering, and incised the Younger Dryas Terrace. In the Atlantic period, fluvial sedimentation on the Late Weichselian terraces started. This was caused indirectly by the rapidly rising sea level; river gradients decreased and this forced the Rhine and Meuse to aggrade. Many avulsions occurred, resulting in a complicated pattern of channel belts and floodbasins. The avulsions occurred predominantly between 5000 and 4000 BP, around 3000 BP, and around 1800 BP. Between 4000 and 3000 BP virtually no avulsions took place. The alternating avulsion frequencies correspond with the alternating transgressive and regressive tendencies that are widely recognized in the coastal areas of the southern North Sea. Between 5000 and 4000 BP,

the fluvial style was predominantly meandering in the east and anastomosing in the west of the study area. After 3000 BP, meandering rivers prevailed all over the study area. A special case is formed by Meuse channels in the south of the area, where the subsoil consists of easily erodible Pleistocene coversand. Although these palaeo-rivers show mainly characteristics of meandering rivers (lateral accretion, high width/thickness ratios and few crevasse splays) they consist of bifurcating and rejoining channels which is typical for anastomosing rivers. This may be explained as a result of the large ratio (100:1) between maximum and minimum discharge of the Meuse. After 2000 BP, the meander wavelength of both Rhine and Meuse increased significantly, suggesting a strong increase of peak discharge, that may be related to deforestation in the drainage basins.

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