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Towards a Habitat Map of The Netherlands, German and Danish Wadden Sea

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ABSTRACT

To achieve better conservation and management of the NW-European Wadden Sea, about one hundred scientists from almost all institutes in and around the area have compiled the ecological literature and unpublished data in a series of handbooks and habitat maps.

The procedure used for compiling the habitat maps of the Wadden Sea is presented. The overall 1:100 000 outline map shows the habitats of the littoral and supralittoral parts of the Wadden Sea, a shallow sedimentary coastal sea 450 km long and bordered by the southeastern North Sea. The map is a potential-biological map for benthic organisms, based on an integration of the environmental factors emersion period and sediment composition. Conspicuous communities of organisms have been added (mussel beds, seagrass beds, salt marshes).

The map shows the overall geographical distribution of morphological forms and habitats. Based on this large-scale variation, the Wadden Sea has been subdivided into eight regions, which differ in respect of the importance of the barrier system, the shore of emerging flats, exposure to wave action, sediment composition, the distribution of seagrasses and salt marshes and the occurrence of islands within the area.

1 INTRODUCTION

A 'Wadden Sea Working Group' consisting of about one hundred scientists from almost all institutes in and around the Wadden Sea area,

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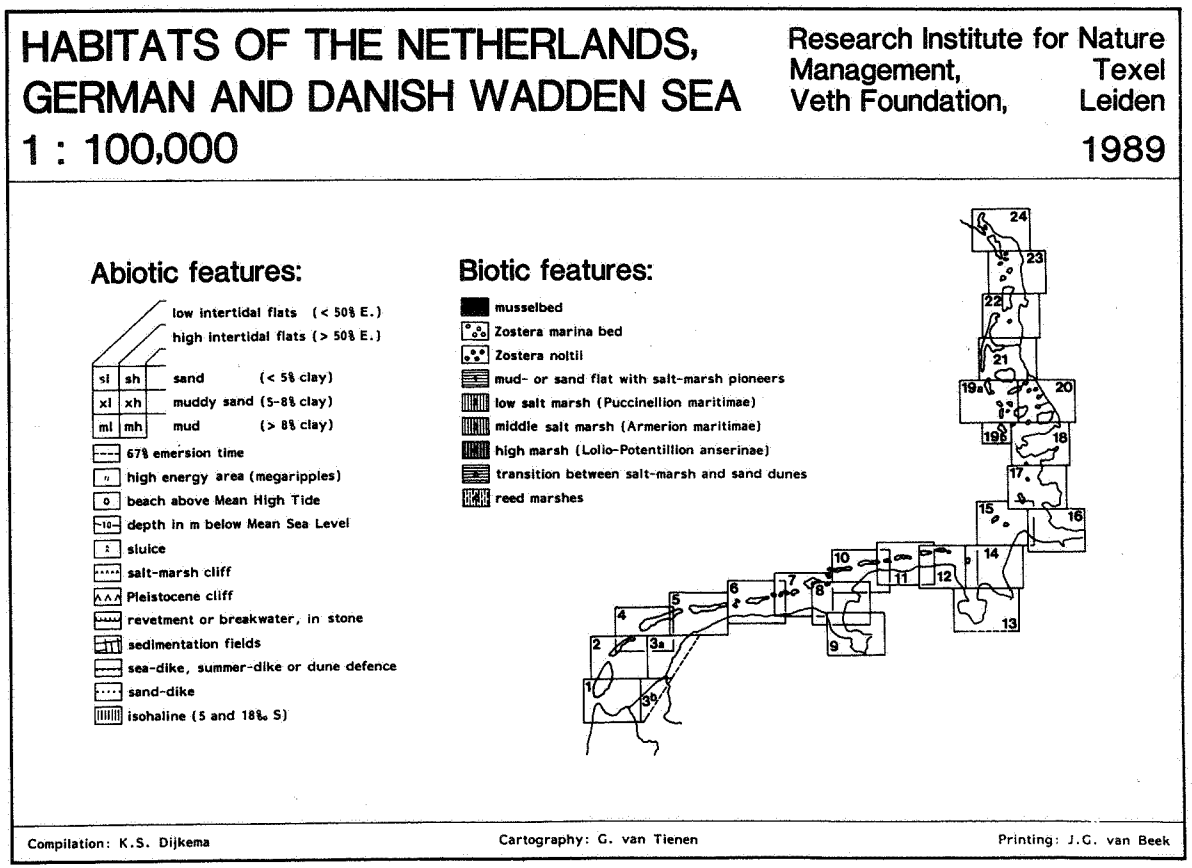

Fig. 1. Legend of the habitat map of the Wadden Sea and layout of the sheets with numbering.

has compiled ecological literature and unpublished data in a series of handbooks on the ecology of the Wadden Sea.[1–12] The working group was under the leadership, initially of the late Dr J. Verwey, and then the late Prof. Dr J. J. Zijlstra, both directors of the Netherlands Institute for Sea Research, Texel. The aim of the working group was to achieve better conservation and management of the Wadden Sea and the various islands.

For a coherent characterization of the landscapes and environmental types, a mere compilation of the basic information was not considered sufficient. An analysis and integrated presentation were required, presenting in one document the overall spatial distribution of the landscapes and the environmental types of the Wadden Sea. Two different outline maps at a scale of 1 : 100 000 were prepared. The first is a vegetation map of the terrestrial zones, including the sand dunes and salt marshes of the barrier islands and mainland coastal areas.[12–14] The second map includes the habitats of the intertidal zones within the Wadden Sea and—overlapping with the first map—the salt marshes.[15] This habitat map (Fig. 1) will be discussed in this paper.

The aims of these outline maps are: first, to demonstrate the ecological–geographical coherence of the area; second, to give an ecological–geographical background for research, management planning and environmental impact studies; and third, to make it possible to estimate the range of ecological processes in the Wadden Sea.

The habitat map of the Wadden Sea includes 24 coloured sheets and an explanatory text, which are presented in the form of an atlas. The atlas is published by the Research Institute for Nature Management and the Veth Foundation, Texel, The Netherlands.

2 THE NW-EUROPEAN WADDEN SEA

The Wadden Sea is a shallow coastal sea some 450 km long, bordering the northern and western coasts of The Netherlands, Germany and Denmark (Table 1, Fig. 2). An island barrier consisting of 23 islands with sand dunes and 14 elevated sandy areas without dunes separates this largest estuarine area of Europe from the southeastern North Sea. Over 35 tidal inlets experience tides with an amplitude between 1 and 4 m. The Wadden Sea is the most important nursery area for North Sea fishes and shrimps.[1] Two-thirds of the tidal area is exposed during low tide, and form an important food resource for millions of migrating waterfowl from the East Atlantic flyway.[5] The intertidal area is fringed by the largest continuous system of salt marshes in Europe.[16]

TABLE 1
Aerial Extent of the More Important Landscape Types in the Countries around the Wadden Sea

	Total Wadden Sea area		*Salt marshes and summer polders (part of 1 and 2)* (km^2)
	Islands (1) (km^2)	*Wadden Sea (2)* (km^2)	
The Netherlands	385	2500	85
Niedersachsen, Bremen and Hamburg (Germany)	155	2100	120
Schleswig–Holstein (Germany)	280	2500	70
Denmark	165	850	80
Total	985	7950	355

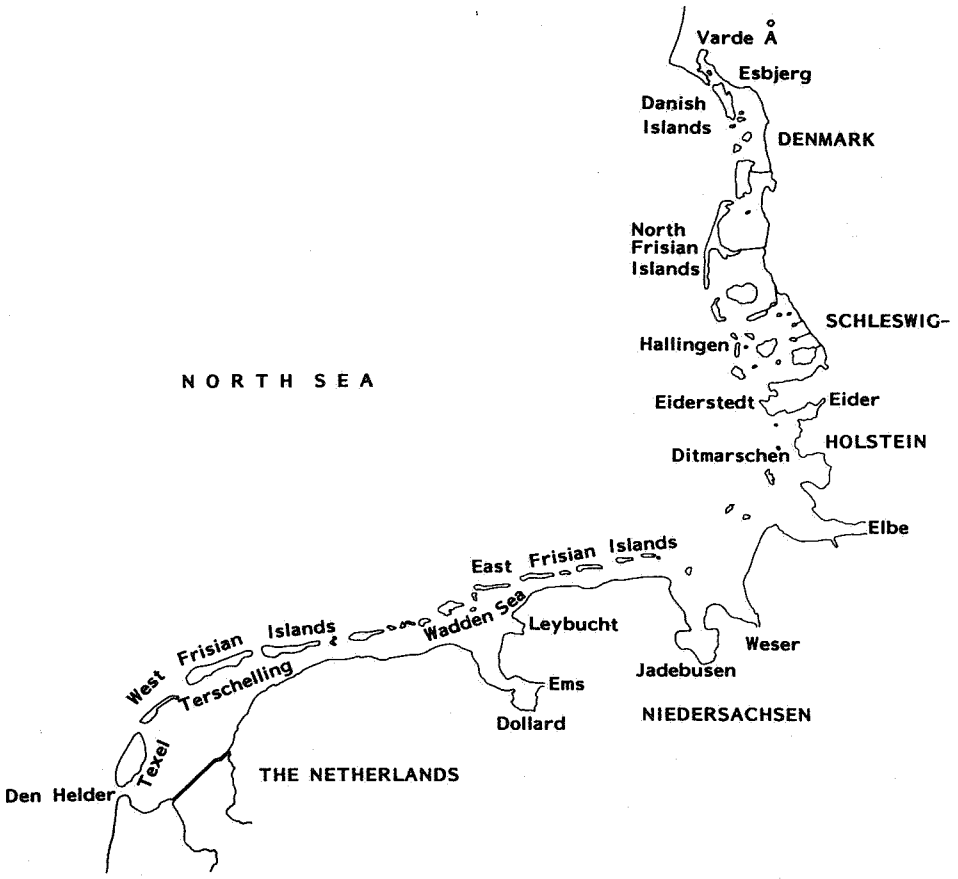

Fig. 2. The Netherlands, German and Danish Wadden Sea.

3 MAPPING PROCEDURE

An overall picture of the entire Wadden Sea is only possible on a small scale, in this case 1:100 000. Local patterns are obscured on a map at this scale, but the main trends of landscape development through the spatial patterns of the habitat types are more clearly visible. Due to the base material used, the habitat map represents the situation of the Wadden Sea at the end of the 1970s. Therefore, some recent reclamations (Tøndermarsken, Nordstrander Bucht) are not included.

The habitat map was prepared in the following way. First, there was the assembly of existing bathymetric, ordnance survey, sediment, and biological maps, and also aerial photographs. Each sheet of the habitat map cites the source of data. Because of the spatial extent of the area, embracing three countries, material with a wide variation in quality had to be processed. Bathymetric maps at scales varying between 1:10 000 and 1:25 000 for the most part represent 1970s sources.[17,18] Sediment maps for The Netherlands and Niedersachsen at scales 1:25 000 to 1:200 000 are similarly derived (e.g. Refs 19 and 20). For Schleswig–Holstein, the data, dates and scales of the sediment maps vary from between the Second World War and 1981, and from 1:25 000 to 1:700 000 (e.g. Refs 21 and 22). The only sediment map based on satellite imagery is from the Danish Wadden Sea[23] (1:350 000), but the map is not perfect and the data need further refinement. Recent biological maps of larger intertidal areas are only available for Niedersachsen (from the Forschungsstelle Küste, Norderney). Information on seagrasses has been collected from other sources, of which Michaelis *et al.*[24] and Völkl *et al.*[25] are the most complete. Salt marshes have been taken from the terrestrial outline map.[14] Isohalines in the estuaries are from the literature (Refs 26 and 27 for the Ems, Refs 28 and 29 for the Weser, Refs 30 and 31 for the Elbe, Refs 32 and 33 for the Eider, and Ref. 34 for the Varde A). Tidal data are from the Rijkswaterstaat and the Deutsches Hydrographisches Institut. Aerial photographs used are paperprints of black and white panchromatic vertical images at scales 1:15 000 to 1:40 000, with stereo overlap and black and white panchromatic mosaics at scales 1:25 000 to 1:60 000.

Second, there was integration of data on elevation and sediments on to a new base map. In order to ensure consistency of the boundaries between the map units covering the entire area, immersion periods were calculated from tidal curves and added to the bathymetric source maps. The various sediment types were embodied in one simple classification. In the next step, the new legend units were integrated into six habitat types (Table 2), and a new base map was compiled.

TABLE 2
Integration of Emersion Time and Sediment Composition into Six Habitat Types

	Low intertidal flats (<50% emersion time)	*High intertidal flats (>50% emersion time)*
Sand (<5% clay)	sl	sh
Muddy sand (5–8% clay)	xl	xh
Mud (>8% clay)	ml	mh

Third, systematic interpretation of the aerial photographs was carried out using a mirror stereoscope to add high energy areas (megaripples), mussel beds, and salt marshes to the base map. From the black and white imagery, and the wide variation in the data used, it is not possible to distinguish more than six habitat types, as was achieved by Botzen[35] for the Netherlands Wadden Sea, and by Michaelis[36] for the Jadebusen (the latter being based on false-colour photographs). For example, the dark colours on the photographs used in this study are better correlated to the water content than to the mud content of the tidal flats. The smallest unit that can be included in the final map is some 2 mm × 5 mm. At a map scale of 1:100 000, this is equivalent to 200 m × 500 m (10 ha) in the field. For groundtruth, the source references have been used, as well as flights over the area and observations in selected areas. Finally, the distribution of seagrasses, some topographical features, and the isohalines were transferred to the base map.

The habitat map has served as a model for an ecological base map of the Netherlands Wadden Sea, as a basis for combatting oil pollution.[37,38] This ecological base map is at a scale 1:50 000 and is designed for use in the field. The map is based on the same integration of data as described above for the habitat map. The distribution of resting, feeding, and breeding birds, and of resting seals, has been added. The ecological base map combines the ecological values of the Wadden Sea with the accessibility of the area in respect of combatting oil pollution.

4 ELEMENTS OF THE HABITAT MAP

The legend of the habitat map consists of 19 abiotic and 9 biotic types (Fig. 1). Because of the dynamic character of the Wadden Sea, and the lack of recent data on the distribution of benthic organisms, the habitat map has been based on an integration of the two most important

TABLE 3
Principal Zonation of the Wadden Sea, Related to the Daily Tidal Cycle and Compared with the Legend Units of the Habitat Map

Zones relative to the daily tidal cycle	*Biotic zones*	*Legend units*
Terrestrial zone above Mean High Tide	Supralittoral	* beach * salt- and brackish marsh zones
Intertidal flats	Littoral	* salt-marsh pioneers * 3 tidal flats zones * 3 sediment types * seagrass beds (2 species) * mussel beds
Permanent water bodies below Mean Low Tide	Sublittoral	* subtidal flats * tidal channels (larger ones marked by the −10 m depth line)

environmental factors, namely emersion time and sediment composition. Such a map enables one to identify which organisms might be expected to occur. Clearly visible communities of organisms have been added to the map. Attention has been paid to the apparent boundaries of various organisms: isohalines (Venice system) in the estuaries, sluices, coastal cliffs, sedimentation fields, stone revetments, sand-dykes, and seawalls. High energy areas (megaripples and sand waves)[39,40] have been included, since they are important for sand transport and are poor in benthic organisms. From the spatial patterns of the habitat types on the map, an overall zonation, related to the daily tidal cycle, can be made for the Wadden Sea and the outer deltas (Table 3); and this includes supralittoral, littoral, and sublittoral zones.

The sediment classification has been simplified after Sindowsky,[41,42] into three types: sand, muddy sand, and mud. The limiting values are mostly at 5 and 8% clay particles ($<2 \times 10^{-6}$ m), but silt and sand may also form part of the classification. Most other sediment classifications could easily be transformed to this scale (e.g. Ref. 43), and most biological publications on the Wadden Sea use a comparable division. Sindowsky also gives a simple field scale, which points to the clear differences between these sediment types (Table 4).

TABLE 4
Simplified Sediment Classification for the Habitat Map (Adapted from Sindowski[40,41])

Sediment type	*Grain size distribution*			*Field scale*	
	% clay (<2)	*% silt (2–63)*	*% sand (>63)*	*Surface*	*Footprints*
Sand	0–5	0–10	100–90	Rough	Negligible
Muddy sand (mixed sed.)	0–8	0–50	95–42	Slightly slippery	To the knuckles
Mud	8–75	0–92	92–0	Silky, shining	Deep

5 RELEVANCE OF THE HABITAT MAP FOR BENTHIC ORGANISMS

The limiting values within the legend units, relating to emersion time and sediment state, are based on the ecological amplitudes of benthic plants and animals in literature.[21,34,36,44–66]

The highest values for biomass and the number of species of benthic animals occur at average values for emersion time and sediment condition.[54,62] This is due to the wide niches of most benthic organisms in the littoral zone, a strategy designed to survive the harsh environment. Therefore, a wide overlap exists in the environmental requirements of these benthic animals; while overlap is of course mostly found at the average values.[62]

More specific reasons for the position of selected limits based on emersion time are:

—An emersion time of 50% is the upper limit for an optimal growth of benthic animals called suspension feeders, and which filter suspended food from the overlying water; like the bivalves *Cerastoderma edule* (cockle), *Mya arenaria* (sandgaper), and *Mytilus edulis* (blue mussel). They can occur up to the 67% boundary.

—An emersion time of 50% is roughly the lower limit for optimal light conditions for benthic diatoms in the winter months, and for the seagrass *Zostera noltii*; *Zostera marina* grows mixed with *Zostera noltii* or alone lower in the littoral zone.

—In higher parts of the littoral zone (67% emersion time is an arbitrary lower limit for this zone), higher densities of juveniles of several benthic animals like *Arenicola marina* (lugworm),

Cerastoderma edule, Mya arenaria, Mytilus edulis, Macoma balthica (Baltic tellin), and *Nereis diversicolor* (ragworm) occur, because the predation pressure is low compared to that at the lower intertidal flats. Moreover, *Hydrobia ulvae* (laver spire shell) and other small benthic animals occur in these higher edge zones.

—Benthic animals that search sediment for food, known as deposit feeders, are more equally distributed in relation to emersion time; examples would be the polychaetes *Arenicola marina, Heteromastus filiformis, Pygospio elegans,* and *Scoloplos armiger,* the amphipod *Corophium volutator,* and the bivalves *Macoma balthica* (again a suspension feeder) and *Scrobicularia plana.*

—Suspension feeders are more important for biomass than deposit feeders; hence the highest biomass figures are found between some 25% and 60% emersion time. [54,67]

Sediment type is no longer considered the only important factor for the distribution and abundance of benthic animals.[62,68–70] Sediment type is obviously important for the availability of food for deposit feeders, and for the potential of benthic animals to build tubes or burrows. Indirectly, however, the sediment type is an expression of, among other things, the exposure to tidal currents and waves (note the megaripples marked on the habitat map) and the availability of food in the overlying water for suspension feeders. More specific distribution patterns[62] are exemplified by the bivalve *Angulus tenuis,* amphipods *Bathyporeia* sp., and the polychaete *Scolelepis squamata,* found in coarse sandy sediments in exposed areas far offshore; *Corophium volutator, Hydrobia ulvae, Mya arenaria,* and *Nereis diversicolor* in sheltered areas within 2–4 km of the coast; the polychaetes *Nephtys hombergii* and *Scoloplos armiger* and the amphipod *Urothoe grimaldii poseidonis* found in sandy sediments; *Arenicola marina* in sand and muddy sand, *Cerastoderma edule* in muddy sand; *Scrobicularia plana* in muddy sand and mud; and *Heteromastis filiformis,* also in muddy sediments.

The highest biomass figures for benthic fauna are limited to mussel and cockle beds (over 100 g ash-free dryweight m^{-2}); low biomass figures (less than 10 g m^{-2}) are found in coarse sandy sediments in exposed areas far from the coast and along the major tidal channels; while higher than average biomass figures are found in sandy sediments which are not too coarse or too silty.[67]

6 LARGE-SCALE VARIATIONS IN THE BARRIER ISLANDS AND COASTAL PLAIN

The morphology of sedimentary coastal areas is determined by the interaction of several processes, of which tidal range has the greatest

effect in determining the large-scale patterns in geomorphology. The coastal-plain shorelines of the world can be categorized as follows[71,72] (according to wave energy level, there is some variation in the tidal range limits). First, in the case of microtidal shores (tidal range some 0–1 m), these are shaped by wave action and storm deposits, leading to an almost continuous barrier system with lagoons or river deltas. Their distribution in western Europe includes Denmark (except for the Wadden Sea), the southern Baltic, southern England, and the Mediterranean countries. Second, with mesotidal shores (tidal range some 1–3·5 m), a significant amount of the sedimentary material is deposited by tidal currents, leading to a chain of barrier islands with tidal inlets, tidal flats and salt marshes. Examples exist in western Europe: for example, western Iceland, northern Norway, the Danish, German and Netherlands Wadden Sea, the north Norfolk coast, Les Landes in France, and Faro in Portugal. Thirdly, there are macrotidal shores (tidal range in excess of 3·5 m), and these are dominated by tidal current deposition with an orientation perpendicular to the coast. There is no protecting barrier chain; tidal flats and salt marshes are important forms. Their distribution in western Europe includes the Elbe, Weser, Solway Firth, Bristol Channel, Thames, the Wash, the Western Scheldt, northern France, the 'Havres' in Normandy, the Bay of Mont St Michel, Gironde, Tejo, and Sado.

The large-scale morphologic variations in the barrier system of the Wadden Sea are more easily understood in the context of tidal range. The islands and high sands are both elements of a barrier system which extends along the entire southern North Sea coast from northern France to northern Denmark. Along the microtidal western Netherlands coast, this system extends as a continuous barrier, from the Rhine estuary as far as Den Helder. The tidal range increases to the mesotidal type (1·4–3·0 m) in an easterly direction, and the barrier develops into the chain of West and East Frisian islands, which progressively become shorter to the east. Towards the inner German Bight (with a tidal range in excess of 3·0 m), the barrier chain is replaced by a series of high sandy areas, wide-mouthed estuaries, and tidal inlets, which are characteristic of a macrotidal coast. North of the mainland sand dunes of Eiderstedt, the decreasing tidal range (3·0–1·4 m) is again accompanied by a mesotidal barrier chain: the North Frisian and Danish Islands. North of Blavandshuk, where tides are small (1·4–0·5 m), a continuous barrier is found in the form of a lagoon coast.

The positions of the Pleistocene substratum, or Pleistocene outcrops consisting of boulder-clay, have a large share in determining the topography of the barrier system and thus of the entire Wadden Sea

area. Such points are the barrier island of Texel, the Borkumriff, the barrier islands of Amrum and Sylt, and the Horns Rev in front of Blavandshuk.

The mainland coastal plain is highly cultivated and consists of polders (embanked salt marshes) followed by peat and elevated Pleistocene landscapes. In one area (the Schwimmendes Moor in the southeastern Jadebusen), the peat actually borders on a salt marsh. The Dollard, Leybucht, and Jadebusen have developed as a result of past encroachments of the sea. All the other bights have since been embanked. Transitions from Pleistocene to tidal landscapes are found on the former island of Wieringen, in the Jadebusen, south of Cuxhaven, north of Husum, between Højer and Ballum, and north of Esbjerg. In the North Frisian Wadden Sea, a Pleistocene island (Föhr) and two polder islands (Pellworm and Nordstrand) occur, remnants of land flooded in the Middle Ages.[73] The mainland coast is interrupted by the estuaries of the rivers Ems, Weser, Elbe, Eider, and Varde A.

7 LARGE-SCALE VARIATIONS IN THE INTERTIDAL HABITATS AND SALT MARSHES

The transition from the barrier islands and the mainland coast to the intertidal flats is formed by a fringe of salt marshes and locally by summer polders (salt marshes protected by low dykes against low summer floods). The Netherlands western Wadden Sea is different, in that it has a very low share of salt marshes, 0·3% compared to about 4·5% in the remaining Wadded Sea. Inside the North Frisian Wadden Sea, several very characteristic 'Halligen' (small salt-marsh islands formed at the sites of formerly flooded areas) occur. The Halligen suffered significant recession, and are presently protected by stone revetments. Comparable to the Halligen are the islands of Jordsand, Helmsand, Griend as well as the Punt van Reide peninsula.

The intertidal habitats display an important zonation from the tidal inlets towards the coast and the tidal divides. This zonation is expressed by the occurrence of megaripples, muddy sand- and mud flats, and salt marshes. The flood and ebb deltas inside and outside the tidal inlets are the most dynamic parts of the Wadden Sea, as demonstrated by the presence of megaripples. The inner areas, towards the mainland coast and the tidal divides are more stable. Most of the muddy sandflats, mud flats, and salt marshes are located there.

Special environmental conditions are found in the inner estuaries and the few embayments which are left. Due to the shelter, and to silt

accumulation,[9] the most extensive mud flats and marshes of the Wadden sea are located there. Moreover, a salinity gradient causes special benthic communities in the estuaries.[29,30,49,68,74]

A major difference can be seen between the Netherlands western Wadden Sea and the remainder of its area. West of the Terschelling tidal divide, emerging flats comprize 30%, as compared to some 70% in the remainder of the Wadden Sea. A low proportion of emerging flats is also found in the Lister Dyb tidal basin. In addition, the tidal flats west of the Terschelling tidal divide are poorer in fine sediments compared to the rest of the Wadden Sea.[43] A larger proportion of sand flats is also found in Dithmarschen.

8 CONSPICUOUS BIOTIC STRUCTURES

Mussel beds occur in the lower part of the littoral tidal zone, mostly along the larger tidal channels or at the extremities of smaller tidal gullies. A sufficient supply of food and limited exposure to tidal currents and waves seem to be the most favourable conditions for littoral mussel beds. Sublittoral mussel beds and mussels on culture plots (also sublittoral) play an important role,[75,76] but these are not indicated on the habitat map. The abundance of mussels belies considerable fluctuations because of storms, ice and fishing, though the general pattern of distribution is fairly constant over several years.[77]

The most striking distribution concerns the littoral seagrasses: almost nil in The Netherlands and Dithmarschen, far more in Niedersachsen and Denmark, and clearly abundant in the North Frisian Wadden Sea. Both seagrass species occur predominantly in the upper part of the tidal zone. The present boundary between what might be described as 'the rareness of seagrasses in The Netherlands and the abundancy in Germany' is abrupt in the Ems estuary (the State border!) and is yet to be explained. These phenomena are being studied in relation to the environmental factors, and will eventually be published. Sublittoral seagrasses were observed up until 1932 in the Netherlands western Wadden Sea,[78] in the Norderaue near Föhr, in the Königshafen near Sylt, and in the Ho Bucht and the Varde A estuary in Denmark.[79] They disappeared after the outbreak of the 'wasting disease' in 1932.

The salt and brackish marshes occur as four zones, based on elevation.[10,16] Barrier island salt marshes in the main have a natural morphology, with creek levees and basins; and a thin cover of clay-present layers, starting from a former sandy beach plain. The sediment layer of the mainland salt marshes is more clayish, and of a greater thickness. Most mainland salt marshes are man-made, with the

help of sedimentation fields and open field drains. On the mainland salt marshes, *Halimione portulacoides* (creek levees due to artificial draining), *Puccinellia maritima* (grazing), and *Aster tripolium* (clayish soil) are characteristic, and on the barrier-islands *Limonium vulgare* (basins) and *Elymus pycnanthus* (less grazing, sandy soil). The North Frisian Halligen take up an intermediate position as far as the morphology and the vegetation are concerned. On the larger Halligen, and on some extensive mainland marshes, the construction of summer dykes led to impoverishment of the specific halophytic vegetation (high-marsh type 4). Transition to sand dunes can have a relatively high species diversity (transition type 5). A gradient according to the decreasing salinity in estuaries causes special brackish marsh communities, e.g. the reed–marsh type 6.

9 REGIONAL SUBDIVISION OF THE WADDEN SEA

Based on the large-scale variations on the habitat map, the Wadden Sea can be subdivided into eight regions. These regions differ in the importance of the barrier system as related to tidal range, the proportion of emerging flats, the exposure to wave action, sediment composition, the distribution of seagrasses and salt marshes, and the occurrence of islands within the area (Table 5, Fig. 1). Based on numbers of fish species, a comparable division of the Wadden Sea was formed.[80] The eight regions are:

1. The Netherlands western Wadden Sea from Den Helder to the Terschelling tidal divide (maps 1–4).
2. The Netherlands eastern Wadden Sea between the Terschelling tidal divide and the Ems estuary (maps 5–7).
3. The East Frisian Wadden Sea between the Ems estuary and the Jade (maps 8 and 10–12).
4. Embayments of the Dollard estuary, the Jadebusen (saline), the inner Weser estuary, and the inner Elbe estuary (maps 9, 13 and 16 east).
5. The macrotidal Wadden Sea of Butjadingen and Wursten between the Jade and the Elbe estuary (maps 14 and 15).
6. The macrotidal Wadden Sea of Dithmarschen between the Elbe estuary and the Eider estuary (maps 16 west, 17 and 18 south).
7. The North Frisian Wadden Sea from Eiderstedt to the Hindenburgdam (maps 18 north–21).
8. The Danish Wadden Sea from the Hindenburgdam to the Varde A estuary (maps 22–24).

TABLE 5

Regional Subdivision of the Wadden Sea. Description of the Eight Regions in the Text

Region	*Maps*	*Mean tidal range in m*	*Barrier system*	*Emerging flats*	*Exposition*	*Sandy sediments*	*Sea-grasses*	*Salt marshes*	*Halligen*
1	1–4	1·4–1·8	***	*	***	***	*	*	*
2	5–7	1·8–2·6	***	***	**	**	*	**	—
3	8, 10–12	2·3–3·0	***	***	**	**	**	**	—
4	9, 13, 16E	3·0–3·8	—	***	*	*	*	**	*
5	14, 15	3·0–3·5	*	***	***	**	**	**	—
6	16W–18S	3·0–3·5	*	***	***	***	—	**	*
7	18N–21	3·5–2·0	**	***	**	**	***	**	***
8	22–24	1·8–1·4	***	***	**	**	**	***	*

* Less than average.
** Average.
*** More than average.
— Not occurring.

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EDITOR'S NOTE

Two sample maps, albeit in black and white only, are reproduced from the *Habitats of the Netherlands, German and Danish Wadden Sea* publication produced by the Research Institute for Nature Management, Texel and the Veth Foundation, Leiden, The Netherlands. They appear at the end of this paper.

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(Appendix overleaf)

APPENDIX

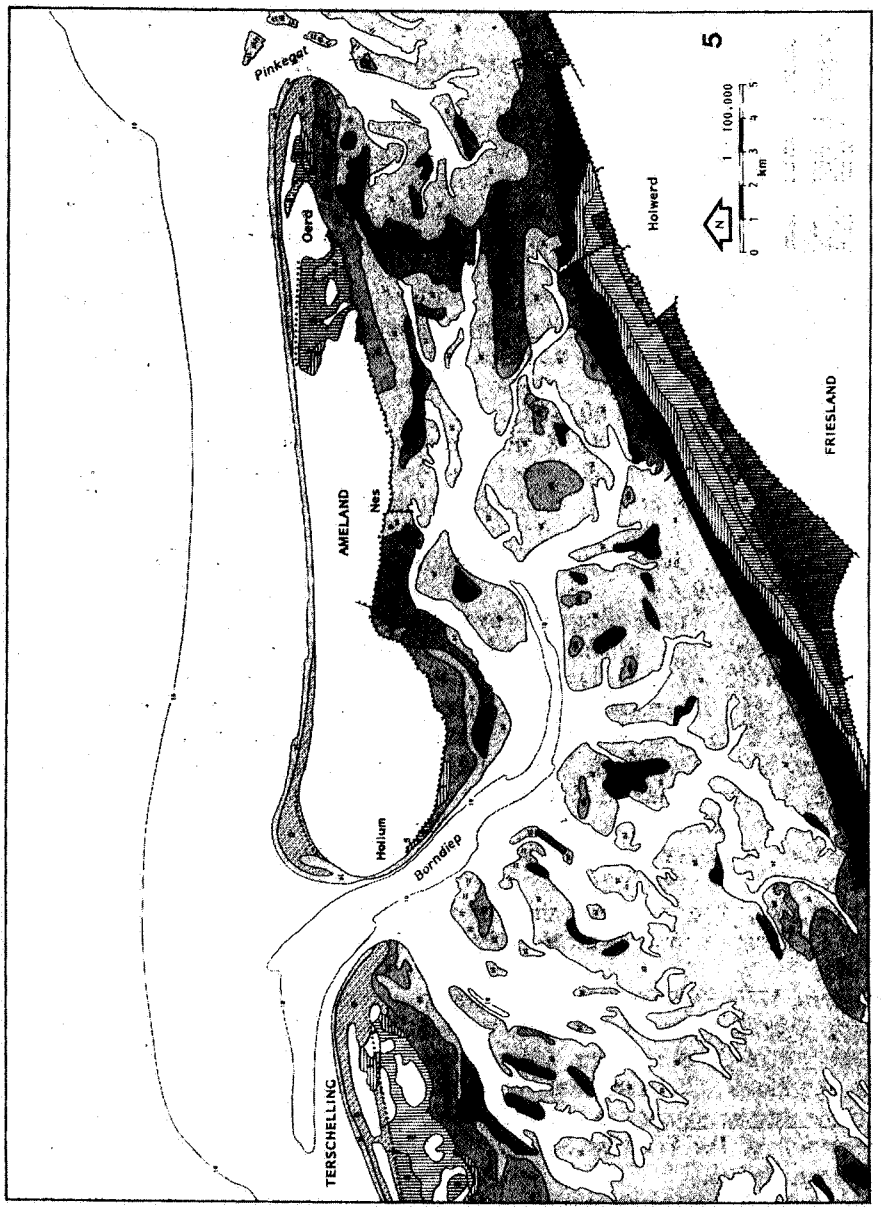

Fig. A1. Example of the habitat map, sheet number 5.

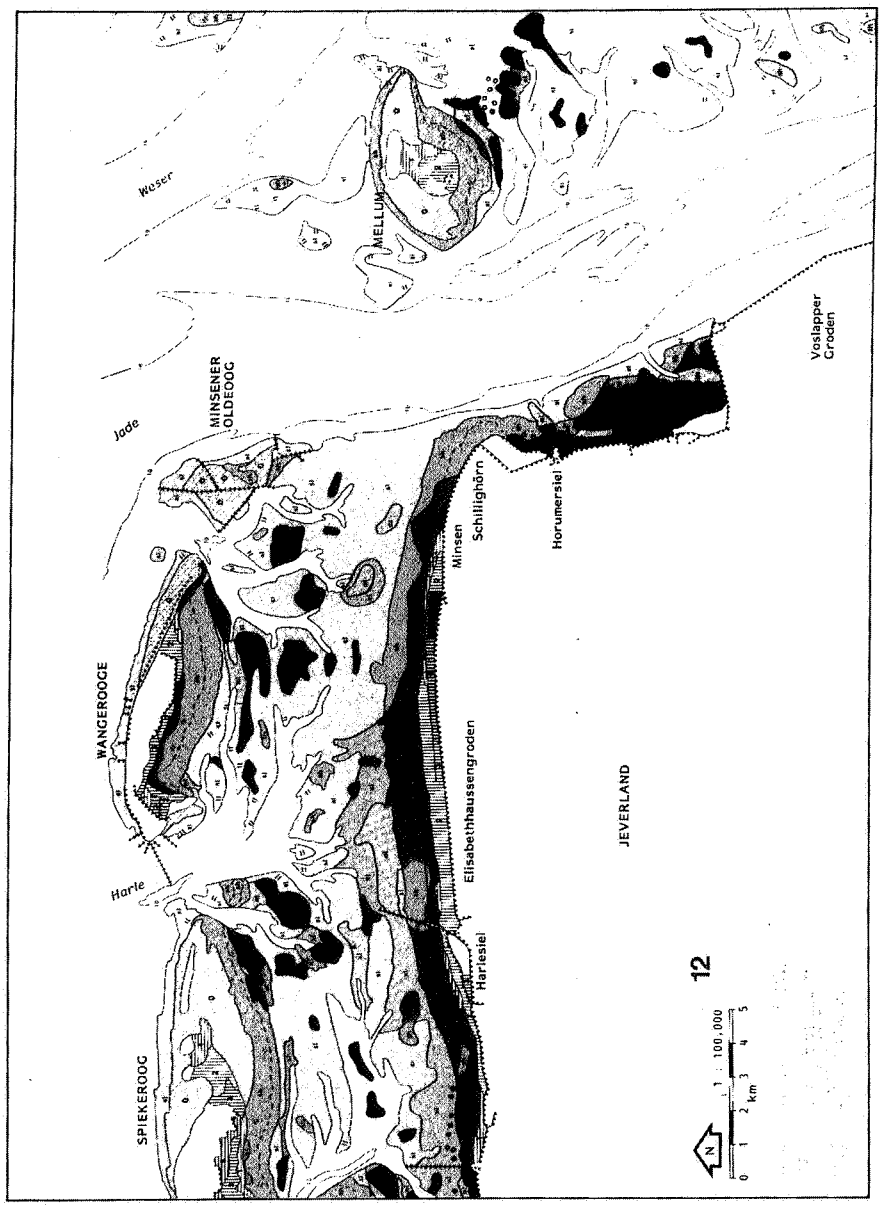

Fig. A2. Example of the habitat map, sheet number 12.