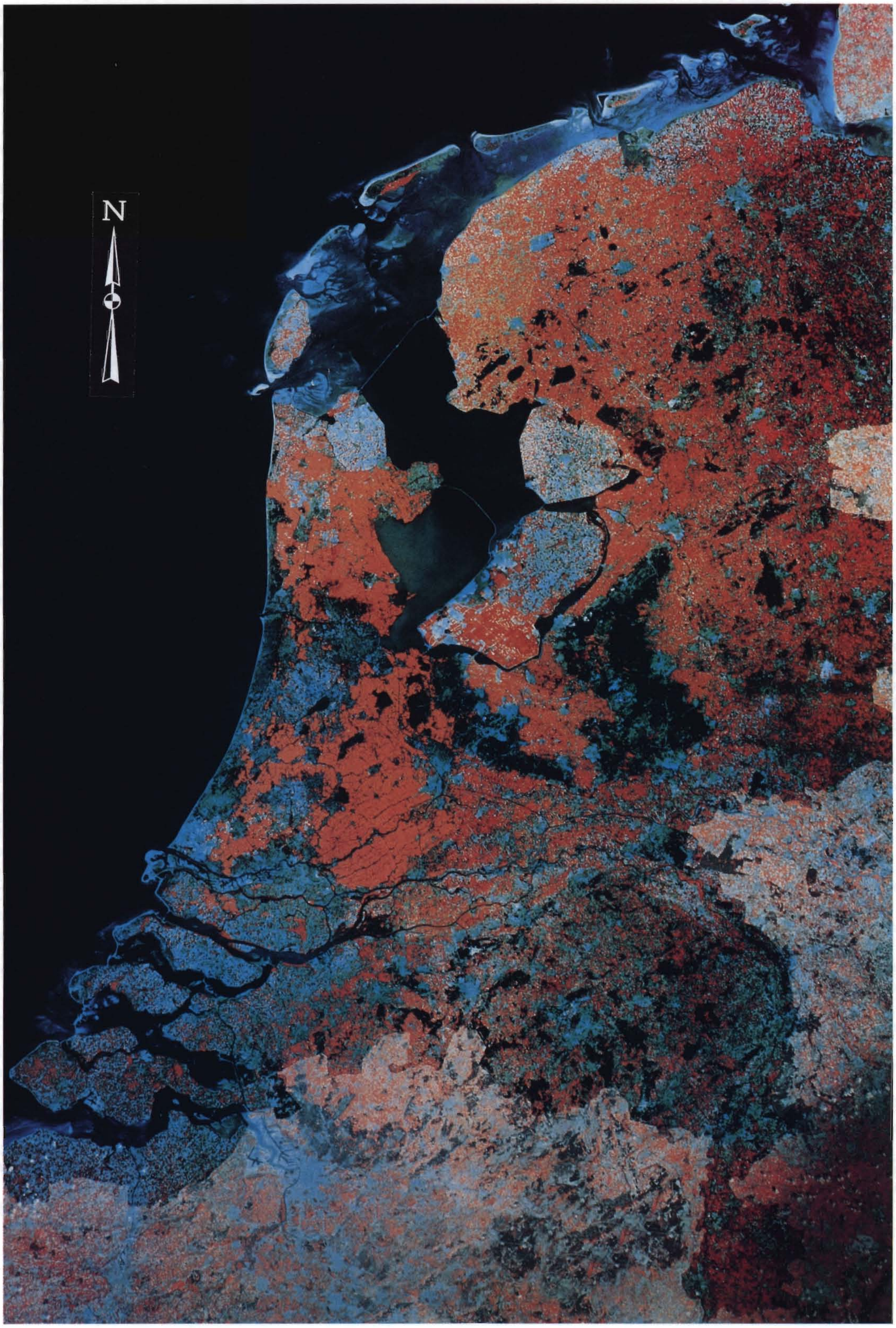

Plate 1. During the Holocene the present Rhine-Meuse deltaic plain was formed, far inland from the lowstand deltas. The deltaic plain, which still contains glacial features, can be subdivided into a fluvial area, an estuarine area, and a coastal dune area.

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Birds-Eye View of the Rhine-Meuse Delta (The Netherlands)

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ABSTRACT

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The Rhine was formed in the Miocene. During the Pleistocene it dumped large amounts of glacial debris into the subsiding North Sea Basin, which resulted in a maximum thickness of Quaternary deposits of about 1000 m. During the Holocene the present deltaic plain was formed, far inland from the lowstand deltas. The deltaic plain, which still contains glacial features, can be subdivided into a fluvial area, an estuarine area, and a coastal dune area. Sea level rise played an important role in the Holocene evolution of the deltaic plain. The abandunce of sand in the shallow North Sea basin caused progradation of the coast, once the rate of sea level rise decreased (after 5000 BP). Human influence in the delta has been great since the Middle Ages: peat was dug, lakes were drained, and new land was gained by building new dikes and draining the enclosed areas, tidal inlets were closed by dams, thus profoundly influencing hydrology and ecology. This paper provides a review of these components of the Rhine-Meuse delta in addition to potential future developments along the coastal area.

ADDITIONAL INDEX WORDS: *Geology, natural environment, sea level rise, human influence Rhine-Meuse delta.*

INTRODUCTION

The Rhine-Meuse delta of the Netherlands is one of the best studied deltaic areas in the world. Its high population density (15 million inhabitants in an area of only 35,000 km^2) and high level of industrialization, together with the natural conditions (a weak subsoil and about 40% of the country lying below sea level) require a thorough knowledge of natural conditions to protect the country from the sea and flooding by the rivers, and, at the same time, to maintain a balanced environment. This explains the Dutch preoccupation with the sea.

In this paper an overview is presented of the geological history, human influence, present-day and future problems associated with the Rhine-Meuse delta. The origin of the river and the formation of the deltaic plain is first reviewed, followed by an overview of the present situation and possible future problems.

GEOLOGICAL FRAMEWORK

General Characteristics

The Rhine-Meuse deltaic area is situated in the southeastern corner of the North Sea Basin, where it forms part of a coastal plain of varying width that extends from the Strait of Dover in the south to Denmark in the north (Figure 1). This area, although referred to as "the Rhine-Meuse delta," is not a delta in a strict sense (Kruit, 1963). Virtually all of the Holocene delta has a subaerial origin and was formed by river sedimentation in a back-barrier area or by peat formation. Outside the present river mouths, estuarine and tidal flat areas prevail. On the longer time scale of the Quaternary (Figure 2), however, practically the entire Netherlands is part of a delta formed by the rivers Rhine, Meuse, Scheldt, Elbe and Weser.

The present mean annual discharge of the Rhine is approximately 2200 m^3/s; that of the Meuse is smaller by about a factor of ten (Table 1).

Tertiary and Pleistocene

The oldest sediments of the Rhine date from the Miocene when it was a small stream draining the graben of the Lower Rhine Embayment. From a geological perspective, the apex of the Rhine delta, therefore, is located near Bonn (Germany), where the Rhine leaves the Rhenisch Massif and enters the North Sea Basin. The North Sea Basin formed because of Mesozoic stretching related to the opening of the Atlantic Ocean (Ziegler, 1990). Neogene uplift of the Rhenish Massif (Germany) and the Ardennes (Belgium) led to increasing drainage areas both for the Rhine and Meuse. The alluvial and delta plain sediments of this primitive Rhine and Meuse cover much of the southeastern Netherlands. At the Pliocene/Pleistocene boundary, the Rhine captured the river Aare (Switzerland), and extended its drainage area in the Alps (Zonneveld, 1980), which is clearly demonstrated by the heavy mineral composition (*i.e.,* the presence of saussurite) of the Rhine sediments.

Marine deposition predominated in the Netherlands (Figure 3, insert a) until the early Pleistocene (2.5 million years

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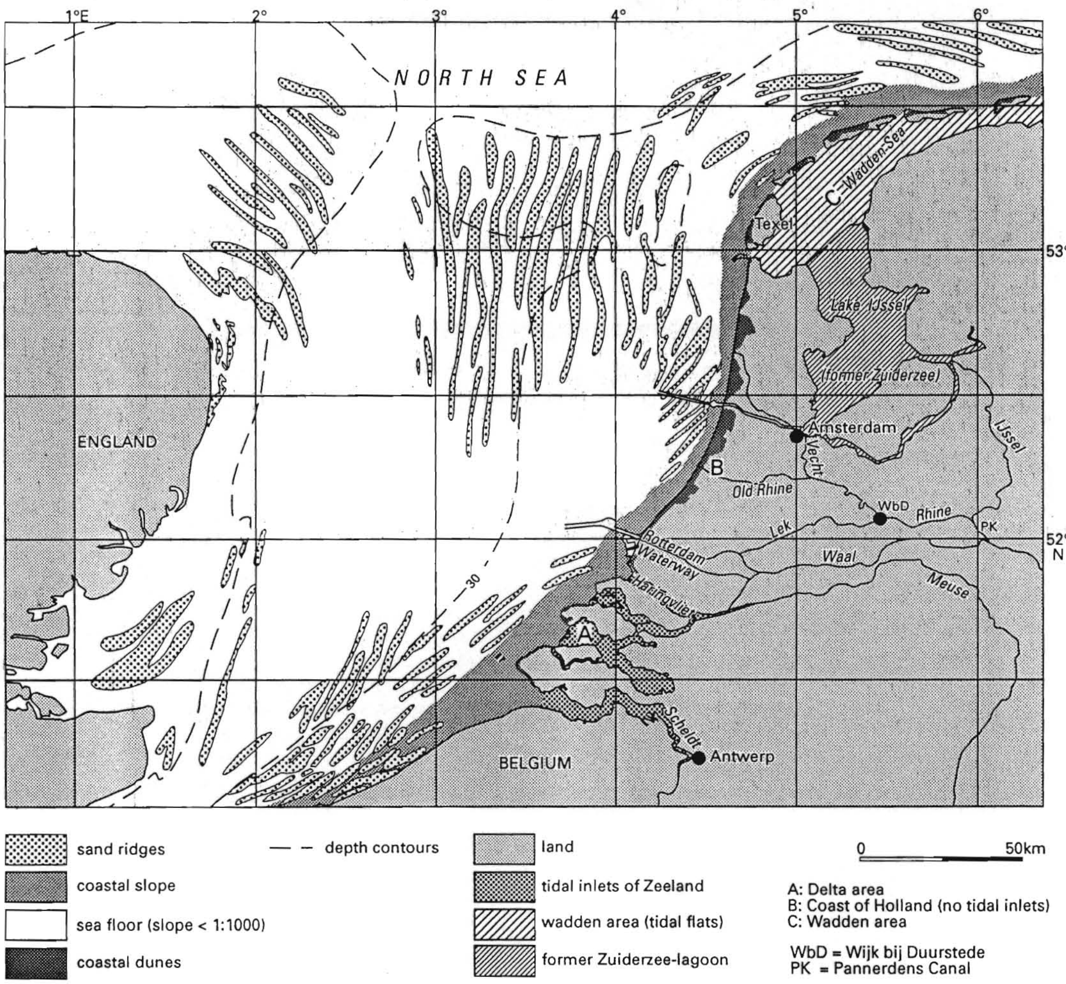

Figure 1. The North Sea Basin and subdivision of the Dutch coast (after Van de Meene, 1994).

ago). General regression at the site of the southern North Sea Basin began during the Pliocene, and, despite increased subsidence during the Pleistocene, the supply of debris was so great that during the interglacial Tiglian (Figures 2 and 3, insert b) the coastline at highstands was located seaward of the present coast (ZAGWIJN, 1989). Glaciation, both of the Baltic shield and the Alps was the main cause for this rapid regression. In addition to the rivers Rhine and Meuse, large amounts of sediment were supplied by rivers draining the ice cap of the Baltic shield and debauching at the northeastern side of the Netherlands. These latter rivers, as well as rivers draining northern Germany, supplied sediment until approximately the Middle Pleistocene (Early Cromerian, Figure 2). Except for the Pretiglian, the combined lowstand delta fronts of these rivers occur offshore (CAMERON *et al.*, 1986; SHA and DE BOER, 1991). Onshore alluvial plain sequences of early Pleistocene age exceed 100 m in thickness locally.

The area between Bonn and the Dutch border was uplifted during the Quaternary. Here, alternating glacial and interglacial conditions produced a series of terraces (ZAGWIJN, 1989). The hinge line between net erosion and net sedimentation practically coincides with the Dutch-German border, which means that from a geomorphological point of view, almost the entire Netherlands can be seen as a deltaic plain.

Subsidence of the North Sea Basin increased considerably in the Quaternary: a Quaternary sequence of up to 1000 m thick is reported from the central part of the North Sea area (BERENDSEN, 1997a).

In the middle and late Pleistocene, the Scandinavian ice caps reached the Netherlands (Figure 3, insert c). The Elsterian ice cap scoured up to 400 m deep subglacial channels in the unconsolidated Quaternary sediments of the North Sea Basin (ZAGWIJN, 1989). The Saalian ice cap reached even farther south and significantly altered the landscape, forming 100 m high glaciotectonic ridges (visible in Figure 3, insert d) that are still important elements in the present landscape. The Saalian ice front forced the rivers Rhine and Meuse to shift their northern course westwards. Since that time, this has remained the main course of the rivers. At present the ridges control the width of the fluvial plain, thereby determining the areal extent of the Holocene delta.

By the end of the Weichselian (= Wisconsinan) glaciation

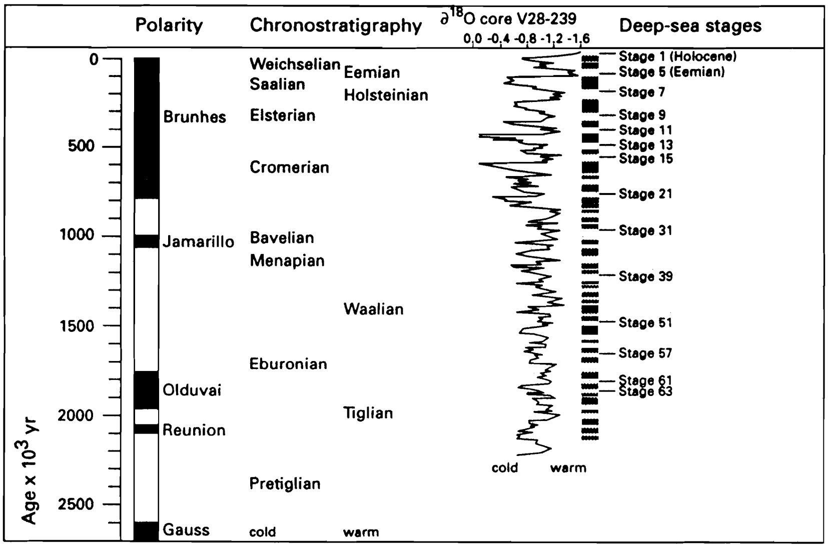

Figure 2. Pleistocene stratigraphy (after Zagwijn and Van Staalduinen 1975, modified by Berendsen, 1997a).

(in which the ice sheets did not reach the Netherlands) most of the Netherlands became covered with eolian sands. The Rhine and Meuse flowed westward through two valleys that are still visible in the morphology of the Late Glacial surface (Figure 3, insert d).

During the Weichselian, sea level was at least 100 m lower than today. In the shallow North Sea area, rivers had a comparatively low gradient. In the vicinity of the present coastline downcutting of some 20 m could take place, resulting in deep late glacial valleys that influence the morphology of the coastline and the course of the rivers until the present. In the eastern part of the country downcutting was some 6 to 7 m. Debris was carried far into the present North Sea, probably even into the Channel area. The northern part of the North Sea was narrowed down to the Norwegian Channel by glacier ice.

When the glacier ice began melting, around 18,000 years ago, sea level rose, but because of the topographic situation in the present-day southern North Sea area, this rise became significant only comparatively late (around 7000 BP). Pleniglacial braided-rivers changed to meandering incising streams in the relatively warm Bølling-Allerød interstadial (13,000 to 11,000 BP), and back again to a brief braiding (incising) stage in the Younger Dryas stadial (11,000 to 10,000 BP). This enhanced eolian reworking of river sand and gave rise to extensive river dune formation on the river plain (BERENDSEN *et al.*, 1993). These dunes are still visible in the present-day landscape and, because of their relatively high elevation, became the site of early settlements.

Because of the morphology of the North Sea Basin, the Pleistocene lowstand deltas of the Rhine-Meuse system occur far seaward of the highstand deltas. Consequently, the Holocene wedge occurs not on top of the preceding lowstand delta, but overlies alluvial plain sediments of early-to-late Pleistocene age on top of a delta front sequence of early Pleistocene age. Most of the alluvial plain sediments in this section represent deposition during glacial lowstands, but thin remnants of delta plain sequences of interglacial highstands occur in the shoreward part of the present delta plain. The predominance of lowstand deposition is probably largely caused by the strong increase in the supply of debris and the discharge of the rivers. During the glacials, the North Sea Basin became the dumping site of huge amounts of glacial debris supplied both by the Scandinavian ice sheet and by the Alpine ice cap by way of the river Rhine. It is estimated that peak discharge of the Rhine increased at least tenfold (compared to present annual discharge, Table 1) when draining the Alpine ice cap during cold stages. Hence, peak discharge during glacials was comparable to the the present mean annual discharge of the Mississippi and Yangtze rivers.

Table 1. *Present discharge in m^3/s of the rivers Rhine, Meuse, Rhone, and Mississippi.*

	Rhine	Meuse	Rhone	Mississippi
Minimum	620	30	360	5600
Mean annual	2200	250	1670	12000
Maximum	13000	3000	13000	56000
Min/Max ratio	1:20	1:100	1:36	1:10

Holocene

The shoreline of the present coast during the Holocene is basically one of retrogradation, and its convex shape (Figure 1) is at least partly a Pleistocene relict. During the Holocene evolution of the fluvial and coastal plain, the following factors are of significance: (1) the morphology of the Pleistocene subsurface, which influenced Holocene evolution up to the present; (2) relative sea level rise (the result of eustatic sea level rise, isostatic subsidence of the land, tectonic subsidence of

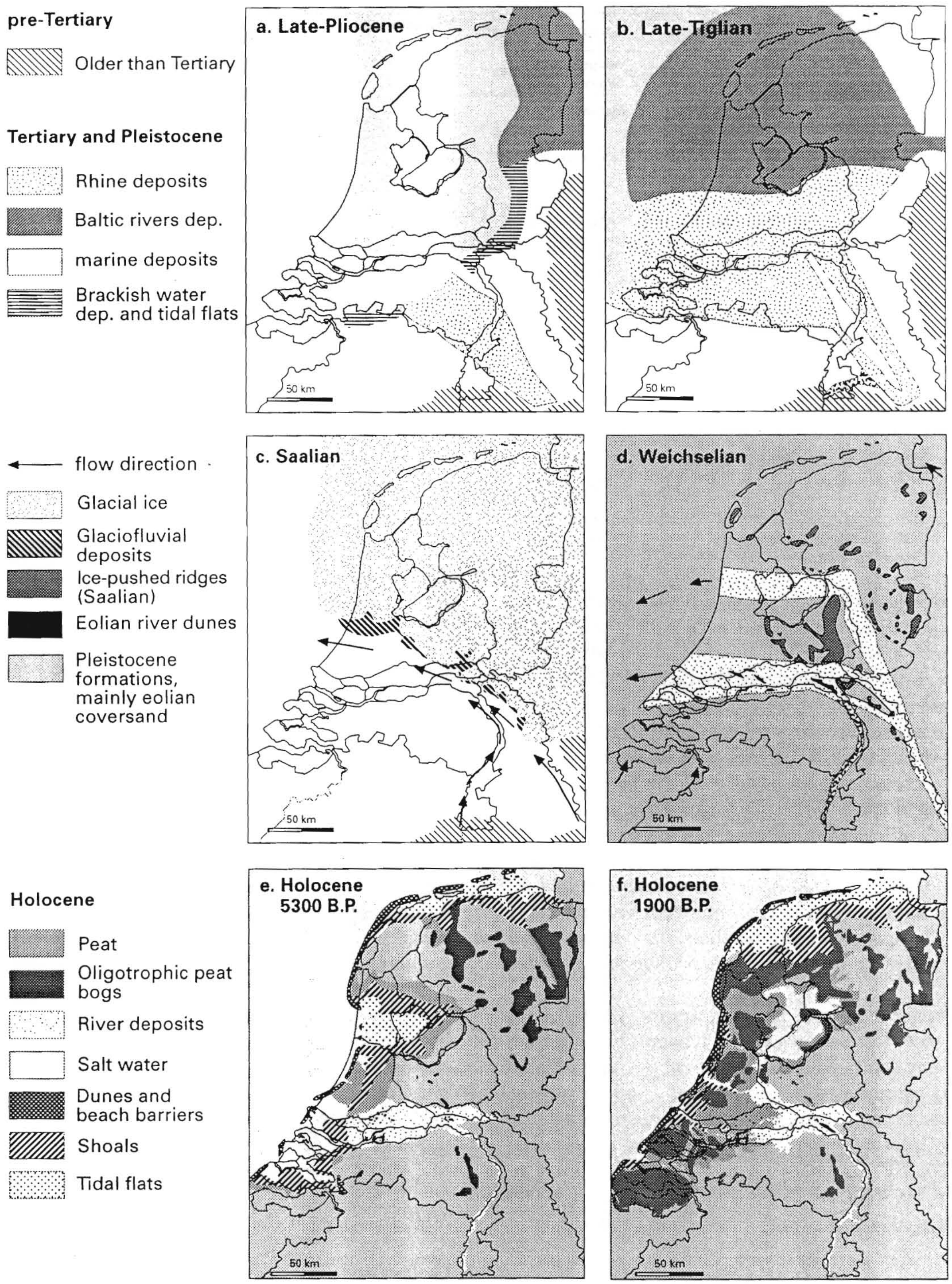

Figure 3. Palaeogeography of the Rhine-Meuse delta at various time intervals (essentially after Zagwijn, 1986).

the North Sea Basin and compaction of underlying sediments); (3) the availability of sand for the building of barrier beaches and coastal dunes (the sand is largely reworked Pleistocene sand, mixed with some Rhine and Meuse sand); (4) the tidal range, which varies from almost 4 m in the southwest to 2 m along the central part of the coast and then increases again to almost 3 m in the northeast (it is generally accepted that tidal differences have not changed much over the last few thousand years); and, (5) inundation of the rivers, giving rise to flood basin deposits and peat formation in the back-barrier area of the coastal plain (Figure 4).

The Holocene Rhine-Meuse deltaic area can be subdivided into the following categories (Figure 4):

- The fluvial area, characterized by meandering rivers, 1 to 2 km wide channel belts and relatively small flood basins.
- The back-barrier coastal plain with strong fluvial influence, sometimes referred to as the "perimarine" area (HAGEMAN, 1969). This area is characterized by narrow channel belts and anastomosing rivers during part of the Holocene. Flood basins are large and contain thick layers of peat.
- The estuarine and back-barrier tidally influenced area, with intertidal deposits of Atlantic and Subboreal age, covered with peat. Sedimentation processes in this area have been described in brief by DE JONG *et al.,* (1962). Where peat has been excavated for fuel and salt extraction, lakes occur. Since about 1450 many of these lakes have been pumped dry. In those cases Atlantic tidal deposits occur at the surface.
- The barrier beach and coastal dune area. The oldest preserved barrier beaches with low dunes are located farthest inland (ZAGWIJN, 1984). The coastal area can be subdivided as (1) the southwestern coast, characterized by tidal inlets and the estuary of the Scheldt; (2) the Holland coast, without tidal inlets, where wave action is the dominant process; and, (3) the northern coast of the Wadden Sea, with islands, tidal inlets, and large tidal flats, that are inundated only with high tide. Strictly speaking, the Wadden Sea lies outside the Holocene delta area.

Fluvial Area and the Back-barrier Coastal Plain

In the early Holocene, the temperature increased, and restoration of the vegetation led to a decrease of peak discharges of the rivers, a general decrease of sediment load, and a relative increase in sediment load of fines. This resulted in a change of river pattern from aggrading braided rivers to incising meandering rivers. In the fluvial plain, aggradation started only in the early Atlantic (7000 BP), after sea level rise (Figure 5) started to influence river gradients. The sea first invaded the mouths of the Pleistocene river valleys (Figure 3, insert e). Since the influence of sea level rise was experienced earlier in the lower western part of the country, clayey flood basin deposits on top of the sandy Pleistocene subsurface are younger in an eastern direction (Figure 6). Similarly, avulsions took place earlier in the western part of the deltaic plain than in the eastern part (STOUTHAMER and BERENDSEN, 1997). In the river area, the rapid rate of sea level caused an anastomosing river pattern between approximately 8000 and 4000 BP (Figure 5, TÖRNQVIST, 1993). As sea-level rise slowed, in the younger part of the Holocene, meandering rivers dominated. The total thickness of the Holocene clayey fluvial basin deposits varies from approximately 1 to 2 m near the German border to approximately 25 m near the Dutch coast.

Estuarine and Back-barrier Tidally Influenced Area

Sea level rise (Figure 6) has had a significant influence on the development of the Holocene stratigraphy in the estuarine area. The rate of sea level rise was very high: about 1 m/100 ^{14}C years but gradually decreased during the Holocene. Although detailed sea level reconstruction has been attempted, based on the dating of peat samples on top of the Pleistocene subsoil (VAN DE PLASSCHE, 1982), small fluctuations in the rate of sea level rise ($<$0.5 m over a time scale of hundreds of years) has not been proven thus far. It is generally accepted that the steep rise of sea level before 6000 BP is caused by the melting of the Weichselian ice sheets; the slower rise of sea level during the younger part of the Holocene is mainly caused by isostatic subsidence. Subsidence in Zeeland appears slightly less than in the northern Netherlands (ZAGWIJN, 1986).

The rapid Holocene regression of the coastline caused an overall stack in backstepping pattern, and peat formation moving in an inshore direction (Figure 6). The back-barrier intertidal and estuarine deposits were formed during two main periods of transgression: during the Atlantic (8000–5000 BP) and during the Subatlantic (3000 BP to present). The deposits are known as "Calais Deposits" and "Dunkirk Deposits," respectively. Attempts have been made to further subdivide these deposits on a lithostratigraphical or chronostratigraphical basis (ZAGWIJN and VAN STAALDUINEN, 1975), but these subdivisions are no longer generally accepted because they are often beyond the resolving power of ^{14}C dating, while at the same time the synchroneity of these "transgressions" is seriously questioned (BERENDSEN, 1982; TÖRNQVIST, 1993).

From about 500 AD onwards, large-scale erosion of the peat occurred by marine ingressions. Tidal inlets were formed in the eastern and western Wadden Sea and in Zeeland, the southwestern part of the Netherlands, leading to a differentiated coastal development (Figure 3, insert f). In the present IJssel Lake region, a large lake (Lake Flevo, Figure 3, insert f) existed, which became connected with tidal inlets in the Wadden Sea and resulted in further erosion of the peat and the formation of the former "Zuyderzee."

The Barrier Beach and Coastal Dune Area

In the coastal dune area, the transgressional phase lasted until approximately 5300 BP, when barrier beaches were formed just east of the present coastline (Figure 3, insert e). Behind these barriers, an environment comparable to the present Wadden Sea existed. As sea level rise slowed, new barrier beaches were formed westward of the older ones. From that time on considerable coastal progradation occurred, especially in the central part of the "coast of Holland" (Figure 1), although sea level continued to rise. The rates of deposition were greater than the rate of sea-level rise; obviously, wave action in the shallow, sandy North Sea was able to transport large amounts of sand towards the coast. An important source of sand probably was the protruding northwestern coast (Figure 3, insert e) near the island of Texel (Figure 1), where Pleistocene sands occur at relatively high elevations. The resulting wide barrier beaches offered better

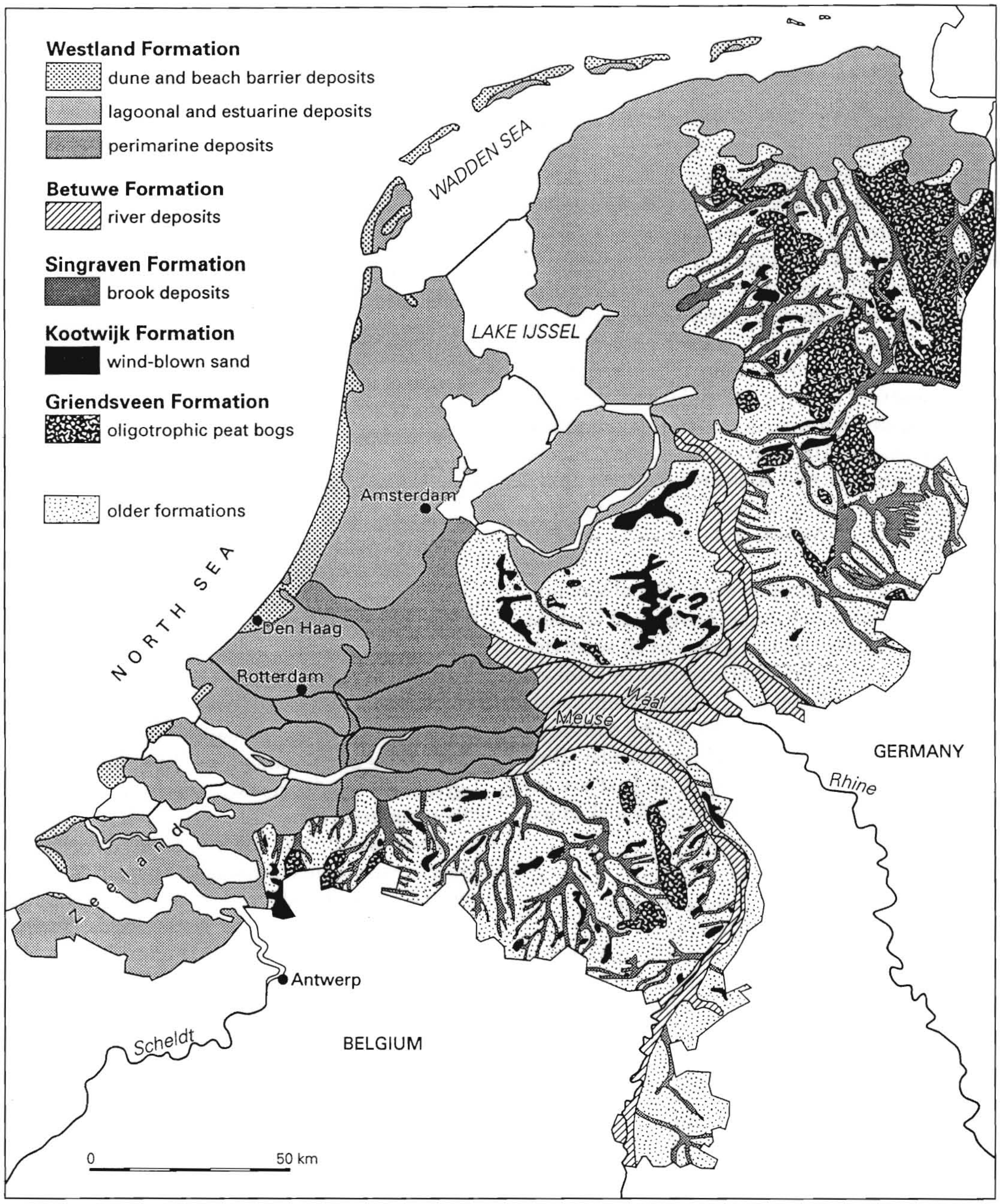

Figure 4. Holocene deposits in the Netherlands (partly after Hageman, 1969, modified by Berendsen, 1997a).

protection against marine ingressions. In the back-barrier area a large swamp existed. River inundations and precipitation gave rise to large-scale peat formation during the Subboreal and early Subatlantic (Figure 3, insert f), from about 4000 BP to 2000 BP. During the last 2000 years, differentiated coastal development is seen because of the dimunition of sand sources available for progradation (ebb tidal delta, rivers), and locally different current and wave patterns. Sand used for coastal build-up is mainly reworked Pleistocene sand, supplemented by a minor Rhine provenance (an estimated 10%). Because of similar mineralogy, the two sources cannot be separated (VAN DE VALK, 1992).

HUMAN INFLUENCE AND MODERN DEVELOPMENTS

Humans have been present in the Rhine-Meuse delta for at least 200,000 years; however, human influence on the landscape is generally believed to be small until the Neolithic (6400 to 3650 BP), when forests were cleared and agriculture

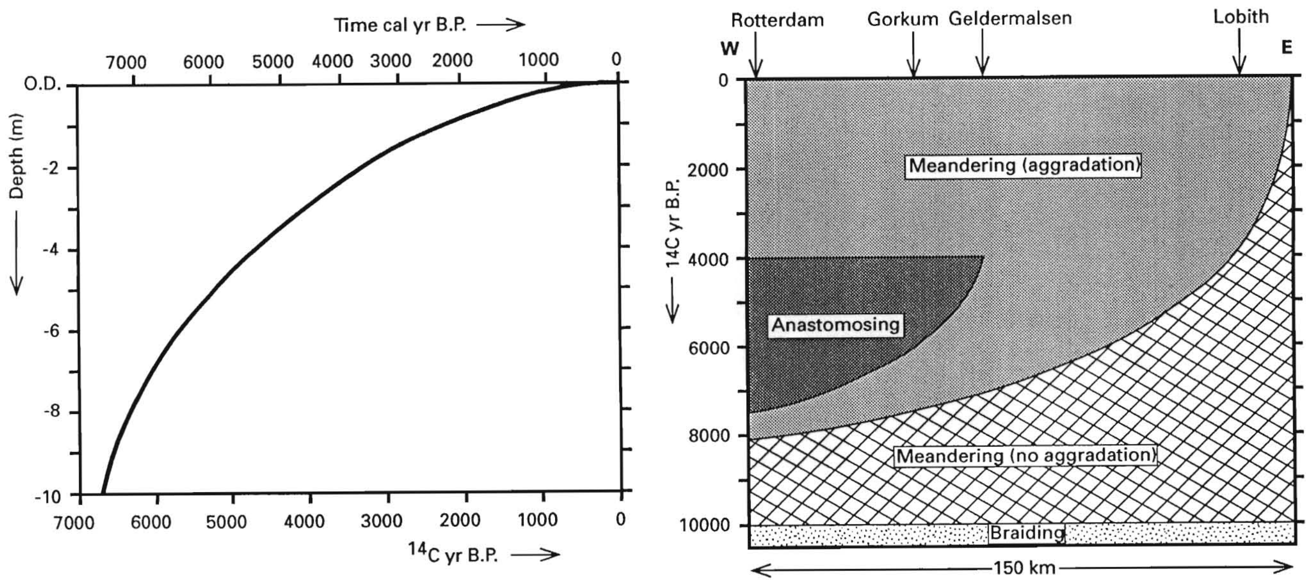

Figure 5. Changes in fluvial style during the Holocene and relation to sea level rise (after Törnqvist 1993).

began on the natural levees and on higher Pleistocene sands. Around 2000 BP the northernmost branch of the Rhine (Vecht, Figure 1) silted up and the Old Rhine (which had been the most important Rhine branch since 5000 BP) became the northern border of the Roman Empire during most of Roman times (50 BC to 400 AD). Roman occupation left many archeological traces in the subsoil, and many villages were founded. The Romans even influenced locally the course of rivers by digging canals.

Human influence increased enormously during the Middle Ages, especially from 1100 AD onwards. A first step was the embankment of the rivers, which was completed around 1300 AD. During the same time period the Old Rhine was dammed near Wijk bij Duurstede in 1122 AD (Figure 1) and the river mouth of the Old Rhine degraded. The ebb-tide delta was eroded and the sand became available for transport to the coast. This stimulated the formation of the so-called Younger Dunes, which form dune ridges up to 40 m high. The damming of the Old Rhine branch reduced the number of Rhine branches to the present three: the Lower Rhine-Lek, the

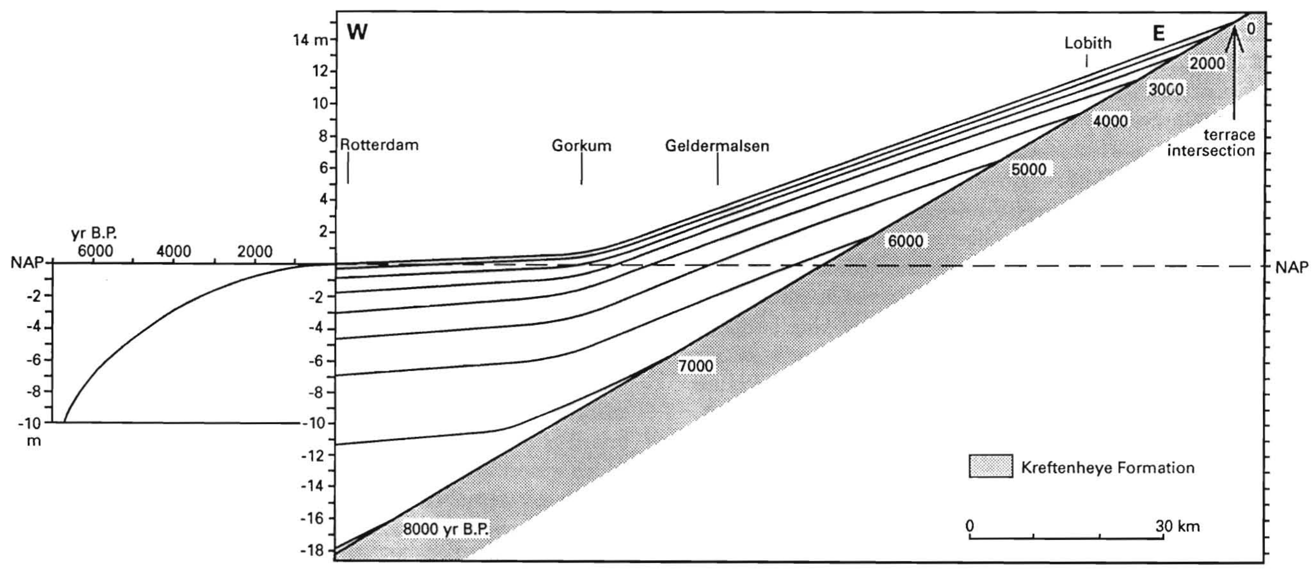

Figure 6. Sea level rise and gradient lines of the lower river courses (after Van Dijk, Berendsen and Roeleveld, 1991).

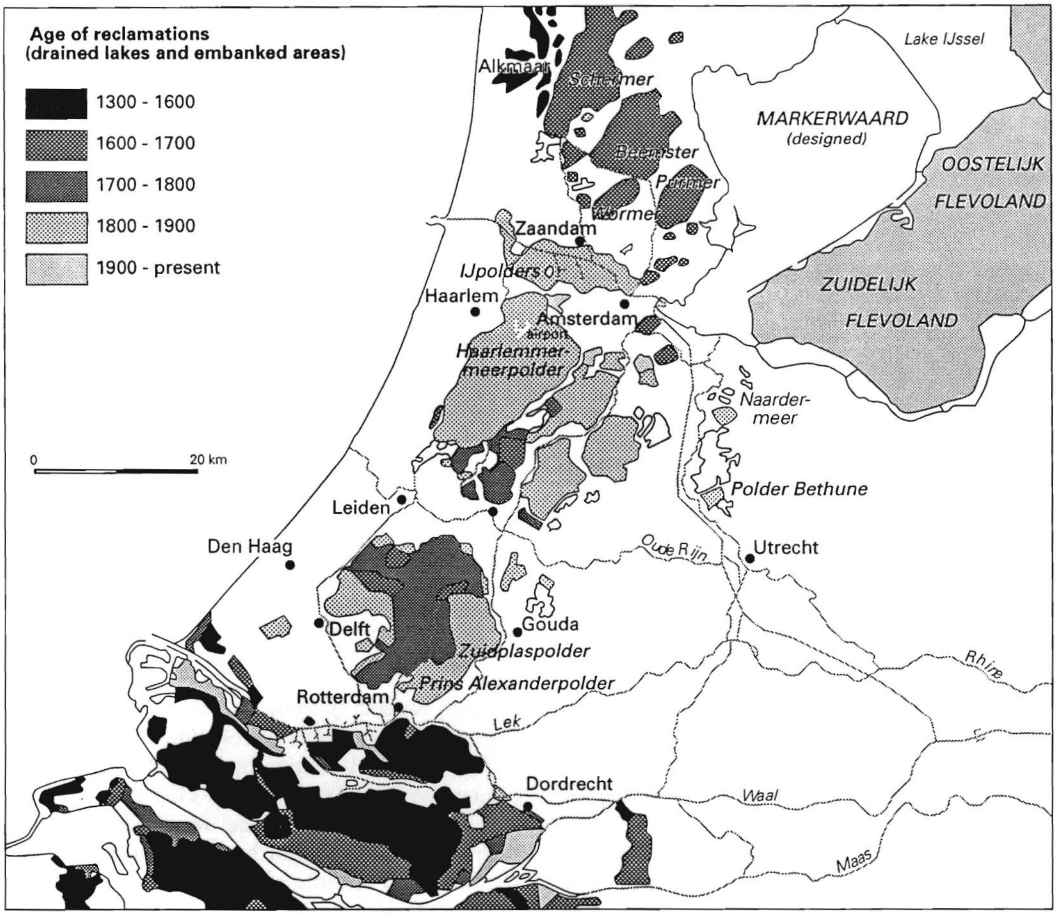

Figure 7. Reclamations (lakes pumped dry) in the central part of the western peat area (Berendsen, 1997d).

Waal, and the IJssel (Figure 1), and there was a tendency for the main flow to shift southwards. The Waal gradually became more important, and both the Meuse and the Lower Rhine-Lek joined the Waal before debouching through the tidal inlet of the Brielsche Maas, just south of the present Rotterdam Waterway. The Lower Rhine-Lek tended to silt up, which led to protests by local inland ports. Finally, the Pannendens Canal (Figure 1) was dug in 1707, and the discharge distribution over the Rhine distributaries was significantly altered. Since then, the discharge distribution has remained the same: Waal 6/9, Lower Rhine-Lek 2/9, IJssel 1/9 of the total discharge of the Rhine. The Brielsche Maas silted up gradually, and the Haringvliet soon became the main outlet. In recent years the Haringvliet has been closed off (see below), forcing the main flow through the Rotterdam Waterway, which was dug in 1872.

The embanking of the rivers opened the possibility of draining and reclaiming the peat bogs in the western part of the deltaic plain. In the Late Middle Ages, peat was dug and used for fuel or to extract salt for the population of the growing cities. Since groundwater levels were high, these peat excavations rapidly turned into lakes. Storms enlarged the lakes by wave action. In the long run, this created a dangerous situation, and many lakes were pumped dry successively (Figure 7), especially between 1600 and 1900. One of the best known examples is the Haarlemmermeerpolder (the location of Amsterdam airport), the first lake that was pumped dry in 1852 using three steam engines.

The largest reclamations date from the 20th century. After the construction of a barrier dam in 1932 across the former Zuiderzee, the present fresh water lake "IJsselmeer" (Lake IJssel, Figure 1) came into existence, and the new "IJsselmeerpolders" were constructed between 1927 and 1968. In this way 1650 km^2 of new land was gained (BERENDSEN, 1997d) that initially was meant for agriculture but is now increasingly used to accommodate the overflow of the rapidly growing big cities.

In the southwestern part of the delta, human interference took a different course. Here, there were no lakes because marine ingressions formed large estuaries. Sand bars and shoals were embanked and added to the old islands successively. In this way, a completely new "manmade" landscape was formed (Figure 8). Nevertheless, the area was a puzzle of islands in the beginning of the 20th century, and plans were made for shortening the coastline by closing off some of the estuaries and connecting the islands by dams, bridges

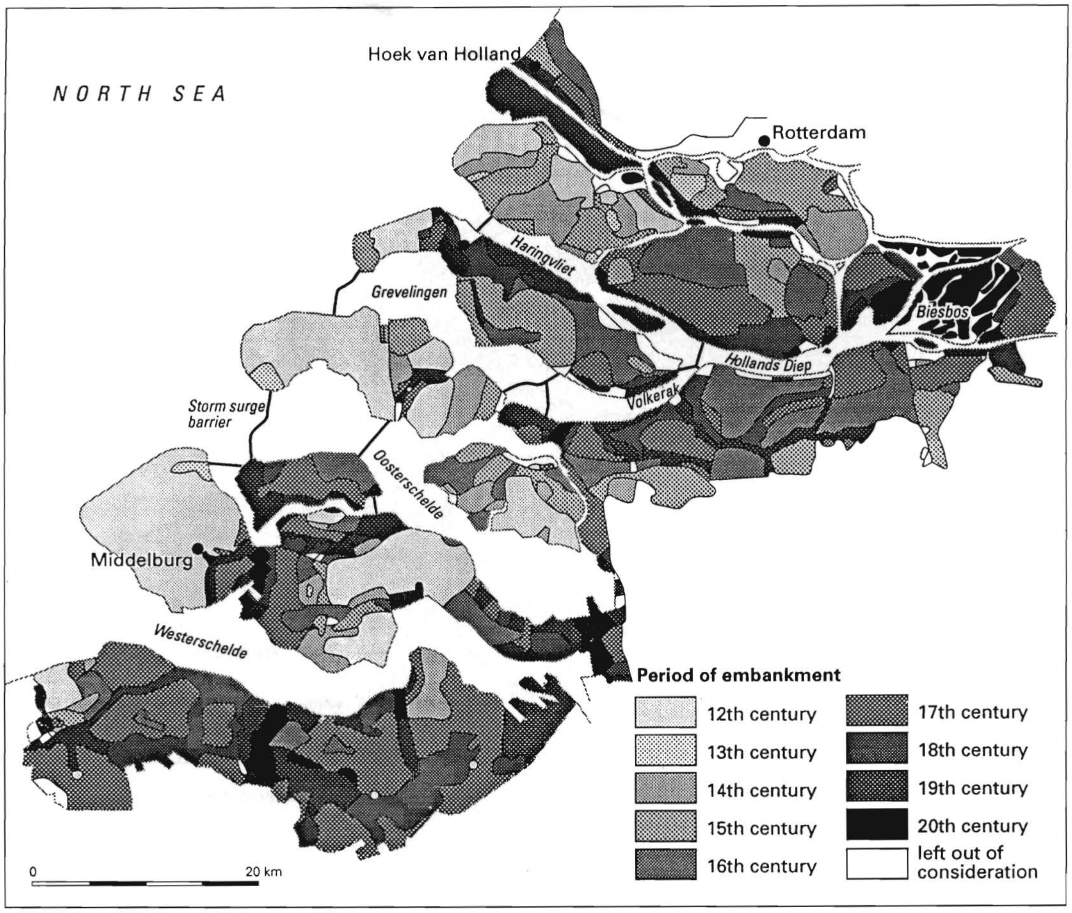

Figure 8. Land gained in the southwestern part of the delta (Zeeland), after De Jong *et al.* (1962)

and new roads. In 1953, a disastrous storm surge caused 600 dike breaches, resulting in inundation of an area of 2000 km^2. About 1800 people drowned in this flood. This hastened government action and resulted in the so-called "Deltaplan." The plan would have dammed all the tidal inlets, except the Westerschelde (Figure 8), which is the outlet of the river Scheldt, and the entrance to the port of Antwerp (Belgium). However, the plans were changed during the process: in the interest of fisheries and the environment not all the estuaries became freshwater lakes (Figure 9) as originally intended. The Grevelingen became a lake with stagnant salt water, and the Oosterschelde was (after much political debate) closed off by an open dam costing 3 billion dollars. This unique dam leaves tidal currents more or less unchanged (though tidal volume is reduced by about 30%). The dam is only closed off completely in severe weather. The Deltaplan was completed in 1996 with the construction of a storm surge barrier in the Rotterdam Waterway (the entrance to the port of Rotterdam). The closing of the Haringvliet tidal inlet forces the Rhine discharge to flow through the Rotterdam Waterway, thus assuring sufficient water depth for shipping. In addition, this counteracts the intrusion of salt water. As was expected, the Deltaplan has drastically changed the situation in the southwest. Drainage is intensified, as well as communication, tourism, and industry, and population has grown.

The closing off of the estuaries also had some unforeseen effects on the near-shore area, where the ebb tidal deltas of the former estuaries are now being eroded by wave action. The result is the formation of a new pattern of sandy ridges parallel to the coast, a process that is on-going.

Since 1300 AD, the embankment of the rivers increased sedimentation rates in the embanked floodplains, thus reducing the capacity to accommodate large floods. This was counteracted effectively by the digging of clay for brick-making. MIDDELKOOP (1997) showed that many of the embanked floodplain sections have an entirely different origin than previously thought. The original idea was that the river essentially had the present shape at the time of embankment, and that after embankment only vertical accretion occurred. However, human interference seems to have been a main factor in the formation of embanked floodplains: islands were connected to the dikes and were planted with reed, thus enhancing the trapping of sediments. In this way new land was gained from the river bed (Figure 10). The resulting morphology resembles a bar and swale topography but often has a completely different origin. The construction of groynes, es-

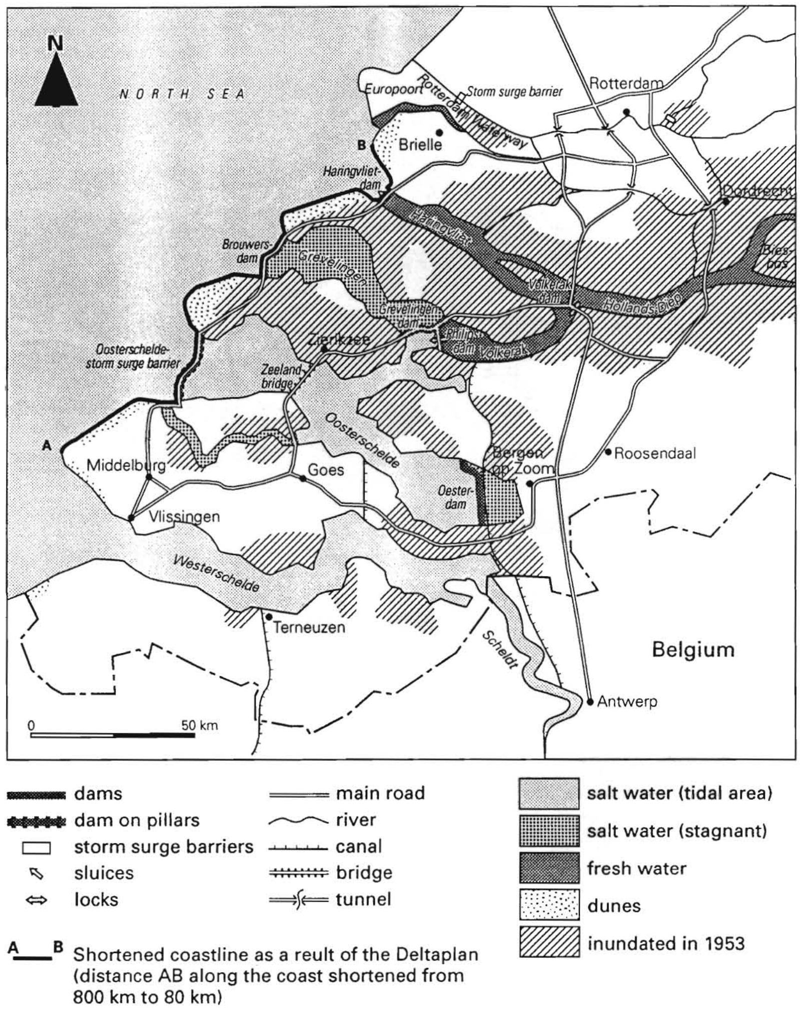

Figure 9. Closed off estuaries in the southwestern part of the delta (Zeeland), after Berendsen (1997c).

pecially since 1850, has caused narrowing and deepening of the river beds, thus enhancing the shipping industry. When the entrance to Rotterdam harbor was widened, river water levels were lowered, and tidal influence is now experienced approximately about 20 km further upstream compared to a century ago (RIJKSWATERSTAAT, 1964).

In recent years, pressure on the embanked floodplains has increased—agriculture, industrial activity, nature conservation, and recreation all demand space, resulting in conflicting interests. Plans are now being made to dig clay and sand and thus lower the level of the embanked floodplains. At the same time, "side-channels" are dug to recreate a more natural and diverse environment for plants and animals. In many cases the importance of abiotic factors in these plans is still underrated.

The weak, clayey and peaty subsoil in the western part of the Netherlands poses many problems for large-scale construction because heavy-weight buildings require a foundation on the sandy Pleistocene subsoil that usually occurs at 8 to 15 m below the surface. This makes building expensive. In some exceptional cases (the IJ-tunnel underneath the North Sea canal near Amsterdam) structures were founded as deep as 70 m. By virtue, this necessitates the importance of a detailed knowledge of the composition of the subsoil.

It is perhaps ironic that for a country so rich in water, the availability of fresh water is a regional problem in the western part of the delta because, at shallow depths, the groundwater is brackish or salt. Underneath the coastal dunes there is a fresh water reservoir, but this is too small to provide all the water that the large cities require. Therefore, water from the Rhine is kept in large storage basins in the Biesbos area (Figure 8) for the drinking water needs of Rotterdam. Amsterdam gets much of its water by pipeline from a nearby polder where excessive seepage from the higher Pleistocene ice-pushed ridges occurs.

FUTURE DEVELOPMENTS

From the previous discussion, it is clear that in the Rhine-Meuse delta, natural processes are effectively controlled by

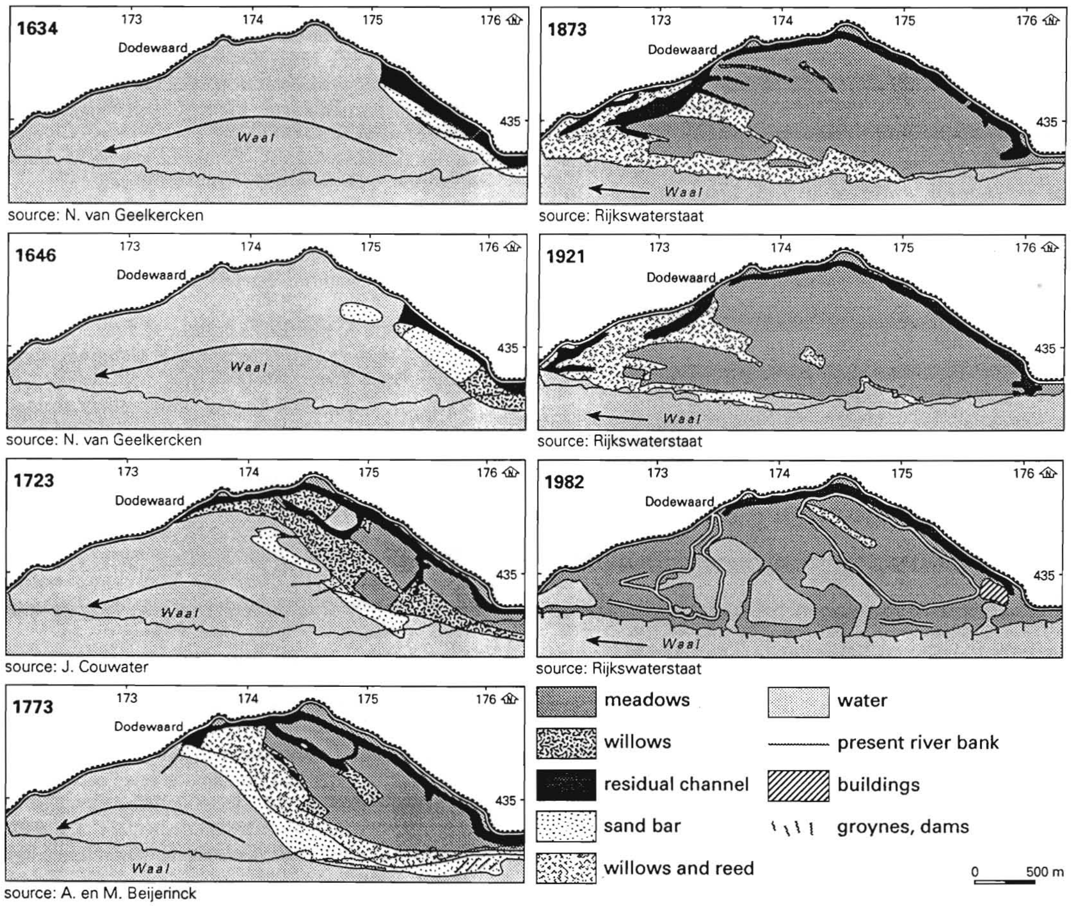

Figure 10. Formation of man-induced counterpoint bars (after Middelkoop, 1997).

humans. Space is so precious in the Netherlands that practically every square meter is defended. Still, this viewpoint has come under attack in recent years, and discussions now focus on how to adapt more to the natural conditions whenever possible.

From an ecological point of view, efforts are being made to reduce pollution and eutrophication levels in the rivers and in groundwater, in order to re-introduce certain plant, fish and bird species. To help nature conservation, agricultural land has been purchased by government agencies and turned into nature reserves (BERENDSEN, 1997c).

Over the past century, sea level has risen approximately 10 cm, which is much faster than before. However, the exact relationship between sea level rise and an enhanced greenhouse effect is still unclear. Important studies have been undertaken in recent years to estimate the changes in behavior of the rivers and coastal areas caused by possible future climatic changes as a result of an enhanced greenhouse effect (*e.g.*, KWADIJK, 1993; MIDDELKOOP, 1997; ASSELMAN, 1997; and LOUTERS and GERRITSEN, 1994). These studies, which are concerned with time scales of about a century, show that on a time scale of the next few decades, problems that can be expected in the Netherlands are still manageable; but, on a longer time scale this may change. Sedimentation in the embanked floodplains is expected to increase. In the long run, high water levels are expected to become higher, while low water levels in the summer may become lower (KWADIJK, 1993). This may have consequences for dike construction.

In some coastal areas, a continuing sea level rise may generate problems in the next century and make adaptions necessary for dams and dikes, especially as it is the policy of the Government to maintain the present coastline. This implies that in areas of coastal erosion, sand is supplemented. The damming of the former Zuiderzee and the Lauwerszee (a smaller tidal inlet in the north) has reduced the total tidal storage capacity of the Wadden Sea. As a result, the size of the tidal inlets decreases and more sand is deposited into the Wadden Sea (LOUTERS and GERRITSEN, 1994). This sand is partly eroded from the ebb-tide deltas that are gradually degrading. On a longer time scale there may not be enough sand to satisfy the "sand hunger" of the Wadden Sea. If accelerated sea level rise occurs, the Wadden Sea may slowly drown by the end of the next century because there is not enough sand to keep the aggradation rate in pace with sea level rise (BERENDSEN, 1997b). This would mean the loss of the only remaining more or less natural tidal area in the Netherlands, an area that is very important from an ecological point of view because it serves as a refuge for many fish, plant and bird species.

The last reclamation in the IJssel-lake region, the designed polder Markerwaard (Figure 7), was never completed because agricultural demand for new land has decreased. Plans have been made to build a new airport in this polder in the future or to use it for storage of water at a high level in order to generate electricity. However, these plans still await political approval, which is not likely to come within the next five years. Alternatives are now under study, for example, a new airport off the Dutch coast. Process-studies are underway to predict the effects on the coastline.

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