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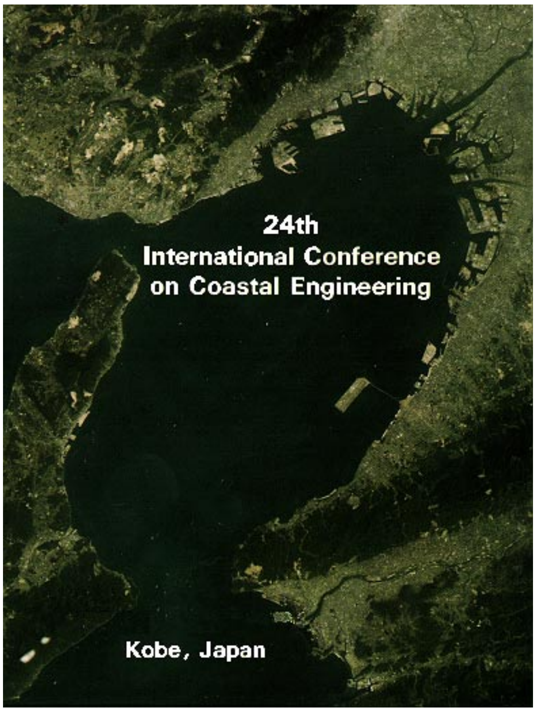

Hanz D. Niemeyer

LONG-TERM MORPHODYNAMICAL DEVELOPMENT OF THE EAST FRISIAN ISLANDS AND COAST

Niedersachsen

LONG-TERM MORPHODYNAMICAL DEVELOPMENT OF THE EAST FRISIAN ISLANDS AND COAST

Hanz D. Niemeyer[1]

Abstract

The morphology of the East Frisian Islands and Coast has experienced enormous changes in the course of the last centuries. The resedimentation of medieval sturm bays has played a dominant role within these morphodynamical processes which could no longer only be credited to the impacts of littoral drift. Reconstructions of former coastal morphology have been used to quantify the long-term development of significant parameters for the tidal basins of the East Frisian Wadden Sea. Additionally also the tidal volumes for situations since 1650 could be determined. On this basis the long-term stability of common empirical relationships was checked.

Introduction

The East Frisian Islands and Coast are part of the Frisian Wadden Sea which ranges from the eastern part of the Dutch across the German to the southern part of the Danish North Sea coast (fig. 1) and consist of a chain of seven barrier islands separated by tidal inlets from each other through which the tidal basins with intertidal areas and supratidal salt marshes are filled and emptied during each tidal cycle. The tidal range is about 2,5 m and the yearly mean offshore significant wave height is about 0,7 to 1,0 m. It is therefore a mixed energy tide-dominated coast according to the classification of HAYES [1975]. The littoral drift is predominantly eastward directed.

The East Frisian Islands and Coast have been performed at the end of the holocene transgression [KRÜGER 1911; LÜDERS 1951; STREIF 1990] and have experienced enormous morphological changes since then. Though no detailed information is available for that time firstly a superposition of human impacts on this natural development is expected to have been effective when the mainland coast was closed consecutively against the sea by constructing sea dykes since the beginning of this millenium [HOMEIER 1969]. Later on and particularly for the last 350 years the morphological behaviour of the East Frisian Islands and Coast is well documented by the horizontal position of the morphologically represantative markers tidal low and high water lines, dune foot and border lines of supratidal salt marshes [HOMEIER 1962]. Additionally there is even information with lesser accuracy on certain areas available concerning situations until more than 600 years ago (fig. 2). The migration of tidal inlets and barrier islands

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has been superimposed interactively by further large scale human impacts interferring with the natural processes. In the course of the last centuries the two most important ones have were:

1. Artificial acceleration of resedimentation of the medevial storm surge bays at the mainland coast in respect of land reclamation and afterwards consecutively executed partial enclosures of these areas by dyking.

2. The fixation of the four migrating ones of the six tidal inlets separating the East Frisian barrier islands since the middle of the 18th century in order to protect there developing holiday and health resorts.

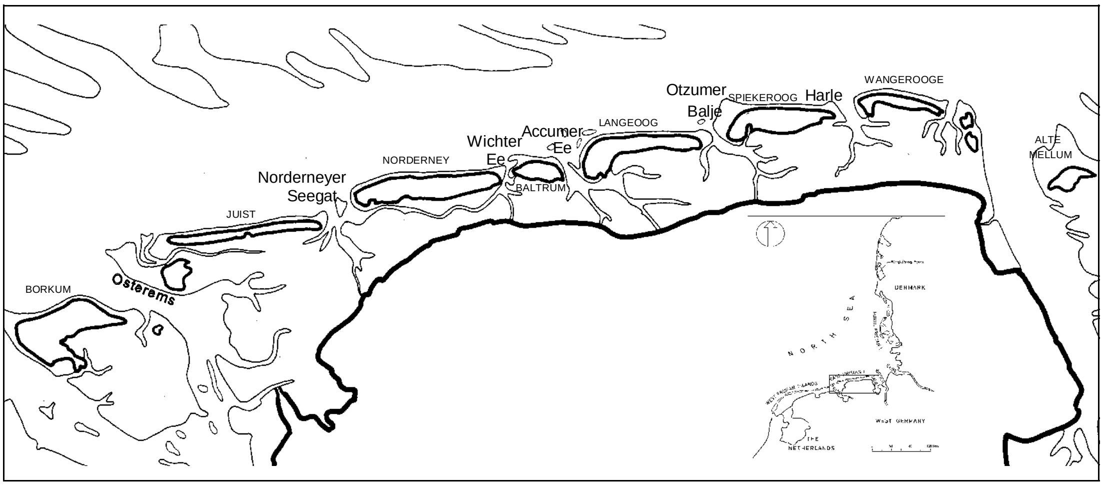


Figure 1. East Frisian Islands and Coast with inserted overview of the North Sea

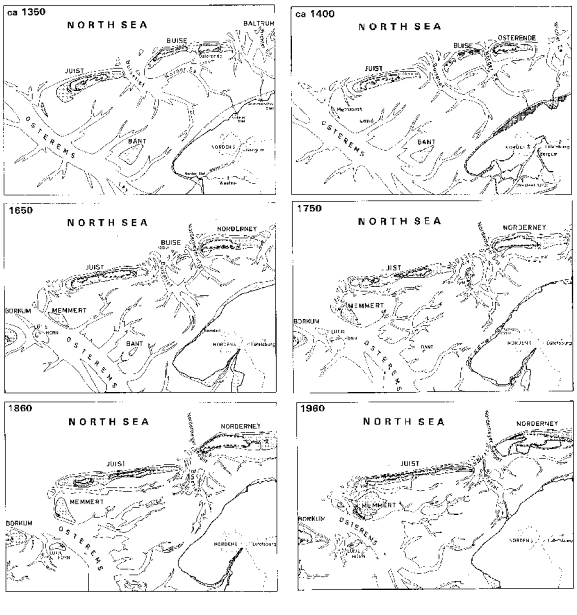


Figure 2. Reconstruction of the western East Frisian Wadden Sea since 1350 by HOMEIER [1964]

These large scale morphodynamical processes have mainly taken place in the western and eastern part of the East Frisian Wadden Sea whereas the tidal inlet Accumer Ee and its basin in the central part have remained rather stable in the course of the recent centuries. Beside geological boundary conditions it is also remarkable that in this area no large storm surge bay was ever existent. A detailed knowledge about the background of these developments is of high interest. Not only for improving backward directed process knowledge but also for the development of long-term prognostic tools like empirical morpho-dynamical models. In order to create a data basis for this purpose the charts containing historical reconstructions of coastal morpho-logy elaborated by HOMEIER [1962] and hydrographic charts have been transferred into a Geographical Information System (GIS) which is used as a database for further evaluation and parametrization.

Extension and enclosure of medevial storm surge bays

Ley Bay

The Ley Bay ever got its largest extension due to the erosional effects of the catastrophic storm surges of the 14th century and especially due to those of the "First Dyonysis Surge" in 1374 [HOMEIER 1972]. The storm surges in that time were very effective in respect of eroding the flooded areas after dyke failures as their soil consisted predominantly of very erodible peat. Due to that fact the losses of land to the sea were much higher than usual, the extension of the bay did afterwards not fit with the hydrodynamical boundary conditions in order to reestablish a morphodynamical equilibrium. This imbalance caused sedimentation leading to the rise of salt marshes at the borders of the bay supported and accelerated by interfering human reclamation works. These processes changed the system again resulting in further sedimentation [NIEMEYER 1984, 1991b]. The rise of salt marshes allowed a subsequent reclamation and partial enclosures of formerly lost areas (fig. 3). In the course of the centuries the areal extensions of the enclosures decreased until the beginning of this century. But in recent years the advanced tools then available in coastal engineering made even the dyking of intertidal flats possible and not only of those areas which had already reached the stage of supratidal salt marshes. These measures interfered with hydrodynamical-morphological interactions to a much higher extent than the dyking of salt marshes.

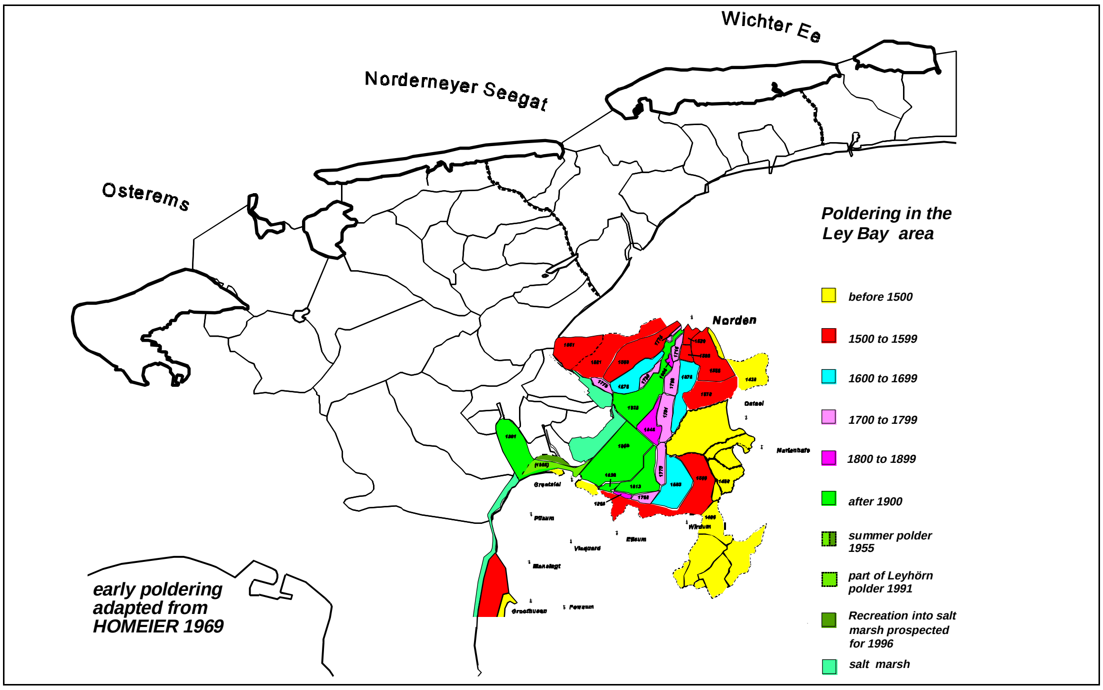
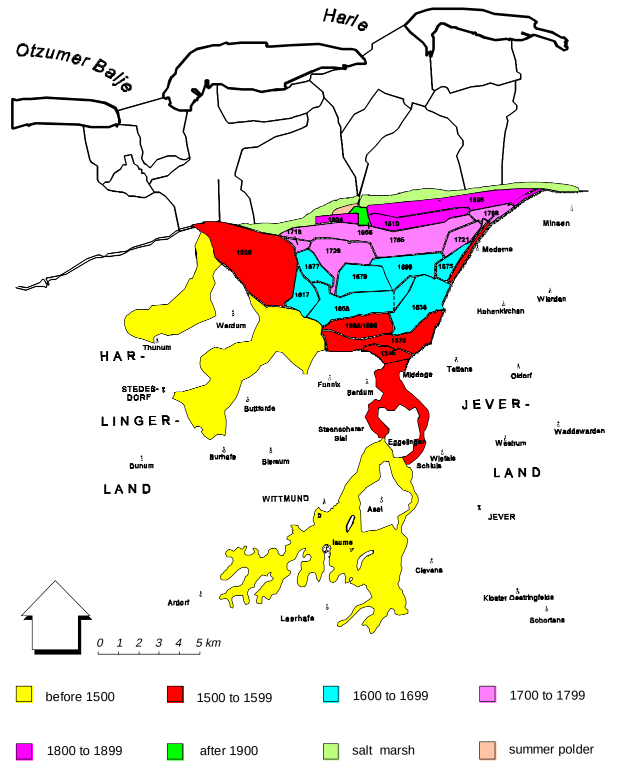


Figure 3. Partial enclosures of the Ley Bay during the last six centuries

Harle Bay

The Harle Bay already existed at the beginning of dyke construction at the end of the last century. It was silting up and the dyking of growing salt marshes is reported for the 12th and 13th century [HOMEIER 1969, 1979]. In the middle of the 14th century an unknown number of subsequently following storm surges caused the destruction of dyke lines and created erosion in the flooded areas. But the enlarged size of the tidal basin was not in tune with the dynamical equilibrium and in particular the higher intertidal areas silted up due to the absence of waves



Poldering of the Harle Bay (adapted from HOMEIER 1979)

Figure 4. Partial enclosures of the Harle Bay

with sufficient energy to prevent siltation and the subsequent growth of supratidal salt marshes. The nearly continuous silting up occured since then was followed by partial enclosures of the emerged supratidal salt marshes. More than 50% of the bay area had already been reclaimed at the end of the 16th century and two hundred years later only small remnants of the formerly large Harle Bay existed which mostly were reclaimed until the end of the 19th century. The Harle Bay had disappeared totally and a closed straight coastline was established (fig. 4).

Morphodynamical impacts of storm surge bay enclosures

General remarks

The enclosure of medevial storm surge bays has lead to the following consequences: reduction of basin area, of basin volume, of tidal basin volume and of ebb delta volume in order to provide the basin's requirements for sedimentation. All these changes provoked additionally changes of local wave climate in the basin leading to a further increase of sedimentation, resulting reduction of tidal volume and again sedimentation until a new equilibrium stage was achieved [NIEMEYER 1991b]. In areas where only small storm surge bays had been created as i. e. g. in the basin of the tidal inlet Accumer Ee in the central part of the East Frisian Wadden Sea (fig. 1) morphodynamical changes during the last centuries have been less dramatic than in those where storm surge bays performed a quantitatively remarkable part of the total basin area.

Western East Frisian Wadden Sea

In comparison to its present total area of about 334 km² the basin of the tidal inlet Osterems has experienced a remarkable reduction of about 100 km² since the 14th century due to the numerous partial enclosures (fig. 3). Surprisingly the total basin area has nearly remained unchanged since 1650 (tab. 1) whereas more than 40 km² have been reclaimed in the Ley Bay during that period (fig. 5). This development and the morphodynamical processes in the remaining parts of the offshore areas must have substantially interacted. A comparison of the situations of 1650 and 1960 using the historical maps evaluated by HOMEIER [1962] makes evident that the basin of the tidal inlet Osterems has compensated nearly all its losses by an eastward extension of its watershed against the basin of the tidal inlet Norderneyer Seegat which can probably be explained by the remarkly larger tidal volume of the Osterems tidal basin. This process cannot be explained due to the direction of the littoral drift, because the migration of the tidal inlet Osterems [HOMEIER & LUCK 1977; STEPHAN 1994] is counterdirectional. This development is in tune with the increase of relative area and respectively tidal volume in the eastern part of its basin which performs nowadays its largest subsystem. These facts indicate strongly that the morphodynamical processes due to the migragation of the tidal inlet Osterems (fig. 5) could be credited to the silting-up and consecutively reclamation by partial enclosures of the Ley Bay.

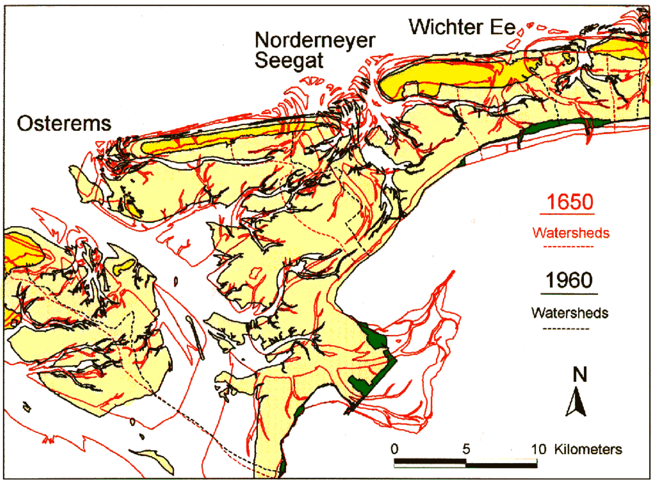


Figure 5. Morphological development of the tidal inlets Osterems, Norderneyer Seegat, Wichter Ee, of their basins and watersheds between 1650 and 1960 (reconstruction from HOMEIER [1962])

Indirectly also the eastern shift of the watershed between the Osterems and Norderneyer Seegat basins is remarkably influenced by that and not only a consequence of littoral drift. Even the migration of the tidal inlet Norderneyer Seegat must at least partly be regarded as a consequence of the consecutive reduction of the Ley Bay superimposing here littoral drift effects. This statement is contradictory to the qualitative migration models of LUCK [1977] for tidal inlets of the Norderneyer Seegat and Harle type basing on reconstructions of HOMEIER [1962, 1964] and being causually supplemented by NIEMEYER [1990] considering hydrodynamical impacts on ebb deltas and barrier islands. The explanation of migration processes by LUCK [1977] is still very useful in order to provide insight into processes which happened in the past but their cyclic character is doubtful due to regarding littoral drift as steering force of inlet migration. Considering the impact created by the areal reduction of the Ley Bay on primarily the shift of watershed between Osterems and Norderneyer Seegat basin and secondarily on the migration of the tidal inlet Norderneyer Seegat itself a continuation of inlet migration at the same scale could -even in the case of no human interference- not be expected because after the large areal reduction of the Ley Bay an important steering force has nearly disappeared.

The consequences of the migration of the Norderneyer Seegat for its ebb delta and respectively for the sediment balance on the beaches on the island of Norderney have been described as well as the measures to preserve the coast line and to combat erosion there [LUCK 1977; NIEMEYER 1990, 1991a; KUNZ 1991]. Moreover inlet migration and subsequent morphological changes have also had remarkable impacts on the adjacent mainland coastline [NIEMEYER 1990]: The gradual disappearance of the remnants of the former island of Buise and the reunification of the two inlets to a wider channel with wider spread swash bars in its ebb delta rendered as well possible the impact of higher wave energy up to the opposite mainland coast as the accompanying extension of sublittoral areas between the inlet and the coast (fig. 6). In 1650 there was a broad stretch of supratidal salt marshes in front of the mainland dykes. In 1750 the

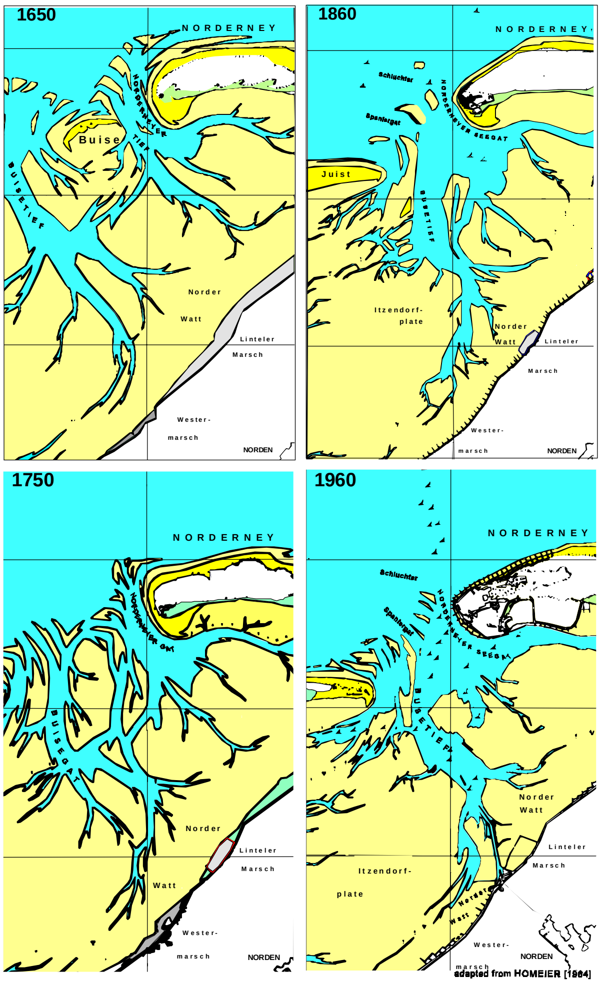


Figure 6. Impact of tidal inlet migration between Juist and Norderney in the period from 1650 to 1960 on the adjacent mainland coast (reconstruction from HOMEIER [1962]) ➔ polders

salt marshes in front of the mainland dyke of the Westermarsch had disappeared and a coastline retreat had become necessary after the dyke breaches during the storm surge of 1717. On the one hand the shadow effect of the remnants of the former island of Buise was no longer effective. On the other had the migration of the inlet channels and of their tributaries led to the superposition of wave systems entering via Buisegat and Norderneyer Gat from the North Sea into that coastal area. Easter of this area the salt marshes in front of the dyke of the Linteler Marsch must have been sufficiently stable in order to encourage people to build a polder. In 1860 the inlets Buisegat and Norder-neyer Gat merged to a one-inlet-system called Norderneyer Seegat. The consequences are primarily a less pro-nounced ebb delta with smaller shallows being spread wider. The higer concentration of tidal energy effects also a relative increase of sublitoral areas in the basin close to the inlet. Secondarily this allows in tune with the wider inlet the input of higher wave energy into the basin upto the mainland coast. Particularly the eastern part of the regarded area has lost shelter due to the morphological changes of the ebb delta and the inlet. The resulting effect is the total disappearance of salt marshes there and as well the des-truction of the 1750 already existing polder and of a second one which had been erected at the beginning of the 19th century. Both were flooded during the storm surge of 1825 and had afterwards to be abandoned. Starting about 1860 the tidal inlet was successfully fixed by the construction of groynes ranging across the eastern slope of its deep channel.

The areal losses of the Osterems tidal basin have been compensated by an eastward shift of its watershed at the cost of that one of the Norderneyer Seegat. The same process repeated itself in the interaction of the basins of the Norderneyer Seegat and of the Wichter Ee (fig. 5): Again the basin with the larger volume shifted the watershed between both remarkably into eastern direction between 1650 and 1860. The western shore of the island of Baltrum experienced in the same period enormous erosion and moved more than 4 km eastward. Since the eastern watershed of the Wichter Ee tidal basin did not shift to the same extent into eastern direction as the western one the basin area was enormously reduced (tab. 1). The differences in the eastward shift of the western and the eastern watershed of the Wichter Ee tidal basin indicate also the impact of the partial enclosures in the Ley Bay on the morphodynamical processes of the tidal inlets and basins in its eastern neighbourhood.

Eastern East Frisian Wadden Sea

Another example of subsequent consequences of the enclosure of a medevial storm surge bay becomes evident regarding the tremendous relative reduction of the basin area of the tidal inlet Harle since the middle of the 14th century due to the land reclamation in the area of the former Harle Bay leading finally to its total enclosure. The reduction of basin area and corresponding tidal volume initialized consequently as well a decrease of coss-sectional area and width of the tidal inlet as of the seaward extension and volume of the ebb delta (fig. 7). This process was accompanied by an eastward migration of the tidal inlet Harle, an erosion and retreat of the eastern shore of the island of Wangeroog, a remarkable eastward extension of the island of Spiekeroog and a corresponding shift of the watershed between the tidal basins of the Otzumer Balje and Harle, whereas the eastern watershed of the Harle tidal basin did not move remarkably within the same period. A comparable eastward shift of the latter one was probably impossible because the neighbouring Jade estuary with its much higher tidal volume and resulting kinetic energy hampered such a reaction. Since also the watershed between the basins of the Accumer Ee and Otzumer Balje has migrated easterly to a much lesser extent than that one between the Otzumer Balje and the Harle, the basin area of the latter one experiences a large reduction while the Otzumer Balje basin's area increases significantly. Correspondingly the island of Spiekeroog enlengthened by more than 4 km or more than 80 % (fig. 7).

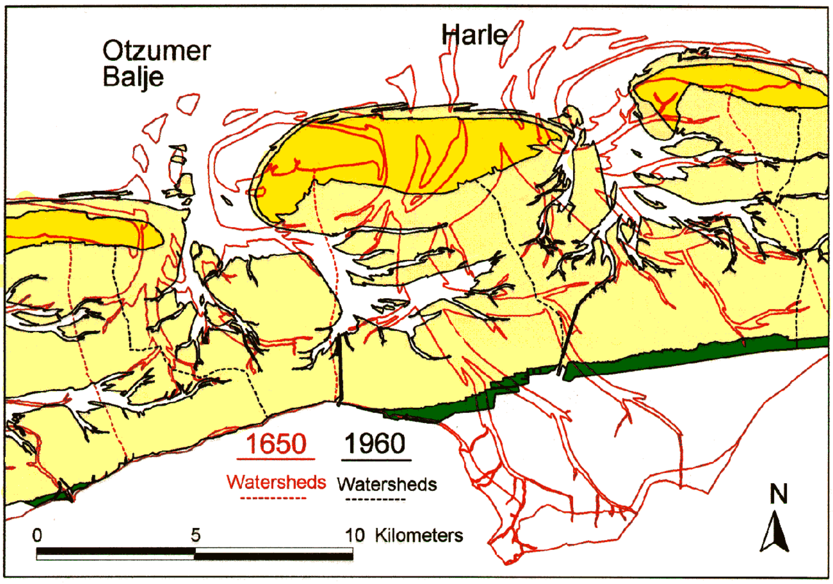


Figure 7. Morphological development of the tidal inlets Otzumer Balje and Harle, of their basins and watersheds between 1650 and 1960 (reconstruction from HOMEIER [1962])

This differences in inlet, ebb delta, island and migration are not explainable by littoral drift though not counterdirectional. But it is evident that the reduction of area and tidal volume of the Harle basin is intensively steered by the silting up of the Harle Bay. Therefore this must be regarded as the major steering impact for the enormous morphodynamical changes in this area.

Quanttittave change of characteristic basin parameters

Total basin areas A_b

The total area of the tidal basins in the East Frisian Wadden Sea experienced a reduction of more than 13 % between 1650 and 1860 and afterwards fluctuated around a value of 85 % of the 1650 existing area (fig.8, tab. 1). The losses must mainly be credited to the reduction of the

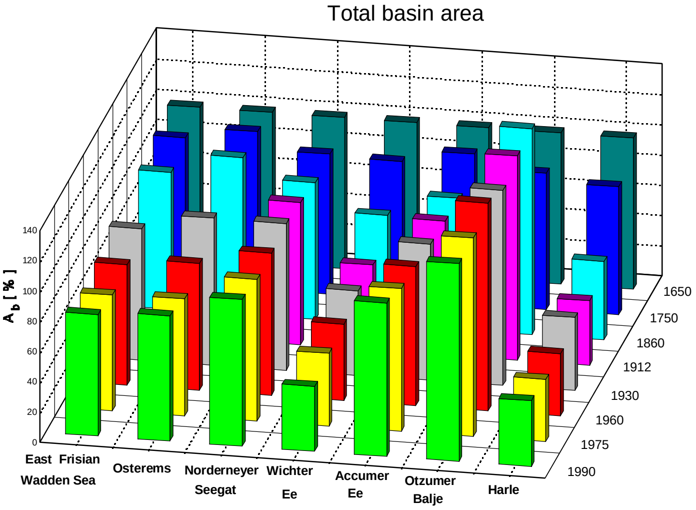


Figure 8. Relative development of total basin areas A_b (in percentages) in the East Frisian Wadden Sea

storm surge bays, particularly to that of Ley and Harle Bay with an reclaimed area of more than 80 km² during that period. Corresponding to the already described morphodynamical development of the western East Frisian Wadden Sea the basin areas of the Osterems and of the Norderneyer Seegat experienced maximal losses of about 10 % being later reduced to about 5 % whereas the basin area of the Wichter Ee was reduced by more than 55 % (fig. 8, tab. 1). The total reduction of the three basin areas is somewhat larger than the corresponding reduction of the Ley Bay between 1650 and 1960, but this could probably be explained by a phase shift of morphodynamical adaption to former silting up of bay areas.

		1650	**1750**	**1860**	**1912**	**1930**	**1960**	**1975**	**1990**
East Frisian Wadden Sea	A_b [$10^6 \cdot m^2$]	835,00	806,37	755,54		723,83	666,28	637,72	669,54
	A_b [%]	100,00	96,57	90,48		86,68	79,79	76,37	80,18
Osterems		358,32	372,76	371,70		348,26	301,20	276,52	296,22
		100,00	104,03	103,73		97,19	84,06	77,17	82,67
Norderneyer Seegat		109,83	101,79	99,31	103,44	106,50	103,28	102,70	106,47
		100,00	92,67	90,42	94,18	96,96	94,04	93,51	96,94
Wichter Ee		53,93	49,16	38,93	30,27	30,10	27,20	25,93	23,09
		100,00	91,17	72,20	56,13	55,82	50,43	48,08	42,82
Accumer Ee		100,21	99,69	87,01	88,88	90,20	92,25	94,30	101,54
		100,00	99,47	86,83	88,69	90,01	92,05	94,10	101,32
Otzumer Balje		56,90	51,29	77,53	76,82	73,50	78,17	74,57	74,47
		100,00	90,14	136,25	135,00	129,17	137,38	131,04	130,87
Harle		155,80	131,68	81,06	66,37	75,27	64,18	63,70	67,75
		100,00	84,52	52,03	42,60	48,31	41,20	40,89	43,49

Tab. 1 Total basin areas 1650 - 1990

The basin area of the Accumer Ee has remained in the same order of magnitude independently from the enormous morphodynamical developments both in the western and eastern neighbourhood of that area. In the eastern East Frisian Wadden Sea the tidal basin area of the Otzumer Balje increased by about 30 % between 1650 and 1960. This increase was compensated by losses of basin area of the Harle of more than 45 % (fig.8, tab. 1). The total loss of area for both basins is also higher than the correspondingly reclaimed areas in the Harle Bay. But here also the same explanation fits as for the western part of the East Frisian Wadden Sea. The area of partial enclosures was until the end of the 19th century only an indirect measure of long term silting up, because in that time dykes were only built on supratidal salt marshes which had been silted up earlier. In connection with the phase shift of morphodynamical adaption this quantitative differences must not necessarily be inconsistent with the basic idea. Moreover the phase shift of morphodynamical adaption of the seaward basin area to bay reduction becomes i. e. g. evident by the response of the Harle basin with a remarkable areal decrease until 1912 (fig. 8, tab. 1) whereas the most partial enclosures had already been carried out at the end of the 18th century (fig. 4).

Sublittoral and Intertidal basin areas A_{sl} and A_i

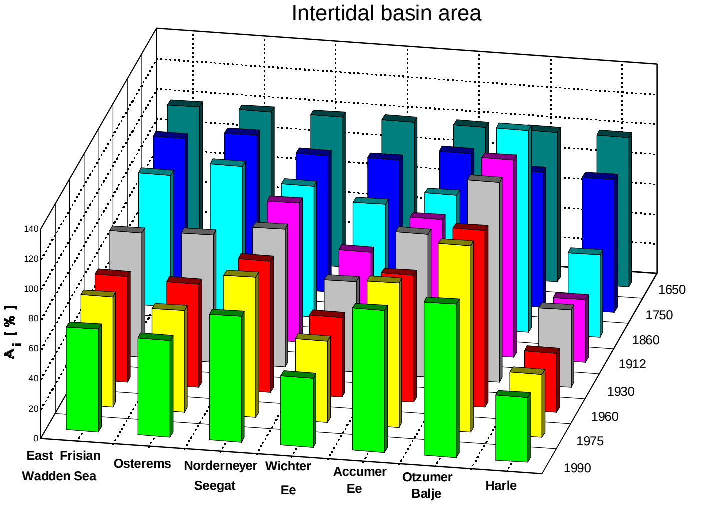


Figure 9. Relative development of intertidal basin areas A_i (in percentages) in the East Frisian Wadden Sea

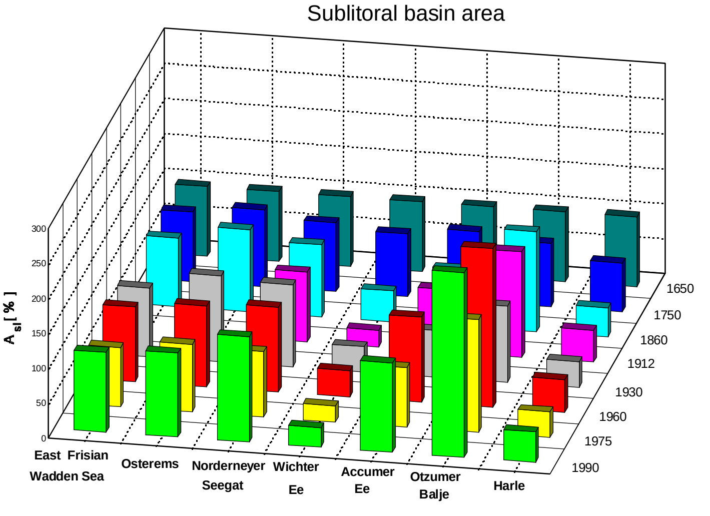


Figure 10. Relative development of sublittoral basin areas A_{sl} (in percentages) in the East Frisian Wadden Sea

The intertidal areas of the East Frisian Wadden Sea have both absolutely and relatively much more decreased (fig. 9, tab. 2) than the total basin areas (fig. 8, tab. 1). Correspondingly the sublittoral areas have as well absolutely as relatively increased (fig. 10, tab. 3). But this tendency is not uniform for all tidal basins: It is valid for those ones with as a small reduced total area like Osterems and Norderneyer Seegat, a nearly constant one like Accumer Ee or even enlarged one like Otzumer Balje. Contradictory in those basins which total area experienced reduction like those ones of the Wichter Ee and the Harle the tendency is different. In the Harle basin both intertidal and sublittoral areas have experienced nearly the same amount of relative reduction whereas in the Wichter Ee basin the sublittoral areas have been relatively more reduced than the intertidal ones (fig. 9, tab. 2; fig. 10, tab. 3). In total the tendency of reduction for the intertidal areas being evident until 1960 has been substituted by a fluctuation of less than 3 % since then (fig. 9, tab. 2) which is generally in tune with the development of the total basin areas (fig. 8, tab. 1). Contradictory the until 1930 rather stable figures for the sublittoral basin areas tend to fluctuate more significantly since then (fig. 10, tab. 3). Partly this effect might also be caused by changes in the seaward boundary of the basins for the different surveys due to the chosen determination of the seaward inlet cross-section for computations.

		1650	**1750**	**1860**	**1912**	**1930**	**1960**	**1975**	**1990**
East Frisian Wadden Sea	A_i [$10^6\cdot m^2$]	623,35	596,07	548,41		515,86	439,63	458,02	428,60
	A_i [%]	100,00	95,62	87,98		82,76	70,53	73,48	68,76
Osterems		242,28	245,48	235,76		205,60	166,85	164,30	156,81
		100,00	101,32	97,31		84,86	68,87	67,81	64,72
Norderneyer Seegat		88,69	80,95	77,54	82,35	81,65	77,65	82,90	74,61
		100,00	91,27	87,43	92,85	92,07	87,55	93,47	84,13
Wichter Ee		43,90	40,15	34,52	27,87	26,48	23,40	23,82	20,29
		100,00	91,45	78,64	63,48	60,32	53,31	54,26	46,22
Accumer Ee		80,52	79,95	70,88	71,30	77,00	68,32	77,56	76,34
		100,00	99,29	88,03	88,55	95,63	84,85	96,32	94,81
Otzumer Balje		46,86	42,19	63,15	61,70	62,60	55,39	58,40	47,96
		100,00	90,02	134,76	131,66	133,58	118,20	124,61	102,34
Harle		121,10	107,36	66,55	50,57	62,53	48,01	51,04	52,59
		100,00	88,66	54,96	41,76	51,63	39,64	42,15	43,43

Tab. 2: Intertidal basin basin areas 1650 - 1990

		1650	**1750**	**1860**	**1912**	**1930**	**1960**	**1975**	**1990**
East Frisian Wadden Sea	A_{sl} [$10^6\cdot m^2$]	211,63	210,29	207,13		207,97	226,65	179,92	240,93
	A_{sl} [%]	100,00	99,37	97,87		98,27	107,10	85,02	113,84
Osterems		116,04	127,28	135,94		142,66	134,35	112,22	139,41
		100,00	109,69	117,15		122,94	115,78	96,71	120,14
Norderneyer Seegat		21,14	20,84	21,77	21,09	24,85	25,64	19,80	31,86
		100,00	98,54	102,96	99,75	117,52	121,25	93,65	150,68
Wichter Ee		10,02	9,02	4,41	2,40	3,62	3,79	2,33	2,80
		100,00	89,94	44,00	23,94	36,12	37,84	23,25	27,94
Accumer Ee		19,69	19,74	16,13	17,58	13,20	23,93	16,74	25,20
		100,00	100,23	81,92	89,28	67,01	121,50	85,03	127,95
Otzumer Balje		10,04	9,10	14,37	15,12	10,90	22,77	16,17	26,51
		100,00	90,70	143,20	150,62	108,59	226,90	161,08	264,07
Harle		34,70	24,32	14,50	15,80	12,74	16,17	12,66	15,16
		100,00	70,10	41,79	45,55	36,73	46,62	36,49	43,69

Tab. 3: Sublittoral basin areas 1650 - 1990

Supratidal salt marsh areas A_{sm}

The interactions of hydro- and morphodynamics in the storm surge bays created favourable boundary conditions for the growth of supratidal salt marshes as described before. But these were more and mored dyked by subsequent partial enclosures. The deceleration of silting-up due to the reduction of the bays' oversize effected primarily also a deceleration of salth marsh(fig. 3 + 4). Though only insufficient data are available for the time before 1650 the areal development of salt marshes from then still reflects that process (fig. 11, tab. 4): The total area of supratidal salt marshes in the East Frisian Wadden Sea has been reduced from 1650 to 1750 by about 20 % and then again until 1860 by another 12 %. The decrease between 1860 and 1930 has again decelerated to less than 5 % even followed by an increase of nearly 4 % until 1960. The subsequent reduction of about 5 % until 1975 has growth and secondarily in tunewith partial enclosures a reduction of existing salt marsh areas been a consequence of the enclosures of salt marshes by construction of new dykes due to the guidelines for coastal safety established after the catastrophic storm surge of 1962 seawardly of the old ones.

Regarding the tidal basins separately the developments do not reflect the same uniform tendency (fig. 11, tab. 4): The Osterems tidal basin has lost nearly 60 % of its supratidal salt marsh areas between 1650 and 1860, particularly due to the partial enclosures in the Ley Bay. But it regained about until 1975 about 20 %, particularly to salt marsh growth in the Ley Bay in spite of executed partial enclosures in the same period. The initial losses of salt marsh areas in the tidal basin of the Norderneyer Seegat have already been explained as a consequence of inlet migration and changes of local wave climate with a drecrease of about 55 % from 1650 to 1750. But alredy between 1750 and 1860 the continuous losses (fig. 6) were overcompensated by salt marsh growth in other areas of the basin. Since then salt marshes areas have increased until 1975. The losses of supratidal salt marsh areas in the tidal basin of the Wichter Ee must particularly be regarded as a consequence of the enormous reduction of its total basin area which is also evident for the changes between 1960 and 1975. The pursued re-duction of salt marshes in the tidal basin of the Accumer Ee since 1650 must be primarily credited to the seaward move-ment of dyke lines whereas the continuous growth of salt marsh areas in the tidal basin of the Otzumer Balje is partic-ularly a consequence of the described extension of its total basin area since 1650.

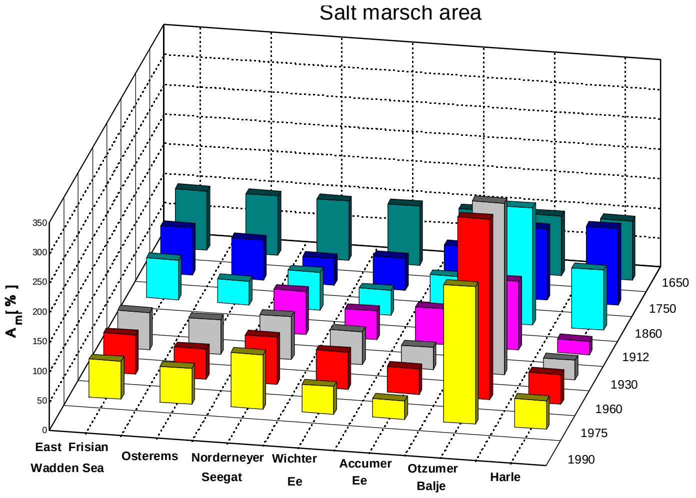


Figure 11. Relative development of salt marsh basin areas A_m (in percentages) in the East Frisian Wadden Sea

		1650	1750	1860	1912	1930	1960	1975
East Frisian Wadden Sea	A_m [10^6·m²]	45,59	36,24	30,60		28,50	30,26	29,22
	A_m [%]	100,00	79,49	67,12		62,51	66,37	64,09
Osterems		16,96	11,47	6,82		9,93	8,65	10,23
		100,00	67,63	40,21		58,55	51,00	60,32
Norderneyer Seegat		5,85	2,61	3,70	4,26	4,23	4,65	5,38
		100,00	44,69	63,34	72,90	72,40	79,53	92,02
Wichter Ee		5,15	2,78	2,15	2,52	2,86	3,23	2,41
		100,00	53,95	41,71	48,88	55,56	62,74	46,84
Accumer Ee		6,74	5,46	4,90	4,06	2,54	2,92	2,11
		100,00	80,98	72,72	60,22	37,63	43,31	31,28
Otzumer Balje		2,10	2,52	4,14	2,42	6,06	6,37	4,87
		100,00	120,50	197,44	115,44	289,27	303,87	231,90
Harle		8,80	11,40	8,89	2,01	2,88	4,45	4,22
		100,00	129,57	101,09	22,80	32,69	50,58	48,01

Tab. 4: Salt marsh areas 1650 - 1975

The reduction after 1960 is an effect of the dyking of salt marshes. Between 1750 and 1912 salt marsh areas in the tidal basin of the Harle have as well decreased as the total basin area due to resedimentation and partial enclosures of the Harle Bay. Until 1960 then a certain growth appeared in tune with the stabilization of the tidal basin which only experienced a slight reduction after 1960 due to dyking of salt marshes.

Evaluation of tidal volumes

The parametrization of Wadden Sea areas in the framework of the project WADE was carried out in order to establish empirical relationships between these parameters describing morphodynamical equilibrium conditions. A parametrization of morphological parameters like areas must is insufficient for that purpose, the evaluation of hydrodynamical parameters is additionally necessary for reaching the aim. The most common hydrodynamical parameter used in empiral morphodynamical relationships is the tidal volume. The evaluation of tidal volumes for defined areas is no problem if detailed surveys or maps are available and the represantative tidal high and low water peaks are known. But in the case of the reconstructed historical coastal morphology of 1650, 1750 and 1860 by HOMEIER [1962] there are only the contour lines of mean tidal high and low water and the border lines ot the supratidal salt marshes available. Furthermore measurements of tidal water levels providing reliable data have been carried out in the East Frisian Wadden Sea since the end of the 19th century (fig. 14). Therefore the evaluation of tidal volumes for these dates requires extra efforts.

The substitution of complex tidal basin morphology by only mean high and low water contour lines has been exercised by WALTHER [1972] in order to avoid enormous computational efforts without the aid of modern computers:

$$V_T = TR \cdot (A_b + A_{sl}) / 2$$

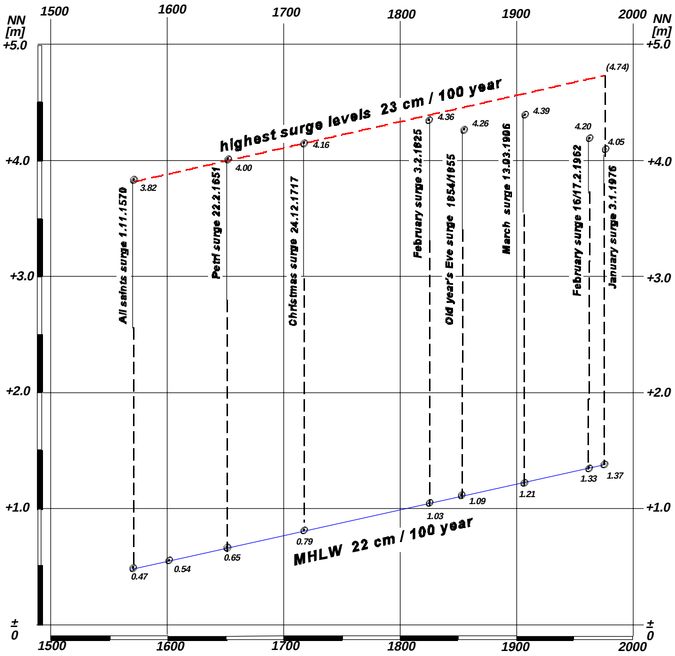


Figure 12. Reconstructed historical mean high tide and storm surge water levels and long-term trends, island of Wangeroog, tidal inlet Harle [LÜDERS 1977]

Since there is nothing reported about the accuracy of this method a calibration test for recent data sets was carried out with the data of all six East Frisian tidal basins from the surveys of 1960, 1975 and 1990. Surprisingly the deviation from data being evaluated with the aid of a GIS was on the average about 6 % (fig. 12) which is in the same or even in a lower order of magnitude as the measuring accuracy of data from hydrographic surveys. Based on these results the method of WALTHER [1972] is a suitable tool for the evaluation of tidal volumes for the situations of 1650, 1750 and 1860 for the reconstructed coastal morphology. In order to keep the data comparable the tidal vol-umes for the surveys since 1912 were also determined by the same method.

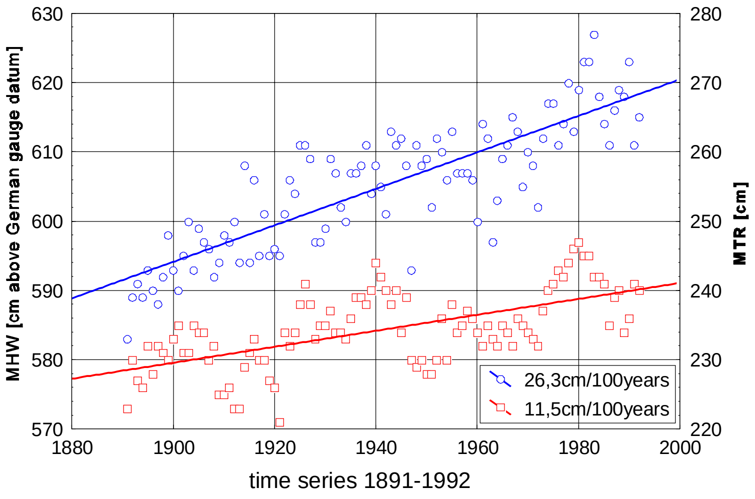


Figure 13. Yearly mean high water levels and tidal ranges since 1896 and corresponding mean trends, island of Norderney, tidal inlet Norderneyer Seegat

Beside the before mentioned data of tidal water levels there are also reconstruction of historical mean higher water and storm surge levels available. A very valuable data set has been elaborated by LÜDERS [1977] for the island of Wangerooge at the shore of the tidal inlet Harle (fig. 1) based on historical levellings being transferred to present datum and metric scale (fig. 13). These long-term data set has nearly the same rising velocity as that one being measured in the course of the last 100 years at the tidal gauge at the island of Norderney in the tidal inlet Norderneyer Seegat (fig. 1 + 14). The measured data make also a paralell increase of tidal range with rising high water levels evident (fig. 14). Referring to the documented rise of high water levels since 1570 it is reasonable that the tidal range has increased since then by nearly the same order of magnitude as for the last century. Based on this assumption the tidal volumes for the morphological situations of 1650, 1750 and 1860 have been evaluated by taking into account an increase of tidal range between 1650 and 1900 of 10 cm per century (fig. 15, tab 5). This figure is used in order to consider the long-term tendency of tidal boundary conditions of the morphodynamical development in the investigation area. The evaluated tidal volumes are quantitative not very sensitive against a possible inaccuracy of ± 5 cm/century, the fluctuation of the tidal volumes is therefore less than 2,5 %.

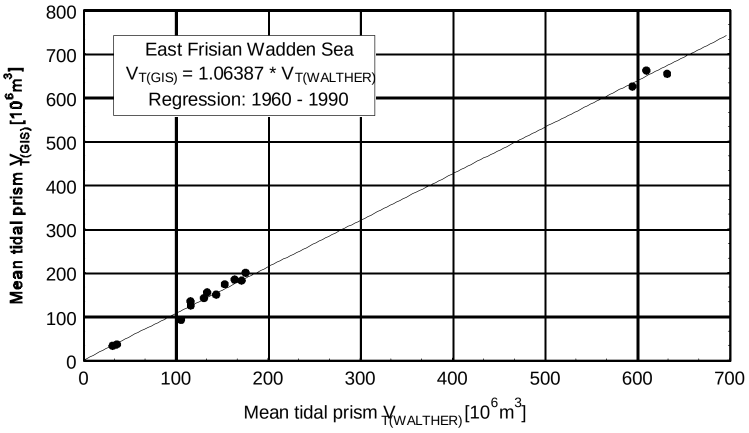


Figure 14. Comparison of tidal volumes computed with a GIS from detailed morphological maps and evaluated by the metod of WALTHER [1972]

The tidal volumes of the tidal basins in the East Frisian Wadden Sea have in total remained nearly constant over the regarding the long-term development. The increase of tidal range measured since the end of the 19th century (fig.14) and expected to have also occured with a similiar coincidence to the rise

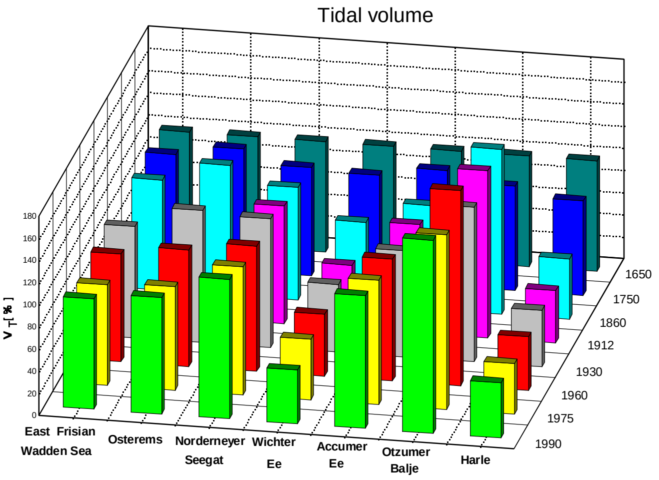


Figure 15. Relative development of tidal volumes (in percentages) of the tidal basins in the East Frisian Wadden Sea

		1650	1750	1860	1912	1930	1960	1975	1990
East Frisian Wadden Sea	V_T [$10^6 \cdot m^3$]	1135,35	1149,22	1131,64		1141,33	1105,40	1032,77	1133,23
	V_T [%]	100,00	101,22	99,67		100,53	97,36	90,97	99,81
Osterems		498,08	550,04	583,79		594,01	524,83	466,48	524,93
		100,00	110,43	117,21		119,56	105,37	93,66	105,39
Norderneyer Seegat		134,25	131,82	136,22	142,58	156,30	152,12	155,58	169,45
		100,00	98,19	101,47	106,20	116,42	113,31	115,89	126,22
Wichter Ee		65,55	62,54	48,76	37,40	40,13	36,57	35,89	31,72
		100,00	95,54	74,39	57,06	61,22	55,79	54,75	48,39
Accumer Ee		131,90	137,34	123,78	129,35	126,66	145,22	148,25	158,42
		100,00	104,12	93,84	98,07	96,03	110,10	112,40	120,11
Otzumer Balje		76,98	72,48	114,88	116,30	107,61	135,77	121,58	134,29
		100,00	94,15	149,23	151,08	139,79	176,37	157,94	174,45
Harle		228,59	195,01	124,22	108,06	116,62	110,89	104,99	114,41
		100,000	85,31	54,34	47,27	51,02	48,51	45,93	50,05

Tab. 5: Tidal volumes of the East Frisian Wadden Sea tidal basins 1650 - 1990

of mean tidal high water since the 16th century (fig. 13) has compensated the reduction of basin areas. For the midterm development of the last decades with nearly stable total basin areas the tidal volume has not experienced a remarkable increase whereas the tidal range has also increased during this period (fig. 14); for 1975 even a significant reduction occured (fig. 15, tab. 5) which can partly be ex-plained by the reduction of the total basin areas (fig. 8, tab.1). According to the reduction of total areas the tidal volumes of the Wichter Ee andHarle have decreased significantly. Correspondingly the tidal volume of the Otzumer Balje has increased overproportional in respect of other tidal basins. The Accumer Ee has in 1990 a tidal volume which is 20 % higher than 1650, whereas the total basin areas for both dates are nearly constant. The tidal volume of the Osterems has experienced remarkable fluctuation which are generally in tune with the development of its basin areas. That one of the Norderneyer Seegat has generally increased. The fairly reduction of its basin areas must have been compensated partly by the increase of tidal range. Furthermore the shape of the basin and the relation of intertidal and sublittoral areas might have been of importance.

Long term stability of empirical relations

The morphological changes in the East Frisian Wadden Sea [HOMEIER 1962, LUCK 1977] has decelerated enormously in the course since the middle of the last century and particularly since the beginning of this one. The fixing of four of the six inlets since the beginning of this century and particularly the coincidently nearly finnished resedimentation and land reclamation in the areas of the medevial storm surge bays has effected that development. Therefore morphodynamical changes in the East Frisian Wadden Sea occur not only self-evidently on much lower time scales but also on smaller length scales leading to a morphodynamical quasi-equilibrium, which in the long run is expected to be only temporarily. But nowadays a mid-term dynamical equilibrium could be assumed which is expressed by a number of well-established semi-empirical relationships being evaluated on a data basis with sufficient density for that purpose. That method for a functional parametrization of morphodynamical processes has proved as a success for coastal research and for coastal engineering planning since decades [O'BRIEN 1931; WALTHER 1972; EYSINK 1979, 1991; NIEMEYER 1991]. One of the important relationships describing a morphodynamical equilibrium is that one between total basin area and tidal volume which has been introduced by EYSINK [1979] and was used in the framework of the Dutch coastal defense study as a tool for the estimation of the impacts of an accelerated relative sea-level rise.

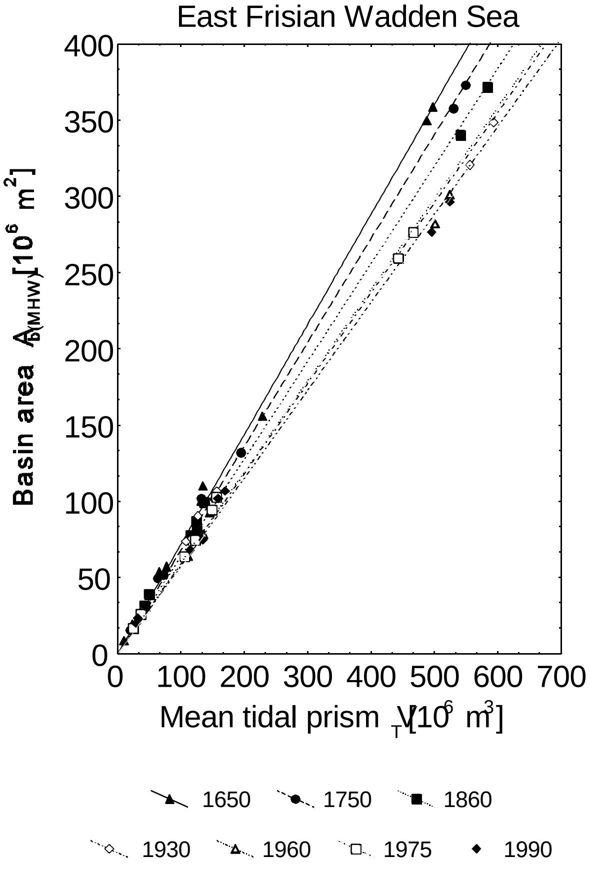


Figure 16. Correlation of total basin areas A_b and tidal volumes V_T since 1650

In order to get a deeper insight into those documented long-term morphodynamical processes occuring at the East Frisian coast since 1650 these relationship has also been adapted to the evaluated parameters being available for all situations from 1650 to 1990 beside that one of 1912 for which not a complete data set was available. Though the incorporated assumption of a dynamical equi-librium could not be assumed as valid for the situations between 1650 and 1860 the relation e. g. between tidal volumes and intake areas of the basins are for all situations rather strict (fig. 16). In respect of the experience gained from recent data [EYSINK 1979, 1991] this result is not trivial, because these data sets incorporate also a variation in tidal range due to its regional differences. Looking at the data sets from 1960, 1975 and 1990 including also the subsystems of the tidal basins for the same parametrization for the East Frisian Wadden Sea this effect is evident only for the larger values of 1990 (fig. 17). A first explanation of this discrepancy is the only use of data for mid-term developments: As tidal ranges varies to a much lesser extent than for the long-term time scale, statistal scattering is of the same or even bigger order of magnitude than the structural differences due to tidal range variation.

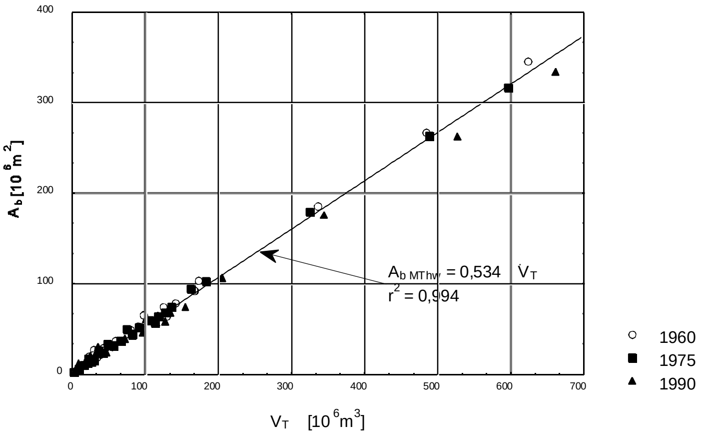


Figure 17.Correlation of basin areas and tidal volumes for the tidal basins and subsystems in the East Frisian Wadden Sea (surveys 1960, 1975, 1990).

Further emphasis will be laid on finding a reliable explanation and detecting the mechanism steering that process. The solution to this problem is of high importance because these relations provide the basis for conceptual or empirical model like the Box-model of VAN DONGEREN & DE VRIEND [1994] being up to now the only promising tool for morpho-dynamical modelling of future mid- and long-term develop-ment. A successful treatment will therefore deliver a valu-able basis not only for current problems with structural ero-sion but also for the forecasting of prospected long-term morphodynamical processes due to changing boundary conditions like an expected acceleration of relative sea-level rise.

An obvious explanation would be a change of hydrodynamical boundary condition. Considering that possibility the changes of tidal range over the time were taken into account though no measured data before 1891 were taken into consideration and the figures for 1860, 1750 and 1650 were evaluated on the basis of an assumption. But this assumption is regarded as rather sound and in every case as a sufficient basis to look for indications for a qualitative change of empirical relationships for morphodynamics: The data reflect a pronounced correlation of the factor a of the relationship

$$A_b = a \cdot V_T$$

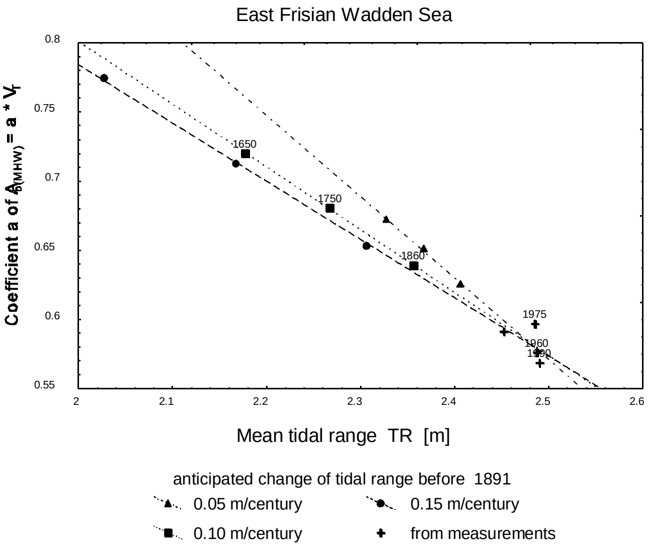


Figure 18.Correlation of the coefficient a from $A_b = a \circ V_T$ with tidal range TR

and tidal range range TR (fig. 18). Obviously those correlations depend particularly on the anticipated change of tidal range before 1891. In order to estimate the effect of a misjugdement a variation of ± 5 cm per century is taken additionally into consideration. The result makes evident that the tendency of the correlation is still evident (fig. 18). Therefore it must be concluded that for long term investigations in the same area the variation of the tidal range must be taken into consideration in order to describe the relationship between total basin areas and tidal volumes with sufficient accuracy.

Conclusions

The resedimentation of storm surge bays at the East Frisian mainland coast has been a major steering impact of morphodynamical processes in five of the six tidal basins of the East Frisian Wadden Sea during the last centuries. As well the shifting of basin watersheds, the migration of inlets as the changes in size and position of the barrier islands can no longer only be credited to littoral drift. Furthermore they could not be regarded as a cyclic process which would have continued without the fixing of tidal inlets since the middle of the last century.

A reliable quantitative approximation of tidal volumes is also possible for the reconstructions of historical coastal morphology of Wadden Sea areas. The accuracy of these figures is sufficient for use in the framework of empirical relationships used for empirical and conceptual morphodynamical modeling. It has become evident that relationships being used for empirical or conceptual modeling which have been established for data sets covering only a period of a few decades or even less could not in every case be regarded as valid for long-term periods like centuries. This was demonstrated for the well known relationship of tidal basin areas and tidal volumes which is in the long run dependent on tidal range variations.

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