5 Synthesis

5 Synthesis:

long-term landscape evolution of the Netherlands and conclusions

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In this summarizing chapter a synthesis is given of the Holocene landscape evolution of the Netherlands as discussed in this thesis and visualized in Figs. 2.4 – 2.14. The major conclusions about the coastal palaeo-landscape development and the influence of sea level, climate and human activities are summarized.

5.1 Early Holocene landscape before the marine inundations (map 9000 BC)

In the early Holocene the coastline lay further west than today and a large part of the bottom of the North Sea was land. Great Britain could be reached walking from the European continent. The sea-level rise was 1 m to 2 m per century (Hijma & Cohen, 2010; Fig. 1.16). The Holocene relative sea-level rise varied due to differences in tectonic and glacio-isostatic subsidence per region (Kiden et al., 2008). Around 9000 BC, the relative sea level in the southern North Sea, near the Strait of Dover, was 26 m below the present level, while in the northern North Sea (near the Dogger Bank) it was about 55 m lower than today. Around 7500 BC the southern and northern North Sea became connected, and thus Great Britain became an island.

The rivers Rhine and Meuse changed from braided rivers into a meandering river system in the late Weichselian, because river discharge became more regular towards the warmer Holocene (e.g. Hoek, 1997). Around 9000 BC the floodplains of Rhine and Meuse were predominantly dry. Only the lower parts of the system, with meandering rivers, were occasionally flooded during extremely high water. Vegetation in the river plain was scarce and dominated by pine. The floodplain remained dry for large parts of the year and local sand drifts led to the formation of river dunes, aeolian dunes in (nearly) dry river beds where the groundwater level was sufficiently high to moisten and stabilize the aeolian deposits.

Deltaic deposition in the Maasvlakte area started at a depth of 22 m –NAP around 7250 BC (Chapter 4.1). Organic-rich sediments in the floodplain were the indirect result of the rising sea level. The groundwater table rose and the floodplain was inundated more frequently by river floods. Due to the continuing sea-level rise around 6500 BC, this part of the river delta was flooded by the sea. Also the lower valley systems (below 20 m –NAP) in Noord-Holland and the Northern Netherlands were inundated since then (Chapter 3.2).

5.2 Drowning of the coastal plain due to rapid sea-level rise (map 5500 BC)

Around 5500 BC the (relative) sea-level rise was still rather fast (~0.80 m per century), and the coastal zone below 8 m –NAP was drowned. Thus the inundated lower parts of the Pleistocene valley systems became tidal basins. At the landward margin of these marine systems, seepage water from the higher Pleistocene sand area caused a rise of the groundwater table. The wet conditions in this marginal zone induced the formation of peat. Due to the continuing rise of sea level, the marine area and peat bogs shifted more and more landward, and tidal sediments were deposited on top of the previously formed Basal Peat layer. In the river mouths of the Rhine-Meuse and the Eems, estuarine deltas were formed and in the Pleistocene valley systems with a small river input, the tidal basins of Boorne, Hunze and Fivel

(Northern Netherlands), the Overijsselse Vecht tidal basin (Noord-Holland) and the Zeeland tidal basin developed (Figs. 1.2 and 3.3.2).

The palaeo-coastline probably was located some 10 km west of the present coastline between Den Haag and Zandvoort between 6000 and 5000 BC. Seismic surveys (Rieu et al., 2003) show that in the subsurface of this part of the North Sea area large tidal (inlet) channel fills occur at a depth of 25-30 m –NAP. Between the inlets beach-barrier ridges were formed. This barrier was probably overstepped – due to the rapid sea-level rise – and therefore eroded and not preserved. After 5000 BC the coastal barrier was located close to the present coastline.

The Schelde River channel –west of the Brabantse Wal – discharged into the Rhine–Meuse Estuary in the NW until about 4500 BC. Then the river found a shorter way to the sea, when in the area of Tholen a channel connection between the Zeeland tidal basin and the Schelde River valley evolved (Vos & Van Heeringen, 1997).

In the Rhine–Meuse area rapid delta aggradation took place. Clastics, sand and clay, were deposited near and in the meandering river channels. The channel belt deposits and crevasses consist mainly of sand, and clays largely filled the adjacent floodplain (Berendsen & Stouthamer, 2001; Cohen et al., 2012). Further away from the channels clayey peat bogs developed. Because peats were formed in large parts of the delta, they were responsible for the larger part of the delta aggradation.

In the tidal basins, peat was only formed at the landward seepage zone adjacent to the higher Pleistocene grounds. The extent and volume of the coastal peat bogs were not yet very large as compared to the situation in the Early Subatlantic (after 2500 BP).

5.3 Turn in the transgressive coastal development due to a decreasing rate of sea-level rise (map 3850 BC)

Around 3850 BC, the sea-level rise had declined to about 0.3 m to 0.4 m per century. The mean sea level was at about 4.5 m to 5 m –NAP, and as a consequence the tidal basins in Zeeland and the IJsselmeer area had expanded landward. Also the tidal basins of the Boorne, Hunze and Fivel rivers in the Northern Netherlands were enlarged due to the continued sea-level rise.

An opposite development took place, however, in the estuarine delta system of Rhine and Meuse, where the delta prograded. This expansion was possible by the sediment input from the Rhine and Meuse and – moreover – by the large-scale peat bog formation in the flood basins. Peat filled the estuarine basin for the larger part, so that sand supplied by rivers could contribute to delta expansion in the coastal part of the delta.

The meandering river channels shifted continuously and new watercourses developed through the delta marsh land (avulsions). This continued until the Middle Ages when this process was stopped by Human embankments. A main shift of the river course of the Rhine occurred at about 4000 BC. Before, the major Rhine channel flew to the Maasmond area, and after a major avulsion the river course changed to the present Kromme Rijn and Oude Rijn (Berendsen & Stouthamer, 2001; Cohen et al., 2012).

Local peat formation occurred in the higher parts of the Netherlands due to the combined rise of the groundwater table (related to the sea-level rise) and the deterioration of local drainage systems. Small valleys filled with peat further deteriorated the drainage process. It was a self-enhancing process, the more peat was formed, the more the drainage deteriorated, leading to further peat growth. The peat acted as a sponge absorbing the rainwater. Since the central high parts of the peat moors were fed only by rain, these peat moors were oligotrophic. Among others in the Peel, parts of Overijssel (De Rooi, 2008) and SE Drenthe and Groningen (Zagwijn, 1986) the peat moors expanded gradually because of the continuously deteriorating drainage conditions. The lower lying coastal peat bogs were still flooded regularly by nutritious water; there mainly reed/sedge peat was formed. In the fluvial area and along the brooks in the Pleistocene area Alnetum peat developed. In the fluvial domain these peats are often very clayey and in the brook valleys the peat alternates with sandy layers.

In the Western Netherlands the coastline had reached its easternmost location by 3850 BC and the transgressive Holocene coastal development ended. Coastal barriers and coastal dunes formed at that time were preserved. The oldest preserved Holocene coastal dunes and beach ridge sediments – with archaeological remains – are found in the beach plain near Ypenburg and Harnasch Polder, east of Den Haag (Cleveringa, 2000; Koot et al., 2008; Louwe Kooijmans & Jongste, 2006). In the Northern Netherlands, the Wadden coastline was still located north of the present one, and dune barriers of the Wadden Islands (with the exception of Texel) have only been preserved since the Iron and Roman Age.

The Zuiderzee connection between the tidal area of the Wadden Sea and the tidal basin of the Oer-Vecht in Noord-Holland / Flevoland did not exist yet (Lenselink & Koopstra, 1994). These tidal systems were separated by a Pleistocene ridge between Wieringen (Noord-Holland) and Gaasterland (SW Friesland).

5.4 The western Dutch coast is closed, the northern Dutch coast remains open (map 2750 BC)

Around 2750 BC the sea-level rise had decreased further, to 0.2 m – 0.3 m per century, and the mean sea level was ~ 3.5 m –NAP. The main cause of the decline of sea-level rise was that the eustatic rise of sea level due to melting polar ice sheets had stopped almost completely so that the tectonic and glaciotectonic (isostatic) subsidence of the Netherlands had become the main factor in the relative sea-level rise. Thus the balance between the deposition in tidal basins and the drowning by sea-level rise turned into the favour of sedimentation, and the tidal basins in the Western Netherlands gradually silted up (Beets & Van der Spek, 2000). This led to enlargement of the salt marsh areas and to a reduction of the tidal volume of the basins. Because the tidal volume (prism) is directly related to the cross-sectional area of the channels, the decline in tidal volume caused a strong reduction of these tidal channel systems, and the coastal barriers expanded seaward. In the hinterland the silting-up of tidal channels and creeks led to a considerable decline of the natural drainage of coastal peat lands in the Western Netherlands. Due to the poor drainage, peat growth expanded and peat covered the salt marsh areas. Large coastal peat bogs arose and grew to several metres above the adjacent tidal area. The central parts of these peat lands were not inundated by nutrient-rich water anymore, making rain the only source of water, leading to oligotrophic peat.

Around 2750 BC the coastline of the Western Netherland was almost closed and behind the beach ridges a huge peat land had evolved. Inlets were present where rivers drained the hinterland, from north to south the Westfriese tidal inlet system, the Oer-IJ, Oude Rijn and Maasmond. In Zeeland the coastline was not closed yet, but also there peat bogs in the hinterland expanded (Vos & Van Heeringen, 1997).

While the coastal plain of Holland was silted up and overgrown by peat, the transgressive coastal development in the Northern Netherlands had continued. The coastline of the Northern Netherlands remained open and the tidal basins of the Boorne, Hunze and Fivel rivers reached their maximum extent around 2750 BC.

The reasons that the coastline in the Northern Netherlands remained open and that the basins were not completely filled with sediment, are:

- Glacio-tectonic subsidence of the Northern Netherlands was stronger than in the Middle and Southwestern Netherlands; thus, more sediment was needed to compensate for the relative sea-level rise. In addition, the sea bottom along the coast deepens more rapidly to the north than to the west, hampering sediment transport towards the coast in the north.
- Although north-westerly storms are the most heavy ones, westerly and south-westerly winds are more frequent so that wave-driven sand transport from the North Sea to the western coastline was larger than to the northern coastline.
- In the Southwestern Netherlands sediment was supplied by the rivers Rijn and to a lesser extent by the Maas.

In the Pleistocene area of the high Netherlands peat formation also expanded. These peat bogs grew together with the bogs in the coastal area and huge peat lands evolved. Where the drainage water stagnated in the lower parts of the peat land, shallow lakes evolved in Flevoland and in the Utrechtse Vecht area (Lenselink & Koopstra 1994; Bos, 2010). During the subsequent period (2750 – 400 BC) these lakes in Flevoland increased in size due to peat erosion by wave action. The lakes expanded especially in Flevoland because in that area there was hardly any clastic sediment supply from the rivers and tidal systems.

In the Rhine-Meuse delta changes were minor. Occasionally the river courses shifted, but the Rhine (in the northern part of the delta) and the Meuse (in the southern part) remained more or less in place. The main course of the Rhine was the Oude Rijn, and most of the river sediment was transported via this channel. As a result, at the mouth, near Katwijk, a delta evolved which grew until the Late Iron Age / Roman Period when the Maasmond became the major outlet of the Rhine again (Van Heteren & Van der Spek, 2008).

5.5 Large-scale regression; first anthropogenic-influenced clay sedimentation in the fluvial landscape (map 1500 BC)

By 1500 BC sea-level rise had decreased to circa 0.15–0.2 m per century and the mean sea level along the coast of the Western Netherlands was at about 2 m –NAP.

The beach ridges and dunes of Zeeland and Holland had expanded further seaward, and an elongate coastal barrier coast had developed (Van der Valk, 1992, 1996). The coastal peat bog behind the barriers had enlarged further, especially in Zeeland, and also the peat bogs in the Pleistocene areas increased in size.

Openings in the coastline were the river mouths of the Oer-IJ, Oude Rijn, Meuse and Schelde. The Westfriese tidal-inlet system in Noord-Holland was closed at that time by a beach ridge (Roep et al., 1979). Thus tidal influence disappeared and peat growth in this area expanded.

In Friesland and Groningen the coastal development also became regressive, and as a result of the filling of the tidal basins the salt marshes prograded seaward and coastal peat lands expanded. The coastline of the Northern Netherlands, however, remained open and the tidal basins of the Boorne, Hunze and Fivel persisted (Chapter 3.3). The supply of sand from the coastal zone was apparently insufficient to compensate the effects of the rising sea level and to fill the basins completely.

In Flevoland large lakes evolved around 1500 BC and expanded due to peat erosion caused by wave action. This erosion continued during the subsequent millennium.

In the flood basins of the Rhine and Meuse delta large peat areas were present. In the easternmost part of the Rijn area, peat expansion was stopped by a clay cover deposited along the active river channels. The expansion of fluvial clay deposition by the Rhine River continued until the Late Mediaval embankments, and expanded to the west due to a large increase in clay supply by the river Rhine. Due to human deforestation in the German hinterland, the affected top soils were washed away during intensive rainfall. The erosion products were deposited in the flood basin, and the expansion of the clay cover layer along the Rhine is the first major influence of humans on the landscape, and is manifest in the palaeogeographic maps (Erkens, 2009).

5.6 Final stage of the regressive coastal development; more than half of the Netherlands covered with peat (map 500 BC)

Around 500 BC the sea-level rise had decreased to about 0.10–0.05 m per century. The mean sea level along the central part of the Dutch coast was about 1.25 m –NAP. Due to a sediment surplus in the coastal zone of the Western Netherlands, the beach ridges and dune area had shifted further seaward and the silted-up Westfriese tidal-inlet was overgrown by peat (Chapter 4.3). In addition the Holland and Zeeland coastal area had not changed very much in comparison with the situation at 1500 BC. The inlets in the coastal barrier of the Schelde, Meuse, Oude Rijn and Oer-IJ still existed. The Oer-IJ tidal system had been connected to the Oude Rijn via the southern Flevo Lake and the Utrechtse Vecht since about 800 BC. This connection made the Oer-IJ the northernmost distributary of the Rijn (Chapter 3.2).

In the Northern Netherlands the salt-marsh areas of the Boorne and Hunze tidal basins grew. From the Early Iron Age onwards these areas had been inhabited. Dwelling mounds ('terpen, wierden') protected people against floodings.

Peat expansion came to an end in most of the coastal area of the Northern Netherlands. The peat lands in western Oostergo were inundated and covered by a salt marsh clay layer between about 1000 and 500 BC. In eastern Oostergo, the inundation occurred later, after 500 BC. Both drownings must have had a natural cause as humans did not interfere in the landscape on a large scale at that time. Migration of tidal inlets and erosion of protecting barriers and marshes are considered the main causes of the inundations of the peat hinterland (Chapter 3.3).

In the map of 500 BC the northern and southern Flevo lakes were still not connected. Because of the later enlargement by erosion, the very margins of the lakes at that time are uncertain. The northern Flevo lake, into which the Overijsselse Vecht drained, discharged into the Waddenzee and the southern Flevo lake was connected with the sea through the Oer-IJ tidal system (Chapter 3.2).

In the Maasmond area the tidal activity of the Gantel system in the region Den Haag / Delft increased (Bulten et al., 2013), but drowning of the peatlands in this area largely occurred in and after the Middle Iron Age. In the area near Vlaardingen the peat was drowned after 250 BC (Chapter 4.2). Large parts of the peat land were uplifted because of floatation during inundations. Inundations after 250 BC are regarded the result of increased Rhine discharge. South of the Maasmond, the Schelde Inlet remained almost unchanged. The Schelde was a relatively small river in a large peat area (Chapter 3.1). One noticeable detail that changed between 1500 and 500 BC was the river meander cut off in Tholen. South of Poortvliet, an oxbow lake formed which was filled up with gyttja (Vos & Van Heeringen, 1997).

On the higher Pleistocene grounds, the peatlands reached their maximum extent around 500 BC. Both in the high Netherlands and in the coastal area large peat domes of oligotrophic peat were formed. In the coastal zone these raised peat domes reached an elevation of up to 4 to 5 m above mean sea level.

5.7 The southwestern Dutch coast is opened and the Zuiderzee develops (map 100 AD)

At about 100 AD sea-level rise had decreased to about 0.05 m per century and the mean sea level along the coastline of Holland was at about 0.75 m –NAP.

In the Late Iron Age and Roman Period, the coastline of the Southwestern Netherlands was eroded, openings in the barrier system were formed and behind these openings small tidal areas ("slufters") developed. The cause of these ingressions likely was the disappearance of the Pleistocene headland before the Belgian coast near Knokke which had been an important source of sand. The Belgium–Zeeland coastline became straight and no or much less sand was transported by longshore currents to the north (Chapter 3.1).

Around 100 AD, in the early stage of the ingressions, the sea did not yet penetrate far into the peat area behind the barrier. The surface of the peat was about one metre or more above the maximum storm surge level. During the Middle Roman Period the openings in the barrier became larger and tidal channels penetrated further inland. This was the result of human activities in the peat area. In order to make the peat inhabitable people had dug ditches and channels since the Late Iron Age. The artificial drainage systems discharged through the new natural openings in the coastal barrier. Through these, the sea penetrated into the hearts of the peat lands of Schouwen–Duiveland, Walcheren, Zuid-Beveland and Zeeuws-Vlaanderen. Moreover, the peat surface subsided due to artificial drainage and peat digging (Chapter 3.1).

The changes in the coastal landscape around the beginning of the Christian era were not limited to Zeeland. Also the coastal landscape in the Maasmond, the Oude Rijn river area and the Oer-IJ region changed. In the Maasmond area the estuarine clay deposition increased due to increasing inundations after 250 BC. This was, to a large extent, the result of the shift of the Rhine towards the Maasmond (Chapter 4.2). As a consequence the importance of the Oude Rijn as the natural drainage system of the fluvial hinterland decreased. The hinterland sediment source fell away, and the Oude Rijn delta system became smaller, also because the erosive degradation by wave action and longshore currents had increased.

To the north of the Oude Rijn delta, along the concave bight of the Holland coastline between Bloemendaal and Egmond, the coastal barrier still expanded slightly seaward. The sediment was largely derived from the eroding Oude Rijn delta and transported by longshore currents (Van Heteren & Van der Spek, 2008). Also the closure of the Oer-IJ played a significant role. The landscape change in the Oer-IJ region started already around 400 BC when marine influence decreased. This regressive process is attributed to a decrease of the discharge from the hinterland so that the Oer-IJ lost its drainage function and the tidal inlet silted up (Chapter 3.2). The loss of discharge was the result of the evolution of the Zuiderzee. The peat bridge (barrier) between the southern and northern Flevo lakes was eroded and an opening to the Wadden Sea formed. From that time onwards, drainage of the peat hinterland of the Utrechtse Vecht and the Eem was northward. Around 200–150 BC, the tidal inlet of the Oer-IJ had been silted up completely, and the Oer-IJ system was separated from the sea by a beach ridge so that tidal activity in the area behind ceased. Only during extreme storms the lower parts of the beach ridge were breached, and wash-over deposits were formed behind the barrier. This lasted until the Early Roman Age.

In the Northern Netherlands the old tidal basins of the Boorne, Hunze and Fivel silted up further, and large salt marshes developed. In these areas mud mounds (wierden, terpen) were constructed. During the Late Iron Age / Roman Age humans started to drain and dig off the margins of the peat areas and to settle there. The consequences were the same as in the cultivated peat areas of Zeeland: the surface of the peat margins subsided and was flooded during extreme tides. As a result salt-marsh clays were deposited upon the drowned peatlands in the marginal zone (Chapter 3.3).

In the river area, the expansion of clay over the peat in the flood basin – related to the deforestation in the German hinterland – continued. The clay layer increased in thickness and expanded westward.

As in the river area, also in South Limburg an increase of human influence is observed. Due to large-scale deforestation of fertile soils, loess was washed away from slopes and plateaus to the creek valleys and to the valley of the Meuse.

5.8 Transgressive coastal development due to human activities (map 800 AD)

During the past 2000 years the relative sea-level rise has been relatively small, on average about 5 cm per century. The landscape changes in the coastal area were, to a large extent, influenced or caused by humans.

Around 800 AD, a large tidal area was formed in the Southwestern Netherlands. It would never have developed if humans had not interfered in the coastal peat landscape. Large-scale drowning started about 270 AD when the Roman cultivation of the peatlands in Zeeland caused a considerable subsidence, as a result of which the area was flooded regularly. This led to the deposition of clay, and the weight of the clay layer caused further lowering of the infirm peat soil. This resulted again in more frequent inundations and more clay deposition (autocompaction). Subsidence of the peat surface, together with the fact that through the drainage canals and ditches the sea could penetrate directly into the centre of the peatland, had catastrophic consequences. Canals and ditches changed into tidal channels and creeks which further eroded the peat. In contrast to sand, upon erosion, peat is lost largely from the sediment balance of a tidal system, because it largely consists of water and organic matter. Due to subsidence and erosion, the tidal volume in the area increased significantly. The process of subsidence, increase in tidal volume, increase of tidal channels, and peat erosion was self-enhancing. About 350 AD the Roman peat reclamation areas had already been inundated completely and further habitation and peat reclamation had become impossible. At about 800 AD, after several centuries of inundation, the elevation of the land by sedimentation gradually surpassed the effect of subsidence and sea-level rise. Large parts of the tidal areas of Schouwen, Walcheren, Zuid-Beveland and Western Zeeuws-Vlaanderen silted up to salt-marsh level and became suitable for habitation again (Chapter 3.1).

Because of the drowning of the South-western Netherlands, openings were created. Part of the drainage of the Rhine–Meuse passed through these new waterway connections. At that time, the Oude Rijn had become a minor branch of the Rhine, which hardly transported any sediment anymore. As a result, the river delta near Katwijk declined further.

The Oer-IJ region remained protected against the sea by beach ridges and dunes in the former mouth of this estuary. The drainage of this region went through the IJ channel and the Zuiderzee to the Wadden Sea (Chapter 3.2). The Zuiderzee had become a large inland sea because of ongoing peat erosion.

Retreat of the coastal barrier occurred between Bergen and Texel, and openings as the Zijpe ingression system were formed. Because of these inlets, Texel was separated from the mainland of Holland. The tidal area between Texel and NW Friesland expanded further. This was related to the evolution and subsequent enlargement of the Zuiderzee.

Also in the Northern Netherlands new ingressions in the peat hinterland occurred. Similarly as in the case of the large inundation of Zeeland, humans were involved by cultivating the peat. The peat margin of the Middelzee area between Leeuwarden, Sneek and Workum was flooded due to anthropogenic peat subsidence. This had started already in the Late Iron Age, stagnated during the Dark Ages, and became significant in the Early Middle Ages. A similar process in the peatlands between Friesland and Groningen led to the development of the Lauwerszee ingression system. This system was connected, through the Reitdiep, with the old Hunze system which had been almost completely silted up at that time. Most likely humans played a crucial role in this connection by digging a connecting canal between both systems (Chapter 3.3).

In the fluvial Rhine–Meuse area, the covering clay layer on the peat had expanded further west, to the line Utrecht–Gorinchem, in about 800 AD. At that time, the Gelderse IJssel came into existence after breaching of a Pleistocene sand barrier, probably between Zutphen and Deventer. Since then, the IJssel has been a permanent river connection of the Rhine to the Wadden Sea (Cohen et al., 2012).

5.9 Coastal and river areas are diked in, large lakes develop in the coastal peat areas due to reclamation activities (map 1500 AD)

Since the Late Middle Ages humans became the dominant factor in shaping the Dutch landscape. Salt marshes and floodplains of coastal and river areas were diked, and almost the whole peat landscape was reclaimed.

The embankments had huge environmental consequences for both the diked landscapes and for the fluvial and marine areas. The dikes prevented the land from being flooded during high tide, so that the storage area of floods was drastically reduced. During floods the waters could not spread out anymore over the marshes and flood basins, but boosted against the dikes leading to a strong increase of maximum water levels (Fig. 3.1.3). This created disastrous conditions, because upon breaching of a dike, floodwater entered with great violence the embanked and artificially lowered areas. Examples of such catastrophes are the Sint-Elisabeth Flood of 1421 in the Groote of Zuidhollandsche Waard and the Sint-Felix Flood of 1530 in the Verdronken Land van Zuid-Beveland (Fig. 3.1.6). In the northern Netherlands, the drowning of the former peat polders in the Dollard region in 1509 was a huge disaster (Chapter 3.3). These flood calamities had in common that they had a large extent, and that land was lost permanently or for many centuries. In the coastal area these permanent losses were the result of the strong subsidence of the peat polders. After dike breaching, tides flew in and out of the drowned polders, creating large tidal channels which could not be repaired in those days (Fig. 3.1.7).

Further inland there also were land losses. In the large peatlands of Holland and Friesland lakes developed as the result of large-scale digging-off of the peat for heating. Where lakes occurred, they were enlarged by erosion of the margins by wave action. Most of these lakes were reclaimed in the 16th and 17th centuries, using windmills (Fig. 3.3.12).

Around 1500 AD, the Zuiderzee had almost reached its maximum extent. Near Kampen where the IJssel River flew into the Zuiderzee, a delta developed creating new land (Ente, 1971).

The increase in population led to more intensive agricultural activities and to the cutting of natural woods. The destruction of vegetation in sand areas led to aeolian sand drifts. The Younger Dune formation in the coastal area can, for a large extent, be attributed to human interference in the dune landscape (Chapter 3.3). Also the large sand drifts on the higher Pleistocene sand areas, in particular from the 15th century onwards, were caused by intensive agriculture and overgrazing.

5.10 Man-made nature (1850 AD)

In 1850 AD the Netherlands had got more or less its present shape, and humans had become the major 'geological factor' in shaping the landscape. Between 1500 and 1850 AD large-scale land reclamation took place all along the coast, at the islands of Zeeland and Zuid-Holland, in the north of Noord-Holland, in Friesland (Het Bildt) and in Groningen (around the Dollard). When a tidal area along the dikes had silted up to the supratidal level, these grounds were embanked for agricultural purposes. Most lakes in the peat land were made dry. In the 19th century also steam engines were used, e.g. in the case of the Haarlemmermeer (1849–1852).

Man did not yet control all processes. Where large sand drifts occurred in the coastal dunes and Pleistocene areas, it was difficult or impossible to stop the aeolian sand transport, and villages and agricultural fields were destroyed. Frequent breaches of the sea and river dikes occurred. Witnesses of these dike breaks in the landscape today are the small lakes in erosion pits (so-called 'wielen').

Coastal erosion was difficult to counteract. E.g. between Castricum and Texel, complete villages such as Egmond aan Zee, Petten and Callantsoog disappeared into the sea.

5.11 Man-made country (2000 AD)

In 2000, except the Wadden Sea area, there is hardly any location in the country that is not Man-made. Also in the Wadden Sea tidal sedimentation is influenced by Man, e.g. by dredging, subsidence due to gas and salt extraction, and sand nourishments along the coasts of the islands.

Striking changes in the 20th century landscape have been the explosive growth of urban areas, the population of the Netherlands having increased from nearly five million people around 1900 to nearly seventeen million today. Former extensive peat areas on the higher Pleistocene areas almost completely disappeared. The remainders are for the major part managed as nature reserves.

Storm flood catastrophes were followed by large closures of sea branches and land reclamation works. This happened in the Zuiderzee area (closure by the Afsluitdijk in 1932 and reclamation of new land) after the flood disaster in 1916, and in Zeeland after the flood disaster of 1953 (the Delta works). During the last decades, new land has been created in the North Sea, in the area of the Port of Rotterdam (Maasvlakte), to facilitate the harbour activities.

5.12 Conclusions

In a broad sense, the subsurface of the Netherlands might be called a delta because during the Quaternary the Dutch lowlands have been built up by the sediments of the rivers Rhine, Meuse and older Eastern German rivers. In the Holocene, however, the delta plain was restricted to the Rhine–Meuse valley system which was formed at the end of the Weichselian. Because of the sea-level rise this valley system was inundated by the sea and became an estuary. The fluvial and marine sediments, which filled the estuary (Fig. 1.4), are described as fluvial- and estuarine-delta deposits. The term tidal basin is used for the drowned valleys – which became tidal systems in the first part of the Holocene. There, only small brooks and small fluvial streams drained to the sea (Chapter 1.3.1).

To describe the deposits of the tidal systems a new integrated terminology is used (Chapter 1.3.4). Coastal sediments are grouped according to the depositional system to which they belong (e.g. Boorne tidal-basin deposits), the sedimentary environment (lithofacies) in which they were formed (e.g. salt-marsh deposits) and/or the lithostratigraphic unit of which they form part (e.g. Wormer Member). It is a flexible approach to describe the Holocene coastal deposits of the Netherlands. The terminology is flexible because the different terms can be used together (e.g. salt-marsh sediments of the Wormer Member within the Boorne deposits).

The clastic coastal deposits in the Netherlands were formed during two 'major' transgressions: a 'sea-level driven transgression' in the first half of the Holocene and 'accommodation space driven transgressions' (or ingressions) in the last part of the Holocene.

In the Early and Middle Holocene, the rapid sea-level rise was responsible for drowning of the coastal area in the Western and Northern Netherlands. During this period the marine deposits of the Wormer Member were formed. In the Western Netherlands the tidal basins were closed from the open sea by beach ridges between about 3500 and 2500 BC (Chapter 3.2) and the formation of the Wormer deposits ended in this area. The coastline of the Northern Netherlands stayed open. The formation of the Wormer deposits – at the landward side (Fig. 1.6) – continued in the tidal basins of the Boorne, Hunze and Fivel to about 2000 to 1500 BC (Chapter 3.3).

During the sea-level high stand in the Late Holocene (Fig. 1.20), the marine ingressions were primarily the result of the creation of new floodwater storage areas (accommodation space) in the coastal peat lands which were formed at that time (Chapters 3.1 and 3.2). These areas were lowered by compaction and oxidation of the peat as a result of natural and/or anthropogenic drainage. Due to the enlargement of the flood storage areas, the tidal systems became larger and the tidal volumes (Fig. 1.24) of these systems increased. This process induced the formation of larger tidal channels and the deposition of a clay layer on top of the peat. Erosion and autocompaction of the peat led to a further increase of the tidal volume and this caused a self-enhancing drowning process (Chapter 3.1).

Natural causes were morphological changes in the tidal system such as the erosion of a protecting coastal barrier and salt-marsh ridges along the peatlands (Fig. 3.3.4) or avulsion of a river system creating a new opening to the sea (Fig. 3.3.5). From the Late Iron Age onwards, human interference in the coastal landscape played a major role in the creation of new accommodation space. Intensive artificial drainage of the marginal zones of the coastal peat bogs caused substantial lowering and led to a drowning of these areas (Fig. 3.3.6). Examples of anthropogenic ingressions are the drowning of Zeeland during the Roman and Early Mediaeval period (Chapter 3.1) and the development of the Dollard area (Chapter 3.3; Fig. 3.3.7). These ingressions can be considered 'anthropogenic transgressions'.

Each ingression system has its own depositional history (Fig. 3.3.3) because different forcing factors were involved (Chapter 3.3). Not only the human interference in the coastal landscape but also changes in the water discharge from the fluvial and peat hinterland played a significant role. The drowning of the peat landscape along the Rhine-Meuse Estuary near the town of Vlaardingen in the Late Iron Age can be attributed to changes in the watercourse (avulsion) of a main distributary of the River Rhine around 250 (Chapter 4.2). At the same time, the Oer-IJ Estuary was isolated from the sea by the development of a beach ridge. This closure could happen because the Oer-IJ Estuary lost its drainage function for the fluvial and peat hinterland. Around 400 BC a new water course was formed in the Zuiderzee region. Water of the Utrechtse Vecht and peat brooks discharged from that time onwards via the Flevo lakes to the Wadden Sea (Chapter 3.2).

The closure of the Oer-IJ mouth by a beach barrier in the Late Iron Age implicates that there was no direct water connection between the harbour of the Roman Castellum Flevum to the North Sea. Roman ships could navigate via the Utrechtse Vecht to the Roman border, the Limes, and through the Zuiderzee connection to the Wadden Sea (Chapter 3.2).

Human interference in the coastal landscape led to the evolution of the Westerschelde or Honte connection as main distributary of the Schelde River, at the expense of the Oosterschelde connection (Chapter 3.1). This definitive break-through of the Honte took place after the large storm flood catastrophes of 1530 and 1532 AD (Fig. 3.1.6) when large parts of the polders between the Oosterschelde and Westerschelde area were permanently lost (Verdronken Land van Zuid-Beveland; Drowned Land of Zuid-Beveland). This drowning led to the formation of a large opening (cross-sectional area) between the Westerschelde and Oosterschelde, and caused a shift of the watershed to the inundated areas. As a result, the maximum current velocities in the Oosterschelde near Woensdrecht decreased significantly, which led to a fast infilling of the Oosterschelde channel. Already in 1572 Spanish troops could cross the channel at that place (Chapter 3.1).

Climate and sea-level change were the main driving forces of the large-scale environmental changes during the glacial and interglacial periods in the Pleistocene. However, during the Holocene the magnitude of climate fluctuations has been limited (Chapter 1.6; Fig. 1.21). The influence of climate variations on the morphological changes of coastal depositional systems is difficult to detect because many natural and/or anthropogenic driving factors are involved in the architecture of these systems.

The Holocene climate changes were too small to generate eustatic sea-level fluctuations causing transgressive and regressive cycles. The many storm-flood catastrophes in the 15th to 17th centuries (Fig. 3.1.6) are more related to dangerous situations created by Man (lowering of the polders and increase of the extreme HW level; Fig. 3.1.3) and the poor maintenance of dikes due to political and socio-economic problems, rather than to the climate change of the Little Ice Age.

The role of climate in the increasing wetness and peat bog expansion around 800 BP in Westfriesland, which led to the abandonment of the Late Bronze Age settlement in the area, is arguable. The increasing wetness is better explained by the deterioration of the natural drainage of the area because of the closure of the Westfriese inlet system. At the same time, the reverse process is observed in the peat margin of the Oer-IJ system near Assendelft (site Q). At that location oligotrophic peat growth stopped due to cultivation and occupation of this part of the peat land by prehistoric settlers (Chapter 3.2).

The observations in the PWN dune area and Middensluiseiland show that humans disturbed the dune vegetation on a large scale. Therefore, they played a major role in the aeolian sand transport and dune formation. Because of the human interference, a role of climate in the intensity of the aeolian sand transport can hardly be detected (Chapter 3.2).

In the Holocene causal relationships between observed palaeo-environmental changes and alleged climate variations have to be regarded with great caution. The magnitudes of the climate fluctuations are too small for a great impact on the sedimentary systems. Autonomic and self-enhancing processes within these systems overruled the climate effects. Natural and anthropogenic morphological changes in tidal systems during the Late Holocene led to regional changes in MHW and EHW levels (Figs. 1.27 to 1.30) which are of a larger order than the relative seal-level rise at that time (Fig. 1.20).