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THE HISTORY OF THE DUTCH COAST IN THE LAST CENTURY

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ABSTRACT

The aims of this paper are:

1. To publish some available coastal measurements and computations of more than local importance.
2. To investigate the influence of groynes in practice.
3. To investigate the motion of the gullies in the outer deltas.

The following conclusions are drawn:

1. The gross littoral drift[1] along the Dutch coast is of the order of 1.5 to 2 mln m^3/year; (computed with the CERC-formula) the resulting net drift is mostly within the order of accuracy of the computation.
2. The erosion of the areas with groynes was much less than the erosion of the adjacent areas; partially this effect is due to lee-side scour but mainly to decreased erosion in the protected areas.
3. The gullies in the outer deltas on the Wadden mainly rotated clockwise, which is probably the direction of the resultant transport there.

INTRODUCTION

The Dutch coast can be divided into three parts (fig. 1) (annex 1)

1. The Rhine-Scheldt Delta
2. The uninterrupted coast of Holland
3. The Wadden area.

It is a sandy coast ($D_m \approx 200\,\mu$); the tidal range varies between 4 m near the Belgium border, down to 1.5 m near Hook of Holland, to 1.3 m near Den Helder and then up again to 2.2 m near the German Island Borkum. The gully systems in the Rhine-Scheldt delta and that of the inlets between the Wadden Islands in the North have quite a different shape, since the tidal basins are quite different. In the

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[1] Gross littoral drift means the sum of the transport in the Northward and Southward direction.

South the basins are rectangular with an open short side towards the sea and in the North they are rectangular with the long side parallel with the coast-line; this side is bordered by the Wadden Islands with narrow inlets in between. Therefore the Wadden coast can be compared with lagoon coasts, as they occur in many parts of the world. The Wadden Sea is a tidal flat, which is submerged during every high tide. Most information will be given about the Holland coast and the Wadden area, as DRONKERS [1] stresses the research in the Delta-area.

The main purpose of this paper is to supply data, to enable international comparison. This paper gives a summary of many reports of regional study-branches of Rijkswaterstaat, made over a period of about 50 years. Amongst the former papers, covering the same subject, special attention should be given to WENTHOLT (1912) [2], who investigated in particular the effect of groynes, VAN VEEN (1936) [3], [4], who dealt with the origin of the Dutch coast and the shape of the gullies, VAN BENDEGOM [5], who investigated the hydraulic laws for the motion of the gullies, VAN STRAATEN [6], who considered the directional effects of winds, waves and currents, and concluded that the sand drift must be strong (west to east) along the northern barrier islands and small between Katwijk and Texel, EDELMAN and EGGINK [7], who drew morphological conclusions from the curvature of the coast. PER BRUUN and GERRITSEN [8] dealt with the cross section of gullies and the stability of coastal inlets. BIJKER and SVASEK [9] gave a treatise about IJmuiden harbour. The following paper gives more recent data than WENTHOLT. The conclusions of VAN VEEN, VAN STRAATEN, EDELMAN and EGGINK are reviewed in the light of modern theories about sand transport of CERC, BIJKER and SVASEK, making use of tidal computations.

BEACH MEASUREMENTS

Figure 2 and 3 (annex 2 and 3) show the erosion and accretion of the low-tide line, the high-tide line and the dune foot in periods of 10 year. First the 10-year average of each of these lines was determined, for instance 1856-1865; the distance between two successive 10-year averages is plotted in fig. 2 and 3. The positions of groynes, seawalls or harbour moles are shown and their dates of construction are also indicated.

The area of the Holland coast (fig. 2) has been highly influenced by the building of the harbour moles of Hook of Holland and IJmuiden in 1870. The low-tide line shows the influence of climatologic changes [6]; the overall picture is a large amount of erosion between 1860 and 1880 and accretion between 1880 and 1900. These periodical changes are very strongly damped in the line of the dune foot and here one finds the general trend as indicated by EDELMAN and EGGINK [7], i.e. a general accretion of ½ m/year, with erosion near Hook of Holland and Den Helder (fig. 4) (annex 1). The Hondbossche Seawall at the moment lies much further seaward than the adjacent dunes because of the erosion of these dunes.

The influence of the harbour moles (length 1400 m) at IJmuiden, built in 1870 is shown in detail in fig. 5 (annex 4). Fig. 2 shows that the low-tide line and high-tide line near IJmuiden reach a point of stability about 1900, but that the dune foot changes up to 1930. Fig. 5 gives a plan view of the 5-years average of the low-tide and high-tide lines (seaward scale exaggerated with respect to the longshore scale). The total gain of sand was 9.10^6 m^3 to the North and 6.10^3 m^3 to the South of the IJmuiden harbour moles [9]. In 1965 the harbour moles were lengthened to 3000m. On the right hand side of fig. 5 the change of the mean of the low-tide and high-tide line since 1965 is shown. Now the accretion on the South side is more than on the North side. Although a changing of the wave climate may have had an effect[6], [9], the fact that at the moment an extensive area with only small currents prevents the entrainment of material from the surf zone around the head of the mole, must be important.

The changes of the Wadden Islands are shown in fig. 3. The change at the ends are large compared to the changes in the middle of the islands, partly due to the changes in the gully-systems in the inlets; the silting up of a gully may sometimes have the effect that a shoal grows onto the end of an island. After that, a sandwave along the coast is generated [10]. The relatively large erosion on both ends of Texel is obvious. We shall return to this subject.

GROYNES

The Dutch groynes have a length of about 200 m. The distance between the successive groynes can be found from fig. 6 to 8 (annex 5, 6, 7) (about 200 m). In the considered area they are broad-crested stone structures, lying at about mean sea-level. In order to investigate the behaviour of groynes in practice three areas were considered, on which groynes were constructed during the period of the measurements: South-Holland km 97 to 105 (fig. 6), North-Holland km 8 to 20 (fig. 7, derived from [11]) and Vlieland km 41 to 52 (fig. 8). In the figures 6, 7 and 8, the 5-year averages of the low water line have been shown (for instance 1858 to 1862 for 1860). The scale perpendicular to the reference line is exaggerated with respect to the longshore direction by 10 times in fig. 8 and by 20 times in fig. 6 and 7. In each figure two successive lines are plotted together, the black areas show the erosion in 10 years, the grey areas the accretion. The groynes built from 1853-1862 are plotted through the line of 1860, and so on. The hatched area gives the protected coastal area.

Fig. 8 seems a striking proof of the benefit of groynes. The erosion near km 47 to 51 in 1860/70 can hardly be ascribed to the groynes 5 km away. The reduction of the erosion after the building of the groynes is quite clear. Of course, this does not mean that groynes are the most economic way of coastal protection. The same kind of effect can be seen in fig. 6, 1860/70, although less convincingly. The influence of the lee-side scour also plays a big role here. A rough estimation of this lee-side scour (giving also a measure for the net littoral drift in this zone) would be about 100,000 m^3/year (i.e. erosion of about 2 m/year over 3 km). Less clear still is fig. 7. The Northern part of this area is subject to the movement of the Schulpengat, the Southern branch of the inlet of Texel. The lee-side scour on the Northern side can be observed clearly (km 20, 21; 1860 to 1880 etc.), and also the inverse: the accretion near km 13, 14 between 1900 and 1910 on the luff-side.

Analysis of the effect of the groynes is very difficult. Comparison with unprotected parts of the beach is senseless, since groynes are constructed only on eroding beaches. A before- and after-comparison will be obscured by climatological changes (cf fig. 2 and 3, low-waterline): We chose the areas of fig. 6, 7 and 8 for comparison (all eroding beaches, gradually more and more protected with groynes) and computed for each area for each 10-year period the mean erosion/year of the protected part and of the unprotected part (fig. 9a, b, c) (annex 8). Thus the erosion on the same area could be compared for when this area was protected (later on), and for when it was not (in the beginning). In order to eliminate local influences all three areas were put together and again the mean erosion per year of the protected and of the unprotected areas was computed (fig. 9d). An impression of the climatological changes gives fig. 9e, in which the mean regression and progression per 10-year period of the low-tide line of the uninterrupted coast of Holland is shown. Only the relative changes are of importance. Finally in fig. 9f the erosion of the protected part of fig. 9d is plotted against the erosion of the unprotected part, from which a considerable reduction of the erosion can be concluded. Although nearly all the considered unprotected areas were subject to lee-side scour, fig. 8 shows that the reduction is not mainly caused by that, but that the building of groynes reduced the erosion.

SAND TRANSPORT BY WAVES AND TIDES

VAN STRAATEN [6] and EDELMAN and EGGINK [7] both give qualitative considerations about the sand transport by waves. Since their publications, so much data has been collected about the relation between the longshore component of the wave energy and the sand transport, that it is worthwhile to apply such formulae to the Dutch coast, in order to obtain more quantitative conclusions. However, these conclusions cannot be better than the available data; i.e. the visual wave observations made on the Dutch lightvessels. These measurements from 1949 to 1957 have been statistically analysed by DORRESTEIN [12], giving the probability of occurrence for each wave condition, (characterized by height, period and direction of the waves). HARREVELD [13] correlated the visual wave height of the Goeree lightvessel (at 10 km from the coast) with the wave height observed on the step resistance wave gage "Triton" at 3 km from the coast, and concluded from this that the low waves were estimated too low and high waves too high, the significant waves 1 to 2 m being estimated

Probability (fr. in °/oo) the occurrence of a certain value of P_1

site orientation of the coast with respect to the North The size of P_1	Vlieland1) 060°-240°	Texel2) 030°-210°	IJmuiden3) 15°-195°	Scheveningen4) 045°-225°	
$-33 < P_1 < -31$				.13	
$-31 < P_1 < -29$			.52		
$-25 < P_1 < -23$			.17		
$-23 < P_1 < -21$		.13	.24		North
$-19 < P_1 < -17$			.42	.27	
$-17 < P_1 < -15$		.13	.70		
$-15 < P_1 < -13$	.03	.25		.92	
$-13 < P_1 < -11$	.27	.50	1.1	1.6	to
$-11 < P_1 < -9$	.25	.76	3.1	.35	
$-9 < P_1 < -7$	1.2	2.4	8.7	5.6	
$-7 < P_1 < -5$	.82	4.3	3.4	2.0	
$-5 < P_1 < -3$	8.9	19	26	26	South
$-3 < P_1 < -1$	32	56	120	119	
$-1 < P_1 < 0$	166	203	159	200	
$-\infty < P_1 < 0$	210	287	323	355	
$P_1 = 0$	529	401	299	316	
$0 < P_1 < 1$	155	196	272	188	
$1 < P_1 < 3$	53	70	86	92	
$3 < P_1 < 5$	29	31	15	28	South
$5 < P_1 < 7$	11	6.1	4.0	10	
$7 < P_1 < 9$	5.4	4.2	.88	6.0	
$9 < P_1 < 11$	1.4	2.1	1.3	.56	
$11 < P_1 < 13$	1.0	.61	.15	2.9	to
$13 < P_1 < 15$	1.1	.84			
$15 < P_1 < 17$	.84	.47		.56	
$17 < P_1 < 19$	.81	.24		.22	
$21 < P_1 < 23$	.34	.23		.44	North
$23 < P_1 < 25$	.42				
$29 < P_1 < 31$	.12				
$0 < P_1 < +\infty$	261	312	379	329	

1) From data lightvessel.
2) From data lightvessel Texel.
3) Probability of wave characteristics: mean between lightvessels Texel and Goeree.
4) From data lightvessel Goeree.

correctly. The regression coefficients between lightvessel and wave gage were different for each wave direction, which is clear for the offshore waves because there is a different fetch. But also for the onshore waves there must be some influence of site. From the visual wave period of the lightvessels an "equivalent wave period" T_{eq} was derived, according to BATTJES [14].

$$T_{eq} = 1.23\ T_m \qquad (T_m = \text{mean period of upward zero-crossings})$$

The equivalent wave period is the period, for which the energy/m^2 and the energy-flux/m of the replacing sinusoidal wave are equal to those in the real wave. HARREVELD [13] found the visual Goeree lightvessel period T_{vi} about equal to 1.5 T_m, from which $T_{eq} = 0.82\ T_{vi}$. The longshore component of the wave energy-flux, P_l was computed from:

$$P_l = 1380\ D_{br}{}^3\ \frac{\sin \varphi_o}{C_o} \quad (P_l \text{ in W/m}', D_{br} \text{ in m})$$

in which φ_o and C_o were the deep-water wave direction and phase velocity, and the breakerdepth D_{br} was found from:

$$D_{br} = \left[\frac{H_{sign}{}^2\ C_o\ \cos \varphi_o}{2(0.4)^2\ \ 1.4g\ \cos \varphi_{br}}\right]^{2/5}$$

The theoretical basis of these formulae is given in [16]. The results are given in the next table. Fig. 10 (annex 8) gives one of the probability distributions. From this it is easy to compute the mean energy flux and the mean littoral drift Q using the CERC-formula:

$$Q = 1.4 \times 10^{-2} \cdot \frac{P_l}{1/16\ \rho_w\ g} \qquad (\rho_w\ g = \text{specific weight water}),$$

$$Q^* = 2300\ P_l \qquad (Q^* \text{ in } m^3/\text{year}, P_l \text{ in W/m}').$$

However the used data and formulae are not accurate enough to justify this computation since the probability distributions are about symmetrical. Only along the Vlieland coast the resultant drift is significant (about ½ mln m^3/year). The resultant net energy-flux was always less than 0.3 KW/m'.

The gross littoral drift (sum of transport in both directions) can be computed from the summations of the products of the absolute value of P_l and the corresponding probability of occurrence (called pr (P_l))

$$Q^*_{gross} = 2300 \sum_{\text{all prob.}} \left\{ |P_l| \cdot \text{pr}(P_l) \right\}$$

This gross littoral drift is found to be of the order of 1.5 to 2 mln m^3/year (thus about 1 mln m^3 in each direction).

Assuming for instance no influence of tides, the distribution of the littoral drift over the surf zone has been computed by an adapted method proposed by SVASEK [8]; the method of computation is illustrated in another paper presented to this conference, [15] and is treated in more detail in [16]. The result for Scheveningen is shown in fig. 11 (annex 9).

Considering which influence is more important, that of waves or tides, in [17] and [18] the driving forces of waves and currents are investigated. The total driving force of the longshore current in the surf zone is [19]

$$\tfrac{1}{2} E_{br} \sin 2\varphi_{br} = 1/16 \rho g \gamma^2 D^2_{br} \sin 2\varphi_{br},$$

in which E_{br} is the wave energy per m^2 in the breaker zone, φ_{br} the angle of wave incidence, D_{br} the breaker depth and γ the ratio between H_{br} and D_{br}.

The driving tidal force over the breaker zone assuming a rigid bottom slope with gradient m is:

$$\frac{1}{2m} D^2 \cdot \rho g \frac{\partial h}{\partial x}$$

in which $\frac{\partial h}{\partial x}$ is the gradient of the water level in longshore direction, of which for a sinusoidal tide $(a. \cos(wt-kx))$ is the maximum value: i.e. ak.

The ratio between the longshore-current force and the tidal force is therefore

$$1/8 \; \frac{m\gamma^2}{ak} \sin 2\varphi_{br}$$

which is mostly large except for very small angles of wave incidence.

Assuming that the waves stir the material and the currents transport it, it is reasonable that the transport in the surf zone, according to the former computation, is rather well reproduced, except for the case where zero transport is computed. A computation, taking the tidal currents into account, based on a simplified BIJKER-method (cf [9]) is in preparation.

In order to get an impression of the influence of the tide a tidal computation has been carried out with the numerical tidal model of which fig. 12 (annex 9) gives the scheme [20]. We assumed a gully system parallel and perpendicular to the coast. On the ends the vertical tide was given; at the junctions the vertical tide was computed and in the gullies the horizontal tide. The computer program was developed by BOOY according to the explicit leap-frog method; non-linear terms were considered, but Coriolis was neglected. In each gully at every time was computed: $\sum_t Bvh. \Delta t$, in which B is the width of the gully, v the current velocity, h the water depth at the moment and Δt the time step. From this, the resultant currents were found as indicated in the upper part of fig. 12; about 3 cm/sec in the shallow regions and 6 cm/sec in the deeper regions.

THE OUTER DELTAS

The boundary conditions for the motion of the coast are given by the inlets. Therefore it is important to consider the motion of the gullies. Fig. 13, 14 and 15 (annex 10, 11, 12) give the motion of the gullies in the inlets of Texel, Vlie and Eems respectively. The arrows give the motion of the gullies since the last recording. What is known about these deltas?

The cross-sections of the gullies fit in reasonably with the theory PER BRUUN and GERRITSEN [8]. As a variation HARING [21] found that the quotient of the tidal volume (ebb + flood) and the total profile area of the gully was about 55 cm/sec, except for the inlet of Texel and the inlet of the Vlie, where it was 75 cm/sec (cf DRONKERS [1]). This higher velocity might be influenced by the littoral drift because that will possibly narrow the gullies. VAN VEEN [22] states, that the largest gullies are mainly orientated in the direction of the greatest water gradient, averaged per tide. If the tidal amplitude is everywhere the same (which is often not the case), this direction is perpendicular to the cotidal lines (fig. 16) (annex 14):

the gradient between A and B is much larger than between A and C.

Two reasons can be given for erosion of the coast near these inlets.

As has been pointed out by van BENDEGOM [23], the submerging of the Wadden during flood-tide takes place with higher velocities than the retreating of the water over the shoals during ebb-tide. Thus, the water loses a part of its sediment here, which causes the Wadden shoals to reach an equilibrium at about the mean water level. Now the relative rising of the sea-level in the Netherlands during the last 20 centuries was about 6 cm/century, which would result in a "sand hunger" of the Wadden shoals of about 1 mln m^3/year (distributed over all inlets). However, this will mostly be confined to finer sediments (D_m about 100-150μ).

The second reason is that the water during the flood tide gets an acceleration, entering the inlet, but that during the ebb-tide it gets a retardation and this will give a jet-stream with vortexes on its side. Therefore in the gullies near the beaches, there is surplus of flood discharge and in the center gully a surplus of ebb discharge. The flood erodes the beaches and the ebb gives an outer delta, which can reach up to mean sealevel (Noorderhaaks in Inlet of Texel). This delta gives a shelter against these waves, which would transport material away from the delta. As the waves come alternately from both sides, this process reinforces the erosion of the beaches near the inlets. Thus the erosion of Texel could be rather well explained [24]. After some time an equilibrium should be reached (fig. 19) (annex 14).

Two reasons can also be given for the motion of the gullies: A meandering effect and a longshore sand drift. It will be clear, that the resulting sand drift perpendicular to the gully can not be derived from the velocity of the gully, because of the meandering effect. The high amount of sand transport in the gullies can be attributed to the high current velocities and this meandering.

The motion of the gullies and the effects of their orientation has been investigated (fig. 17) (annex 13). The line in the middle of each of the bars gives the orientation of the gully in course of time. The width of the bar gives the development of the wet surface of the representative cross section. The time-integrated slopes of the water-surface as a function of the orientation have been mentioned (fig. 17¹⁾) as far as known. It gives no evidence about the Van Veen-theory (fig. 16) (annex 14).

In fig. 18 (annex 14), derived from fig. 17, the rotating of the gullies in the Dutch Wadden delta is shown. Mainly they turn clockwise, although very slowly, and there is a slight indication (correlation coeff. 0,24), that the large gullies turn slower than the small ones.

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1) These have been derived from Van Veen [21] and Ferguson [24].

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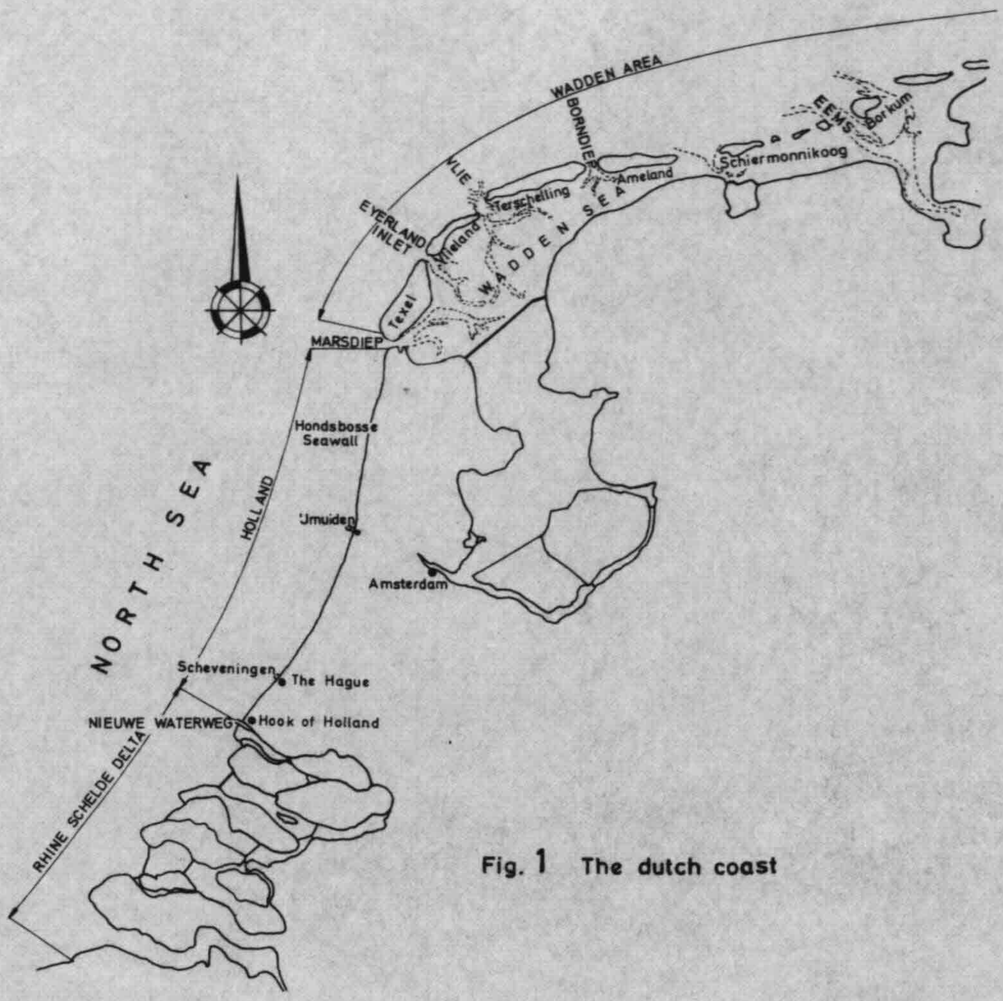


Fig. 1 The dutch coast

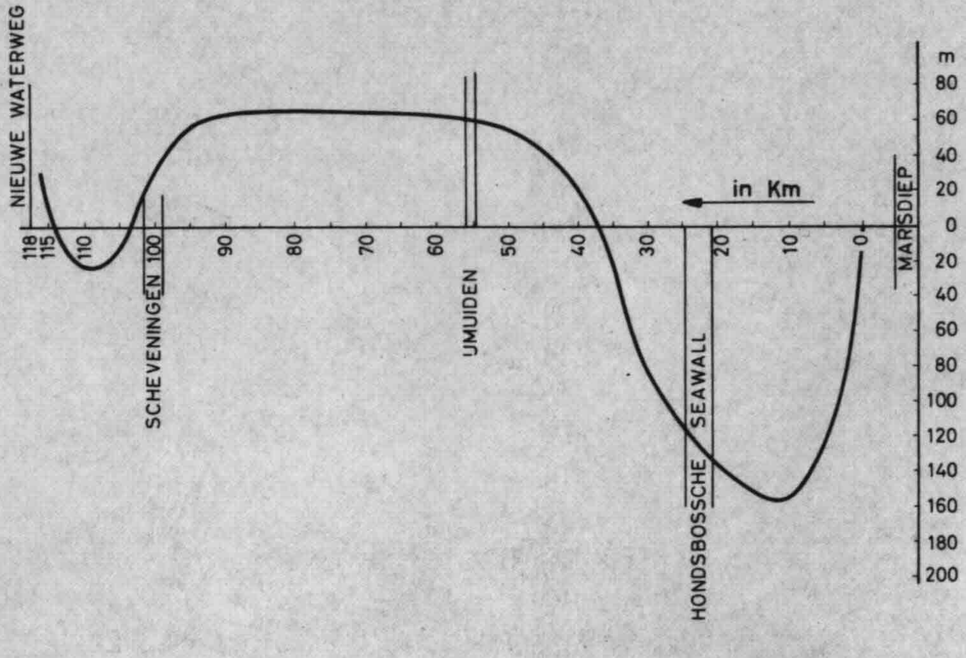


Fig. 4 Mean dune-foot movements from 1860 till 1960 between Nieuwe Waterweg and Marsdiep

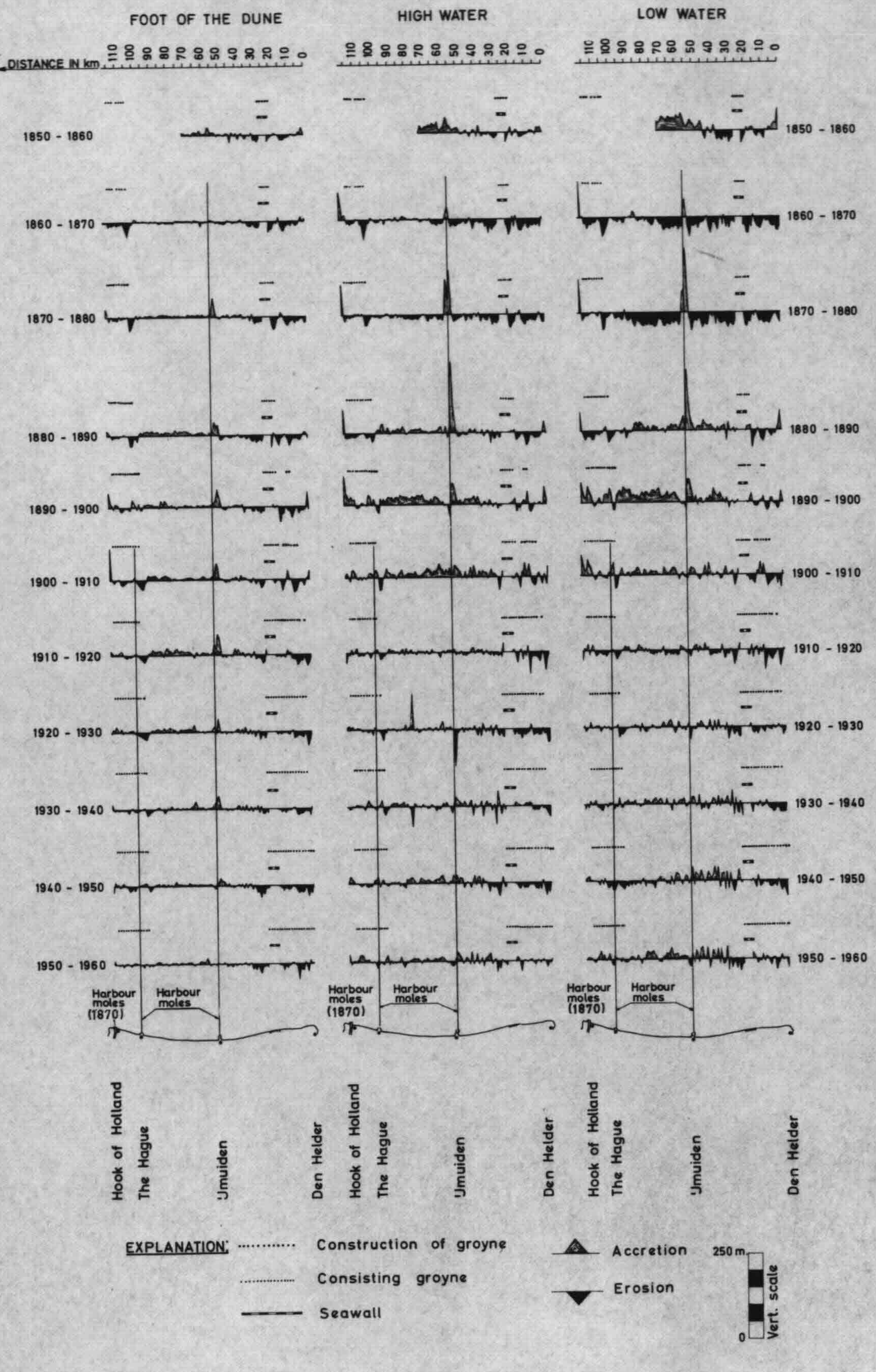


Fig. 2 Accretion and erosion of the coast of Holland

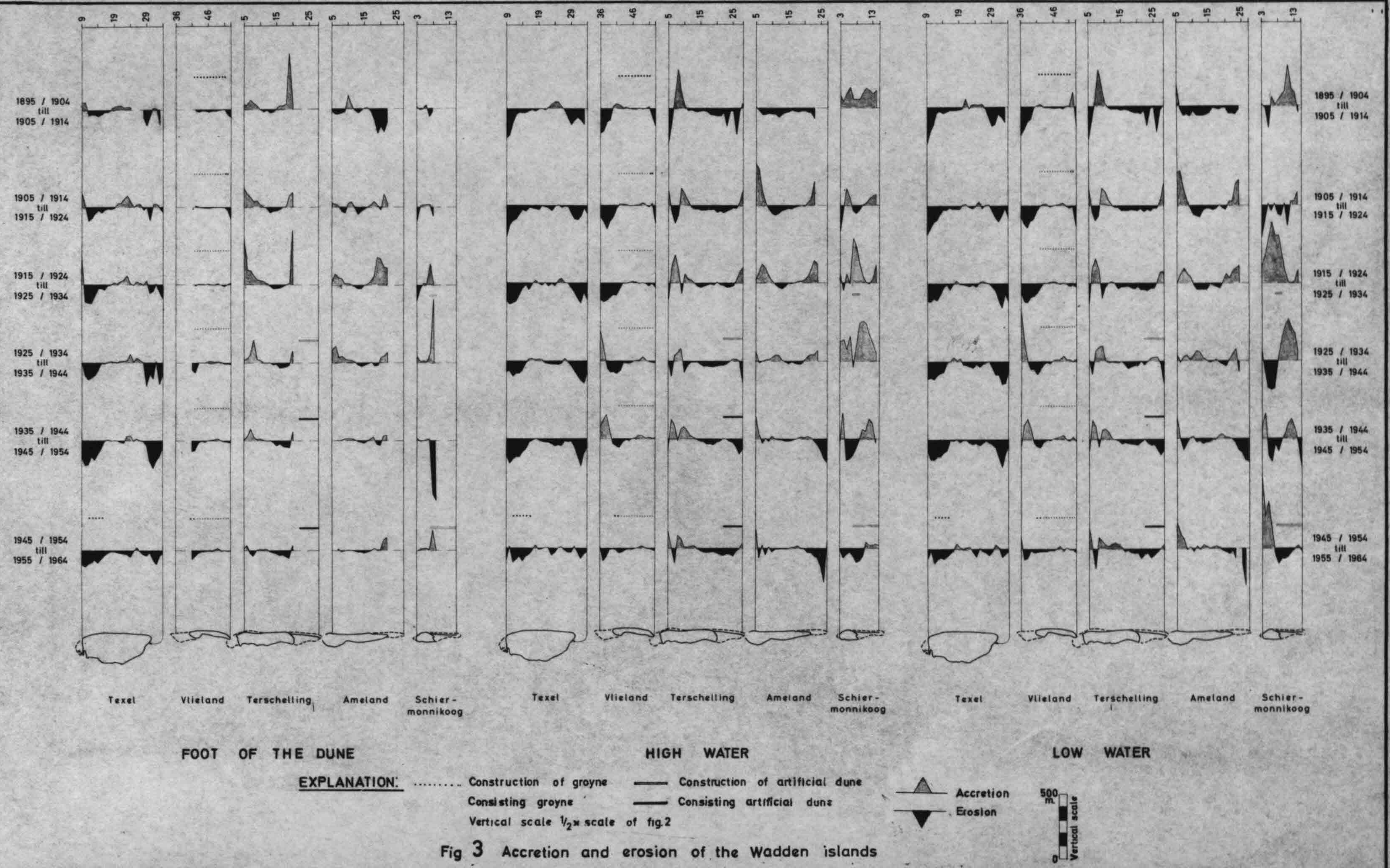


Fig 3 Accretion and erosion of the Wadden islands

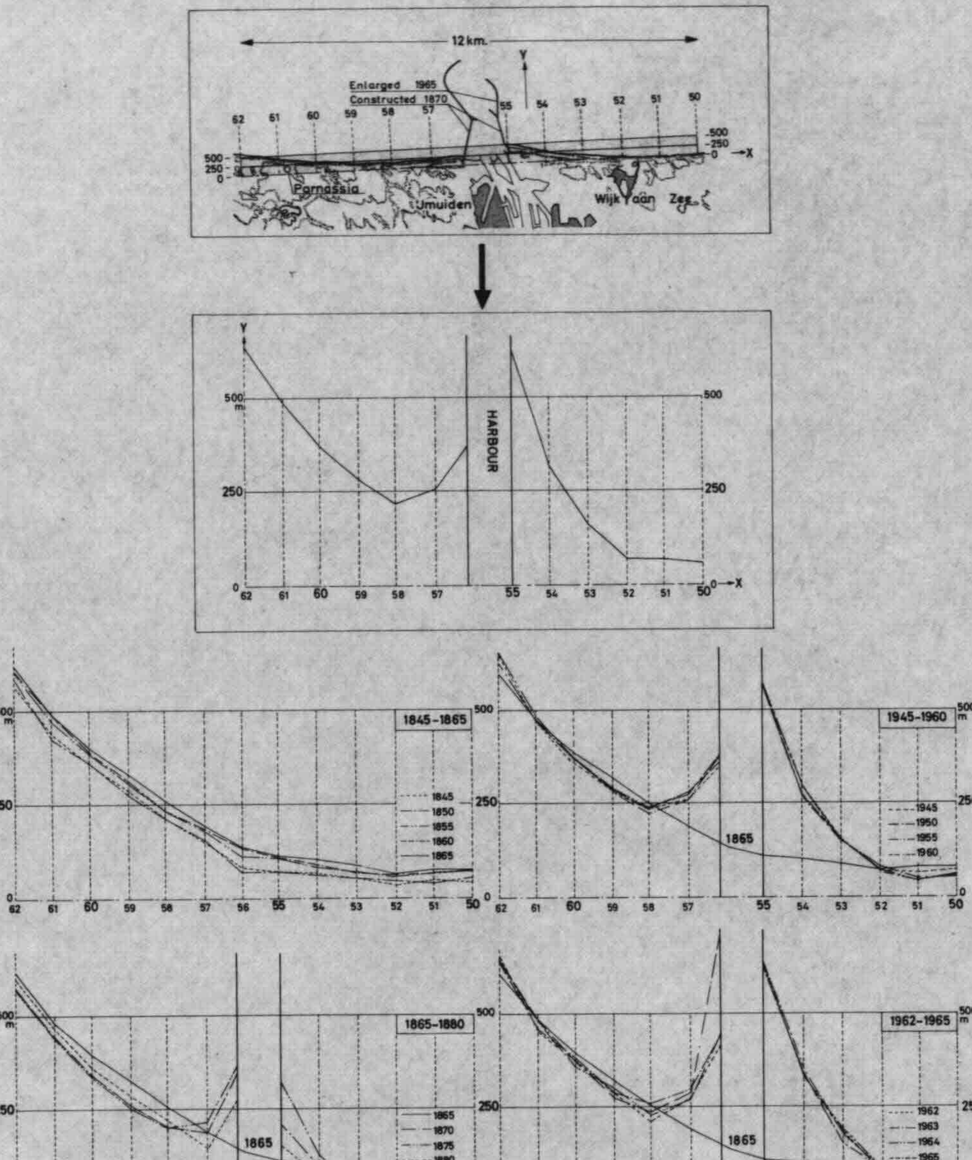


Fig. 5 Development of the waterline near Umuiden

Fig. 6 Erosion and accretion low water line South-Holland

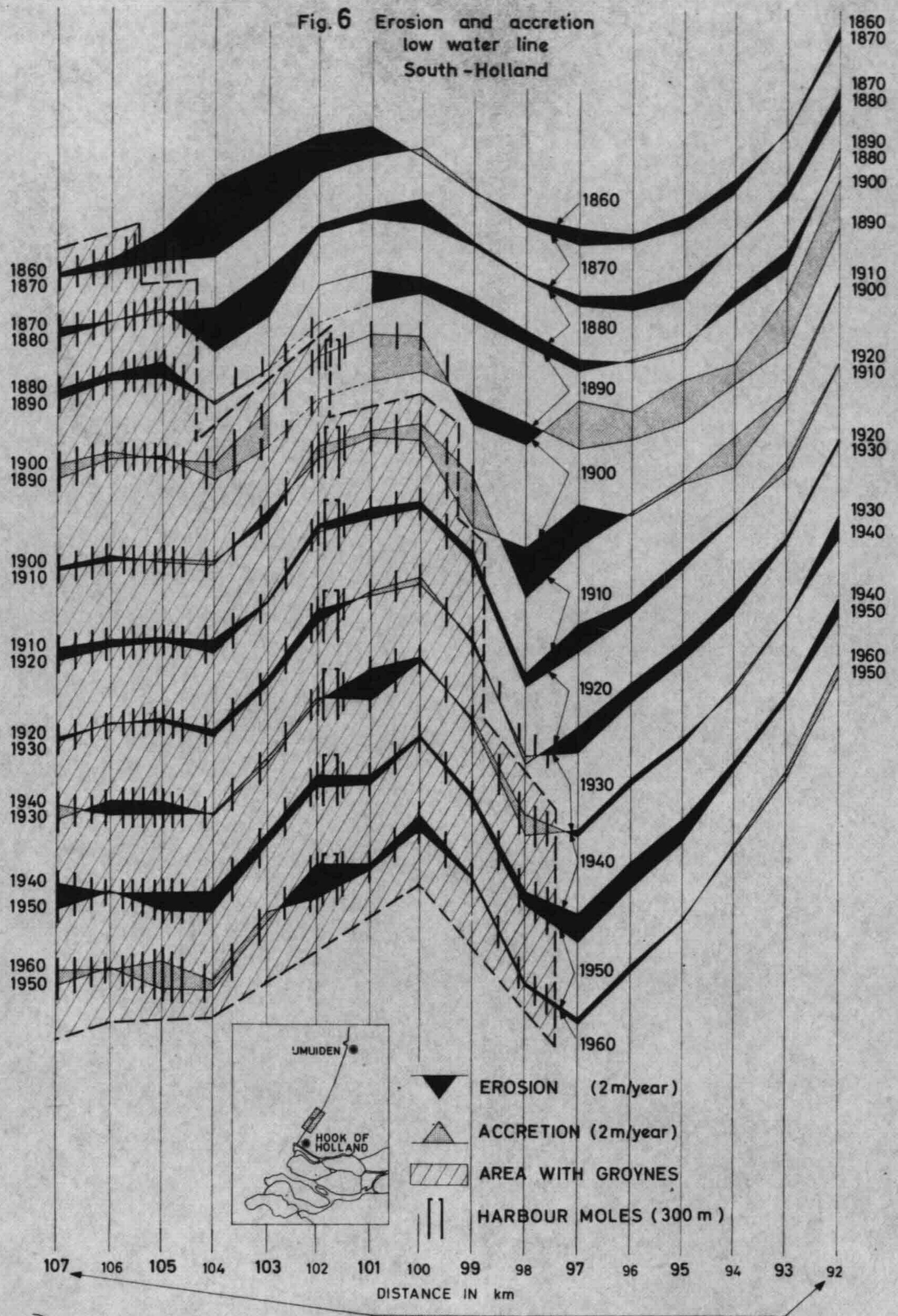


Fig. 7 Erosion and accretion low water line North - Holland

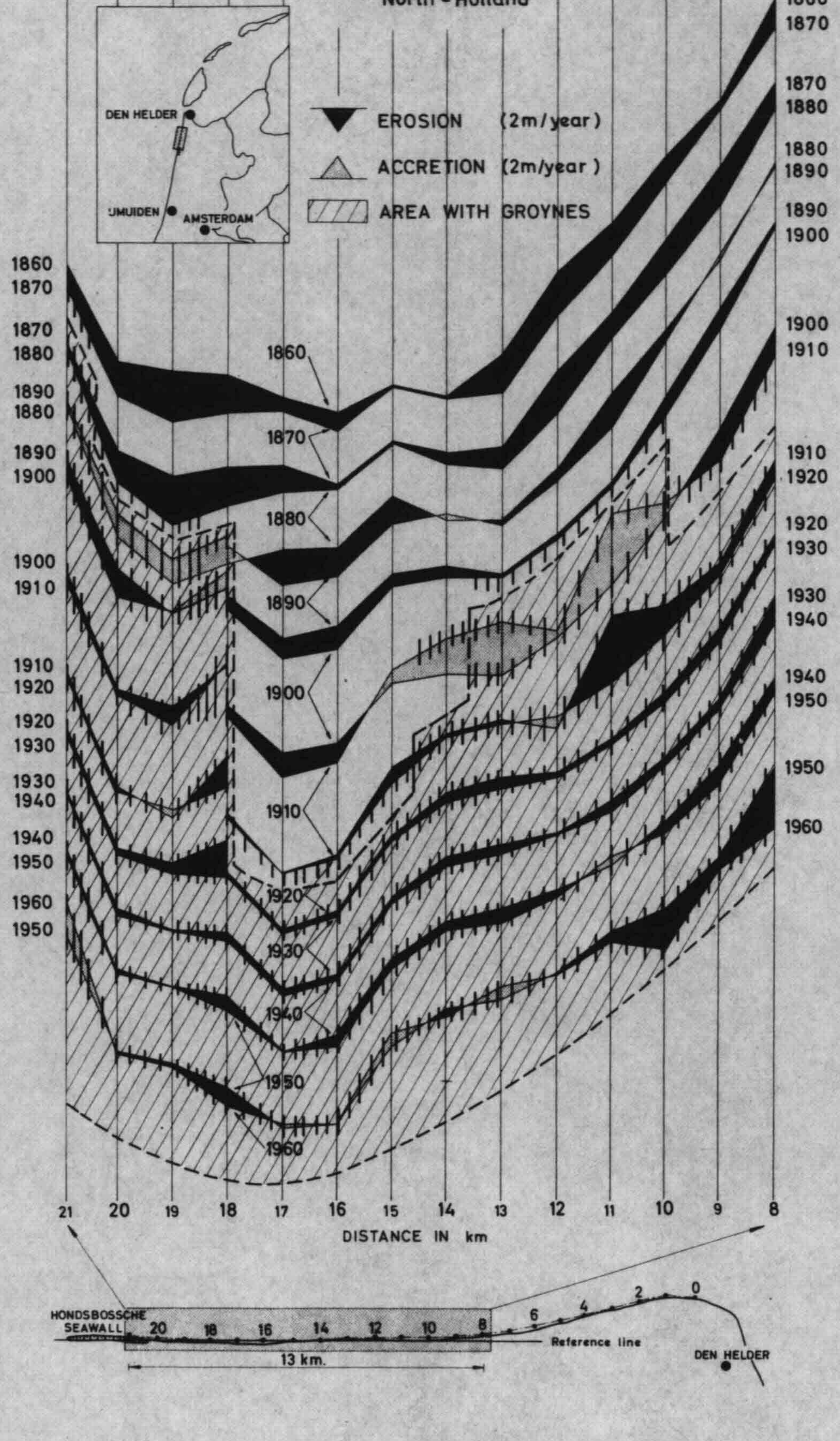
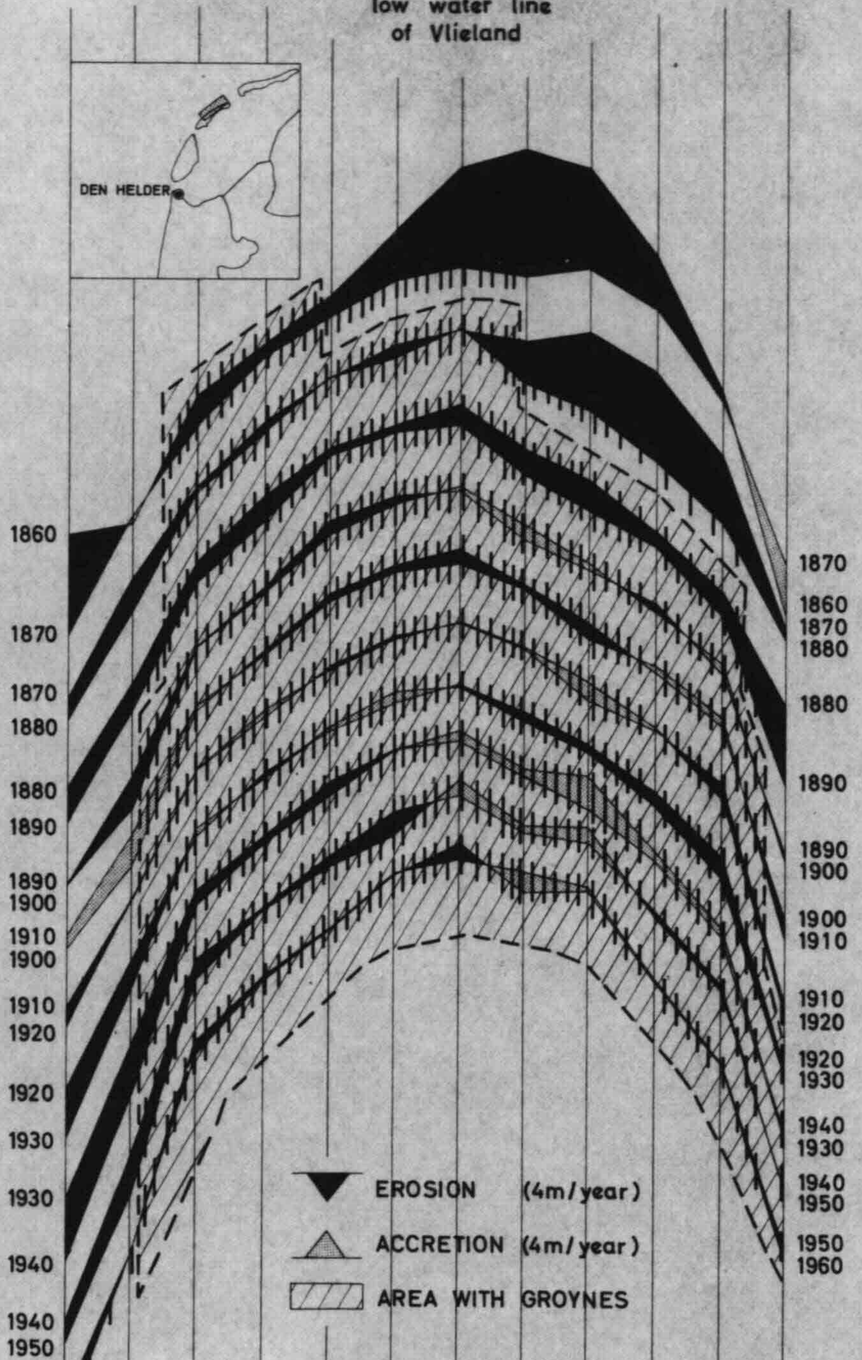


Fig. 8 Erosion and accretion low water line of Vlieland



Vertical scale 1/2x scale of fig. 6 and 7

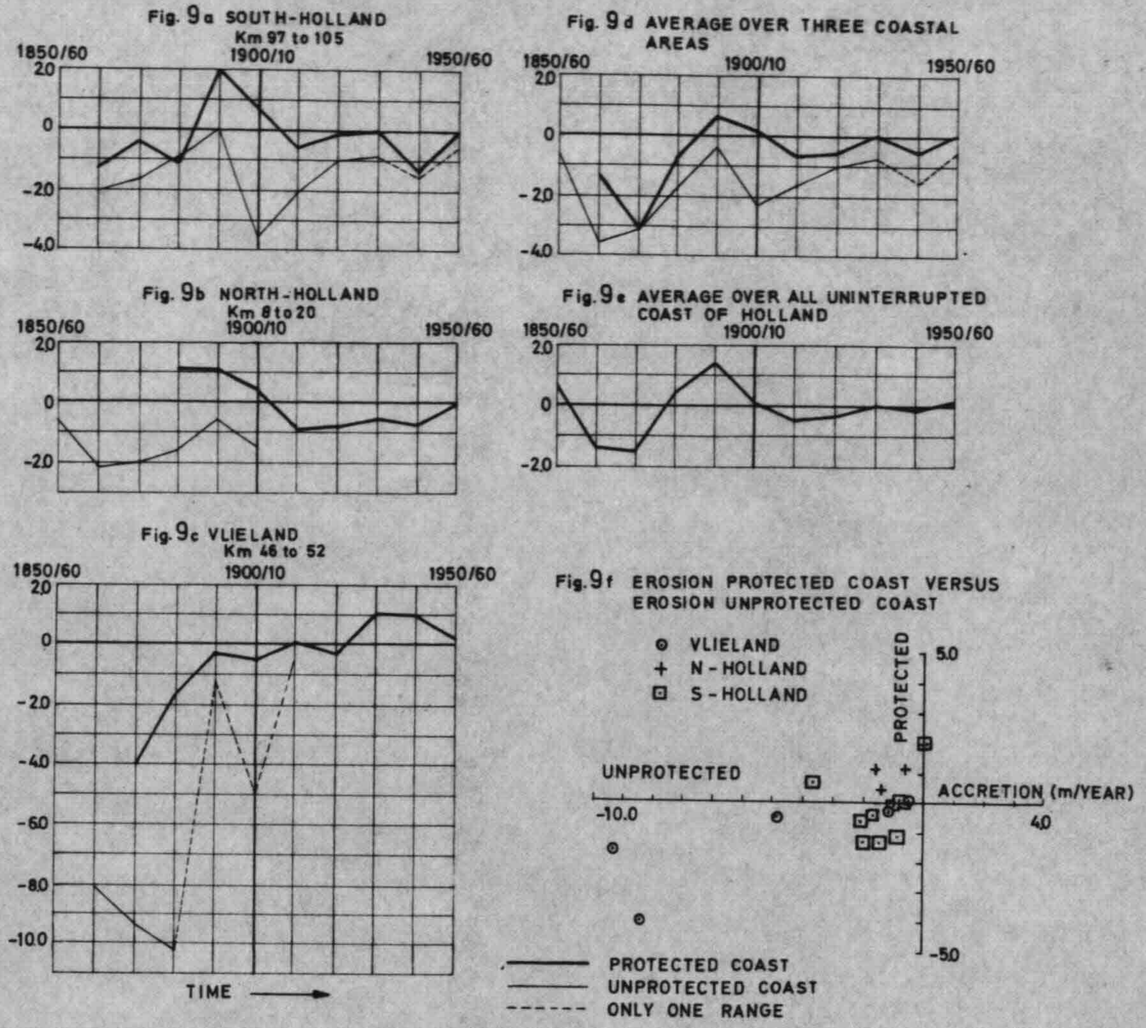


Fig. 9 Comparison of erosion in m/year of protected and unprotected areas

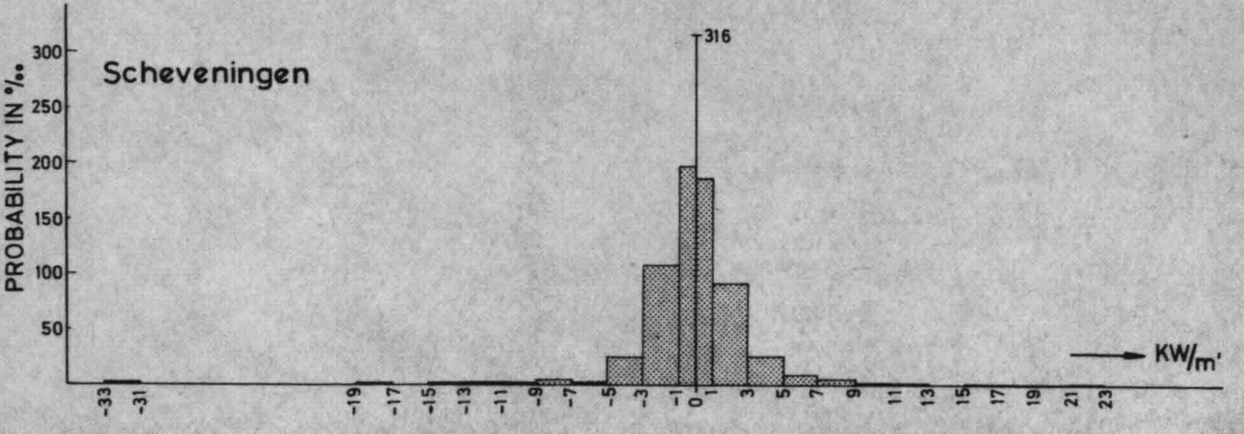


Fig. 10 The probability distribution of the longshore component of the wave energy-flux near Scheveningen

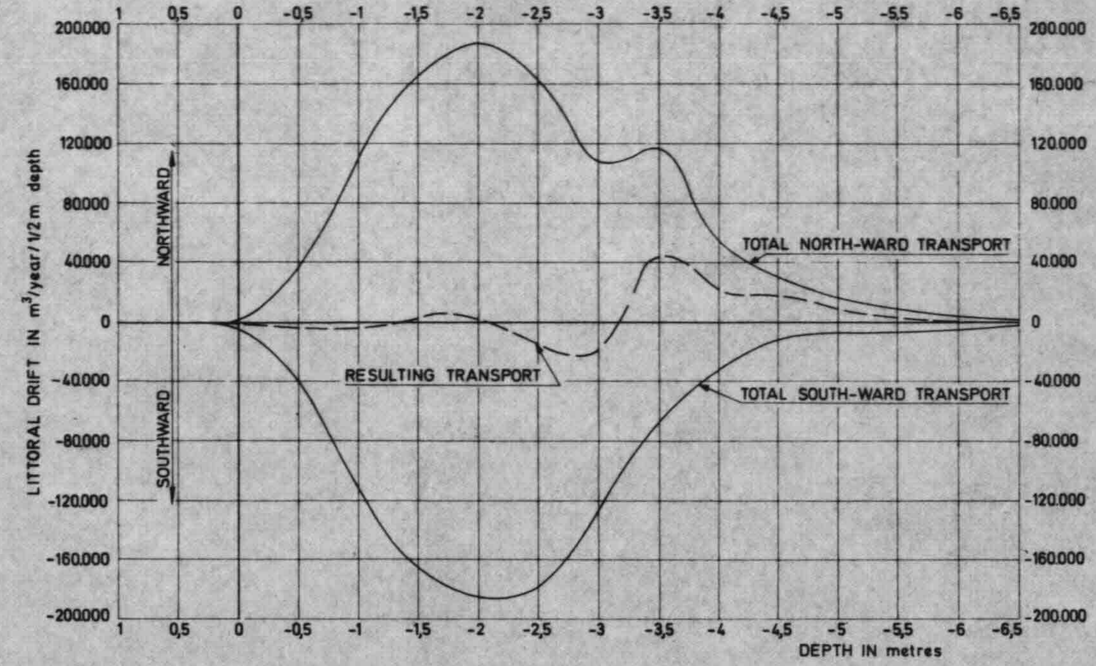


Fig. 11 Littoral drift near The Hague in m³/year between two successive depth contours, with 1/2 m difference in depth.

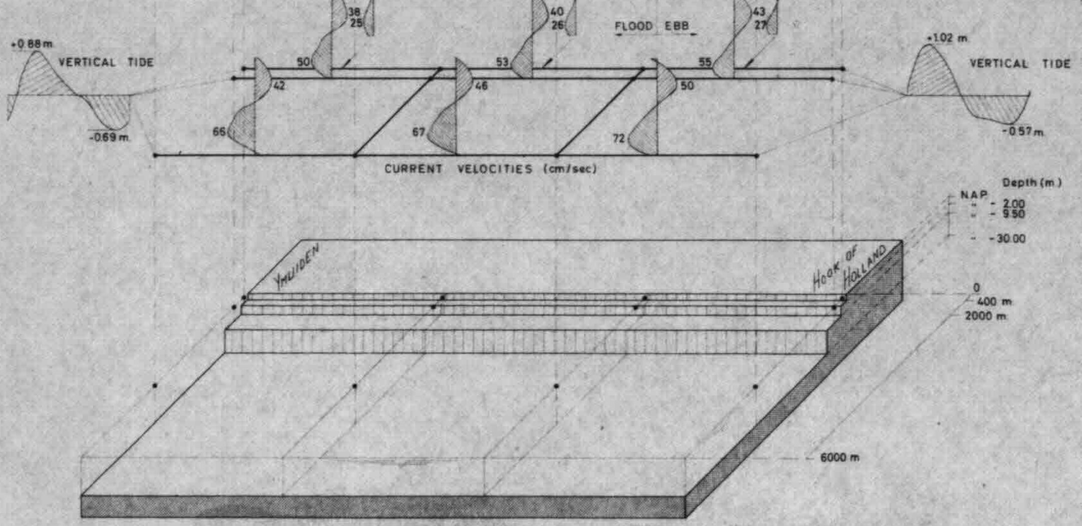


Fig. 12 Tidal model

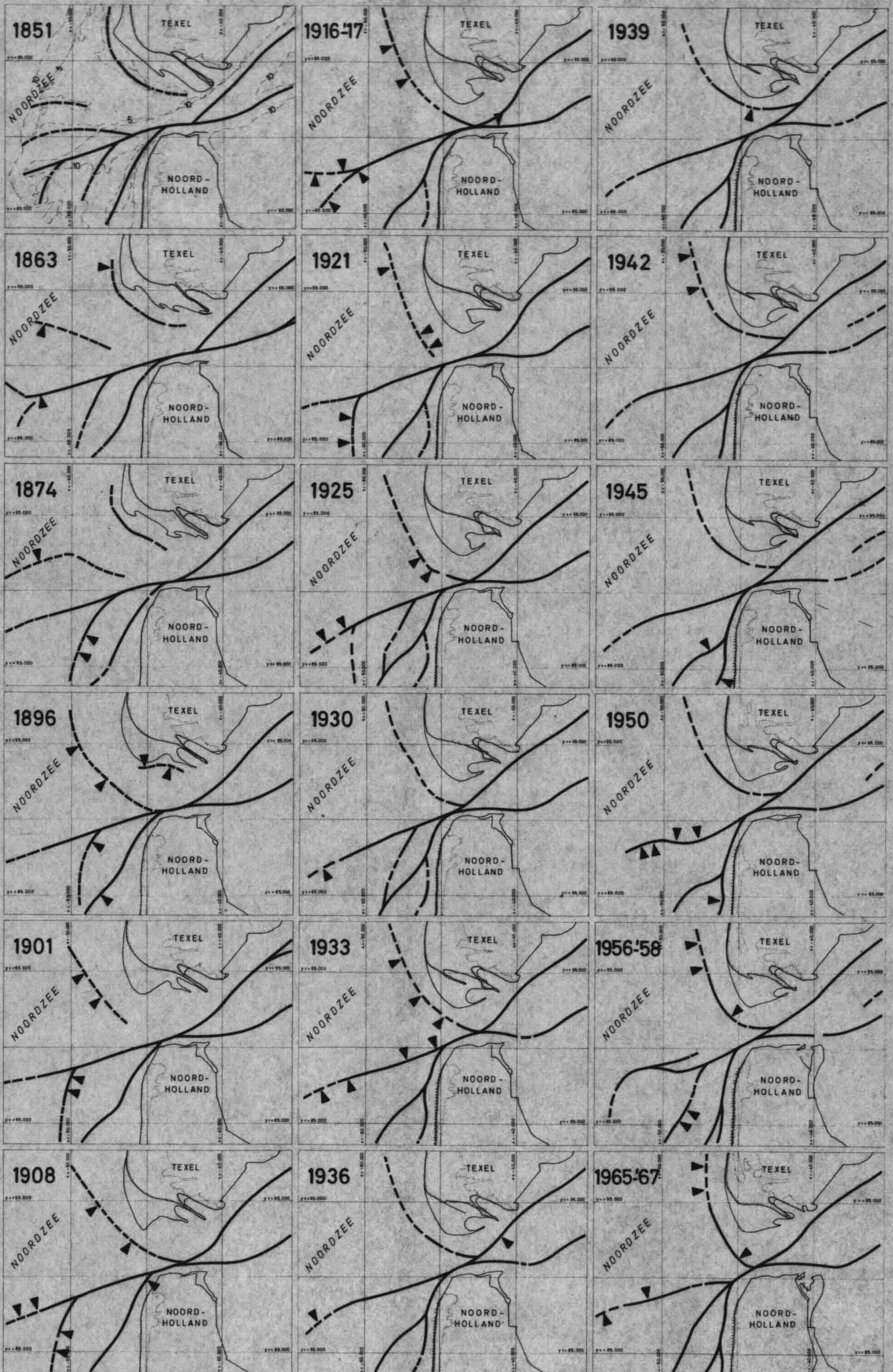


Fig. 13 Marsdiep (from Study department Hoorn, Rijkswaterstaat)

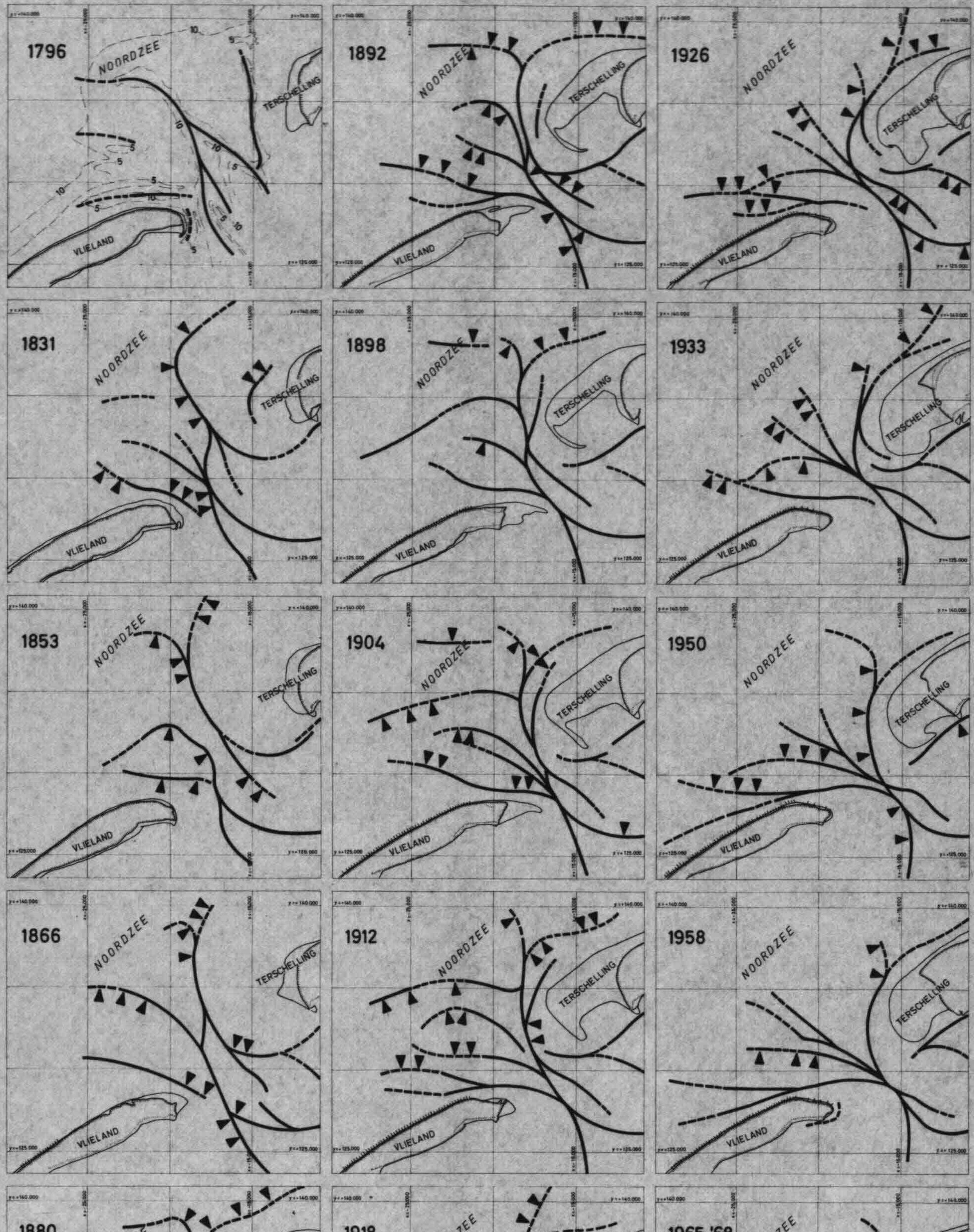


Fig. 14 Vlie (from Study department Hoorn, Rijkswaterstaat)

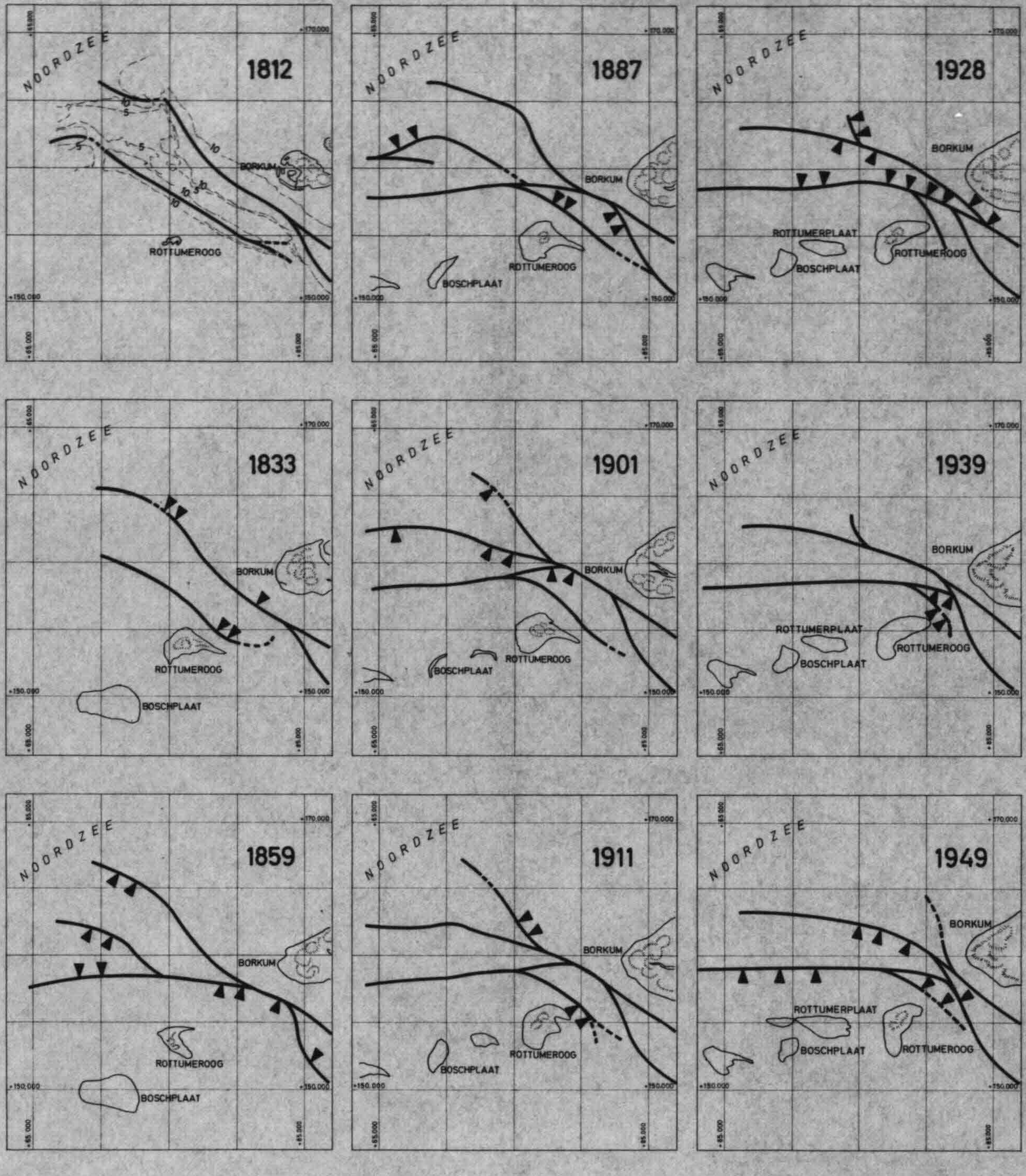


Fig. 15 Eems (from Study department Hoorn, Rijkswaterstaat)

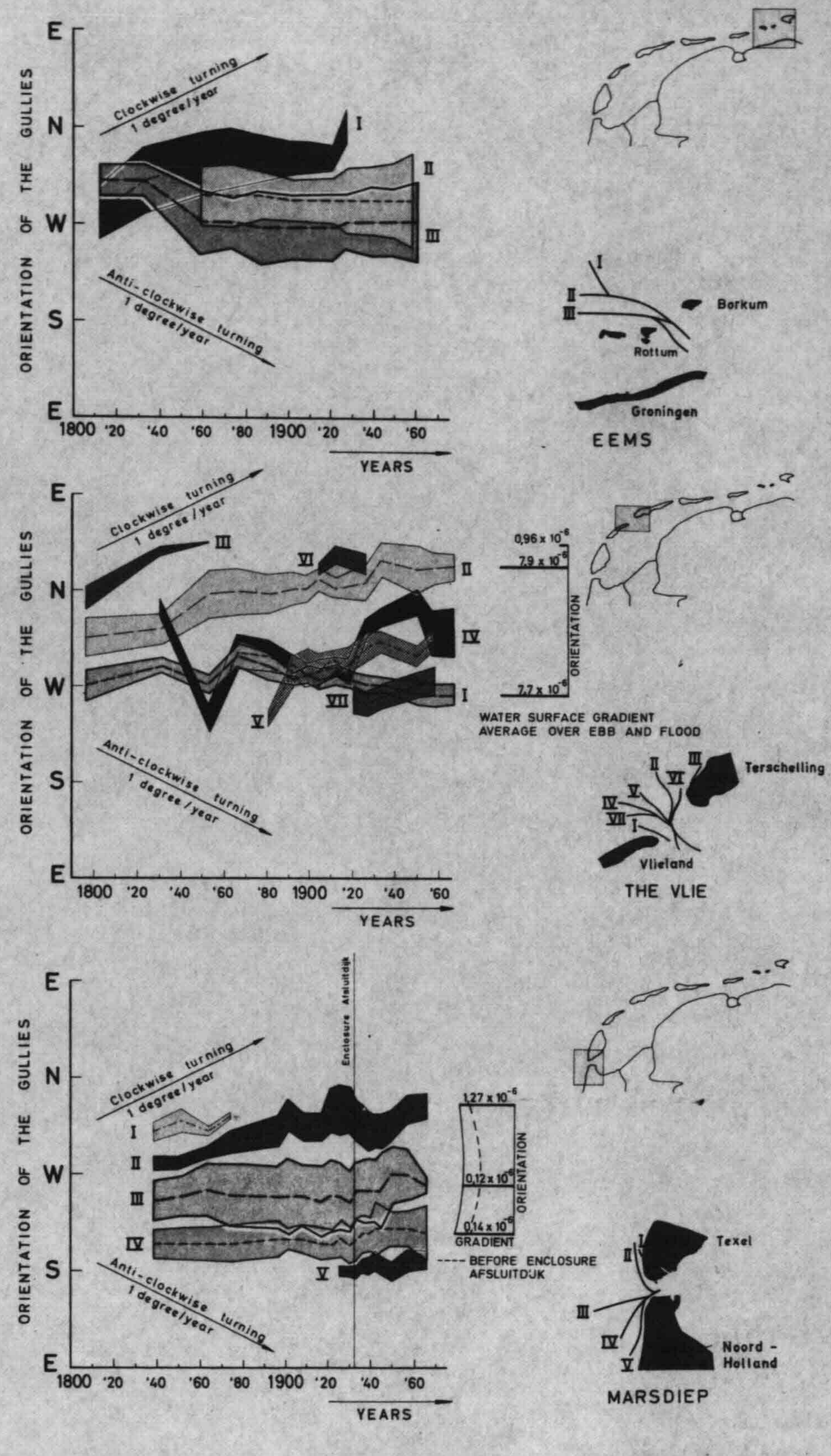


Fig. 17 The direction and the wet surface of the gullies

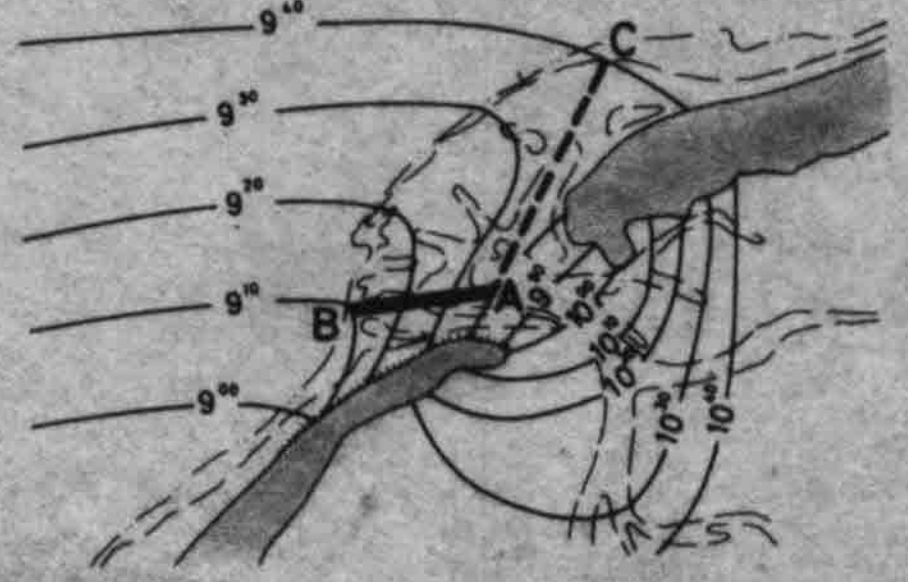


Fig. 16 Oriëntation of gullies according to VAN VEEN theory

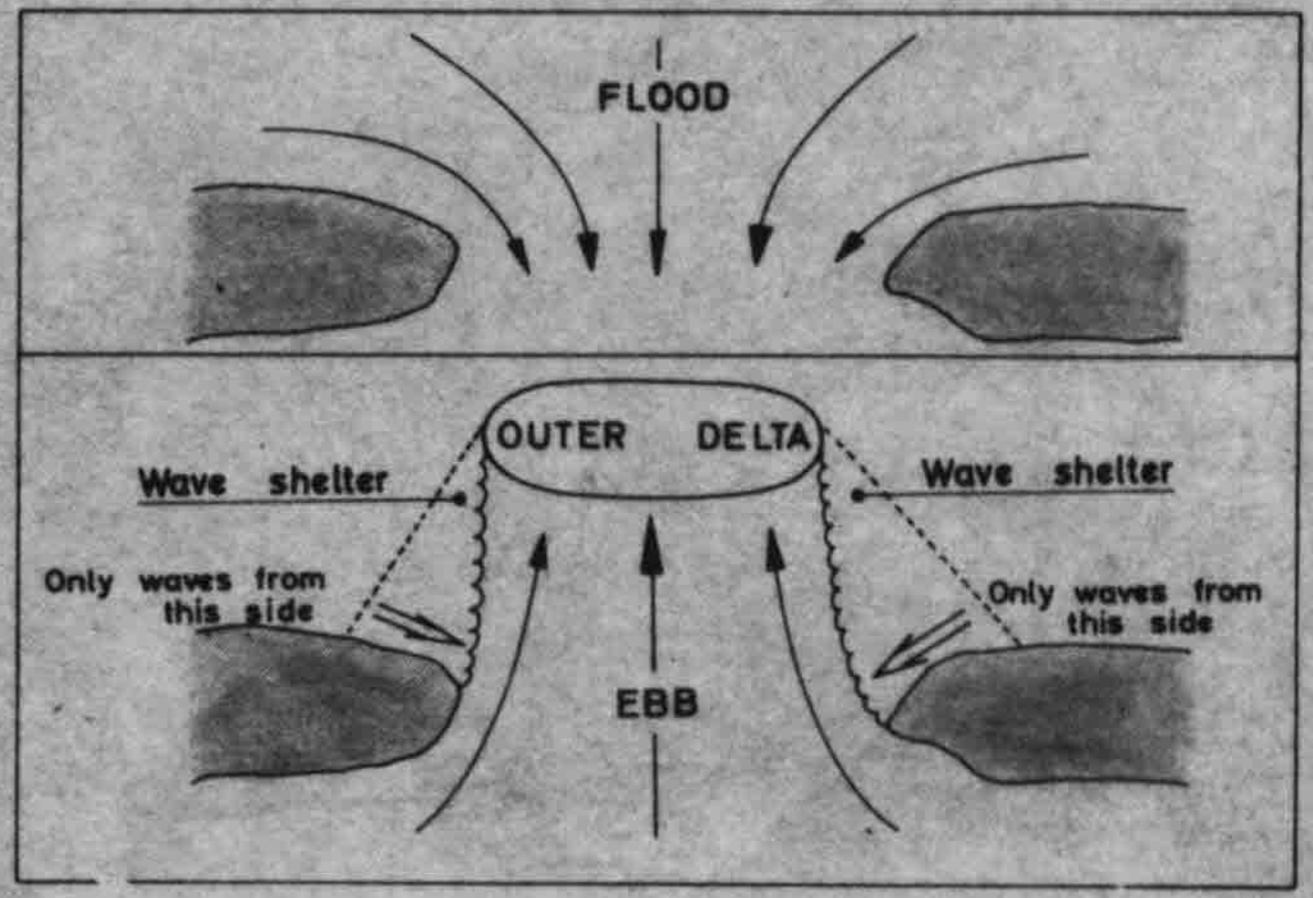


Fig 19 Erosion of the coast by tides and waves near an inlet

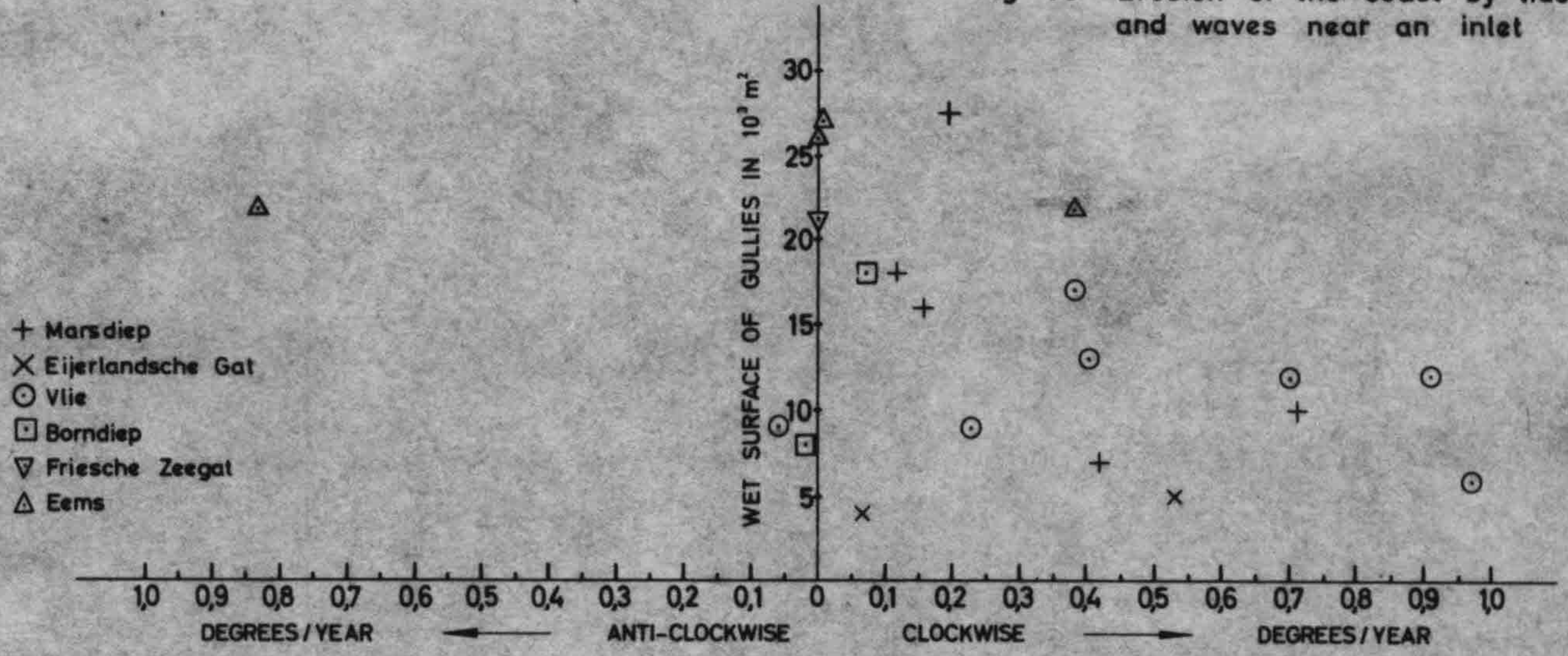


Fig. 18 The correlation between the wet surface and the moving of the gullies