Morphology and movements of nearshore sediments in a non-tidal environment, Køge Bugt, Denmark

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On a non-tidal, medium- to fine-grained sandy coast, the morphology and material budget in the littoral zone – primarily on the nearshore terrace and the shoreface – have been analysed on the basis of 65 detailed maps surveyed in a permanent grid for a period of two months. Simultaneously, records were made of wind, water, and waves. The map drawings and the calculations of variations in sediment volumes were made by EDP.

The investigations showed that the nearshore bar might be built up during high as well as low waterlevels, initiated either by a small breakpoint bar or a swash bar. The observed nearshore bar moved landward up to 30 cm per hour during periods with onshore winds and during constant water-levels and/ or constant wind speeds.

Analyses of the material budget showed that variations in volume (down to minus 1 m) were mainly due to profile adjustments. Especially noteworthy was that, after a gale, the quantities of sediments supplied were larger than those removed from the area during the gale. Furthermore, it was demonstrated that the total quantity of material of the inshore and the beach by and large remained constant in spite of obvious occurrences of nearshore bars migrating towards the coastline during the investigation period. Only an extraordinary gale situation was able to add permanent material to the barrier.

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On a non-tidal, low-energy coast a detailed knowledge of the nearshore dynamics is necessary to understand the conditions governing the stability of the coastal zone.

In any wave situation the inshore zone will be exposed to transformation of energy the morphological effect of which depends not only on the wave parametres, but also on the actual waterlevel. This means that the littoral zone displays a great variety of bed forms all with the essential quality that they are seldom stable for longer periods. The predominant form is here the nearshore bar – which is easy to identify by its shape and its movement pattern.

The present paper is an attempt to illustrate some of the problems connected with the importance of the nearshore bar for the material budget along the Danish coasts. The basic field work was performed on Jersie Strand, Køge Bugt (fig. 1), where any change in forms occurring within an area of 48 × 86 m during the two-month period, from September to November 1971, was registered. Simultaneously, data of wind and water-level were recorded by self-registering instruments (Ott, Schreibpegel, type X and Lambrecht anemometer, type 1438).

Description of the locality

The bay of Køge Bugt is located south of Copenhagen and is hydrographically part of the Baltic Sea. The geomorphological appearance of the bay is due to a late advance of the ice from the SE during the Weichsel glaciation. The water depths in the Køge Bugt area are shallow (maximum 20 m) as are also the fetches, except towards the SE. South of the beach Jersie Strand, in the central part of the bay, a shallow extends about 10 km towards the ESE. The tidal range in this part of the Baltic is less than 10 cm.

Earlier maps show that a barrier was under formation at least in 1860, but not until 1907 was it reproduced as a chain of islets on topographical maps. Development has since then been rapid, and already the topographical map from 1952 shows a continuous barrier system, at least 7 km long and only broken by two tidal inlets.

On the northern part of the barrier, about 400 m north of a tidal inlet where the marine processes were assumed to work undisturbed by the inlet dynamics, the observation area was set up, (figs 1 & 2). The width of the barrier is here about 85 m, and it consists of 2 ridges of which
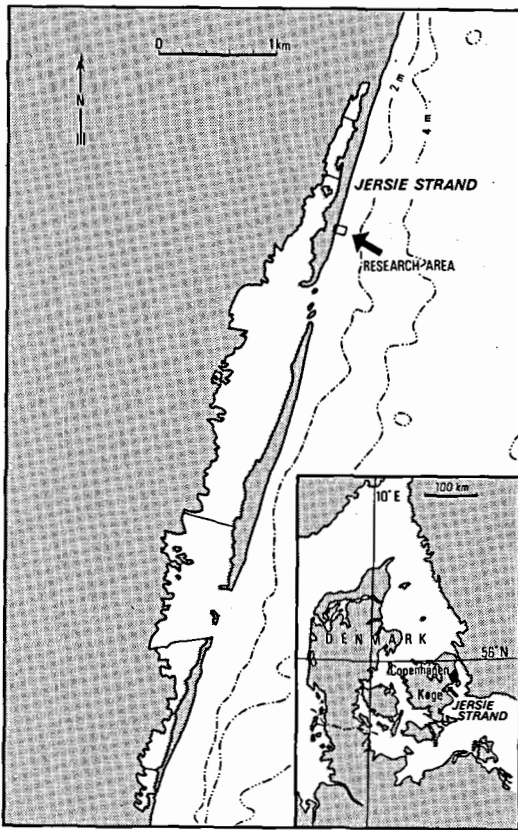
Fig. 1. Map showing the location of the study area in the central part of the bay Køge Bugt.

the oldest one reaches a height of 1.6 m and the youngest 1.9 m. The morphological border between the marine foreland and the beach (fig. 3) shows in the permanent vegetation, here mainly *Elymus arenaria,* at a level of about 1.3 m DNN (Danish Ordnance Datum), corresponding to the average of the highest water-levels.

Fig. 2. Cross profile of Jersie Strand, Køge Bugt. The profile shows the main elements of the coastal zone: the lagoon, the offshore bar, and the nearshore terrace with the investigated section inserted. Zone 1: −5 to +130 cm DNN, width c. 15 m, gradient: 5°. Zone 2: −15 to −5 cm DNN, width c. 50 m, gradient: 1°. Zone 3: −80 to −15 cm DNN, width c. 25 m, gradient: 2°.
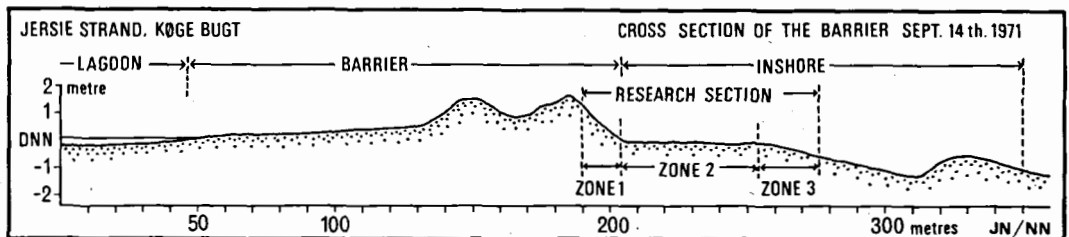
The dynamics and the morphology of the inshore zone have been investigated among others by Schou (1945), King & Williams (1949), King (1959, 1972), Hayes & Broothroyd (1969), Hayes (1972), and Davis & Fox (1972). In these papers there seems to be some uncertainty as to terminology for the easily moved bar type on the nearshore − called the (migrating) nearshore bar by the present authors. The terms ridges and runnels are used by Davis & Fox (1972) for a tideless environment (Lake Michigan); to some degree, they are thus departing from earlier authors' use of this term, such as King & Williams (1949) who define ridges and runnels as bar systems on very broad foreshores in typical tidal environments. Unfortunately, King & Williams, on the other hand, apply the term swash bars for the migrating bars produced in a model basin and which correspond in shape to Davis & Fox's ridges and runnels; however, these artificial bars differ essentially from the accumulation of sediments occurring on the foreshore in consequence of the swash/backwash dynamics during swells.

The names of the different coastal zones treated in this work and their location on the coastal profile appear from the term diagram below (fig. 4). It might be reasonable, however, first to comment on the diagram terms as to the subdivisions of the inshore zone, namely breaker zone, shoreface, and nearshore terrace, each covering a specific relief of the sea bottom where different form elements are produced at rising and falling water-levels. If, for example, we imagine the water-level drops considerably in the investigated area because of a temporary wind set-up in the Baltic, the water surface might cut the nearshore zone at the outer nearshore bar shown on the diagram. The foreshore dynamic would move seaward with a subsequent building up of one or more swash bars on the stoss side of the outer nearshore bar. As the swash zone on tideless coasts is identical with the foreshore, the total

JERSIE STRAND. KØGE BUGT   CROSS SECTION OF THE BARRIER SEPT. 14 th. 1971

Fig. 3. Part of aerial photograph of Jersie Strand from 21/4 1971. The profile line from fig. 2 is inserted and shows the northern border of the study area. 1. breakpoint bar; 2. near-shore bar; 3. beach and 4. swells. (Air photo: LLO).
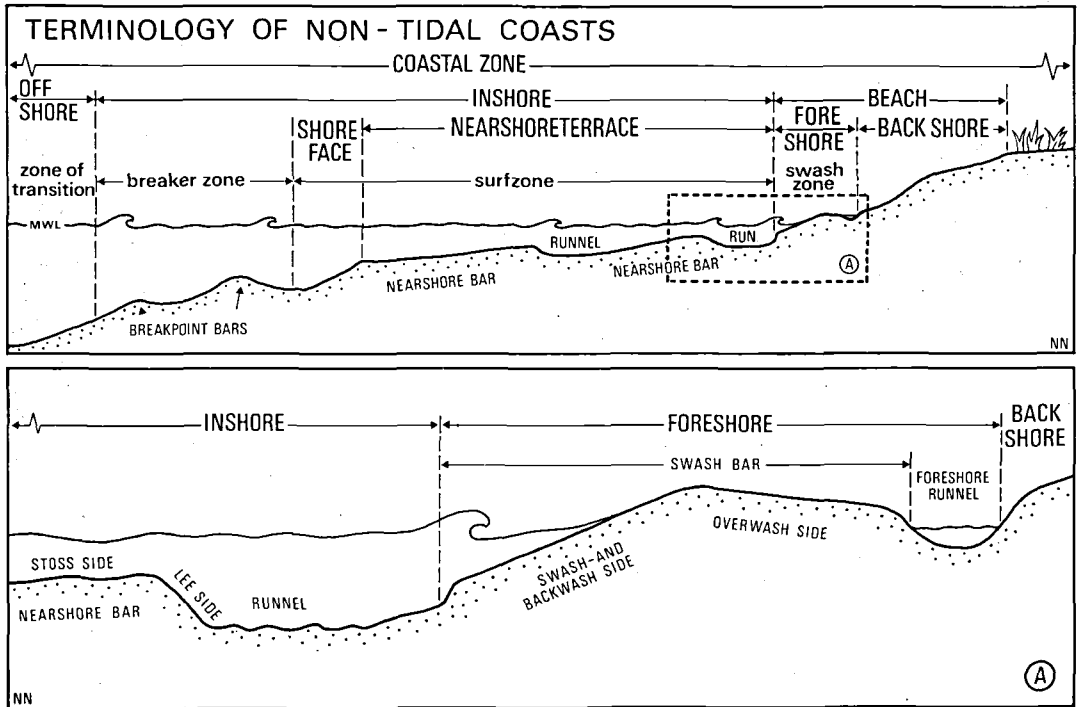
Fig. 4. Terminology of the nearshore environment of a non-tidal
coast.

width of the beach would be considerably enlar-
ged during low-water conditions.

The wave zones and the wave characteristics
change considerably during low-water periods.
These occur mostly with offshore winds. At the
same time, however, the nearshore gradient just
seaward of the swash zone is steeper than by
normal water-levels and this means that the surf
zone will be reduced or disappear even under
moderate wave activities so that the transition
waves dissolve directly into the swash zone.

Collection of data

In order to make the basic contour maps, the
establishment of a rapid, but also accurate
measurement method was necessary. Traditional
surveying on the basis of tachymetrical measuring
would be too timeconsuming both in the field and
during the subsequent calculation and wor-
king-up of the data. The survey procedure was to
fullfil the following conditions: 1) to be operati-
onal in any weather situation, 2) each measuring
procedure was to be so short that the registered

form elements could reasonably be considered a
"snapshot" of it, and finally, 3) that the collected
amounts of data – which were expected to be
large – should not result in more work than could
be coped with.

The authors have earlier made sample
measurements in grid nets with meshes in isome-
tric triangles in order to avoid interpolation diffi-
culties. As it also gives a good basis for electronic
processing, this system was chosen; furthermore
the above three points were fulfilled and the cal-
culation and the working up of the single contour
maps could be made simultaneously. (The pro-
gram was set up by Ole Hebin, Geographical In-
stitute, University of Copenhagen).

The grid net was related to an earlier establis-
hed basis line with points related to DNN. As
secondary basis, a line on the backshore was
used, located parallel with, and about 0.5 m off
the permanent vegetation border. The point net
which covered a morphological unit (nearshore
bar and a rip channel) was built up by means of
13 profile lines perpendicular to the basis line and
with 4 m-intervals (fig. 9). Each line was fur-
nished with poles (diameter: 22 mm) for each 4

Fig. 5. The measuring net ready for use, seen from the SW.

m. The poles were displaced 2 m in every second line to form an approximately isometrical triangle net with a total of 286 points (fig. 5). The top level of the poles were adjusted to same height above DNN. Routine measurements were made by measuring in each point the distance from the pole top to land and then inform the result over radio to a person on the shore. This procedure

Fig. 6. Measuring in rough weather on 23/9. The permanent pole net makes it possible to take records also under conditions when conventional methods are impossible to use. The single records are transferred to land over the radio.

could be performed during all weather conditions in about half an hour with an accuracy of ± 2 mm (fig. 6).

During the period 14/9–11/11 1971 a total of 65 surveys were made. The area was measured at least once a day from 14/9 to 28/10. Furthermore, measurements were made the following days: 30/10, 1/11, 4/11, 7/11 and finally one on 11/11. On days with great wave activity several measurements were made. Thus, two on 16/9, six 23/9, four 27/9, and two 28/9. To avoid misinformation as to the exact location of the nearshore bars, the often sharp border between the surface of the nearshore terrace and the bar front was included in each routine measurement. Furthermore, 13 special measurements were made of the morphological borders existing on the nearshore terrace of rip channels, swash bars, ripple patterns, the border: nearshore/beach etc. The pole net was also applied to investigate the water movements and current conditions in the study area. A balanced float was put out close to a pole and then followed through the net. When passing a pole, coordinates and time were reported over the radio.

The fundamental factors, wind speeds and waterlevels, were measured by means of self-registering instruments. The wind gauge was set up on the barrier itself, whereas the water-level recorder was placed in the harbour of Køge, 6.5 km from the sample area. To control the actual water-level, a board was set up in the measurement area and mounted with transparant tubes to sub-

Fig. 7. The mean grain sizes (M_z) and sorting (δ_1) (Folk & Ward 1957), shown in relation to the most important morphological borders.

line no	1	2	3	4	5	6	7	8	9	10	11	12	13
10	1.81 / 0.42						1.71 / 0.50	Mz / δ_1					1.87 / 0.38
12	1.94 / 0.44		backshore										1.83 / 0.43
14	1.00 / 1.21						1.74 / 0.75						0.89 / 1.62
16	1.88 / 0.95		foreshore										0.79 / 1.34
18	2.20 / 0.48						2.58 / 0.59						2.15 / 0.48
20	2.00 / 0.51		nearshore terrace										2.17 / 0.55
22	2.17 / 0.51						2.61 / 0.44		2.06 / 0.34				2.38 / 0.48
24	2.35 / 0.50								2.22 / 0.40				2.49 / 0.42
26	2.44 / 0.42						2.01 / 0.53		2.26 / 0.35				2.13 / 0.49
28	2.61 / 0.38								2.26 / 0.41				2.32 / 0.43
30	2.52 / 0.46		nearshore bar front				2.30 / 0.44		2.45 / 0.36				2.42 / 0.43
32	2.40 / 0.41								2.50 / 0.35				2.48 / 0.37
34	2.41 / 0.30						2.48 / 0.45		2.32 / 0.41				2.29 / 0.50
36	2.36 / 0.42												2.28 / 0.44
38	2.39 / 0.38						2.68 / 0.38						2.38 / 0.44
40	2.34 / 0.41												2.38 / 0.43
42	2.31 / 0.39						2.30 / 0.39						2.40 / 0.38
44	2.43 / 0.37												2.42 / 0.38
46	2.44 / 0.29						2.44 / 0.31						2.60 / 0.28
48	2.51 / 0.32												2.62 / 0.31
50	2.64 / 0.34						2.71 / 0.35						2.69 / 0.30
52	2.54 / 0.51		2.57 / 0.42	2.66 / 0.42			2.44 / 0.46		2.47 / 0.32		2.68 / 0.38		2.70 / 0.36

due the water column. Unfortunately, we did not have a recorder at our disposal, so wave heights had to be found by means of the waterlevel board, and wave period and -length had to be measured within the pole net. Compared with the quality of the measurements of form elements, we consider those of waves as a weak link in the present work. To illustrate the sediment conditions of the locality, samplings by a 5 cm high aluminium cylinder (diameter 4.5 cm) were made at each pole in lines 1 and 13, and at each second pole in line 7 and in crossline 52 (60 samples). Besides this sampling, which gave a general picture of the grain size distribution of the area, a detailed sampling (29 samples) was made in line 9 across a nearshore bar.

Sediments in the study area

Besides showing a slight difference between the most important morphological zones (backshore, foreshore, nearshore) the statistical parametres demonstrate a homogeneous sediment in the investigation area (fig. 7). A more detailed statistical analysis was therefore only made for the special sampling in line 9 in order to trace possible sorting processes in connection with the formation and migration of the nearshore bar.

Because of the slight variations an F-test was made by pairwise comparison, to investigate whether the sorting of the samples was significantly different. This was only due for combinations of samples from the top of the bar and from the seaward trough; but neighbour samples might mutually originate from the same mother distribution. Where the F-test allowed, a t-test was made on the mean grain size. By means of the t-tests' significance levels, it was now possible to separate 3 sediment types. For each group, a weighted average was calculated (fig. 8).

The largest mean grain size was found on the upper part of the flat stoss side of the nearshore bar, the side most exposed to the dynamic forces.
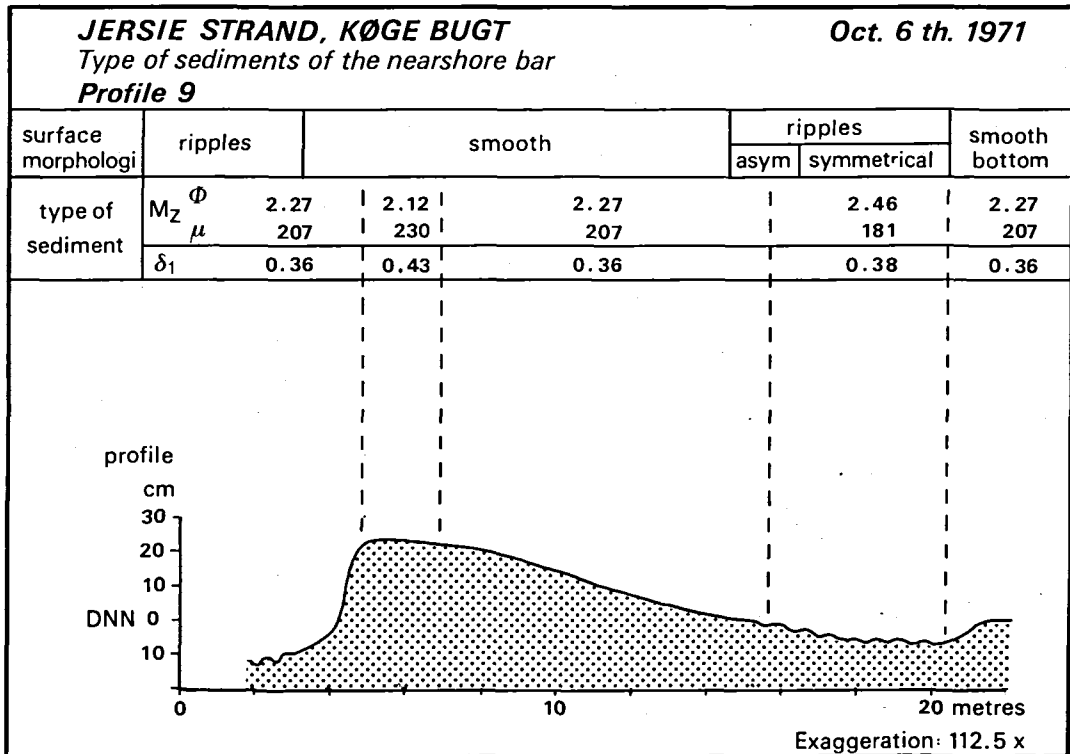
JERSIE STRAND, KØGE BUGT Type of sediments of the nearshore bar Profile 9						Oct. 6 th. 1971
surface morphologi	ripples	smooth		ripples		smooth bottom
				asym	symmetrical	
type of sediment	M_z Φ 2.27	2.12	2.27		2.46	2.27
	μ 207	230	207		181	207
	δ_1 0.36	0.43	0.36		0.38	0.36

Fig. 8. Relationship between grain size parameters, morphology and bedforms on the nearshore bar in line 9.
  During the sampling, variations in the micro morphology of the sea bottom were ascertained. The most coarse-grained sediments were taken at a quite smooth bottom influenced by surf waves, whereas the fine-grained sediments were found in places with ripples formed by the oscillating waves.

The grain size is decreasing both on the leeside and down towards the runnel in front of the next nearshore bar, a pattern which could also be discerned in the general sampling.

Morphological development during the observation period

The general morphological development in the study area appears from the selected contour maps (figs 9a–j). The nearshore bar migrates onshore at varying speeds, but stagnates before it reaches a complete fusion with the foreshore (16/10, fig. 9g), partly because new bars, formed seaward of the old one, absorb a great deal of the wave energy (fig. 1I). A characteristic feature in the development of the nearshore bar is that it does not migrate at right angles onshore, but ob-liquely through the study area. During the last part of the investigation period (4/11 to 11/11, figs 9i–j), the nearshore bar is dissolving just as it leaves the study area.

For more detailed analyses of the morphological development there was constructed besides the contour maps, a map showing the movements of the bar fronts and the swash bars (fig. 12) and a timedistance diagram of the profile lines 1, 4, 7, 10 and 13. The T–D diagram makes it possible to correlate the about 20,000 level records from the 65 contour maps and follow the morphological development in connection with wind- and water level observations (figs 10a–c). There were made no statistical levellings of the recorded wind- and water-level data such as Fourier analyses, as suggested by Davis and Fox 1971 and 1972 because the alterations of form on the beach plane terrace take place during specific weather situations and within very short intervals.
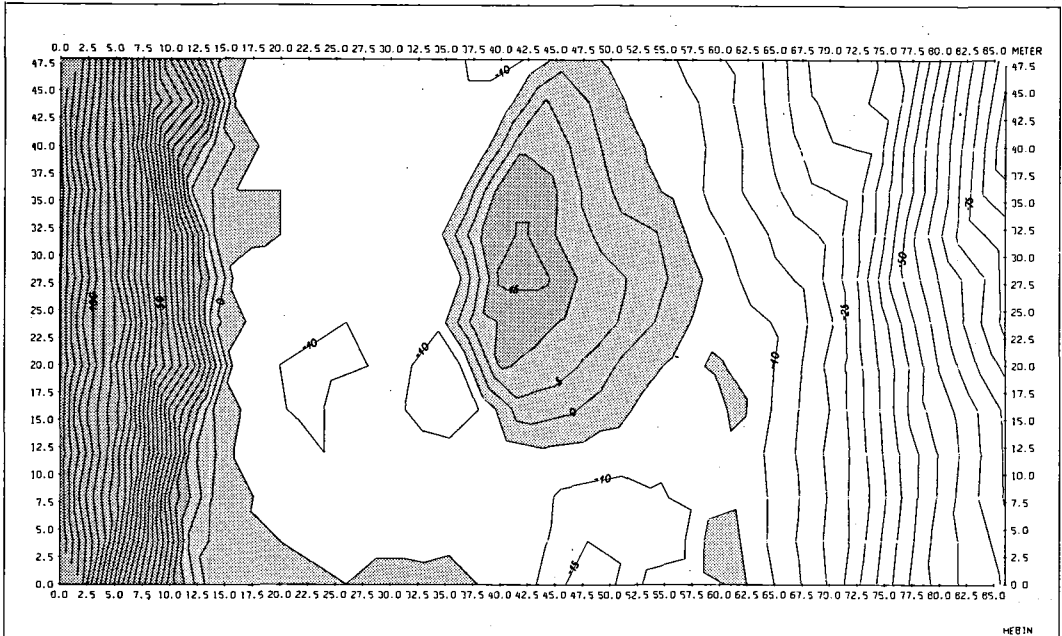
Fig. 9a. Contour map of the study area 14/9–1971 (contour interval: 5 cm) surveyed from 1535 h to 1620 h. Water level: +3 cm DNN, wind velocity: 3 m/sec, from NNW. The figures of ordinate and abscissa are in metres. The ordinate points NNE.

The −5 cm contour delimits the nearshore bar which has the characteristic steep lee side and flat stoss side. To the south, a rip channel drains the water from the trough between the nearshore bar and the beach.
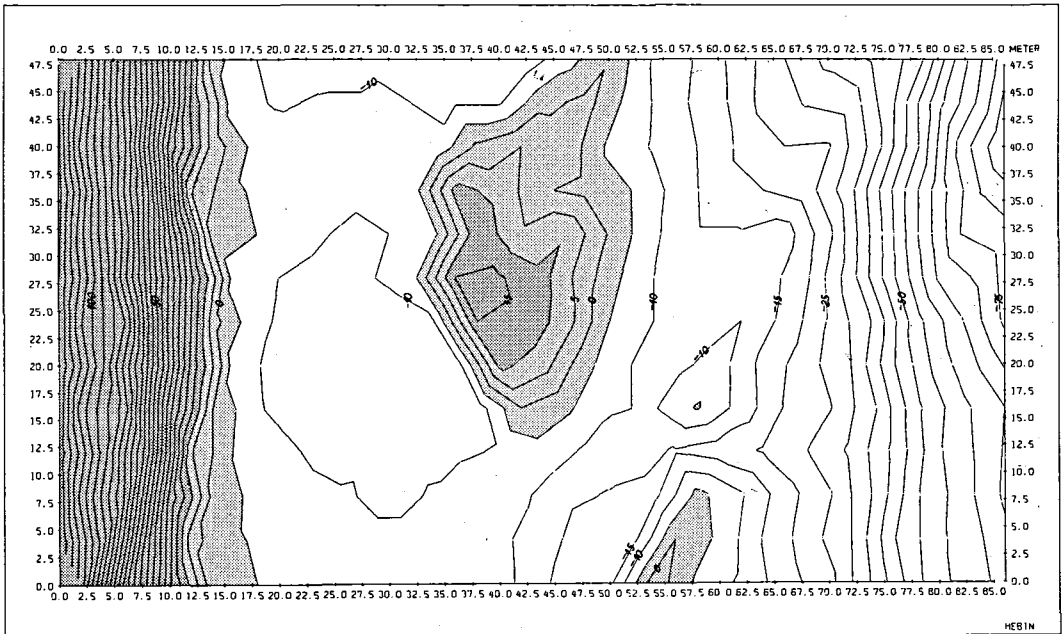

Fig. 9b. Contour map 23/9–1971, surveyed from 1955 h to 2110 h. Water level: +31 cm, wind velocity: 10 m/sec, from SSE.
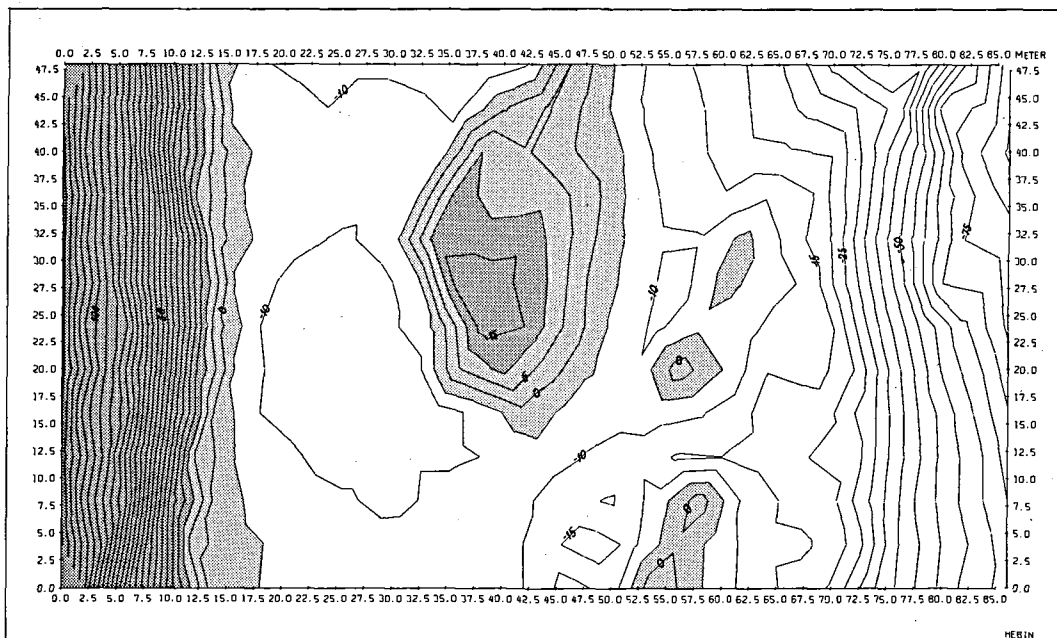
Fig. 9c. Contour map 26/9–1971, surveyed 1840 h. Water level:
+33 cm, wind velocity: 1 m/sec, from WNW.
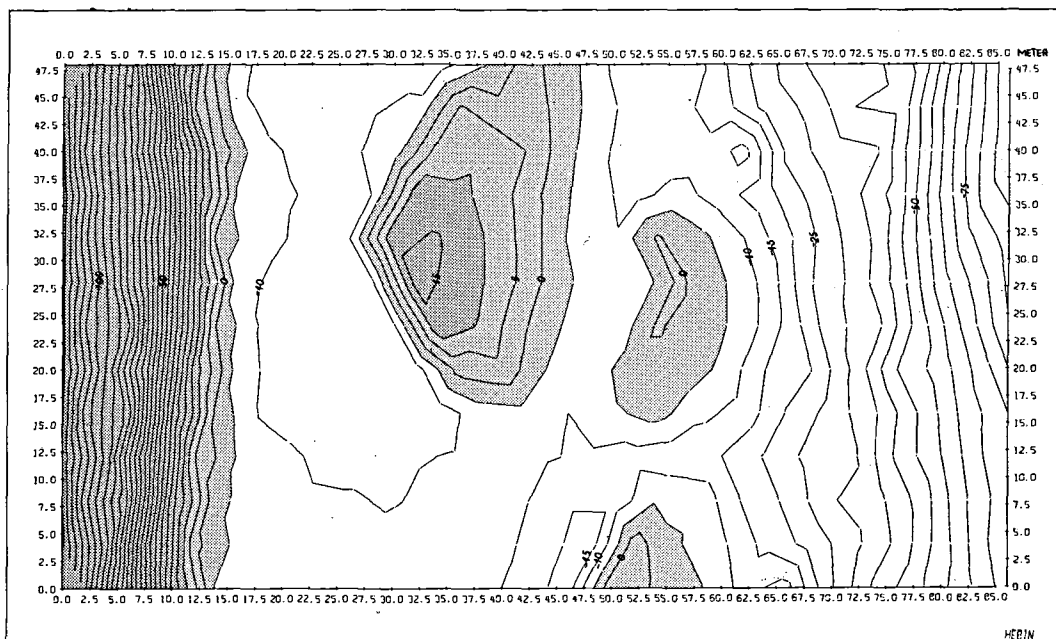
Fig. 9d. Contour map 28/9–1971, surveyed from 930 h to 1040
h. Water level: +25 cm, wind velocity: 9 m/sec, from ESE.

Fig. 9e. Contour map 2/10–1971, surveyed 1640 h. Water level:
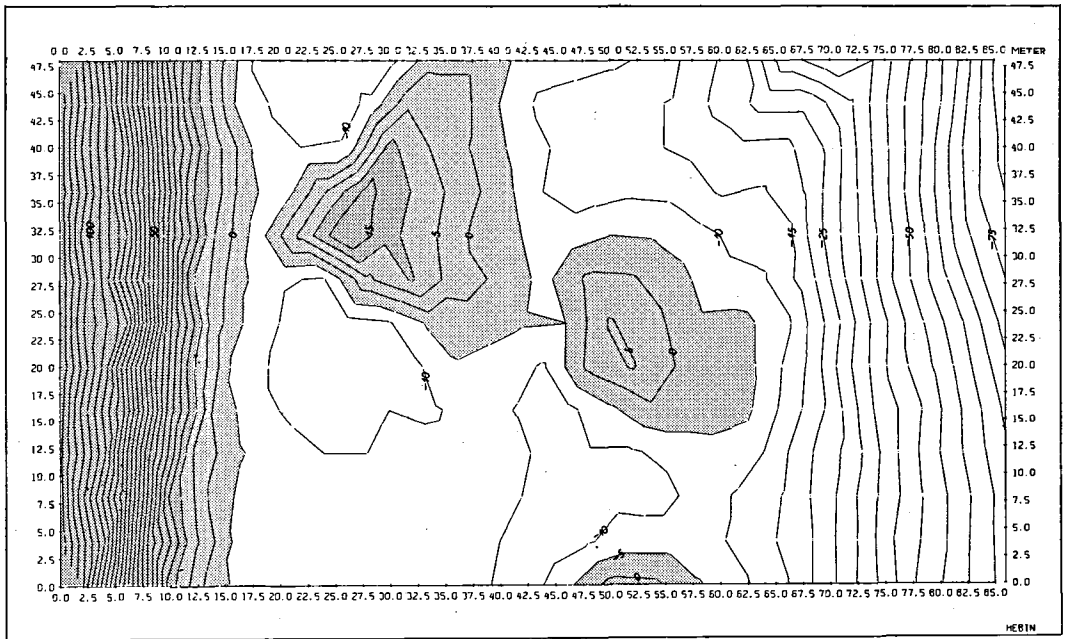+19 cm, wind velocity: 4 m/sec, from WNW.

Fig. 9f. Contour map 15/10–1971, surveyed from 1620 h to
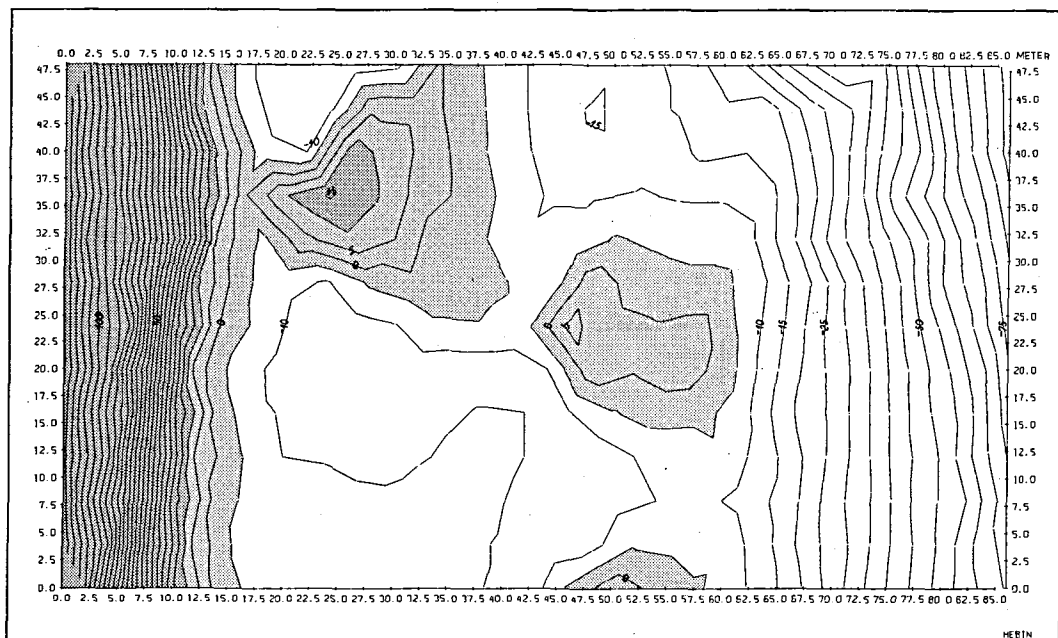1705 h. Water level: +45 cm, wind velocity: 2 m/sec, from SE.

Fig. 9g. *Contour map 16/10–1971, surveyed from 1725 h to 1815 h. Water level: +30 cm, wind velocity: 8 m/sec, from S.*
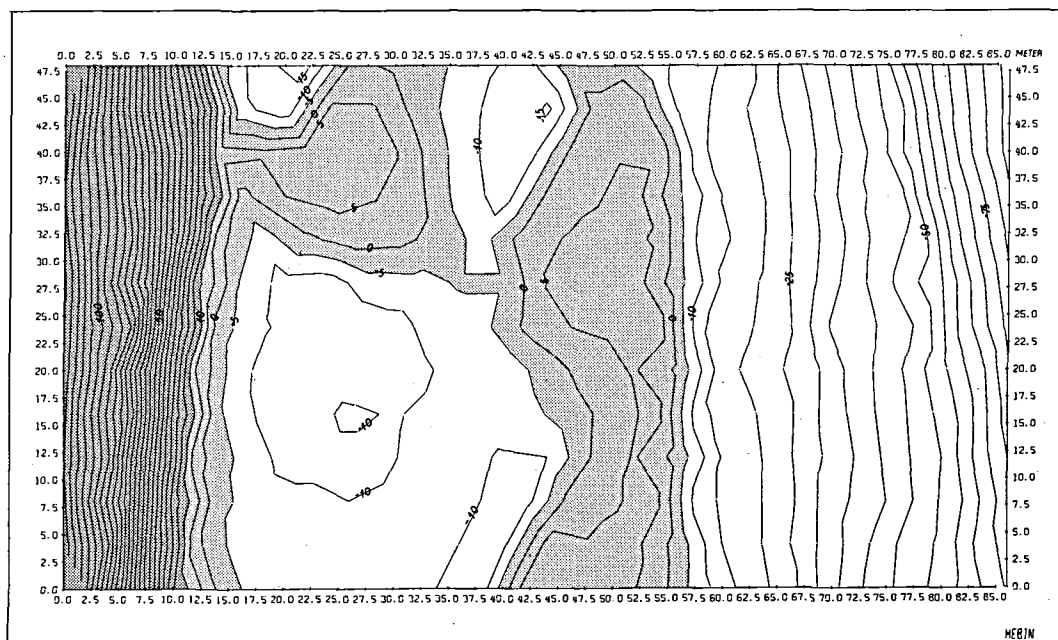

Fig. 9h. *Contour map 18/10–1971, surveyed from 1115 h to 1220 h. Water level: 0 cm, wind velocity: 9 m/sec, from SW.*
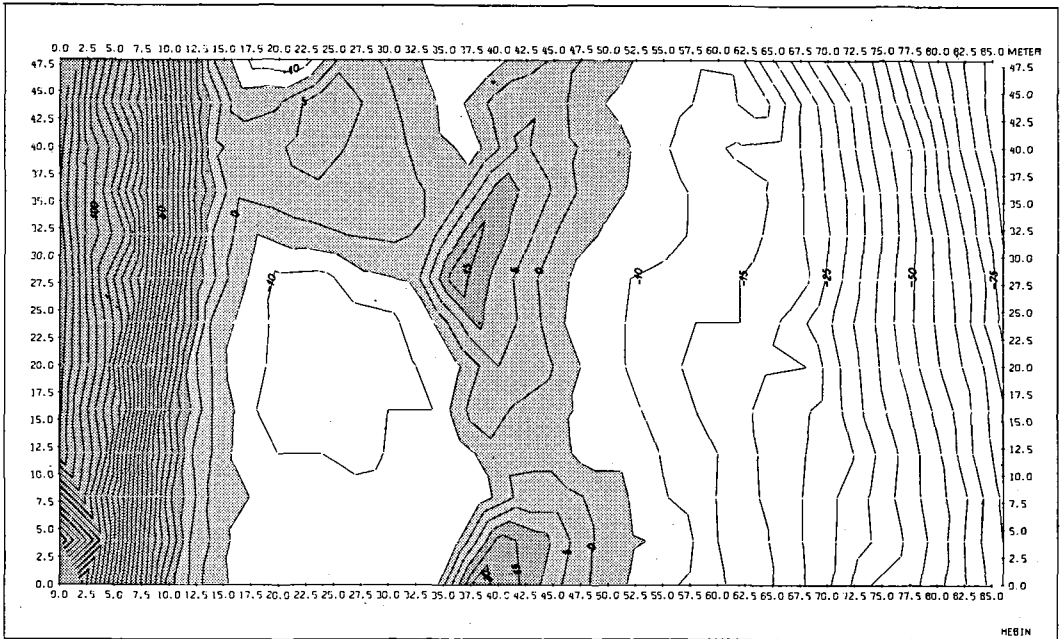
Fig. 9i. Contour map 4/11–1971, surveyed from 1100 h to 1200 h. Water level: +1 cm, wind velocity: 9 m/sec, from WNW.
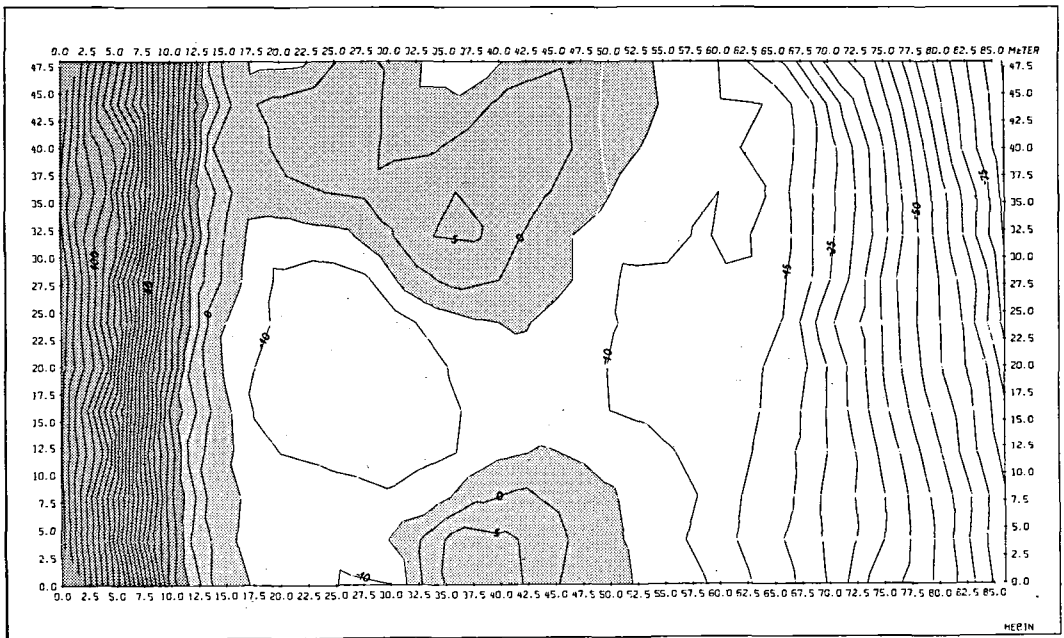

Fig. 9j. Contour map 11/11–1971, surveyed from 1020 h to 1120 h. The last map of the investigation. Water level: +3 cm, wind velocity: 6 m/sec, from WSW.
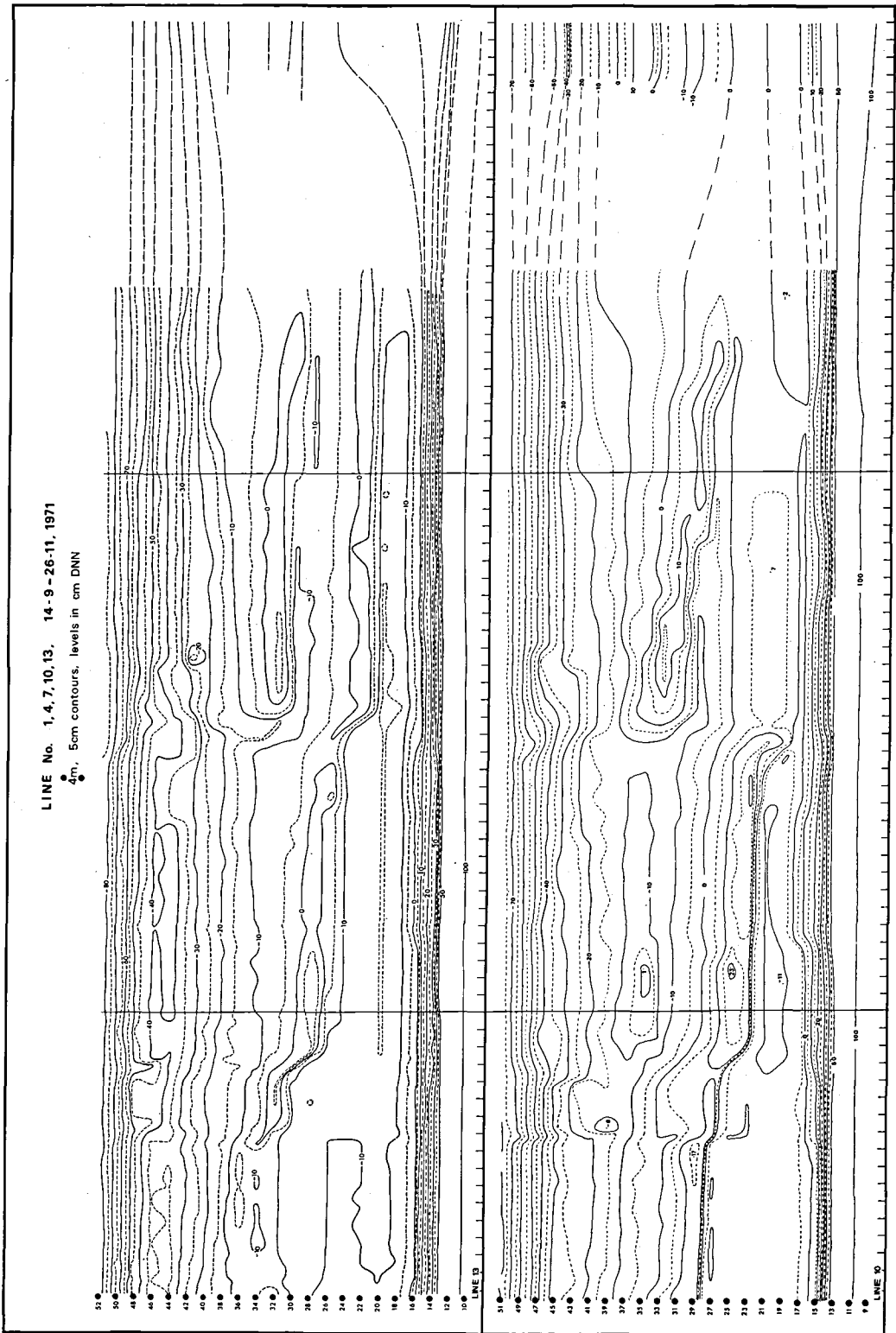
Fig. 10. T–D diagrams for the profile lines 1, 4, 7, 10 and 13. Time is abscissa and the profile the ordinate, indicated by pole-numbers. When an isoline is parallel with the time-axis, the location of the level is stable in relation to the shoreline. If the isoline is not parallel with the shoreline, the profile is changing and the speed of this change increases by the angle between the isoline and the x-axis.
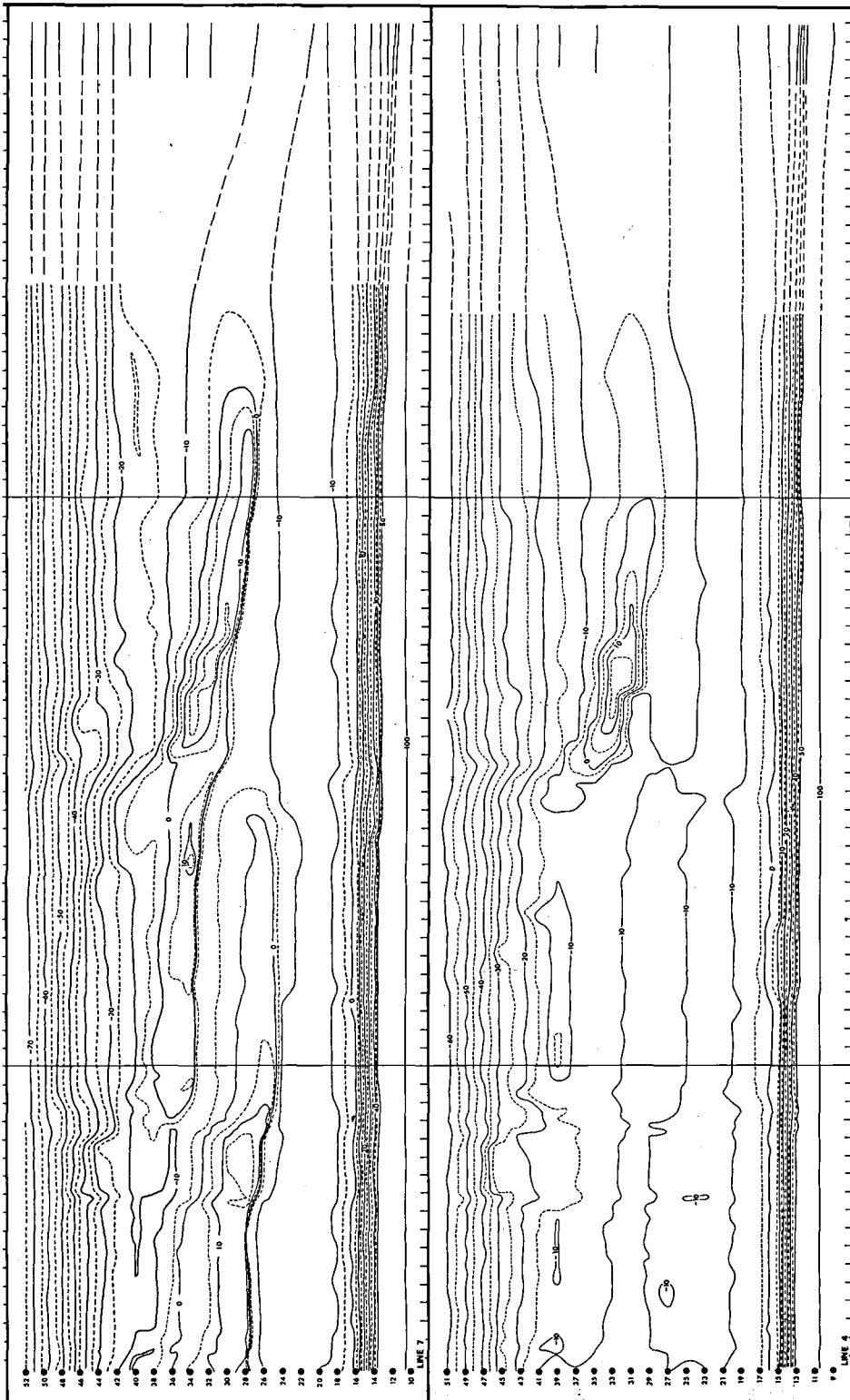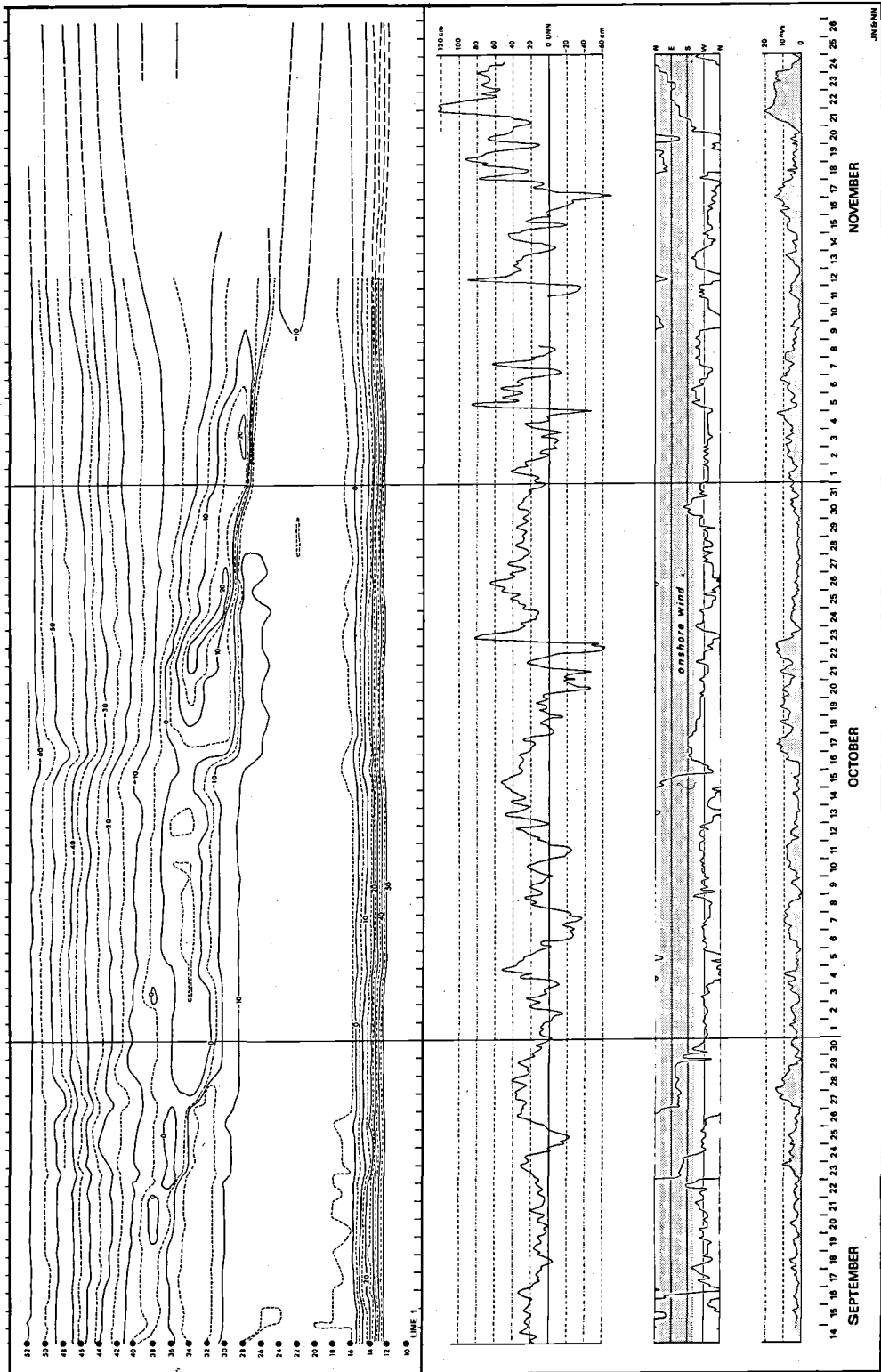
Fig. 10b.

Fig. 10c.

Fig. 11. The nearshore terrace at extreme low-water seen towards the south on 22/10. The innermost nearshore bar is in contact with the beach.

The morphology in the profile, line 10 (fig. 10a) shows the development of the northern part of the study area and central part of the nearshore bar. The dynamic picture in the diagram can generally be divided into two easily separated parts which represent stable and mobile phases. The active periods are: 23/9, 27–29/9 and 15–18/10. The night between 22 and 23/9 the wind turned from the WSW over N to the SE and thereby became active on the coast. Simultaneously the wind speed increased from 0 to maximum 11 m/sec. and the waterlevel from 10 to 30
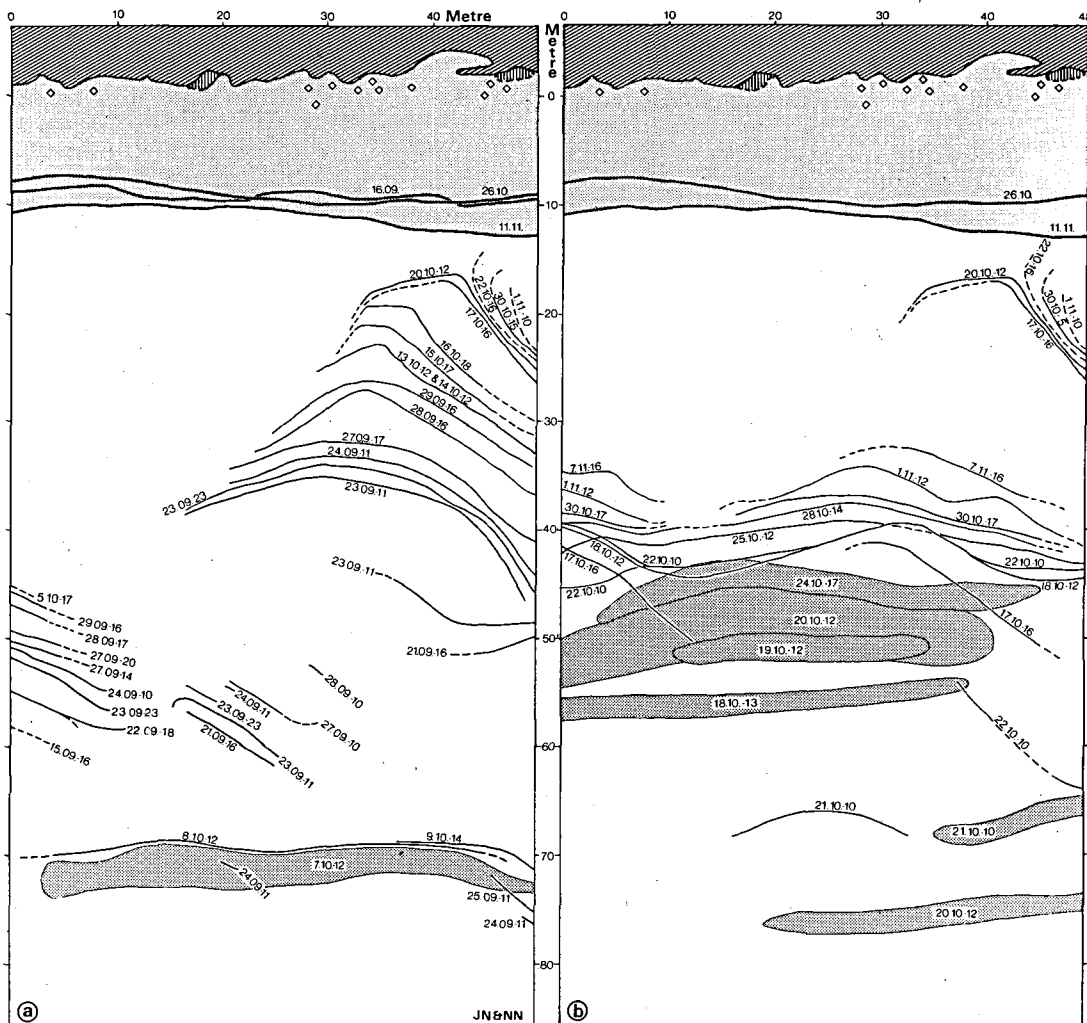
cm DDN (figs 10a, c). The nearshore bar front, which has moved about 1 m onshore during the 9¹/₂ days since the 14/9 (fig. 12) now migrated about 2.5 m onshore during the next 24 hours from 23/9 1100 until 24/9 1100, an average speed of more than 10 cm/hour. Table 1 shows the recorded migration speeds from measurement to measurement.

Although 6 measurements were made 23/9 it is of course only possible to get average values for the bar motion; nevertheless the following interesting thing could be noticed: the migration speed

Table 1. The migration distance and speed of the nearshore bar (from original records) and the simultaneous wave-, wind-, and water-level conditions for the period 22/9–24/9 1971, measured in line 10. The direction of bar movements diverges 25° from the direction of the profile line.

Date	hour	Waves			Water-level (cm) DNN	Wind veloc. (m/sec.)	Direction °N	The bar's front movement (cm) (cm adjust. 25°)		The bar's average speed (cm/h) (cm/h adjust.)	
		H(m)	L(m)	T(sec.)							
22/9	1600	0.04	0	0	8	5	160				
								10	9	0.2	0.2
23/9	1100	0.15	5.0	2	19	5	130				
								10	9	3.3	3.1
23/9	1400	0.4	7.0	3	23	7	140				
								20	18	13.3	12.5
23/9	1530	0.5	8.5	3.6	27	6	140				
								60	54	24.0	22.6
23/9	1800	0.5	11.0	3.4	28	7	150				
								60	54	24.0	22.6
23/9	2030	0.45	8.0	4.2	31	10	150				
								45	41	18.0	16.9
23/9	2300	0.3		3.8	27	7	150				
								65	59	5.6	5.3
24/9	1030	0.2		3.3	21	7	240				
								20	18	1.1	1.1
25/9	1620	0	0	0	–15	6	280				

⌒ 22.10.16	Front of a nearshore bar Oct. 22. 1600 h.
⌒ 22.10.16	Front of a nearshore bar Oct. 22. 1600 h., dim border
⌒ 26.10	Breakpoint step Oct. 26.
7.10.12	Swash bar Oct. 7. 1200 h.

▨	Beach
▨	Dense veg. (Elymus arenarius)
▥	Vegetation (Honckenya peploides)
◇ ◇ ◇	Veg. tufts (Elymus arenarius)

Fig. 12. *The positions of the nearshore bar fronts and of the swash bars during the investigation period.*

increased markedly around noon, about 2 hours after the water-level had submerged the near-shore bar, and the speed increased with the in-creasing wind speed and water-levels the next 6–8 hours. The decline in speed recorded after 2000 followed the decline in both water-level and

wind speed. This accordance was not found, how-ever, between the two measurements: 23/9 at 2300 and 24/9 at 1100, when the bar motion decreased to 5.6 cm/h. The explanation must be the changing wind direction (24/9 at 0400) from the active SSE wind to the passive SW direction.

Table 2. The migration distance and speed of the nearshore bar and the simultaneous wave-, wind-, and water-level conditions for the period 25/9–30/9 1971, measured in line 10.

Date	hour	waves H(m)	L(m)	T(sec.)	water-level (cm) DNN	wind veloc. m/sec.	Direction °N	The bar's front movement (cm)	(cm adjust. 30°)	The bar's average speed (cm/h)	(cm/h adjust.)
25/9	1620	0	0	0	–15	5	280				
								30	26	1.1	1.0
26/9	1840	0	0	0	32	1	300				
								80	69	5.2	4.5
27/9	1015	0.3	9.5	3.8	24	8	120				
								95	82	32.6	28.2
27/9	1310	0.5	10.6	4.1	30	12	120				
								70	60	18.0	16.0
27/9	1650	0.6	10.2	3.9	37	12	130				
								30	26	10.4	9.0
27/9	1950	0.4	9.1	3.3	36	12	130				
								275	238	18.3	15.9
28/9	1005	0.4	10.0	3.5	25	9	110				
								51	44	13.0	11.3
28/9	1400	0.4	8.9	3.0	39	10	130				
								60	52	17.1	14.9
28/9	1730	0.4		4.7	41	10	110				
								144	124	6.1	5.3
29/9	1615	0.2	8.1		33	1.8	150				
								10	9	0.5	0.5
30/9	1100	0.1	7.0	3.0	7	5	240				

27/9 and 29/9 the forms were considerably displaced on the nearshore, and the highest bar front speed was registered 27/9 at noon (32.6 cm/h) as table 2 shows.

When the water-level was high and the nearshore bar submerged, water movements were quite different from the direction of the incoming waves generated on the nearshore terrace. On the 27/9 two current observations were performed. By means of a balanced float the water movements could be surveyed in great detail because of the permanent grid net.

On the landward part of the nearshore terrace, where the waves are transformed into surf waves (at −20 to −30 cm DNN) the floats follow the courses determined by the wave-generated northward current, by the breaking surf waves and the drag of the SE-wind on the water surface. The pattern of the current courses (fig. 13a) is apparently not influenced by a normal return current in the rip channel. On the contrary, the highest landward velocities are found just here (70–100 cm/sec.). Within the nearshore bar area there is a clear trend to increased speed (30 cm/sec.) in a northward direction; this suggests the presence of a rip channel north of the investi-

gation area. Only floats that have passed through the channel will strand on the shore.

On the velocity map (fig. 13b) the wind speed has increased somewhat and the convexity of the current courses is less evident. The difference between the two situations is primarily to be found in the conditions prevailing at the rip channel; as fig. 13b shows, there is an apparently active rip current (no currents head into the channel). The rip channel just N of the study area seems to be partly out of function, however, as all current courses point towards land.

It was demonstrated that rip channels in waters as shallow as these are governed by the same processes – with alternating active periods – as the well-known, larger rip channels in the break point bars. The investigation showed also that the magnitude of these currents, generated so close to the shore, are sediment-transporting and erode both behind the nearshore bar and into the rip channel. Note the topographic development of the nearshore bar on the current velocity maps.

Between 30/9 and 13/10 the nearshore bar only migrated 1.7 m onshore; the graphs for this period show a general low water-level and an offshore wind. On 13/10 the water-level rose to
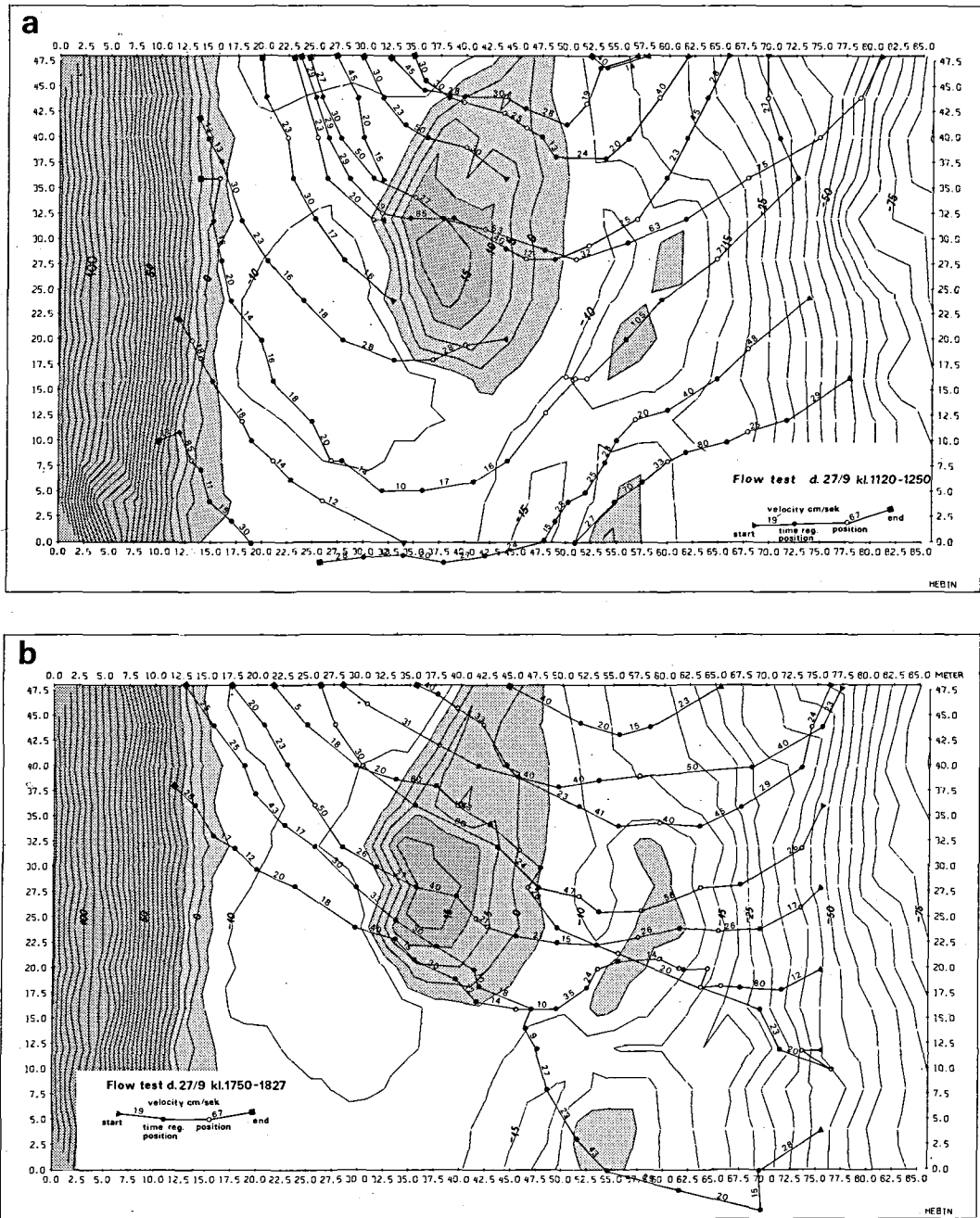
Fig. 13. Float tests made on 27/9. The courses of the float show the current movements around the nearshore bar during a dynamically active period. a) Records from 1120 h to 1250 h, b) from 1750 h to 1827 h. The Contour maps were surveyed a: from 950 h to 1045 h, b: from 1625 h to 1715.

Notice that the direction of the float courses farthest off are SW and almost at right angles to the advance of wind and waves. This can be explained by a south-going coastal current, which generally occur in this part of the day during wind from the E–SE sector.

+50 cm DNN, but the wind had a direction that was inactive for the shore, and the wave activity was very low. These conditions changed during the night between 14 and 15/10, when the high water-level was combined with a change in wind direction from N to E and on to S. Although the wind only blew 1–2 m/sec., the wave observations 15/10 at 1610 show wave heights of 15 cm and a wave period of 4.5 sec. Measurements on the nearshore bar front during the period 14/10 at 1200 until 15/10 at 1600 show, however, that although small, these waves were sufficiently high to induce a front movement in line 10 of more than 2 m. On 16/10 before noon the development accellerated, as the wind speed increased from 1.5 m/sec. to more than 10 m/sec., and the wind turned straight south; i.e. it becomes wave-generating although the entrance angle in relation to the coast normal was very wide. The bar was now covered with 10–15 cm. water, and the wave heights just seaward of the nearshore bar were measured to be 30–35 cm and the wave period to be 3.3 seconds. These small and steep, short-period waves proved to be very effective in displacing the nearshore bar, and the isolines (+5, +10 cm DNN) curved markedly onshore during 16/10 (fig. 10).

The further isoline course shows a stabilization of the area; this may seem odd, as the water-level is still high and the waves 25–30 cm high. The explanation is seen in fig. 12, where the direction of the migrating bar turns sharply NNW in good accordance with the refracted small waves of high frequency from the south.

After the fusion of bar and beach, the changes in forms were insignificant near the beach (18/10–23/10). Further seaward, however, a swash bar was being built up (figs 9h, 14), as the water-level in this period was very low, and the nearshore terrace almost horizontal. Any wave will be a constructive agent under such conditions, i.e. transport sediments onshore and contribute to increase the nearshore gradient. On 23/10 the swash bar was overwashed and was immediately transformed into a nearshore bar (steep leeside) (fig. 9i).

The correlation between variations in weather and the forms in line 1 follows the pattern of the bar located to the north; the same cannot be said of the morphology in line 4. The course of the isolines is seen to be disturbed only during the period 18–24/10 where the rip channel dried up and sediments were deposited in it, producing a swash bar (+15 to +20 cm DNN) (fig. 9h). The

Fig. 14. Exposed swash bar and rip channel in the nearshore terrace.

Fig. 15. Nearshore bars in the investigation area separated by the rip channel in line 4.

transformation into a nearshore bar was also taking place, but here the level declined so much in relation to the nearshore bars north and south of it that the rip channel was re-established down to its first depth (about -10 cm DNN) (figs 9j, 15).

Generally speaking, the current velocities in the rip channel were low (<10 cm/sec.) and lay only a few times above the critical threshold values for sediment motion. When the southern bar nevertheless could not traverse the channel, it was due to two things: During moderate wave situations, but with a water-level just covering the bars, surf waves will be created that are sufficiently effective to transport sediments across the bar. In the rip channel, however, the depth was so much higher that the surf waves did not break. Part of the sediments transported across the southern bar were taken out through the rip channel in spite of the low current velocities, as some sediments were still in suspension when the surf waves reached the lee front of the bar. During decreasing water-level, the rip channel narrowed and for shorter periods – before totally drying up – assumed a river-like character, (fig. 10b); the erosion of the leeside of the southern bar was then obvious.

The isolines are very stable on the outermost part of the nearshore terrace and the nearshore face, except during periods with strong onshore winds (23/9, 27–28/9, and 16–17–18/10). This means that the profile reacts very rapidly (few hours) – especially on the nearshore face – on changes in wave- and water-level parametres, and during this process a "normal weather profile" and a "storm profile" are created. The following temporary transport of material, onshore or offshore, may generate new forms. This can also be observed at several places in the T–D diagrams; as these new forms are preserved simultaneously with the re-establishment of the seaward located part of the nearshore terrace, this must mean a net surplus of sediments. This will later be demonstrated by means of volume calculations.

Concluding remarks on formation and morphology of the nearshore bar

A nearshore bar is formed during extreme wind- and water-level conditions. During high water-levels and strong onshore winds, initial break point bars develop outermost on the nearshore terrace as symmetrical, low, ridge-formed accumulations which, towards the end of the extreme situation, will be transformed into the assymetrical shape of the nearshore bar. The bar's chances of survival depend on the subsequent period with quiet wind conditions and normal water-levels being long enough to allow the bar to migrate

away from the shoreface and on to the nearshore terrace, still increasing in size.

During offshore winds and low water-levels the initial part of the nearshore bar may arise from a swash bar in different places on the nearshore terrace, dependent on the water-level. The subsequent normal water-levels will then transform the swash bar into a nearshore bar. The chance that this nearshore bar will exist for a longer period depends on the location of its 'birth' (fig. 12).

Having left the shoreface and entered the nearshore terrace, the bar migrates towards the shore during any wave situation, if covered with water, or overwashed by the swash; i.e. the bar migrates onshore under the influence of both storm waves and swells. The migrating speed of the nearshore bar varies from a few cm to 30 cm/h.

The characteristic cross profile of the nearshore bar with its steep leeside and flat stoss side is normally maintained under all dynamic conditions, although the gradient of the uppermost part of the stoss side varies with the wave parametres, so that steep waves will level the top to an almost horizontal plane, whereas constructive waves (swells) will increase the top level and thereby also the gradient of the stoss side.

The nearshore bar starts as long ridges parallel to the coast, but in Køge Bugt they do not remain stable. Just after advancing onshore, the ridge splits up into a number of minor islands separated by rip channels. The horizontal shape of the islands will thus largely be influenced by refracting surf waves. Therefore the flanks of elongated islands are often seen with landward directed 'horns', whereas round or ellipsoidal bar islands may develop one or two protuberances on the central part of the leeside; the latter was characteristic for the here investigated nearshore bar.

The nearshore bar does not change in form if exposed during low-water conditions if the water only falls continuously and at a certain speed. If the water-level stabilizes at a low level and cuts the leeside of the bar or the nearshore terrace farther seaward and the waves are moderate to swell-like, a swash bar will be built up in a few hours. With increasing water, the swash bar disappears as a form.

The migration direction is primarily governed by the incidence direction of the waves. When this is different from normal to the coast, the nearshore bar migration will furthermore be influenced by the wave-generated current's ability to transport suspended material parallel with the bar front and deposit it at sheltered places.

As the advance of the bar depends on material removed from stoss to leeside, the nearshore bar will follow the direction of the waves and consequently always be directed onshore. Nearshore bars migrating seaward, however, have also been observed by Davidsson 1963: 114–115, and Davis & Fox 1972: 411. A possible explanation for Davidsson's observation might be that the migration pattern was determined on the basis of a single profile. A convex bar, advancing obliquely onshore, passing the profile line, might be misinterpreted as moving offshore, especially when the flanks are passing. An apparent movement away from the coast might also occur, if there is a conspicuous erosion on the leeside and/or on the flanks by a wave-generated current combined with rip channel dynamics, cf. fig. 13b. This, however, will induce a reduction of the sediments of the nearshore bar and not a dislocation away from the coast of the original bar.

Material budget and development of volume

On the basis of many observation points and the frequent measurements, it has been possible to calculate and construct a curve showing the total volume variations of the area by means of EDP (fig. 16). The volume can be calculated as the sum of the vertical prisms whose bases are determined by the grid net (reference plane: −1 m DNN) and whose surface (level and gradient) is given by 3 measured levels. In order to analyse different parts of the study area we calculated, in the same profile lines as chosen for the T–D diagrams, the material budget in cubic metres gross and net for 24 hours in a belt of 1 metre along the line (fig. 17).

The material budget in connection with the migration of the nearshore bar balances as to changes in negative and positive volumes; net result is consequently zero. At no time during the process is this an obvious trend; on the contrary, the morphologically active periods can be divided into markedly destructive and constructive pha-
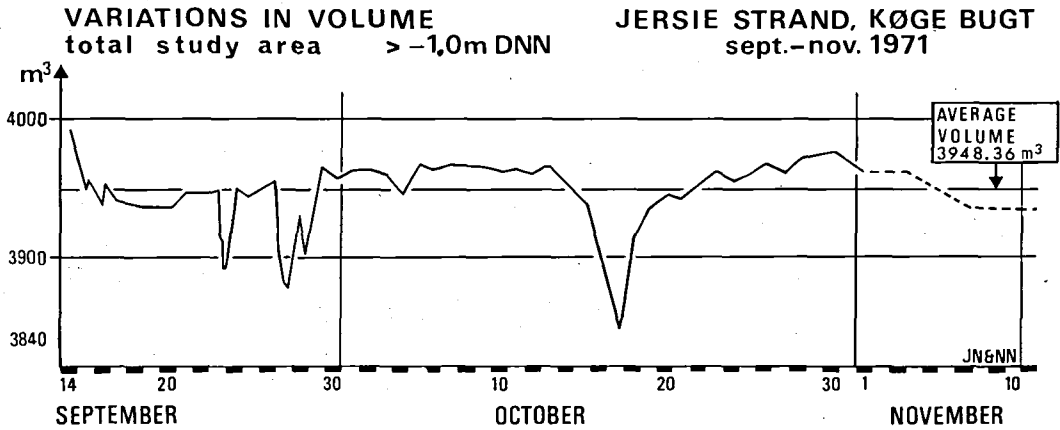
Fig. 16. Volume variations for the total analysed area. −1 m
DNN has been used as reference plane. The three sharply mark-
ed minima on the curve (net erosion for the whole area) are
closely connected with the gale periods 23/9, 27/9, and
15–16/10. Notice also that the total quantity is larger after a gale
than before.

ses, clearly mirrorred in the size of the net volu-
me. This might be due to the oblique migration
direction of the bar on the coast (fig. 12), and
thereby on the orientation of the profile lines:
from fig. 16, however, it is seen that there is a
great loss of material in the total study area du-
ring the destructive phase of the active periods.
Therefore the net values found must contain oth-
er factors than those originating solely from the
migration of the nearshore bar. We may therefore
presume that there is a general profile adjustment
working on the nearshore terrace; during this,
material is removed from the area and taken far-
ther seaward, resulting in a flattening of the pro-
file. Thus we are dealing here with two different
components in this material budget: (1) one con-
nected with the migrating nearshore bar; (2) one
connected with profile adjustments.

To test this hypothesis, the levels of the differ-
ent profile sections were investigated (fig. 18). In
each measuring point all changes in level were
given a volume (4 × 1 m × level change) and a
sign (− for erosion, + for accumulation). The
resulting histogram shows 3 areas with especially
great variations: (1) the foreshore (profile ad-
justments); (2) the nearshore terrace (migrating
bars); (3) the shoreface (profile adjustments).

Simultaneously, highest and lowest level in
each measuring point during the investigation
period have been plotted. This shows the belt
where the variations in profile occur, namely the
sweep zone of the coastal profile. A comparison
between the width of the sweep zone and the
gross budget in the histogram indicates the fre-
quency of the changes in level. Frequent, but
small changes are to be expected in connection
with profile adjustments, and few but great vari-
ations in connection with migrating bars.

The hypothesis that we are dealing with profile
adjustments on foreshore and shoreface is further
supported by the fact that the isolines in the T–D
diagrams resume their original positions after the
active periods.

Line 4, fig. 18, shows a smaller gross budget
that the other lines, but is more uniformly direc-
ted. Line 4 represents the lines off the nearshore
bars and is therefore without the migrating bar's
contribution (same size plus and minus contribu-
tion).

Fig. 16 shows clearly that there is no perma-
nent loss of sediments during the active periods.
On the contrary, there is a clear trend that the
final volume is larger that the initial volume, as
e.g. seen on 28/9. This amazing phenomenon is
due to the rebedding of material during the de-
structive phase in connection with the migration
of the bar; this implies a net transport onshore
from the outer part of the nearshore terrace and a
profile adjustment with a net of transport off-
shore away from the shoreface. For a rebuilding
of the normal profile during the constructive
phase large amounts of material are needed to

Diurnal gross and net sedimentation/erosion per crossline and unit of width (1m)
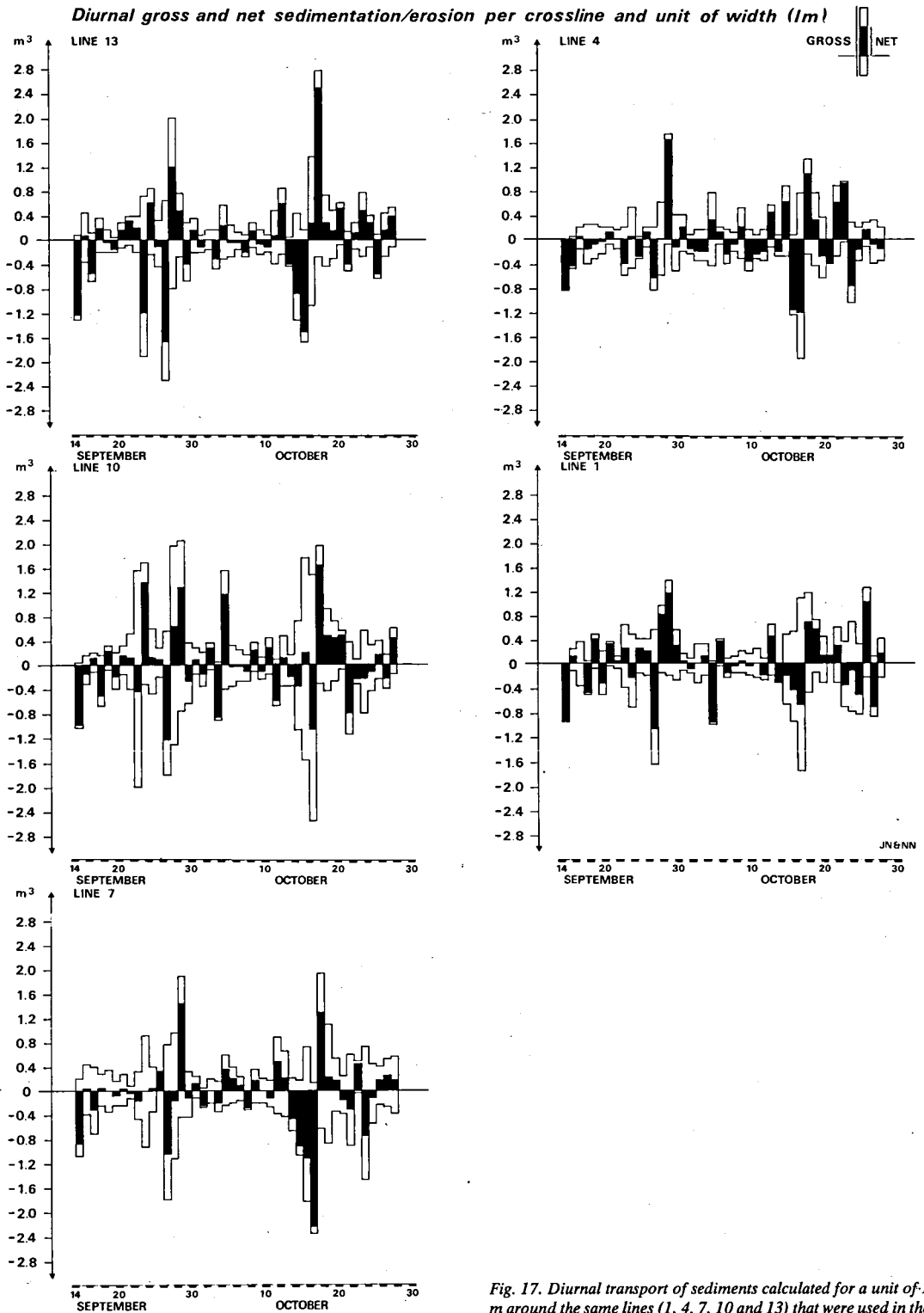

Fig. 17. Diurnal transport of sediments calculated for a unit of 1 m around the same lines (1, 4, 7, 10 and 13) that were used in the T–D diagrams. For days with several measurements, only one measurement was used for the diagram.
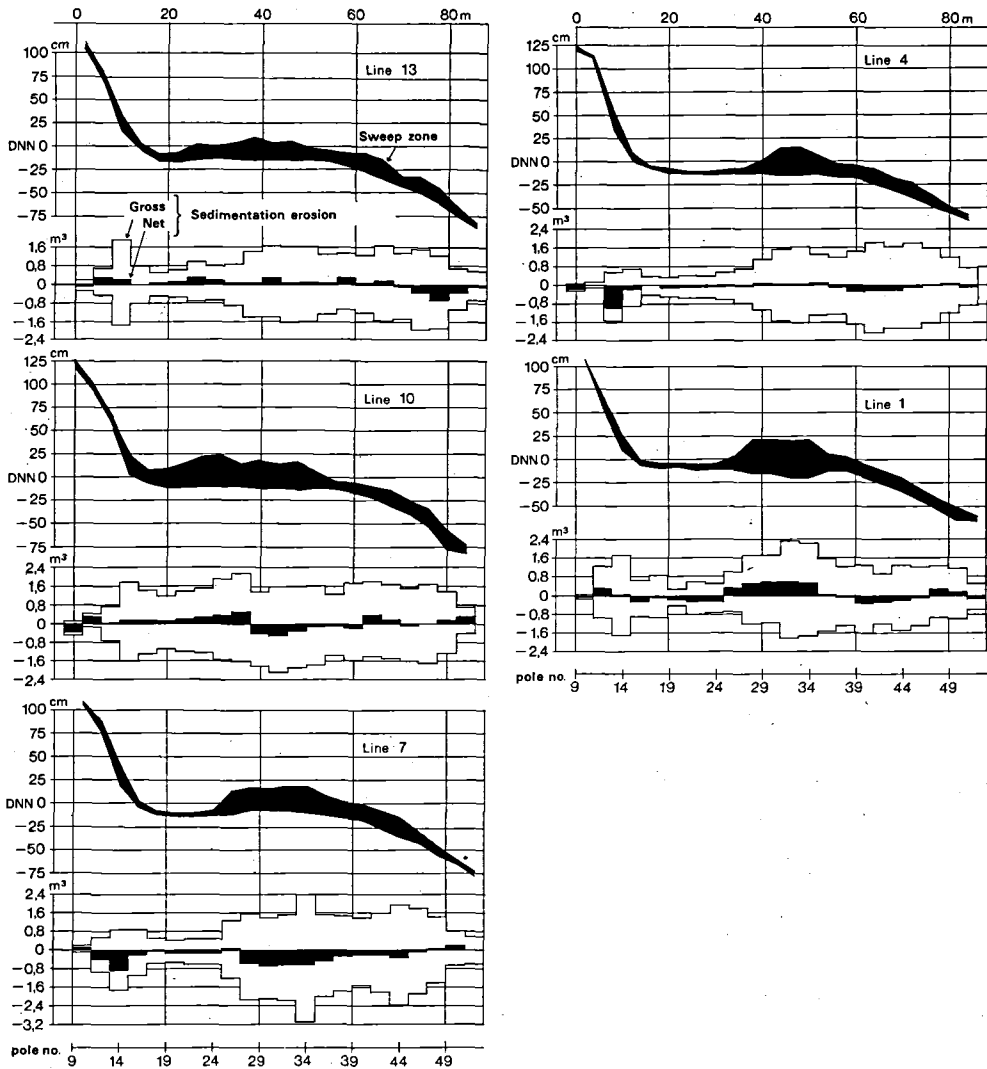
Fig. 18. The sweep zone of the coastal profile and the material transport around the observation points (4 × 1 m) in the selected lines (1, 4, 7, 10 and 13). All records for each line are included in the diagrams. The white columns in the histograms indicate the gross sediment budget, the black columns the net budget.

compensate both for losses produced by the migration of the bar and by profile adjustments. As the migration does not change the volume of the study area, the result will be a surplus of sediments after each active period. Sudden vigorous forces (such as onshore gales) have traditionally been ascribed great importance as to coastal morphological changes, morphological 'leaps' after a long period of stability. For the coast type in question the present investigation suggests that these catastrophy theories are not valid for the sea-covered part of the coastal zone – the near-shore terrace.

Erosion/sedimentation velocity

In order to investigate the relation between processes and budget, the active period from 23/9 to 29/9 was analyzed in greater detail (fig. 19). Until *23/9 at 1100* rising water-level and an increasingly vigorous onshore wind were recorded.
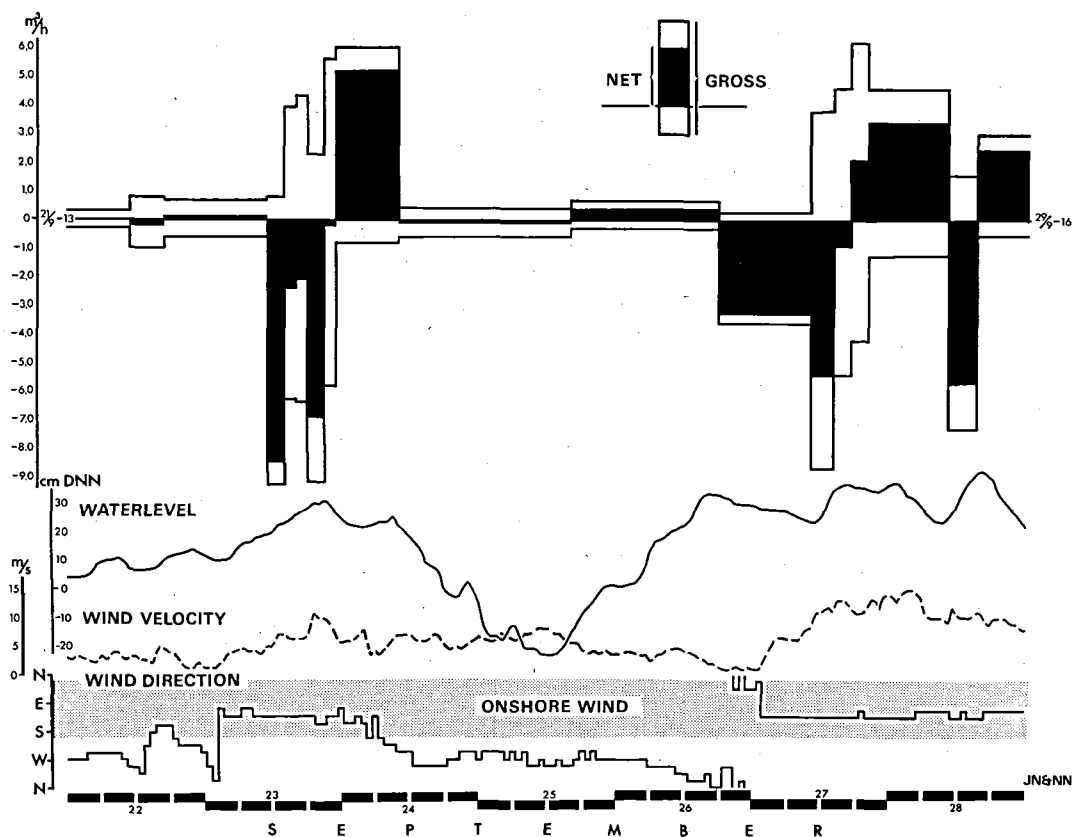
Fig. 19. The resedimentation velocity in m^3/h (this unit was chosen to give an area-true picture) between two subsequent measurements in the total investigation area with corresponding water-level curves, wind speeds and -direction for the period 22/9 − 28/9−1971 (as to wave parametres, cf. tables 1 and 2).

At the time of measurement the water-level is not so high, but sufficient to overwash the nearshore bar, and the resulting material budget is amazingly small compared with later measurements.

3 hours later, *1400,* when both wind speed and water-level had increased, a new measurement was made. The resedimentation velocity is high and it is noteworthy that the net column in the histogram has a negative notation. Thus the main morphological activity is a destructive profile adjustment and only a minor part of the resedimentation (+/−1 m³/h) is due to the migration of the bar.

At *1530 and 1800* a similar development is seen. The water-level steadily increases whereas the wind speed is constant. This first results in a steady adjustment of the profile; at the same time the increasing difference between gross and net values reveals that the migration of the bar is now

taking place at the highest speed, cf. fig. 12 and table 1.

Until *2030* the wind speed increases vigorously and the water-level is still slightly increasing. The changes in the wave parametres involve a much more destructive profile adjustment whereas the material budget of the migrating bar simultaneously decreases.

Between *2030 and 2300* both water-level and wind speed decrease. The profile adjustment has therefore ceased, and the migration of the bar predominates. This can be considered a transition to 1030 on 24/9 with offshore wind and decreasing water-level (at the time of measurement the bar is dry). A conspicuously constructive adjustment of the profile has taken place, whereas the bar has only migrated slightly. Notice that more material has been added than removed during the destructive period (fig. 16). The low

water-level and the offshore wind result in a mi-
nimum of morphological activity during the 24
hours around 25/9.

At *1840 26/9* the water-level is increasing, but
there is still offshore wind (swell situation); as
expected, the morphological activity is a weak,
constructive adjustment of the profile.

During the night of 27/9 the wind turns from N
to E (onshore wind) and simultaneously the wind
speed increases markedly — the water-level de-
creases slightly. At 1000 a markedly destructive
profile development is recorded and an insignifi-
cant transport in connection with the migrating
bar. It deserves notice that the migration is slow
at the beginning of the active periods, see also
23/9 at 1400.

Between *1000 and 1300* this development
continues in consequence of increasing wind
speed and water-level; the migration of the bar
starts, however, and is relatively significant at the
time of measurement. At *1700* the adjustments of
the profile are accomplished, as both wind speed
and water-level have remained constant, but the
material budget in connection with the migration
of the bar is almost the same. Until *1900* the
water-level is constantly, but slightly decreasing,
whereas the wind speed has slowed down. The
magnitude of migration is largely unchanged, but
a constructive profile development has started.
This situation continues over night until 1000
28/9, although with decreasing migration veloci-
ty. Again a repetition is observed on the devel-
opment around the active period 23/9; the mi-
gration of the bar is at a minimum during the
constructive period.

Between *1000 and 1400* the water-level rises
significantly, whereas the wind speed is constant.
This results in an increased destructive adjust-
ment of the profile, which was apparently at its
maximum at the time of measurement.

Until next measurement at 1600 29/9 both
water-level and wind velocity decrease, and the
final constructive development of the profile is
accomplished (fig. 16).

On the basis of the detailed observations it can
be concluded that the material transport in the
investigation area must mainly be explained as
profile adjustments. The frequent measurements
reveal that they occur continuously and very ra-
pidly. It is therefore important to stress that vari-
ations both in wind speeds, -directions and in

water-levels are of great importance; fluctuations
in these parametres, both isolated and together,
induce a great morphological activity and a sub-
sequent material transport.

It must therefore be stressed that each
measurement only represents the morphological
development during the last few hours and that
the calculated gross budgets will generally be too
small when the intervals between measurements
surpass a few hours. It is interesting to notice that
the migration of the nearshore bar is apparently
at a minimum when there is a very active adjust-
ment of the profile.

The main purpose of the volume calculations
was to investigate whether the final phase of the
migrating nearshore bar, when it is joining the
foreshore, means a permanent contribution of
material to the beach. Of the observed two
nearshore bars, the first one did not quite reach
fusion with the foreshore because another near-
shore bar was formed farther seaward, and at the
termination of the investigation the new bar had
joined the first one (fig. 9j). If the migration of
the nearshore bar results in a supplement of ma-
terial, this should be seen in fig. 16 from around
1/11; just at this time there is also a volume
maximum. From a morphological viewpoint the
foreshore is only contributing to this accumula-
tion of material on a small scale which — as later
measurements showed — was not permanent. The
development during the last part of the investiga-
tion (after 1/11 daily measurements were not
taken) was a decrease in volume which was not
obviously due to the dynamic conditions.

A comparison between the two contour maps
from 14/9 and 11/11 (figs 9a and 9j) reveals that
during the observation period, the forms on the
inshore terrace were dislocated northwards. It
was thus to be expected that cyclically determi-
ned volume variations with low values were to
occur just when the measurements were termi-
nated.

With regard to the total material budget for the
study period, table 3, it must be emphasized that
the indicated (measured) gross value must be too
small because of the great intervals between the
measurements; furthermore, that starting and fi-
nal dates were chosen at random which has
greatly influenced the net result. In spite of this, it
is possible to get a picture of the magnitude of
material transport in the area and especially of

Table 3. Material budget for the total investigation period, 14/9–11/11 1971.

		positive m³	negative m³	gross m³	net m³	net/gross %
Total area		1080.2	1137.5	2217.7	−57.3	2.6
Line 13	N	24.9	24.2	49.1	+ 0.7	1.4
Line 10	↑	30.6	28.9	59.5	+ 1.7	2.9
Line 7		25.2	30.9	56.1	− 5.7	10.2
Line 4	↓	21.1	24.0	45.1	− 2.9	6.4
Line 1	S	25.2	24.0	49.2	+ 1.2	2.4

the relationship between net and gross values. The net values for the single lines mirror the fact that the forms have migrated northward, notice especially line 7. The very different results of the lines, placed at only 12 m intervals, emphasize the dubious value of the morphological and sedimentological studies on the basis of one or a few profile lines only.

In conclusion, the volume development must be understood as the sum of profile adjustments during the active periods, and the component parallel to the coast of the nearshore bar's migration. At the termination of the investigations it could not be stated unambiguously whether the migration of the bar permanently yields material to the beach.

Effect of an extreme weather situation

The investigation was terminated on 11/11–1971. About two weeks later a cyclone passed Denmark. The night between 21 and 22/11 the wind turned ESE and increased to above 20 m/sec. Simultaneously the water-level rose from + 20 cm DNN to a maximum of + 124 cm, cf. the wind and water-level curves. The wave heights were not directly observed, but according to prognosis diagrams for coastal waters (Darbyshire & Draper 1962, Petersen & Poulsen 1975) the H_s must have been 3–4 m on 'deep' water.

On 26/11 the study area was measured by tachymetry, (fig. 20) and the volume was calculated by planimetry.

The nearshore terrace shows a levelled morphology and the 'old' nearshore bars can be discerned in the northern part of the map by their higher level. A coast-parallel ridge has been built up c. 50 m out on the nearshore terrace and extends throughout the whole section. The ridge

has probably been formed during the gale's high water-levels as an inner breakpoint bar, is therefore temporary and, on the day of measurement, under transformation into a nearshore bar.

A comparison between the morphology in the area on 26/11 and 11/11 indicates a significant retreat of the beach and a minor decrease in gradient (fig. 21).

In spite of a marked erosion on the beach, the volume (>−1 m DNN) in the proper study area showed a higher value than the average volume and the volumes for the active periods in September and October (fig. 16).

The volume of the study area (>−1 m DNN):

Average	3948 m³
on 29/9	3965 m³
on 31/10	3977 m³
on 11/11	3924 m³
on 26/11	3978 m³

On 21–22/11 the swash transported material over the outermost barrier top (fig. 22) and thus definitely away from the area. A volume calculation for the landward continuation of the study area showed a sediment increase of 32.1 m³.

It is therefore interesting to notice that in spite of a marked erosion on the fore- and backshore the whole barrier unit (barrier, beach and nearshore), showed an increased sediment volume after the gale. It cannot be said whether a gale like this will always have a 'sediment accumulating' effect, because we only have this single event. But it is justified to conclude that the profile adjustment immediately after the gale on 22/11 benefitted from sediment seaward of the study area. In future investigations it will therefore be essential to include the area in front of the nearshore face.
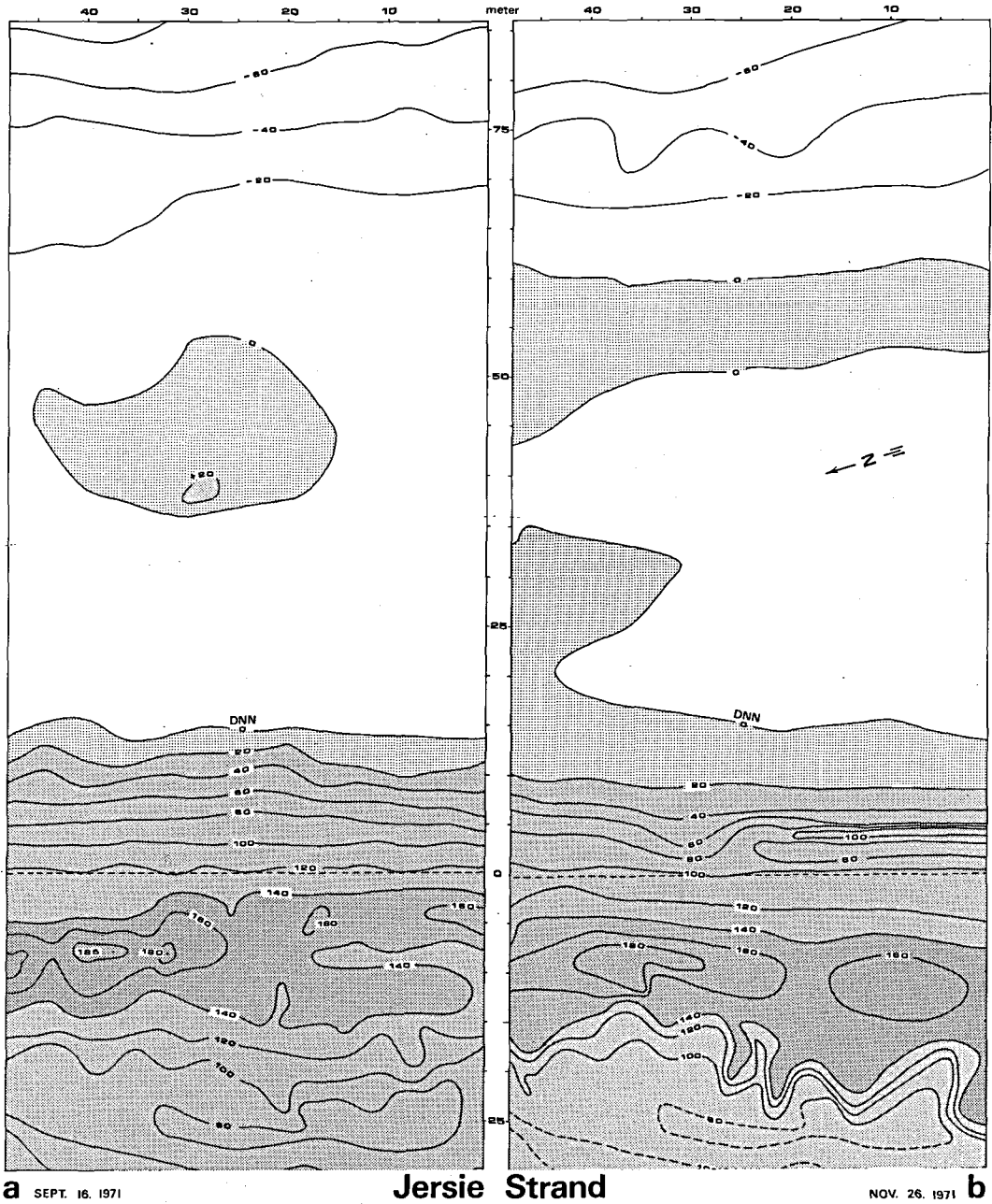
a SEPT. 16. 1971   Jersie Strand   NOV. 26. 1971 **b**

Fig. 20. The investigation area and part of the bar surveyed on 16/9 and 26/11–1971 (tachymetric surveying). The contour picture landward of the 0 DNN 16/9 was stable until the gale 22/11. For 26/11, on the backside of the outermost barrier ridge, the contour picture shows swash tongues which are thus participating in a strengthening of the barrier. The dashed line on the backshore c. 100–120 cm DNN shows the inner limit of the data maps.
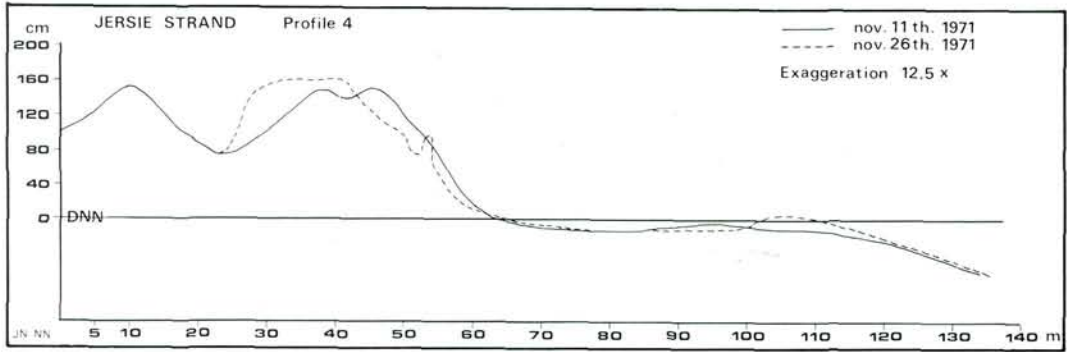
Fig. 21. Cross profile of line 4 measured on 11/11 and 26/11 i.e. before and after the gale 22/11. The nearshore terrace is apparently not influenced by the gale except in the transition into the nearshore face where a secondary breakpoint bar has been formed. Surveying was not made during the gale, but by analogy with earlier records, considerable erosion must have taken place on the nearshore terrace, which has been rebuilt now 3 days after the gale. Notice the large accumulations of material behind the outermost ridge of the barrier.

Concluding remarks

The method described here was chosen in an attempt to benefit from the advantages of a model study and obtain unambiguous and precise point observations, to register short-interval variations and thus avoid the unfortunate and often unforeseeable distortion of scale that basin studies might involve. What it meant in extra time when establishing the measurement net was regained during the routine measurements which were thereby secured a high degree of accuracy. In our opinion the most valuable observations in this investigation were obtained thanks to the permanent grid net which enabled us to take records at short intervals during dynamically very active periods and at any time of the day.

The primary goal was to obtain a better knowledge of the relationship: process/form/change of form; choice of measuring period was therefore of minor importance. It should be added, how-

Fig. 22. Swash tongues on the backside of the outermost bar ridge, formed after the gale 22/11–1971.

ever, that in September–November 1971 the weather conditions were normal for the season with the exception of the gale on 22/11.

Considering the advantages of the described method, it would be of great interest to continue with similar studies, based upon two different criteria: (1) A repetition of the whole measuring procedure for a 1–2 month period on coasts differently exposed and consequently having different wave and water-level parametres. (2) To prolong the measurements to a minimum of one year to investigate the seasonally determined variations in budgets and forms.

Dansk sammendrag

Undersøgelsen ved Jersie Strand, Køge Bugt belyser nogle af de formmæssige variationer, der finder sted i den littorale zone, primært på strandplansterrassen og på strandplansskråningen. Kysten er på denne lokalitet opbygget af mellem- til finsandede sedimenter, og tidevandet er som procesparameter uden betydning.

Studierne blev koncentreret til forholdene omkring morfologiens geometri og til materialeomsætningen. Analysegrundlaget består af 65 detaljerede topografiske opmålinger. Konstruktionen af de 65 kort (areal 48 × 86 m, med 5 cm kurveinterval) er baseret på dataindsamlinger i et fast markeret, tilnærmet isometrisk net. I tidsserieanalysen, der dækker en periode på 2 måneder, indgår desuden kontinuerligt registrerede vind-, vand- og bølgedata. Korttegning og volumenberegninger er foretaget med EDB.

De vigtigste morfologiske ændringer på strandplansterrassen er snævert forbundet med strandrevlens vækst og vandring. Undersøgelsen viste, at strandrevlen kunne opstå såvel ved høj som ved lav vandstand, dels i form af en initial brændingsrevle og dels som en opskylsryg. Strandrevlens vandringsretning var altid rettet mod kysten. Den eneste forudsætning for bevægelse var vanddækning eller blot bølgeoverskyl. Der observeredes invandringshastigheder på op til 30 cm/time i perioder med pålandsvind og under konstante vandstandsforhold og/eller konstant vindhastighed.

Ud fra en analyse af materialets brutto/nettoomlejring kunne der klart skelnes mellem strandrevlens formvandringer og profiljusteringernes materiale-input/output i forsøgsarealet. Særlig bemærkelsesværdig var, at sedimenttilførslen efter en storm var større end den sedimentmasse, der blev fjernet fra arealet under stormen. Endvidere kunne det vises, at strandplanets og strandbreddens (barrierens) samlede materialemængde stort set var konstant (i forsøgsarealet), trods markante forminvandringer i undersøgelsesperioden. Kun en ekstraordinær stormsituation i slutningen af observationsfasen tilførte barrieren materiale af blivende karakter.

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