The influence of the Rømø Dam on the sedimentation in the adjacent part of the Danish Wadden Sea.

By H. A. Olsen.

Within a period of a few years the bottom configuration of the Danish Wadden Sea must be considered, in broad outline, as being in equilibrium. In the course of a longer period the situation of the tidal streams may be more or less displaced; new channels and gullies may appear and old ones disappear. Contrary to this, the vast tidal flats may remain for long periods without being subjected to considerable alterations of the level and of the aspect; however, in case of a change of the natural conditions, as for instance the immigration of a vegetation on high-lying tidal flats close to the coast, the result is a disequilibrium, which has partly a constructive power: the formation of new salt-marshes; partly a destructive tendency: erosion on the windward side of these new salt-marches *(B. Jakobsen,* 1954).

The construction of the Rømø Dam represented an artificial interference in the natural conditions of the Wadden Sea; as a result of this the tidal flats and the channels immediately began to change and to adapt themselves to the new conditions. This offered a favourable occasion for studying the destructive effect and constructive effect of the forces — effects which may normally be difficult to trace, but which now appear in overdimensioned form, until a new state of equilibrium has been established.

In the following is given an exposé of the factors influencing the sedimentation in the Wadden Sea and, further, of the effects which the Rømø Dam has had on the sedimentation to the south of the dam. Special interest has been taken in the informations which can be drawn from these examinations.

The factors which determine the sedimentation.

The factors which are of decisive importance to the sedimentation and to the process of salt-marsh formation can be divided into the following groups:

a) *Astronomical and meteorological forces* which determine the transport of material;

b) *Geographical conditions* which are of special importance to the sedimentation;

c) *Biological forces* which are of essential importance for retaining the sediment.

a): *The astronomical forces* produce *the tide,* the currents of which transport the suspended material, and are thus the first condition for the salt-marsh formation. In the channel Pajdyb to the south of the Rømø Dam (fig. 1) the mean high-water level has been calculated to be +0,96 m. DNN (Danish Ordnance Datum) for the period from July 1942 to December 1943. In the channel Rømø Leje 2 km. to the north of the dam the range of the tide has been calculated to be 1,78 m. in the period from July to December 1956.

The meteorological forces are air pressure, wind and ice formation. From a meteorological point of view the air pressure and the wind are inseparable; however, in the Wadden Sea *the air pressure* is of special importance, as the difference of pressure influences the level of the tide; consequently, the conditions of flooding (i.e. the depth of the water and the size of the waves) act on the sedimentation conditions.

The wind produces waves which are able to suspend the material and to keep it in suspension and, further, to accumulate masses of water. By this accumulation the depth of the water is altered, a fact which contributes to the influence on the size and the shape of the waves. Thanks to equalization currents the accumulation of water is moreover able to hamper or to intensify the tidal streams. All these factors influence highly the sedimentation.

The ice formed in the Wadden Sea will at low tide ground on the high tidal flats and freeze to the bottom. By transport of these ice floes at high tide certain quantities of earth are moved to an even higher level, causing ice-borne sediments. The amount of this sedimentation is often overestimated, because the accumulations of ice after a short thawing become quite black owing to silt on the surface. It seems to deposit an enormous quantity of material, whereas in fact, the greater part of the deposit is still ice. An examination of the remainders after the thawing of all the ice will prove that an ice pack for instance 2 m. high only leaves about 5 cm. of silt at best; such a sedimentation will have an uneven surface, exposed to attacks from wave action; therefore, a certain loss of material is supposed to take place. It often happens that even on high-lying tidal flats ice packs are removed by spring gales and disappear into the Wadden Sea. Observations during many years have shown that the ice disappears in a single tidal period from the Wadden Sea. Only the grounded ice remains. This signifies that in reality the ice causes loss of material.

b): *The geographical conditions,* i.e. the pattern of morphological elements, even of a minor character, are of the greatest importance for the sedimentation. Later in this paper it will be demonstrated how variations of the sedimentation may be attributed to various influences of a geographical nature.

c): *The biological forces* have essentially importance for the fixation of the sedimented material, but also for the reshaping of the finest material, thus allowing the sedimentation to take place. The diatoms and the algae partly maintain the individual grains, partly cover and maintain the whole surface; sea meadow grass (*Glyceria maritima*) and, when in a dense vegetation, glasswort too (*Salicornia herbacea*) create a certain lee, while *the mollusks* of different sorts give passage to the material which is so fine that precipitation is impossible and expel this material in the shape of small pellets ready for sedimentation. In order to illustrate to which extent the mollusks are able to bind the material, it may be mentioned, according to an experiment executed by *L. F. Kamps* (1950) that in a fortnight 80 big mussels produced 4,5 kg. of dry silt from the water.

The Rømø Dam.

During the years 1939—48 the isle Rømø in the Danish Wadden Sea was connected with Jutland by the Rømø Dam, which has a length of 9.170 m. The purpose of the dam was partly to create a road-connection between Rømø and Jutland, partly to accelerate the sedimentation and, thereby, the formation of salt-marsh in this region of the Wadden Sea.

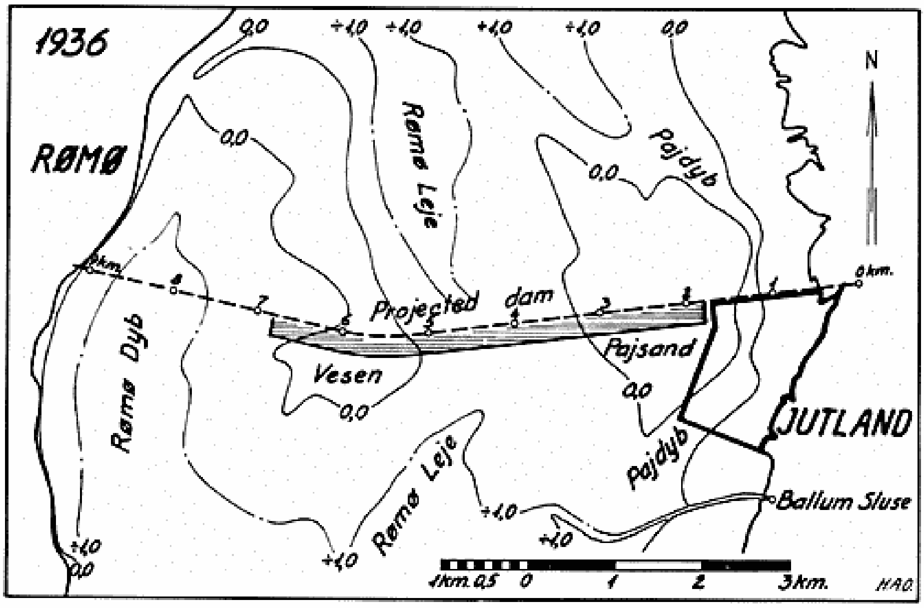

Fig. 1. Part of the Wadden Sea between Jutland and the isle of Rømø 1936 with the projected dam. Only the contours 0,0 m. and — 1,0 m. DNN (Danish Ordnance Datum) are shown. The two framed regions to the south of the dam indicate the areas in which the development of the sedimentation has been examined.

Fig. 1. Del af Vadehavet mellem Jylland og Rømø 1936 med den projekterede dæmningslinie indtegnet. Af hensyn til overskueligheden er kun medtaget kurverne 0,0 m og ÷ 1,0 m DNN (Dansk Normal Nul). De to indrammede områder syd for dæmningen angiver de arealer, hvis sedimentationsudvikling behandles.

The basic material of the researches.

For the examination of the sedimentation along the southern side of the dam a map executed in 1936 by the Committee "Vadehavsudvalget af 1936" has been compared with a series of contouring in the south-western corner between the Rømø Dam and Jutland in the period 1941—59 and with a contouring along the southern side of the dam from the point 1,8 km. to the point 6,8 km. in 1956—57. All these maps and levellings have been executed by the Department of Hydraulic Engineering (Vandbygningsvæsenet), which has kindly placed at my disposal this material as well as a high-water statistics from the tide-gauge at the Højer Sluice.

The natural conditions in the region of the Rømø Dam.

In fig. 1 is shown the section of the Wadden Sea between Rømø and Jutland in which the Rømø Dam has been built. The tides are going to and from the region partly through Lister Dyb to the south and partly through Juvre Dyb to the north of the isle of Rømø.

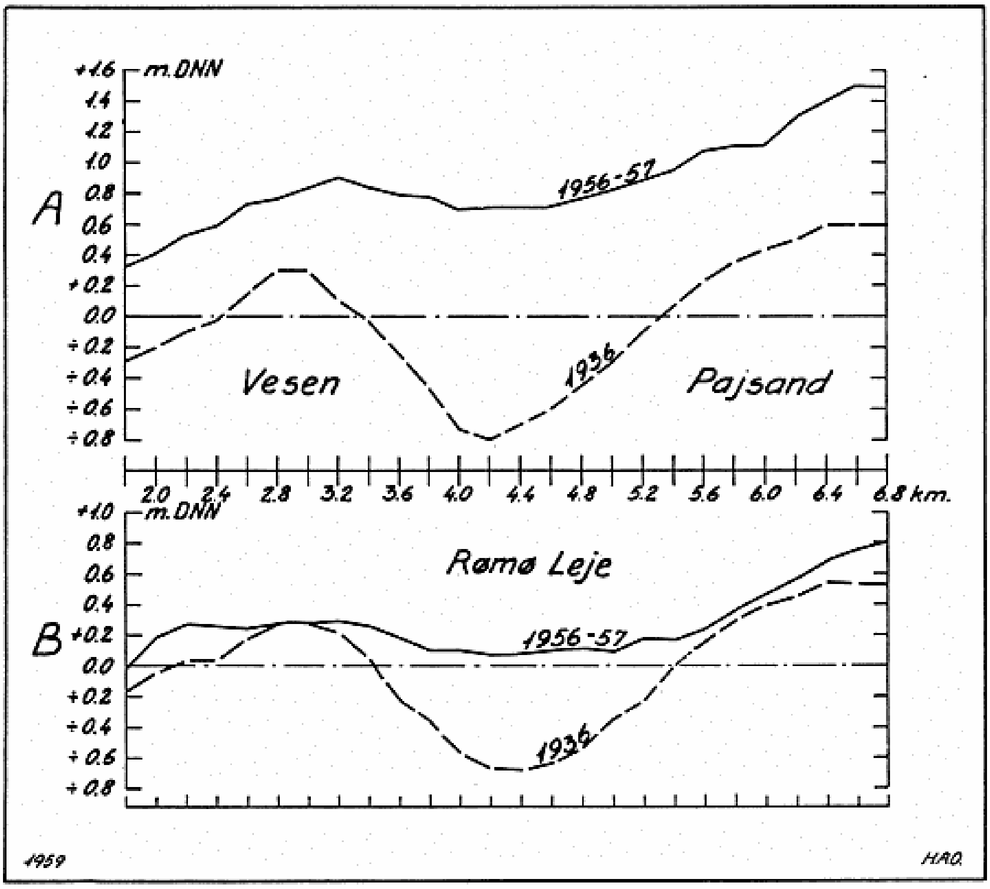

Fig. 2. A shows a profile through the tidal flat 200 m. to the south of the Rømø Dam and parallel to this between the points 1,8 km. and 6,8 km. B is a profile through the tidal flat at the southern base of the dam on the same stretch as A. The two profiles show the levels in 1936 and in 1956-57.

Fig. 2. A er et profil gennem vaden 200 m syd for og parallel med Rømødæmningens fod mellem dæmningens 1,8 og 6,8 km, og B er et profil gennem vaden ved dæmningens sydlige fod på samme strækning som A. De to profiler viser vadeniveauerne i 1936 og i 1956-57.

Owing to the fact that the tide decreases from south to north, and that high water occurs later in Juvre Dyb than in Lister Dyb, an equalization of the water levels at high tide between the two tidal regions mentioned took place before the construction of the dam. This produced a north-going current creating the three channels, mentioned from east to west: Pajdyb, Rømø Leje and Rømø Dyb. Observations of the water levels in 1955 in Rømø Dyb to the south and to the north of the dam on quiet days proved that the high-water level was 2—4 cm. higher to the south of the dam than to the north. As already mentioned, this difference of water level was further increased, because the tide arrived later at Juvre Dyb than

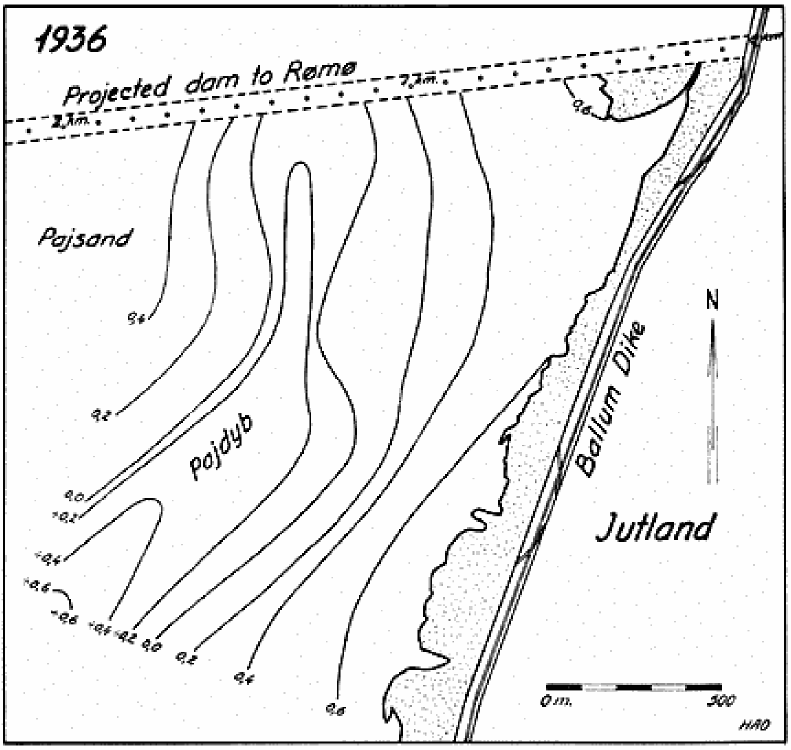

Fig. 3. Map dating from 1936, showing the area between the Rømø Dam and Jutland which in fig. 1 is framed by a thick line. The contours with an interval of 0,2 m. show the levels in Pajdyb and those of the tidal flats before the construction of the Rømø Dam.

Fig. 3. Kort af 1936 over det i fig. 1 med kraftig indramning markerede område mellem Rømødæmningen og Jylland. Kurverne, ækvidistance 0,2 m, viser niveauforholdene i Pajdyb og tilstødende vader før Rømødæmningens bygning.

at Lister Dyb, the water from the south thus being the first to reach the water-shed. The low tide arrives earlier at Lister Dyb than at Juvre Dyb, a fact which formerly should produce a south-going current; however, at low tide the height of the water-shed prevented the creation of such a current; therefore, the resulting current became a one-way, north-going stream. This happened under quiet weather conditions and with wind directions south to west; in cases of north-western and northern winds it can easily be imagined that a south-going current has been predominant. As however, wind-directions WSW are prevailing it will be seen that the wind too has contributed to the north-going direction of the current.

Though the eastern 6 km. of the Rømø Dam have been built at the water-shed between the tidal regions of Juvre Dyb and Lister Dyb it is evident that even this stretch has influenced considerably the equilibrium of the barred channel beds.

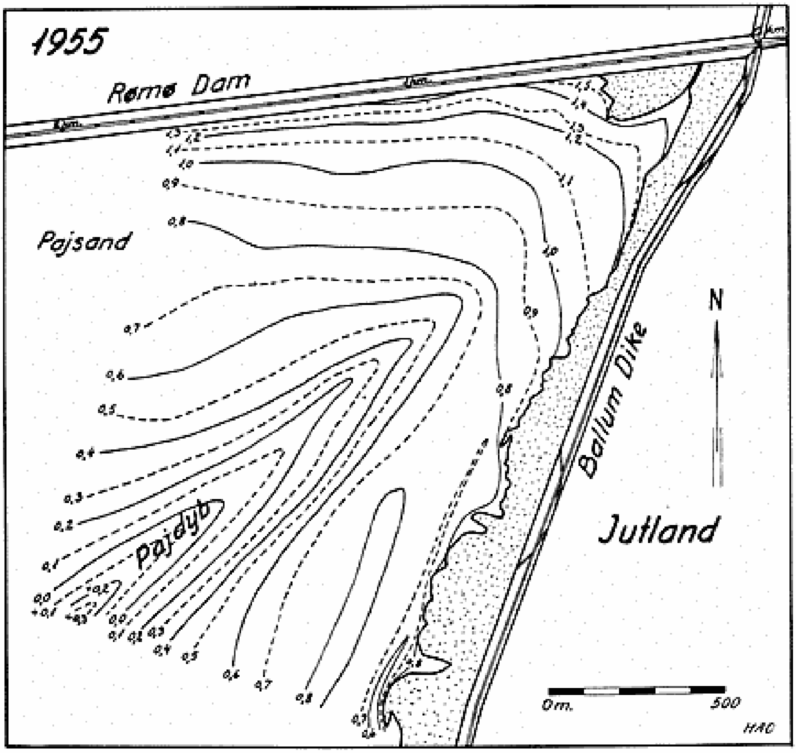

Fig. 4. Map dating from 1955 of the same area as in fig. 3, showing the levels 15 years after the construction of the Rømø Dam. A comparison clearly shows that the contours in the vicinity of the dam have completely changed. The effect of the coast, the bay-effect and the cutting off effect are clearly recognized.

Fig. 4. Kort af 1955 over samme område som fig. 3 og visende niveauforholdene 15 år efter Rømødæmningens bygning. Ved sammenligning med fig. 3 ses tydeligt, hvorledes niveau-kurvernes forløb i dæmningens nærhed er blevet fuldstændig ændret, således at kyst-, bugt- og kuperingsvirkning tydeligt træder frem.

The effects of the Rømø Dam on the sedimentation.

In fig. 1 is framed an area marked by horizontal hatching, of a width of 200 m. and of a length of 5 km. along the southern side of the dam from the point 1,8 km. to 6,8 km. An examination of the variations of the sedimentation in this area makes it possible to point out various geographical effects caused by the presence of the dam in combination with the topography of the tidal flats. The examination has been executed by comparing the maps of 1936 with the maps of 1956—57. By means of these two maps the profiles in fig. 2 have been carried out. A. is a profile through the tidal flat at the base of the dam; the levels of 1936 and of 1956—57 are marked by a dotted line and a full line, respectively. B. is a profile through the tidal flat at a distance of 2200 m. to the south of the dam and parallel to this, the levels of 1936 and of 1956—57 being marked in the same manner as in profile A.

When comparing the two profiles A. and B., a bigger sedimentation on A. will be noticed. This must be due to the presence of the dam, i.e. the effect of forces becoming active in this case when the new-formed, artificial shore line tends to establish a normal beach. This effect on the sedimentation is called *beach-effect.* By a comparison between A. and B. it can be established whether the beach-effect reaches as far as profile B. It appears from profile A. that on Vesen, between the points 5,6 km. and 5,8 km., a sedimentation has taken place since 1936 of a size of about 0,5 m., while in profile B. no sedimentation has taken place; this means that the beach-effect does not reach as far as to distance of 200 m. from the dam. Consequently, the sedimentation which has taken place in profile B. must be due to other effects. It is possible to separate further two geographically conditioned factors, which can be named: the *barring effect* and the *bay-effect.*

The barring effect clearly stands out in fig. 2 in profile A. as well as in profile B. in the barred channel bed of Rømø Leje.

In profile B. is seen a sedimentation on Pajsand which can neither be ascribed to the beach-effect nor to the barring effect; therefore, this sedimentation must be attributed to the bay-effect, which, of course, also reaches as far as the dam. As will be noticed from profile B., none of the three effects appear on Vesen; however, it is probable that a bay-effect exists in Rømø Leje, as this channel is situated between the two high sands Vesen and Pajsand. The bay-effect on Pajsand is probably influenced by the deep bay has situated between the Rømø Dam and Jutland.

From the above it appears that the sedimentation caused by the existence of the dam is dependent on the topographical conditions, the effects of which on the sedimentation along the southern side of the dam can be divided into beach-effect, barring effect and bay-effect. The beach-effect is only of importance in the proximity of the dam and the barring effect in the channels, while the bay-effect has a field of action of a greater extent.

From fig. 2 it will be seen that Rømø Leje is now situated only 20 cm. below the level of Vesen; consequently, the barring effect is coming to a stand-still, and the sedimentation is strongly decreasing. It is true that the beach-effect will move further out simultaneously with the raising of the level along the base of the dam and with the formation of a salt-marsh. By the construction of sedimentation basins (Danish: slikgårde) the coastline is artificially pushed forward, and the outward movement of the land (beach-effect) is accelerated. An extended construction of sedimentation basins on the two protruding high sands Pajsand and Vesen will add to the improvement of the bay-effect.

The sedimentation to the south of the Rømø Dam between the foreland and the point 1,8 km.

In fig. 1 a thick framing marks the region of the Wadden Sea in which the development of the sedimentation during the period 1936—59 is examined. As far as the possibilities of sedimentation are concerned, the geographical conditions correspond to those existing in Rømø Leje; however, the bay-effect is more pronounced, as the bay between the foreland and the high-lying tidal flat Pajsand is fiord-shaped. At a comparison between fig. 3 and fig. 4, the beach-effect, the bay-effect and the barring effect clearly stand out.

Fig. 3 and fig. 4 show the contours of the region in question in 1936 and in 1955, respectively; it is evident that in this period an extremely strong sedimentation has taken place, which is biggest at the base of the dam and smallest at the southern frontier of the area. The extent of this is 200 ha., and the sedimented quantity of material in the period 1936—55 amounts to 1 million cub.m.

The original surface consisted of ordinary tidal flat sand, well-sorted, with a mean grain size of 90 μ and a content of clay ($< 4\ \mu$) of less than 10 % (*Kaj Hansen,* 1951). The material which has been sedimented after the construction of the dam is silt, not too well sorted, with a mean grain size of 6—17 μ and a content of clay of up to 36 % (*Kaj Hansen,* 1956).

It has been examined how the intensity of the sedimentation has been distributed over the area. To this purpose have been used the contourings, executed in 1936 and in August 1955, comprising the whole area, and the contourings carried out in August 1941, March 1943, June 1944, October 1945, October 1947 and February 1959, comprising a zone of a width of 320 m. along the base of the dam.

In the period before the construction of the dam started, the area in question can be considered — within a small number of years — as being in equilibrium; this allows to presume that in 1936 the situation was identical with the one which existed immediately before the construction of the dam started on the tidal flats in August 1940.

On the basis of these eight contourings 6 profiles have been drawn through the tidal flat parallel to the dam and with the following positions: along the base of the dam and at a distance from

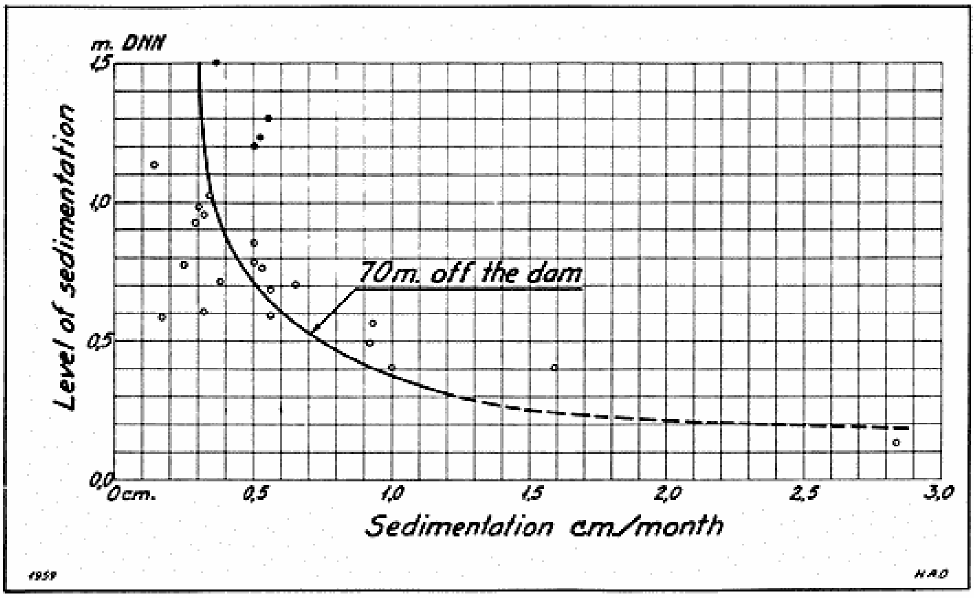

Fig. 5. To show an example of how to make the curves of mean sedimentation the curve for the profile 70 m. to the south and parallel to the dam is drawn here. The individual points represent the sedimentation (cm./month) and the mean level (m. DNN). Table I. The black points to the right of the curve indicate that the sedimentation in these cases has taken place in a *Glyceria* vegetation.

Fig. 5. Eksempel på fremstilling af middel-sedimentationskurven for det profil, der ligger parallelt med og 70 m syd for dæmningsfoden. De enkelte punkter afsættes ved hjælp af tallene i tabel I for sedimentation (cm/måned) og middel-niveau (m DNN). De sorte punkter til højre for kurven angiver, at sedimentationen har fundet sted i Glyceria vegetation.

this — to the south — of 70 m., 170 m., 320 m., 1.200 m. and 2.100 m. In each profile have been chosen 4 verticals at intervals of about 400 m. In each vertical the sedimentation (in cm.) within the respective time intervals has been measured, and the size of the sedimentation in cm./month has been calculated. This is considered as the intensity of the sedimentation in the mean level, i.e. the mean datum between two levelling planes in the vertical.

As an example is given in table I the method of calculation of the 4 verticals in the profile situated at a distance of 70 m. from the base of the dam.

In a system of co-ordinates with the mean datum as ordinate and the sedimentation per month as abscissa are marked out the values of sedimentation and mean level deduced from the 4 verticals in each profile, and a mean curve is drawn. Fig. 5 is given as an example of the profile 70 m. south of the base of the dam and parallel to this.

In table I four of the mean levels have been marked with an x,

Table I.
Tabel I.

Point *Punkt*	Period *Tidsrum*	Number of months. *Antal måneder*	Sedimentation cm. *Sedimentation cm*	cm./mth. *cm/md.*	Levelinterval Datum m *Niveauinterval kote m*	Datum m *kote m*	Meanlevel Datum m *Middelniveau kote m*	
Point 1,6 km.	aug. 40—aug. 41	12	19	1,59	+ 0,30	— + 0,49	+ 0,40	
70 m. south	aug. 41—juni 44	34	19	0,56	+ 0,49	— + 0,68	+ 0,59	
of dam base	juni 44—okt. 45	16	6	0,38	+ 0,68	— + 0,74	+ 0,71	
st. 1,6 km	okt. 45—okt. 47	24	6	0,25	+ 0,74	— + 0,80	+ 0,77	
70 m syd for	okt. 47—aug. 55	94	30	0,32	+ 0,80	— + 1,10	+ 0,95	
dæmningsfod	aug. 55—feb. 59	42	6	0,14	+ 1,10	— + 1,16	+ 1,13	
Point 1,2 km.	aug. 40—aug. 41	12	34	2,84	— 0,04	— + 0,30	+ 0,13	
70 m. south	aug. 41—marts 43	19	19	1,00	+ 0,30	— + 0,49	+ 0,40	
of dam base	marts 43—juni 44	15	14	0,93	+ 0,49	— + 0,63	+ 0,56	
st. 1,2 km	juni 44—okt. 45	16	9	0,56	+ 0,63	— + 0,72	+ 0,68	
70 m syd for	okt. 45—okt. 47	24	12	0,50	+ 0,72	— + 0,84	+ 0,78	
dæmningsfod	okt. 47—aug. 55	94	28	0,30	+ 0,84	— + 1,12	+ 0,98	
	aug. 55—feb. 59	42	22	0,52	+ 1,12	— + 1,34	+ 1,23	x
Point 0,8 km.	aug. 40—aug. 41	12	11	0,92	+ 0,43	— + 0,54	+ 0,49	
70 m. south	aug. 41—juni 44	34	11	0,32	+ 0,54	— + 0,65	+ 0,60	
of dam base	juni 44—okt. 47	40	21	0,53	+ 0,65	— + 0,86	+ 0,76	
st. 0,8 km	okt. 47—aug. 55	94	32	0,34	+ 0,86	— + 1,18	+ 1,02	
70 m syd for	aug. 55—feb. 59	42	23	0,55	+ 1,18	— + 1,41	+ 1,30	
dæmningsfod								
Point 0,5 km.	aug. 40—aug. 41	12	2	0,17	+ 0,57	— + 0,59	+ 0,58	
70 m. south	aug. 41—juni 44	34	22	0,65	+ 0,59	— + 0,81	+ 0,70	
of dam base	juni 44—okt. 45	16	8	0,50	+ 0,81	— + 0,89	+ 0,85	
st. 0,5 km	okt. 45—okt. 47	24	7	0,29	+ 0,89	— + 0,96	+ 0,92	
70 m syd for	okt. 47—aug. 55	94	47	0,50	+ 0,96	— + 1,43	+ 1,20	x
dæmningsfod	aug. 55—feb. 59	42	15	0,36	+ 1,43	— + 1,58	+ 1,50	x

which means that within the period indicated in the second column to the left of the table a dense *Glyceria* vegetation has immigrated. In fig. 5 these four points have been filled up in black, and it will be seen that in reality the curve ought to have had an angle in the vicinity of the level + 1,1 — + 1,2 m. on account of the new factor: dense vegetation, which highly affects the sedimentation.

The curve in fig. 5 and the five other mean curves, executed in the same manner, are shown in fig. 6. They all indicate the inten-

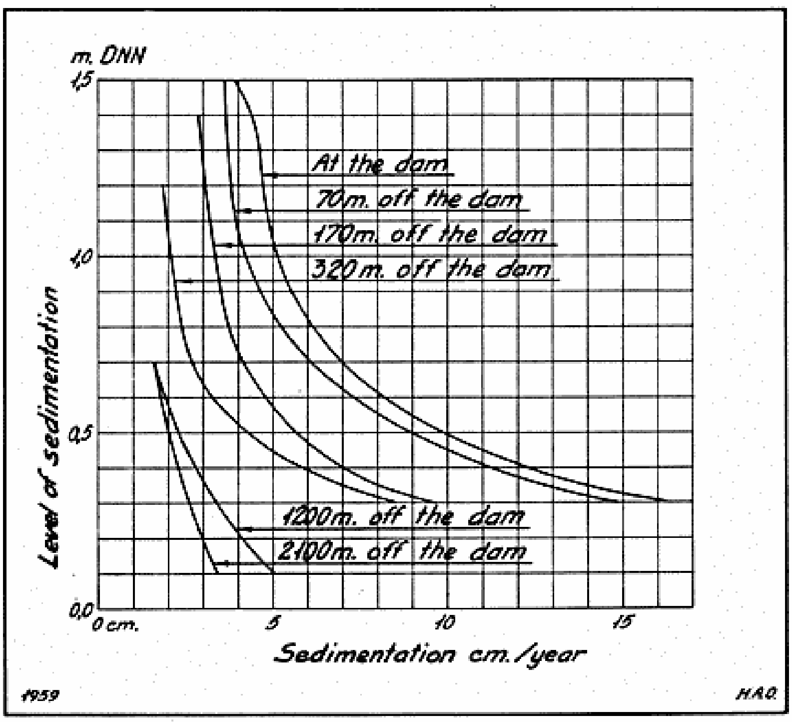

Fig. 6. The mean sedimentation per year in proportion to the level and the distance of the latter from the dam. The curves have been drawn as in fig. 5 and show the sedimentation at the base of the dam and at a distance from this of 70 m., 170 m., 320 m., 1200 m. and 2100 m., respectively.

Fig. 6. Kurver for middel-sedimentationen pr. år i forhold til niveauet og dettes afstand fra dæmningen. Kurverne er fremstillet på samme måde som eksemplet, der er vist i fig. 5, og viser sedimentationen ved dæmningsfoden, samt i en afstand fra denne af henholdsvis 70 m, 170 m, 320 m, 1200 m og 2100 m.

sity of the sedimentation in proportion to the level and to the distance from the dam. In fig. 6 the scale of the abscissa has been altered from cm. per month to cm. per year.

From fig. 6 it appears that at all levels the sedimentation decreases with the distance from the dam, for the first 320 m. at a considerable degree, then gradually lesser. The individual curves show a big sedimentation at the low levels; at rising level the sedimentation is gradually decreasing and, at high-water level ends to become almost even, though feebly decreasing.

When comparing the curves in fig. 6 with the yearly accumulated water-cover at the respective levels we arrive at an expression for the content of deposited material in the water, giving new information about the circumstances of the sedimentation.

A statistics of the changing water levels for 15 years, worked out for the tide-gauge outside the Højer Sluice has been used. This

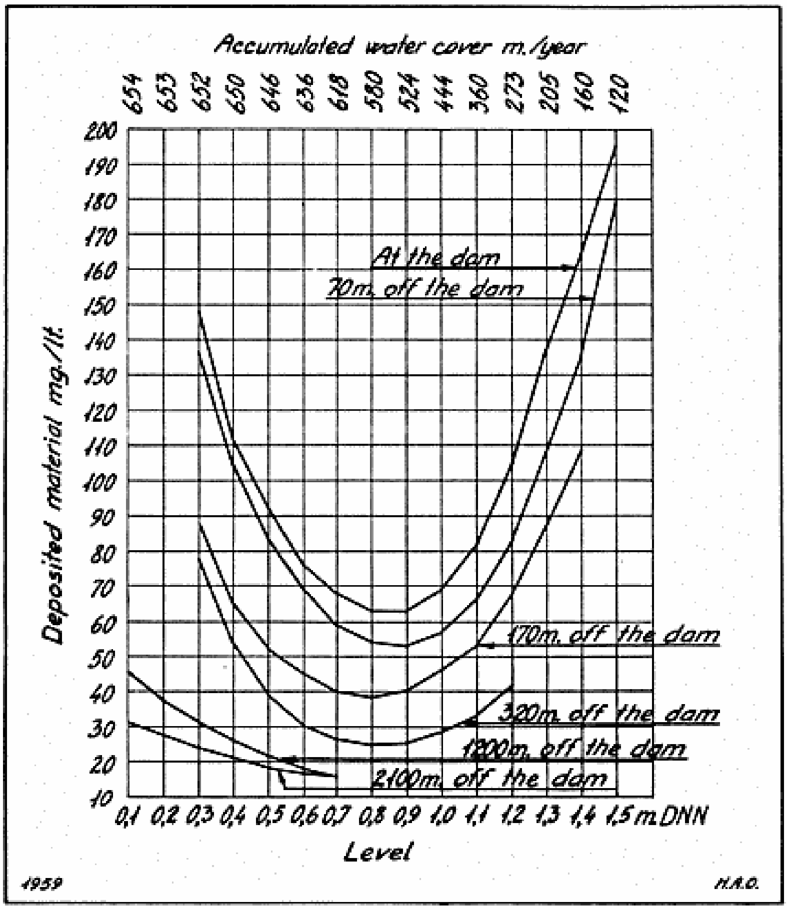

Fig. 7. The quantities of deposited material per year (mg./lt.) in proportion to the level at the base of the dam and at the distances from the dam of 70 m., 170 m., 320 m., 1200 m. and 2100 m. respectively. Each curve represents the quantity of deposited material per litre of the accumulated water cover per year at the different levels. The mean sedimentation in fig. 6 has been compared with the accumulated water cover per year. The specific gravity of the dry wadden-sediment (0,6) has been introduced in order to express the amount of sediment in unites of weight.

Fig. 7. Kurver for årligt sedimenteret materiale (mg/l) i forhold til niveauet gældende for dæmningsfoden og for 70 m, 170 m, 320 m, 1200 m og 2100 m fra dæmningsfoden. Hver kurve udtrykker, hvor stor den sedimenterede materialemængde har været i hver liter af den årlige vanddækning på de forskellige niveauer. Kurverne fremkommer ved at sammenholde middel-sedimentationskurverne på fig. 6 med den årlige vanddækning. For at kunne udtrykke sedimentet i vægtenheder er vægtfylden af det udtørrede vadesediment (0,6) indført.

tide-gauge is situated within the same tidal region and has the same mean high-water level as the area in question.

In table II is indicated the yearly accumulated water-cover in m. above + 0,1 m. to + 1,5 m. DNN and in percentage of the yearly accumulated water-cover at + 0,1 m., calculated as the average of the 15-year period 1941—1955.

Table II.

Tabel II.

Level m. DNN. *Niveau m DNN.*	Accumulated water-cover per year m. *Vanddækning pr. år m*	%
0,1	654	100,0
0,2	653	99,9
0,3	652	99,7
0,4	650	99,4
0,5	646	98,2
0,6	636	97,2
0,7	618	94,5
0,8	580	88,7
0,9	524	80,1
1,0	444	67,9
1,1	360	55,0
1,2	273	41,7
1,3	205	31,3
1,4	160	24,5
1,5	120	18,3

As all the previous measurements of suspended material have been expressed in mg./lt. it is desirable, for reasons of comparison, to express the proportion: quantity of sediments/accumulated water-cower in mg/lt. To this purpose has been taken a sample in nature of the topmost 20 cm. of the moist wadden sediment. The water content was found to be 55 %, which corresponds excellently to the value found by *Kaj Hansen* (1956), and the specific gravity of the desiccated material was determined to be 0,6.

The relation between the level and the intensity of sedimentation is shown in fig. 7 for the six curves in fig. 6. The abscissa indicates the level of sedimentation and the yearly accumulated water-cover corresponding to the respective levels; the ordinate indicates the relation between the quantity of deposits and the total yearly water-cover expressed in mg./lt. From fig. 7 appears the result of the following procedure: The sedimentation in dm. at a certain level is taken from fig. 6, then divided by the yearly accumulated water-cover in dm., multiplied by the specific gravity in dry condition

Table III.
Tabel III.

Waterlevel m. DNN *Vandstand m DNN*	Hour rising water *Kl. stigende vand*	Hour falling water *Kl. faldende vand*	Time difference rising water min. *Tidsdifferens stigende vand min.*	Time difference falling water min. *Tidsdifferens faldende vand min.*	Rising water + falling water min. *Stigende + faldende vand min.*	%
0,0	10,27	18,17	17	10	27	6
0,1	10,44	18,07	18	15	33	7
0,2	11,02	17,52	18	15	33	7
0,3	11,20	17,37	19	17	36	8
0,4	11,39	17,20	24	20	44	9
0,5	12,03	17,00	24	20	44	9
0,6	12,27	16,40	25	25	50	11
0,7	12,52	16,15	31	30	61	13
0,8	13,23	15,45	72	70	142	30
0,9	14,35	14,35				
					470	100

0,6 and by 10^6. The quantity of deposits in mg./lt. at the level in question is found and the point marked out in fig. 7.

The results of this method all show the same tendency: the sedimentation is biggest at a low level, decreases at rising level till + 0,8 — + 0,9 m. DNN (a little below the mean high-water level) and increases again at rising level. This means that *the sedimentation is less at the high-water level than at any higher or lower level,* when leaving out of consideration the variation of the water-cover; in other words, at high-water level the sedimentation is smaller in proportion to the water-cover than at any other level. This phenomenon occurs everywhere in the Wadden Sea; it manifests itself distinctly when an analysis is made of an over-dimensioned sedimentation, like the one in question; however, it may often be difficult to observe.

The causes of this are to be sought in the astronomical and the meteorological forces. Into table III have been introduced the water level and the hour for rising water and for falling water within the period during which the water rises from and again falls to 0,0 m. DNN. The figures have been taken from a random water level curve for the Rømø Leje on a calm day. The time difference, i.e. the time required for the water to rise and to fall 0,1 m., is calculated, and the time differences for rising water and for falling water are added up. In the last column has been calculated for how long a period, in percentage, of the total time of 470 minutes the water remains at the different 0,1 m. level intervals.

It is evident from table III that the water remains much longer within the topmost 0,1 m. than within any other level interval; for instance, it remains 5 times longer between + 0,8 m. and + 0,9 m. than between 0,0 m. and + 0,1 m.

The small waves which are formed by an even rather feeble wind in water of a depth of but few centimetres are inclined to erode in the surface of the tidal flats and to suspend material which has already been deposited. This material is carried away again at ebb-tide. The longer the small waves are allowed to ripple, the more powerful is the erosion; this means that the closer you come to the high-water line the stronger is the erosion. This is just expressed by the left part of the curves in fig. 7, as the sedimentation is constantly decreasing towards high-water level.

The normal water level situations and weather situations, which occur for long periods in the summer, signify consequently a certain loss of material for the tidal flats; this has been confirmed by numerous observations.

It appears from the above that the sedimentation must take place at a time where the water-cover is of such an extent that the wave-action is unable to reach the bottom.

However, the right half of the curves in fig. 7 shows and increasing sedimentation at rising level. The sedimentation which takes place at a level above mean high water must necessarily depend on extraordinary weather conditions, i.e. when gales create extraordinary high-tides by accumulation. Western gales in the Wadden Sea give rise to considerable accumulations of water in which the tides are moving. Measurements carried out under western gales have proved that under such conditions the tide is considerably smaller than normally; the result of this is reduced currents, which are further weakened because the increased depth of water augments the cross section of the flow. The surges create a violent erosion at the bottom on exposed places; consequently, the suspended quantity of material is 50—100 times bigger than normally. Therefore, on favourably situated localities an extraordinarily big sedimentation will take place under western gales; as it appears from the right half of the curves in fig. 7, the sedimentation increases with the level, i.e. stronger wind, higher water level, bigger sedimentation.

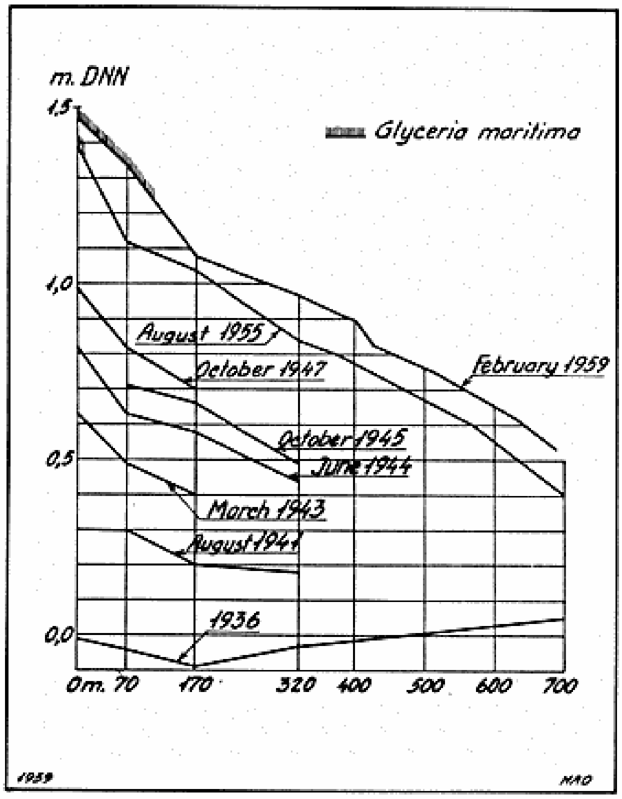

Fig. 8. Profile through the tidal flat to the south of point 1,2 km. of the Rømø Dam. All the measurements executed in the years 1936-59 are marked out. The extent of the *Glyceria* vegetation in this period is shown.

Fig. 8. Profil gennem vaden syd for Romødæmningens st. 1,2 km med samtlige udførte målinger i tiden 1936-59 indtegnet. Glyceria vegetationen er vist i den udstrækning, den er fremkommet.

As mentioned in fig. 5, the *Glyceria* vegetation is also a factor of considerable importance to the sedimentation at the high-water level and above this, because it is able to retain not only the sand-fraction and the silt-fraction, but the clay-fraction too; thus, this vegetation is of decisive importance to the salt-marsh formation.

The erosion at the high-water level.

The erosion at the high-water level is probably the essential cause of the fact that often it is difficult for the vegetation to start on a high-lying tidal flat, though the necessary height for immigration of vegetation ought to be optimal. It has also been observed that even a rather dense *Salicornia* vegetation on a high-lying tidal flat is destroyed by erosion. Contrary to this: once a *Glyceria* vegetation has immigrated it is only with difficulty destroyed, because *Glyceria* catches and retains the material which has been whirled up and, thereby, consolidates its own position; however, on the wind-exposed sides this vegetation will become the subject of border-erosion, which can only be counteracted by artificial means, for instance by fascines.

A more visible form of erosion on sandy tidal flats is the "puddle" form described by *B. Jakobsen* and *K. M. Jensen* (1956), which often occurs at levels at little below the limit of vegetation. At similar levels on silty tidal flats the surface has a crackled aspect with small, water-filled shallow channels with steep walls situated between silt-islands of varying size. This altered aspect in relation to the sandy tidal flat is due to the work carried out by the diatoms to maintain the already deposited material.

Finally is given an example of the development of the surface south of the dam. Fig. 8 shows a cut through the tidal flat at a right angle to the point 1,2 km. of the dam. This cut comprises the surfaces which have been contoured during the period 1936—1959. Until 1955 the tidal flat was practically without vegetation apart from small hummocks of *Spartina Townsendi,* a little *Salicornia* and a narrow stripe of *Glyceria,* 5—10 m. broad, along the base of the dam.

It is characteristic of the whole of this tidal region that the vegetation does not immigrate until a rather advanced stage of development, i.e. at a relatively high level, because the sedimentation has taken place very rapidly. This resulted in a soft and water-filled bottom, which lacks draining and, therefore, offers unfavourable conditions for the vegetation. Contrary to the greater part of the other regions with initial growth in the Danish Wadden Sea, the vegetation here has hitherto had but small importance to the sedimentation.

During the period 1955—1959 a dense *Glyceria* vegetation has immigrated, stretching until a distance of 110 m. from the base of the dam; this is the reason why the level 70 m. from the base of the dam has risen comparatively more than the points: the base of the dam and 170 m. from this.

In 1958 a ditching has been executed at a distance of 400 m. from the base of the dam. The good draining caused by the ditching has immediately had a favourable influence on the vegetation, especially the *Salicornia;* as a consequence of this the limit of dense *Salicornia* vegetation in the autumn 1958 was situated at a distance of 300 m. from the base of the dam.

However, the ditching has had another favourable effect; by drying-up the raw surface of the tidal flat, this has been rendered more resistable against wave-action; which clearly appears from fig. 8 in the 400 m. point; just at this point the curve of February 1959 gets an angle downwards at the place where the limit of the ditching is situated.

Conclusion:

The investigation of sedimentation south of the Rømø Dam for a period of 20 years has proved the existence of three geographically conditioned effects of great importance: *the beach-effect, the barring effect* and *the bay-effect,* factors which it is necessary to consider at the preparation of projects for land-reclamation.

A further result is the demonstration of the considerable *erosion at the high-water level caused by wave-action.* It is necessary to protect this zone by fascines, by ditching and by new-established *Glyceria* vegetation, partly man-made and man-protected.

RESUME

Rømødæmningens indflydelse på sedimentationen.

Et eksempel fra Det Danske Vadehav.

Vadehavets bundkonfiguration kan i sin helhed betragtes som værende i ligevægt. Opstår ændringer i naturforholdene af naturlig eller kunstig art, vil det fremkalde en tilstand ude af ligevægt, som både kan forårsage nedbrydning og opbygning af såvel løb som vader.

En sådan forstyrrelse af en herskende ligevægtstilstand opstod, da man med Rømødæmningens bygning greb kunstigt ind i Vadehavets naturforhold. Herved fremkaldte man såvel nedbrydende som opbyggende processer, hvilke sidstnævnte i det efterfølgende nærmere skal behandles.

Til forståelse af disse processer vil det være formålstjenligt at klargøre sig de sedimentationsbetingende faktorer. Disse er

a) *De astronomiske kræfter* frembringer tidevandet, hvis strømme transporterer materialet. I Pajdyb syd for Rømødæmningen (fig. 1) er middelhøjvandsniveauet + 0,96 m DNN og tidevandets størrelse 1,78 m.

De meteorologiske kræfter er lufttryk, vind og is. *Lufttrykket* påvirker vandfladens niveau og hermed vanddybden. *Vinden* fremkalder dels bølger, der opslemmer materiale, dels opstuver vandmasser, som ændrer vanddybden og dermed bølgestørrelsen samt påvirker strømforhold gennem udligningsstrømme, hvilket altsammen har indflydelse på sedimentationen. *Is,* der fryser fast til bunden, flytter materialemængder, som dog oftest går tabt, da hovedparten af isen sædvanligvis føres ud i Nordsøen.

b) *De geografiske forhold,* d.v.s. et vadeafsnits beliggenhed og form er af største betydning for sedimentationen.

c) *De biologiske kræfter* har fortrinsvis betydning for binding af det sedimenterede materiale og for omformning af det suspenderede materiale, så det kan sedimenteres. De vigtigste aktive elementer er for materialebinding *diatomeer, alger, salicornia* og *glyceria* og for materialeomformning *mollusker*.

I årene 1939–48 blev den danske vadehavsø Rømø forbundet med Jylland ved en 9.170 m lang dæmning. På fig. 1 er vist det afsnit af Vadehavet, hvor Rømødæmningen er bygget. Dæmningen kuperer 3 nord-sydgående strømlejer: Rømø Dyb, Rømø Leje og Pajdyb, og ligger for de østligste 6 km's vedkommende på vandskellet mellem Lister Dybs tidevandsområde mod syd og Juvre Dybs tidevandsområde mod nord. På fig. 1 er indrammet et med vandret skravering markeret område på 200 m's bredde og 5 km's længde, gennem hvis nordlige og sydlige grænse på fig. 2 er tegnet de to længdeprofiler A og B, som viser sedimentationens størrelse 1936 til 1956–57. Ved sammenligning af A og B kan påpeges tre geografisk betingede virkninger på sedimentationen forårsaget af dæmningens tilstedeværelse nemlig: *kystvirkning, kuperingsvirkning* og *bugtvirkning*. Ved kystvirkning forstås effekten af de kræfter, der bliver virksomme, når en nydannet kunstig kyst skal udforme det til enhver kyst hørende strandplan. Definitionen på kuperings- og bugtvirkning ligger i selve ordene. På Vesen er på A sket en sedimentation på ca. 0,5 m, på B ingen, d.v.s. at sedimentationen skyldes kystvirkning, og at denne ikke når ud til profil B. Kuperingsvirkningen træder tydelig frem i Rømø Leje på såvel A som B. Sedimentationen på Pajsand, profil B, må skyldes bugtvirkning, hvilket sandsynliggøres af beliggenheden i den dybe bugt mellem Rømødæmningen og Jylland. Kystvirkningen har altså kun betydning i dæmningens nærhed, kuperingsvirkningen i løbene, mens bugtvirkningen har et mere udstrakt virkeområde.

Sedimentationen i det på fig. 1 med kraftig indramning markerede område undersøges. Fig. 3 og 4 viser kurvebillederne i henholdsvis 1936 og 1955. I denne periode er på det 200 ha store areal sedimenteret en materialemængde på 1 mill. m³. Med hensyn til sedimentationsmulighederne svarer de geografiske forhold til Rømø Leje områdets, idet dog bugtvirkningen må være kraftigere, da bugtens horizontale dybde er større. På fig. 3 og 4 træder kyst-, bugt- og kuperingsvirkning tydelig frem.

På grundlag af 8 fladenivellementer, hvoraf det første fra 1936 regnes for identisk med kurvebilledet, umiddelbart før dæmningen førtes ud på vaden i 1940, er optegnet 6 profiler gennem vaden *parallelt* med dæmningen og med følgende beliggenhed: langs dæmningsfoden, 70 m, 170 m, 320 m, 1200 m og 2100 m syd for dæmningsfoden. På hvert profil er valgt 4 vertikaler med en indbyrdes afstand af ca. 400 m. I hver vertikal er sedimentationens størrelse (i cm) indenfor de respektive tidsintervaller målt og sedimentationens størrelse i cm/måned beregnet. Eksempelvis er i tabel I angivet beregningsmetoden for de 4 vertikaler i det profil, der ligger 70 m fra dæmningsfoden. I fig. 5 er værdierne i tabel I for sedimentation pr. måned og middelniveau indtegnet i et koordinatsystem med sedimentationen som abscisse og niveau som ordinat, og middelkurven er tegnet.

Kurven på fig. 5 og de fem andre på lignende måde fremstillede middelkurver for sedimentationens størrelse i forhold til niveau og dettes afstand fra dæmningen findes angivet på fig. 6, idet dog abscissens målestok er ændret til cm pr. år.

Sammenholdes kurverne på fig. 6 med den årlige vandddækning fås et udtryk for vandets indhold af *sedimenteret* materiale. Den årlige vanddækning på de forskellige niveauer findes i tabel II. For at udtrykke det suspenderede materiale i mg/l er det nødvendigt at kende vægtfylden af det udtørrede vademateriale, der bestemtes til 0,6. For de i fig. 6 viste seks kurver er på fig. 7 fremstillet relationen mellem sedimentationsniveauet (abscisse) og sedimentationsintensiteten (ordinat). Kurverne viser alle samme tendens, nemlig at sedimentationen er størst på lavt niveau, falder med stigende niveau indtil lidt under middelhøjvandsniveauet, men stiger så atter med stigende niveau. Det vil altså sige, at *sedimentationen er mindre omkring højvandsniveauet end på et hvilket som helst lavere eller højere niveau, når vanddækningens variation lades ude af betragtning.* Årsagerne hertil skal søges i de astronomiske og meteorologiske kræfter. I tabel III er for en tilfældig tidevandskurve fra en rolig dag indført vandstande og dertil hørende klokkeslet samt en beregning af tidsdifferencer. Af disse ses, at vandet står meget længere tid i 0,1 m intervallet ved højvande end i et hvilket som helst andet niveauinterval. De småbølger, der af en selv ret svag vind dannes i få cm dybt vand, eroderer i vadeoverfladen og opslemmer materiale, der føres bort af ebben. Jo længere småbølgerne står og vasker, des kraftigere erosion, d.v.s. at des nærmere man kommer højvandslinien, des kraftigere erosion, hvilket netop er, hvad venstre halvdel af kurverne i fig. 7 udtrykker. Højre halvdel viser imidlertid stigende sedimentation med stigende niveau. Den sedimentation, der finder sted over daglig højvandsniveauet, må nødvendigvis finde sted under ekstraordinære vejrforhold, d.v.s. når vindstuvning fremkalder særligt store højvander. I det således forhøjede vandniveau bliver tidevandets størrelse mindre og strømmen derved svagere. Da der tillige under sådanne forhold er meget større materialemængder i suspension, betyder det altså større sedimentation, d.v.s. kraftigere vind, højere vandstand, større sedimentation.

Erosion omkring højvandsniveauet er formentlig den væsentligste årsag til, at vegetationen ofte har vanskeligt ved at få fodfæste på en i niveaumæssig henseende vegetationsmoden højvade.

Fig. 8 viser et profil gennem vaden vinkelret på dæmningens st. 1,2 km. Indtil 1955 var vaden praktisk talt vegetationsløs. 1955–59 er indvandret en tæt *glyceria* vegetation, der strækker sig 110 m ud. Dette er årsagen til, at niveauet 70 m fra dæmningsfoden har hævet sig forholdsvis mere end punkterne dæmningsfod og 170 m fra dæmningsfod. I 1958 er foretaget en grøbling i 400 m bredde ud fra dæmningsfoden. Grøblingen har bl. a. haft den gunstige virkning gennem dræningen at udtørre den rå vadeoverflade, så den er blevet mere modstandsdygtig overfor bølgeerosion, hvilket kommer klart til udtryk på fig. 8 i 400 m punktet, hvor vaden (febr. 1959) netop får et knæk nedad på det sted, hvor grænsen for grøblingen ligger.

Undersøgelsen har givet oplysning om de 3 geografisk betingede virkninger på sedimentationen: kyst-, kuperings- og bugtvirkning, som det kan være af betydning at have for øje, når landvindingsprojekter udarbejdes. Konstatering af, hvor betydelig bølgeerosionen er i og omkring højvandsniveauet, indskærper nødvendigheden af denne zones beskyttelse.

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