SEDIMENTS AND DYNAMICS IN THE VARDE Å ESTUARY

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The Varde Å estuary is supplied with material from two sources: the drainage area and the turbidity maximum in the N-part of Ho Bugt. The first supplies bed load and suspended material, whereas the latter supplies fine-grained, flocculated material only.

The sediments and the dynamics related to sediment transport in the area will be discussed on the basis of investigations carried out in the period from June 1976 to July 1977.

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1. MATERIAL SUPPLIED FROM THE DRAINAGE AREA

Fig. 1 shows a typical grain size distribution of bed load material supplied to the estuary from the drainage area. Using the Folk and Ward (1957) parameters, the material can be generally characterized as follows:

$m_z = 1\ \Phi$ (0.5 mm), $\sigma_{,} = 0.8\ \Phi$ sk $= 0.2$ and kg $= 1.3$.

The log-probability distribution shows two distinct inflection points, one near 0.75 Φ (0.59 mm) and another near 2.4 Φ (0.19 mm). This is in agreement with the distributions found by Visher (1969) and by Sagoe & Visher (1977) who interpret these two inflection points as separating traction- saltation- and suspension populations. Midleton (1976) argued that the »fine« inflection point depends on the wash load content and, consequently, cannot be dependent on the hydraulics, but on the supply of fine-grained material only. He also advocates that the »coarse« inflection point should be interpreted as separating material moving almost exclusively as bed load, and material moving in suspension from time to time when the river reaches the »dominant« discharge. The sample shown in fig. 1 was collected in the middle of a straight river course 12 km upstream from the mouth of Varde Å by means of a box sampler which traps the movable bed load material. After sieving, the different subsamples were analysed in a settling tube where the settling velocities in pure water at 20°C were determined. Table 1 shows the relation between sieving diameter and settling velocity.

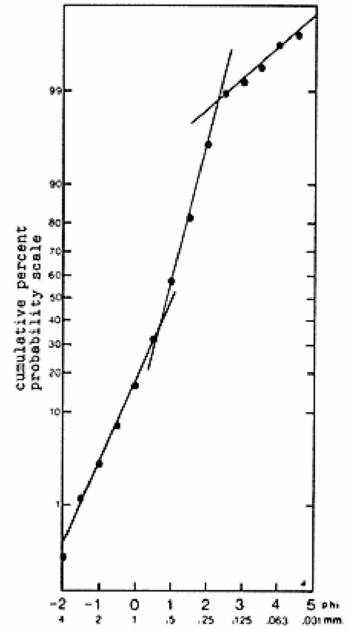


Fig. 1. Log/probability diagram showing the grain size distribution of a typical sample of the bed load supply to Varde Å estuary.
Fig. 1. Log/sandsynligheds diagram der viser kornstørrelsesfordelingen i en typisk prøve af bed load materialet, der tilføres estuariet fra oplandet.

Simultaneously with collecting the bed load sample, the following parameters were measured:

Depth D = 1.29 m, mean velocity over depth V = 0,565 m/s, water surface gradient $I_0. = 1.79 \cdot 10^{-4}$ and water temperature T = 14°C.

Equation (1) was constructed using the data presented in Report No. 12. Subcommittee on Sedimentation (1957), table 4.

$$W_T = W_{20}(1 + (20\text{-}T)\ (8.3\ 10^{-3} + 6.8\ 10^{-3}\ \ln(W_{20})))\quad (1)$$

The equation predicts the fall velocity W_T at a given temperature T (10°<T<20°C), from the fall velocity at 20°C, W_{20} ($2 \cdot 10^{-3} < W_{20} < 2.5 \cdot 10^{-1}$ m/s). The last column in table 1 shows the fall velocity at 14°C fitting the actual, measured water temperature. These values were calculated using equation (1) and the measured fall velocities at 20°C.

According to Engelund and Hansen (1972) the effective friction velocity U_f', left after form drag correction, can be calculated by means of equation 2 and 3:

$$\frac{V}{\sqrt{g \cdot D' \cdot I_o}} = 6 + 2{,}5\ \ln\ \left(\frac{D'}{2.5\ d}\right) \qquad (2)$$

$$U_f' = \sqrt{g \cdot D' \cdot I_o} \qquad (3)$$

Where *d* denotes the mean fall diameter. This was in the actual case determined to 0.556 mm by means of the sieveing analysis, table 1, and the Subcommittee data on fall velocity of spheres.

When solving equation 2 and 3 by iteration, U_f' was found to be 0.028 m/s.

On the basis of data from Guy et al. (1966), Engelund (1973) found that grains with smaller fall velocity than $W_c = 0.8 \cdot U_f'$ are transported in suspension. In the actual case this gave a critical fall velocity of 0.22 m/s, which by means of table 1 can be transformed to a critical sieve diameter of 2.5 Φ (0.18 mm), very close the »fine« inflection point in fig. 1.

The results described here therefore suggest that the interpretation of the »fine« inflection point, in accordance with Visher's analysis, should be the separation of bed load- and suspended load. The problem with different wash load supplies, such as mentioned by Midleton (1976), could probably affect the amount of fine-grained material present in the bed load, and therefore move the »fine« inflection point up and down in the log/probability diagram; the grain size at which the inflection point appears, however, is not likely to reflect this supply.

1.2 Wash load versus suspended bed load material

The suspended materal is divided into two parts, suspended bed load and wash load material. In order to investigate the share of each type, there were, simultaneously with the earlier mentioned measurements, collected two water samples, one C_s from 0.10 m below the water surface and one C_b from 0.10 m above the river bed. C_s contained 16.2 mg/l and C_b 18.5 mg/l (filtered through Watman GFF filters).

As wash load per definition is independent of the immediate hydraulic conditions, the material is supposed to be uniformly dispersed in the water column.

According to Einstein (1950) the suspended bed load material is distributed in the water column following equation (4):

$$\frac{C_y}{C_a} = \left(\frac{D-y}{y} \cdot \frac{a}{D-a}\right)^{Z} ; \; Z = \frac{W}{\kappa U_f'} \qquad (4)$$

In the actual case, C_y is measured as a summation of both suspended bed load and wash load material. Therefore, (4) should be rewritten as (5) by means of the approximation that Z can be calculated by substituting W with the mean fall velocity of the suspended bed load material:

(5):

$$\frac{C_y - C_{wa}}{C_a - C_{wa}} = \left(\frac{D-y}{y} \cdot \frac{a}{D-a}\right)^{Z} \qquad (5)$$

C_y, C_a denote the total concentration of suspended material at level y,a above the bottom, and C_{wa} denotes the wash load concentration.

The mean fall velocity of the suspended bed load material was calculated to 0.006 m/s by truncation of the grain size distribution, at the critical grain size, according to the earlier mentioned suspension criterion.

Sieve diam.		Fall velocity, m/sec	
Φ	mm	20⁰C	14⁰C
-1.75	3.364	0.2335	0.2313
-1.25	2.378	0.1939	0.1906
-0.75	1.682	0.1610	0.1570
-0.25	1.189	0.1336	0.1293
0.25	0.841	0.1109	0.1065
0.75	0.595	0.0872	0.0829
1.25	0.420	0.0633	0.0593
1.75	0.297	0.0459	0.0424
2.25	0.210	0.0328	0.0299
2.75	0.149	0.0185	0.0164
3.25	0.105	0.0104	0.0090
3.75	0.079	0.0050	0.0042
4.25	0.053	0.0025	0.0020

Table 1. The relation between sieve diameter and fall velocity of the bed load material supplied to Varde Å estuary from the drainage area. The fall velocity at 20^0C is measured in the laboratory, and the corresponding fall velocity at 14^0C is calculated from equation (1).

Tabel 1. Sammenhængen mellem sigtediameter og faldhastighed i bed load materialet, der tilføres Varde Ås estuarium fra oplandet. Faldhastigheden ved 20^0C er målt i laboratoriet, og den tilsvarende faldhastighed ved 14^0C er beregnet ved hjælp af ligning (1).

The solution of equation (5) gave a wash load content as high as 16.0 mg/l, which means that 0.1 m above the river bed only (18.5 - 16.0) 2.5 mg/l was suspended bed load material.

The transport rate of this material was found using equation (6) (Einstein 1950, and Engelund 1973):

(6):

$$q_s = 11{,}6 \cdot U_f' \, C_a \, a \left[I_1 \ln \left(\frac{30 \cdot D}{2{,}5 \cdot d}\right) + I_2 \right] \qquad (6)$$

where I_1 and I_2 were determined to 0.8 and -1.0 respectively from the work charts in Einstein (1950). The transport rate of the wash load material was found as:

(7):

$$q_{wa} = D \cdot V \cdot C_{wa} \qquad (7)$$

These calculations gave $q_s = 0{,}6 \cdot 10^{-3}$ kg/s m² and $q_{wa} = 11{,}6 \cdot 10^{-3}$ kg/s m², which means that qs is below 5% of total, suspended transport rate.

The measurements described here were carried out in a period when the river flow was near mean annual discharge.

Distance upstream from the estuary mouth in km	7.5	5.2	3.0	1.1
Manning number M	36	35	43	55

Table 2. The Manning number M as a function of distance to the estuary mouth. M is calculated from the Manning equation $V = M \cdot I_o^{1/2} \cdot D^{2/3}$. V and D were measured in the middle of the cross profiles and I_o over a distance of 2-4 km. The measurements were carried out in the late ebb period with almost stationary flow conditions.

Tabel 2. Manning tal M som en funktion af afstand til mundingen af Varde Ås estuarium, beregnet på basis af Manning formlen. V og D måltes midt i tværprofilerne og I_o over en afstand på 2-4 km. Målingerne blev udført i slutningen af ebbeperioden med tilnærmelsesvis stationær strømning.

Therefore much coarser material is likely to be brought into suspension in flom situations. According to Midleton (1976) the »coarse« inflection point (in this case at 0.75 Φ (0.59 mm)) is inherited from these situations. The present results show, however, that in normal situations most of the suspended material supplied to the estuary from the drainage area, is wash load and only a small proportion is suspended bed load material.

2. BED LOAD TRANSPORT IN THE ESTUARY

The bed load material supplied to the estuary from the drainage area is transported farther through the estuary over a more or less fixed bed of peat and clay. The thickness of this bed load layer varies from a few mm to over 0.5 m, which was the length of the applied auger.

Distance upstream from the estuary mouth in km		$I_{o(max)}$	$D_{(max)}$ m.
7.5		$1.58\ 10^{-4}$	1.80
5.2		$0.92\ 10^{-4}$	1.84
4.3	left:	$0.74\ 10^{-4}$	0.92
	right:		1.32
3.0		$0.49\ 10^{-4}$	1.56

Table 3. Water surface gradient I_o and maximum depth D in different cross sections of Varde Å estuary in a spring-tide situation at maximum bed shear stress. Water temperature = 14°C.

Tabel 3. Vandspejlsgradient I_o og max. dybde i forskellige tværprofiler af Varde Ås estuarium i en springtids situation med max. bundforskydningsspænding. Vandtemperatur = 14°C.

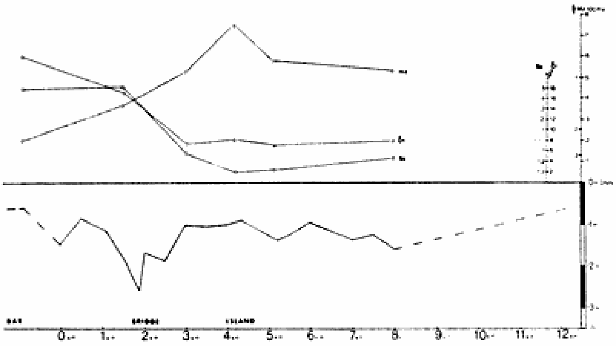


Fig. 2. Mean grain size m_z, standard deviation σ and skewness sk, as a function of distance in the Varde Å estuary. Below is shown the corresponding length profile of the estuary. Reference datum is DNN (Danish Normal Datum).

Fig. 2. Middelkornstørrelse m_z, standardafvigelse σ og skævhed sk, som funktion af afstand i Varde Ås estaurium. Nederst det tilsvarende længdeprofil i forhold til DNN.

In the channel reach between 4-7 km upstream from the mouth, the bed load material builds up channel bars, giving the estuary cross profile an irregular appearance. The transformation from alluvial to non-alluvial conditions is illustrated in table 2 showing the change in the Manning number M down the estuary.

The values in table 3 represent I_o and D_{max} in four cross sections of the estuary during a spring-tide situation at maximum bed shear stress. For all four cross sections this maximum occurred during the ebb period.

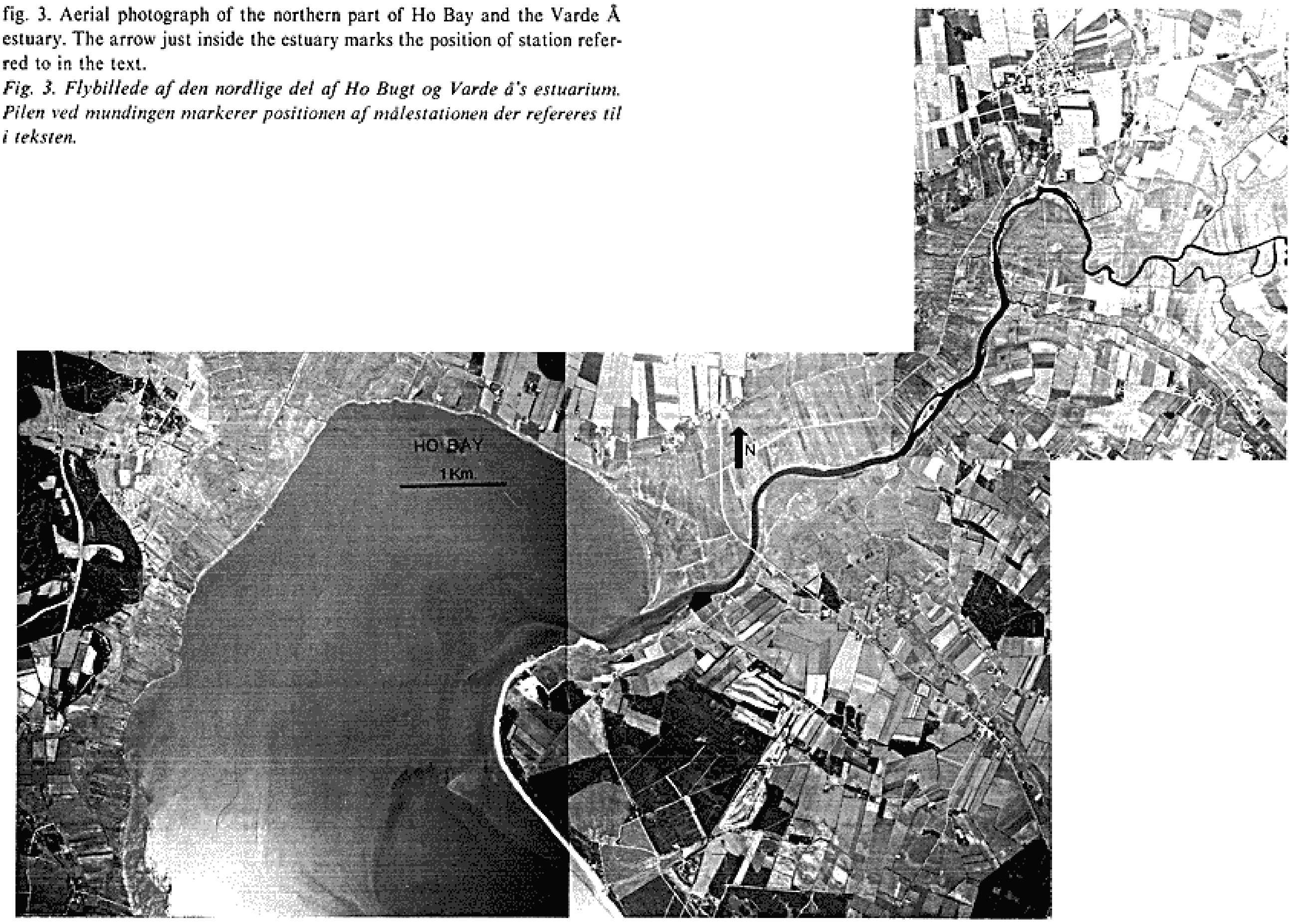
These values give rise to a calculation of the variations in competence in the estuary, based on an iterative reading of Shield's curve (guess diameter, calculate Reynold's number, read θc, calculate from this the new diameter etc). The results are shown in table 4.

The calculations imply that the whole friction velocity is at disposal for sediment transport, which - in contrast to capacity calculations - is a reasonable implication here. The results demonstrate that there is a drastic decrease in competence in the channel reach from 7.5-3.0 km upstream from the estuary mouth; and that this decrease in a normal spring-tide situation affects particle sizes which are present in the bed load supply from the drainage area.

Fig. 2 shows how mean grain size (m_z), standard deviation (σ) and skewness (sk) vary in the estuary. It is here illustrated how the mean grain size rises from the 0.5 mm valid for bed load supplied from the drainage area to 0.7 mm near the island 4.3 km upstream from the mouth see fig. 3. From here the mean grain size decreases to approx. 0.2 mm at the submerged bar outside the estuary.

This variation reflects the above-mentioned decrease in competence, which bring about a concentration of coarse particles not able to pass the estuary. The change in skewfig. 3. Aerial photograph of the northern part of Ho Bay and the Varde Å estuary. The arrow just inside the estuary marks the position of station referred to in the text.

Fig. 3. Flybillede af den nordlige del af Ho Bugt og Varde å's estuarium. Pilen ved mundingen markerer positionen af målestationen der refereres til i teksten.



ness further emphasizes this interpretation, with a minimum of -0.3 mm (too much coarse material) near the island.

The rapid increase in values of skewness up to + 0.5 mm (too much fine material) and the fall in mean grain size downstream of the island however is not only a result of sorting out of coarse particles upstream from here.

This is primarily a result of mixing with fine-grained, flocculated material from the turbidity maximum which in this region increases its influence in the downstream direction. That it is mixing and not sorting which causes this overall change in character of sediments downstream of the island is illustrated in the values of standard deviation. This changes from 0.8-0.7 Φ (moderately sorted) to 2.4 Φ (very poorly sorted) over the same reach.

According to the results described here, the bed load transport through the estuary is affected by decreasing competence; which results in a mean grain size maximum about 4 km upstream from the estuary mouth, and the development of channel bars tending to narrow the cross section of the estuary. The bed load material which escapes this region is mingled with fine-grained, flocculated material and transported downstream to settle at a submerged bar just outside the estuary mouth.

3. MATERIAL SUPPLIED FROM THE TURBIDITY MAXIMUM

In his paper, Pejrup (1980), discusses the existence of a turbidity maximum in the northern part of Ho Bugt. The material-rich water from here is carried up the estuary with the flood current where the major part of the suspended material deposits at high-tide slack water. In the following ebb current, this material is subjected to resuspension and brought back to Ho Bugt. This resuspension goes on during

Distance upstream from the estuary mouth in km		$U_f = \sqrt{g\ D\ I_o}$	$R_{d_{max}}$	θ_c	d_{max}
7.5		0.053	155	0.050	3.4
5.2		0.041	80	0.045	2.3
4.3	left:	0.026	26	0.035	1.2
	right:	0.031	40	0.040	1.5
3.0		0.027	29	0.038	1.2

Table 4. Friction velocity Uf, max. movable grain size Reynold's number $R_{d_{max}}$, critical Shield's parameter θ_c and maximal movable grain size in four different cross sections of Varde Å estuary.

Tabel 4. Friktionshastighed, Reynolds tal for størst bevægelige korn $R_{d_{max}}$, kritisk Shield parameter θ_c samt max. bevægelig d_{max} kornstørrelse i 4 forskellige tværprofiler.

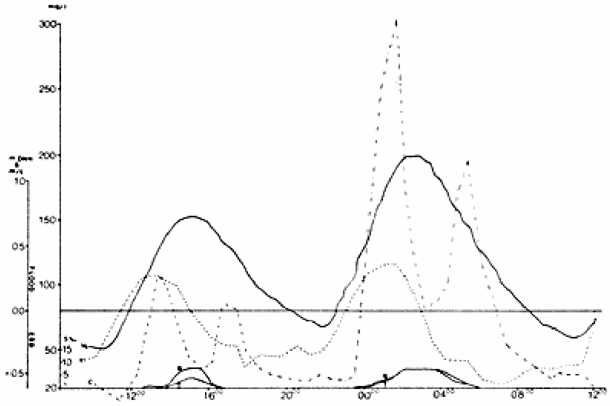


Fig. 4. The dynamic conditions 1.1 km inside the mouth of Varde Å estuary, April 16-17, 1977. V_s = water level, V = measured mean velocity over depth, c = concentration of suspended material (depth-integrated), B and T = salinity at bottom and top respectively. The position of the measuring station is marked with an arrow in fig. 3.

Fig. 4. De dynamiske forhold 1,1 km inden for Varde Å's munding 16-17 april, 1977. V_s *= vandstand, V = målt middelhastighed over dybden, c = koncentration af suspenderet materiale (dybde-integreret), B og T = saltholdighed resp. bund og overflade. Målestationens beliggenhed er vist med en pil på fig. 3.*

the first part of the ebb period; at late ebb, the estuary is filled with freshwater from the drainage area with a relatively low content of suspended material.

Outside the estuary mouth, the tide is clockwise rotating and thus forces the freshwater to leave the mouth area in a more southern direction than from where the estuary is filled during flood tide. This means that the salt water appears very quickly in the estuary after low-tide slack water.

The dynamic conditions just inside the mouth during two tidal cycles are shown in fig. 4. It is here clearly demonstrated how sensitive the concentration of suspended material is, to weather conditions. The first tidal period was characterized by calm weather, and the second by a gale from the SW. During the latter cycle the concentrations of suspended material increased by a factor three, whereas the pattern of variation remained unchanged. Roughly this pattern can be described by dividing the variations into the following 4 phases:

Phase 1: first half of the flood period when the material-rich water from the turbidity maximum in the bay flows into the estuary making a peak on the concentration curve at maximum flood current velocity.

Phase 2: second half of the flood period when the material deposits and give rise to a local minimum on the concentration curve at high-tide slack water.

Phase 3: beginning of the ebb-period when the resuspension of the deposited material shows as a new, but smaller peak on the concentration curve, and finally,

Phase 4: the rest of the ebb period when the concentration decreases to the lowest values of the whole tidal period due to the supplies of relatively pure water from the drainage area.

The concentrations of suspended material were found by filtration of depth-integrated water samples (0.75 l) through Whatmann GFF filters, as prescribed in Whatmann's Publication No. 604.

The above-mentioned dynamic conditions, with relatively high concentrations of suspended material at high-tide slack water, result in mud-flat deposits along the estuarine banks, consisting of fine-grained, flocculated material from the turbidity maximum in Ho Bugt. As stated by Pejrup (1980), this material is of both marine and of fluvial origin. The latter has an organic content of 30-50% (combusted at 500°C) against roughly 10% in the material from the turbidity maximum.

Biological processes in estuarine waters and in the uppermost sediment layers tend to mobilize organic matter (Biggs 1970) and remove it from estuaries; apart from this, there also exists a sedimentological contribution to the removal of organic matter, such as illustrated by the laboratory experiments presented in fig. 5. The experiments showed that, in salt water, organic matter will react much weaker to flocculation than minerogene matter does; this may lead to a selective sedimentation of minerogene material in estuaries, whereas the organic part easier escapes to the ocean.

The experiments also showed that the flocculated freshwater wash load material had almost the same grain size distribution as the flocculated suspended material from the brackisch part of the turbidity maximum.

4. THE DEVELOPMENT SINCE 1804

On the map fig. 6 it is shown how new marsh areas have grown up since 1804 in the area W of the bridge across the estuary just inside the mouth. During the same period, the channel reach between 7.5-3 km inside the mouth has narrowed considerably. On the map from 1804 - only a section W of the bridge is shown in fig. 6 - there is no sign of the island about 4 km upstream from the mouth. By 1870, the island was a small, 25 m wide bar, which in the period until 1955 grew to an approximate width of 100 m. It is remarkable that this growth did not cause any erosion in the adjacent banks; rather on the contrary, both up- and downstream from the island center the banks have been moving forward, as in the rest of the inner estuary.

In the region upstream of the island the narrowing has typically taken place by deposition of bars (bank-near channel bars or point bars) built up of coarse material, stabilized by vegetation and fine-grained material, and thereafter grown together with the original banks by deposition of mud flats in the shelter between bar and bank. Downstream of the island, the narrowing has taken place as mud flat deposition only.

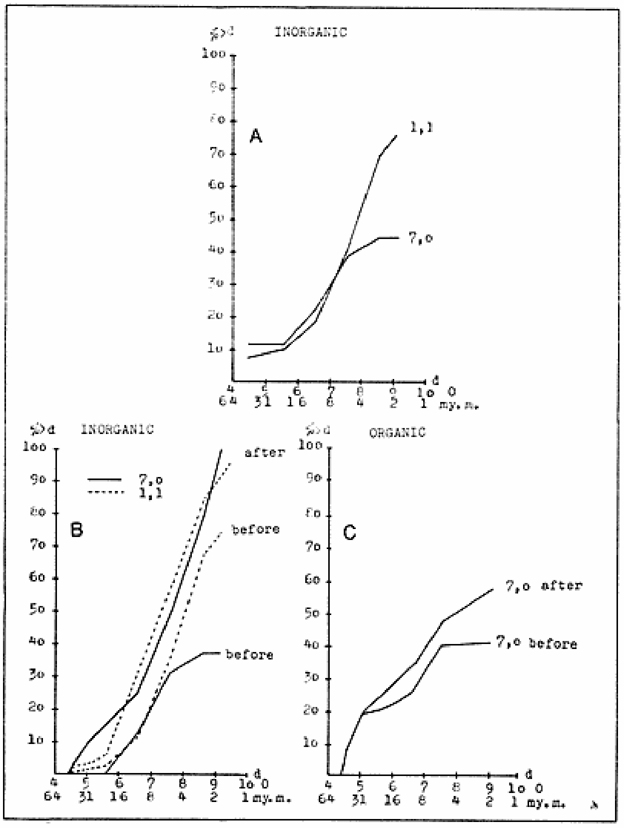


Fig. 5. Results of laboratory experiments with flocculation of suspended particles from Varde Å estuary. 7.0 denotes material representative for the wash load supply to the estuary. 1.1 denotes material representative for the suspended material in the brackish part of the turbidity maximum (salinity 1.2 0/00).

A. Grain size distribution of the minerogene part of sample 7.0 and 1.1 before the conveyance of salt water.

B. Grain size distribution of the minerogene part finer than 45 µ of sample 7.0 and 1.1 before and after flocculation in 10 0/00 salinity.

C. Grain size distribution of the organic part finer than 45 µ of sample 7.0 before and after flocculation in 10 0/00 salinity.

The Grain size distribution is determined as fall diameter measured via pipette analyses directly in the flocculation chamber. The subsamples were filtered through Whatman GFF filters. The organic content is determined after combusting at 500°C. The flocculation has taken place over 48 hours with frequent shaking of the chamber.

Fig. 5. Resultater af laboratorieforsøg med flokkulation af suspenderet materiale fra estuariet. 7.0 angiver materiale representativt for wash load tilførslen til estuariet og 1.1 angiver materiale repræsentativt for den brakke del af turbiditetsmaksimaet (saltholdighed 1,2 0/00).

A. *Kornstørrelsesfordelingen af den minerogene del af prøve 7.0 og 1.1 før tilførsel af saltvand.*

B. *Kornstørrelsesfordelingen af den minerogene del < 45 µ af prøve 7.0 og 1.1 før og efter flokkulation i 10 0/00 saltholdigt vand.*

C *Kornstørrelsesfordeling af den organiske del af materialet < 45 µ af prøve 7.0 før og efter flokkulation i 10‰ saltholdigt vand.*

Kornstørrelsesfordelingen er bestemt som falddiameteren målt med pipette direkte i flokkulationskammeret. Underprøverne blev filtreret gennem Whatman GFF filtre, og organisk indhold bestemt efter forbrænding ved 500° C. Flokkulationen fandt sted i løbet af 48 timer og med hyppige rystelser af kammeret.

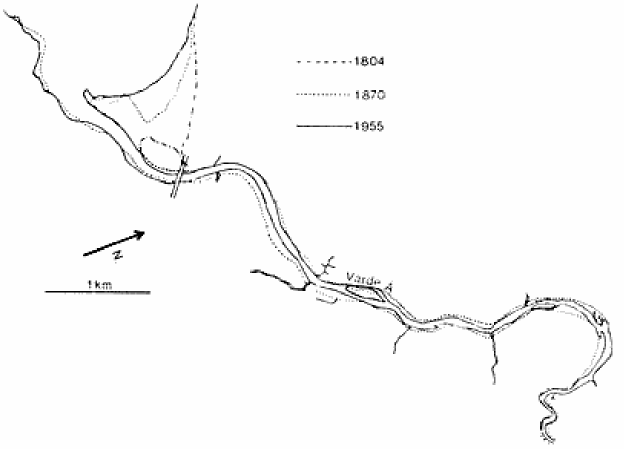


Fig. 6. Map showing the Varde Å estuary in 1804, 1870 and 1955. The coastline from 1804 is only indicated W of the bridge across the estuary.
Fig. 6. Forløbet af Varde Å estuarium i 1804, 1870 og 1955. Kystlinjen fra 1804 er kun vist V for broen.

Myrick and Leopold (1963) found that the well-known regime formula from upland rivers,

$$W = aQ^b \tag{8}$$

also is valid in small tidal estuaries. On the basis of theoretical considerations they determined the exponent *b* to 0.77 and on the basis of measurements in a tidal area to 0.71. This hydraulic geometry is related to a tidal creek which drains no upland. By using Inglis and Allens (1957) data from the Thames estuary, this exponent can be determined to 0.86, i.e. close to the value found by Myrick and Leopold.

By measurements in the Varde Å estuary this exponent was determined to 1.6, a value which reflects the absence of equilibrium with a rapidly narrowing upper estuary. It is believed that the reason is an interaction between the rising sea level and the final stage in the development of the peninsula Skallingen.

The rising sea level (approx. 0.1 cm/year) has lowered the maximum water surface gradient in the estuary. During the last 100-200 years this has apparently reached a critical stage where coarse material supplied to the estuary can no longer be carried through it, and consequently is left building up channel bars. During the same period the peninsula Skallingen has reached its present form, offering an effective protection for the Ho Bugt area against the North Sea. Earlier, when Skallingen was no more than a sand bar, there has probably not been sufficient shelter to build up a turbidity maximum with the now found high concentrations in the northern part of Ho Bugt; consequently, the sedimentation of fine-grained material in the estuary at that time has been limited compared to the actual conditions.

CONCLUSION

1. The log/probability plot of the bed load material supplied to Varde Å estuary from the drainage area shows two distinct inflection points. One near 0.75 Φ (0.59 mm) and another near 2.4 Φ (0.19 mm). Measurements show that the fine inflection point is in agreement with the actual dynamic conditions separating bed load and suspended load.

2. Based on data from Report No. 12, Subcommittee on Sedimentation (1957), the following equation has been constructed:

$$W_T = W_{20}\,(1 + (20\text{-}T)\,(8.3\;10^{-3} + 6.8\;10^{-3}\;\ln(W_{20})))\quad(1)$$

The equation predicts the fall velocity W_T at a given temperature T ($10°C < T < 20°C$), from the fall velocity at 20°C W_{20} ($2\;10^{-3}$ m/s $< W_{20} < 2.5\;10^{-1}$ m/s).

3. In »normal« situations, less than 5% of the total, suspended material supplied to Varde Å estuary from the drainage area consists of suspended bed load material, the rest is wash load.

4. In the channel reach from 7.5-3.0 km upstream from the estuary mouth, there is a drastic decrease in competence. In a normal spring-tide situation this decrease is affecting particle sizes present in the bed load supplied from the drainage area.

5. The bed load transport through the estuary is affected by the decreasing competence; resulting in a mean grain size maximum about 4 km upstream from the estuary mouth, and, in the same region, development of channel bars which tend to narrow the cross section of the estuary. The bed load material escaping this region is mingled with fine-grained, flocculated material, and with this transported farther for deposition at a submerged bar just outside the estuary mouth.

6. At flood-tide, the inflowing water is part of a turbidity maximum in the northern part of Ho Bugt. At high-tide slack water, the suspended material deposits inside the estuary. During ebb-tide, it is resuspended and the estuary bottom is »washed clean«. At the end of the ebb period, the estuary is filled with relatively pure fresh water from the drainage area.

7. Organic matter reacts much weaker upon flocculation in salt water than minerogene material does. In estuaries, this difference may lead to selective sedimentation of minerogene material, whereas the organic material easier escapes to the ocean.

8. The upper part of the estuary is narrowing very quickly giving it a pronounced funnel shape. The exponent b in the regime formula $W = aQ^b$ was determined to 1.6, which is high compared with the expected value between 0.7 and 0.9. This non-equilibrium state is believed to be a result of the rising sea level and the relatively new sheltering effect of the peninsula Skallingen.

LIST OF SYMBOLS

a	reference level above the bottom; empirically determined multiplicator
b	empirically determined exponent
C_{wa}	concentration of wash load
C_y	concentration of suspended material at level y above the bottom
d	mean fall diameter
D	depth
g	accelleration of gravity
I_o	water surface gradient (energy gradient)
kg	kurtosis
M	Manning number
m_z	mean grain size
qs	transport rate of suspended bed load material
qwa	transport rate of wash load material
R_d	Reynold's number for grains with the diameter d
sk	skewness
T	temperature
U_f	friction velocity
U'_f	friction velocity left after form drag correction
V	mean velocity over depth
W	fall velocity; channel width
W_c	critical fall velocity before suspension
W_T	fall velocity in pure water at temperature T
Z	$w/\kappa{\cdot}U'_f$ exponent
κ	V. Kármán's constant
σ	standard deviation
θ	Shield's parameter
θc	critical Shield's parameter before transport
τ	bed shear stress

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RESUME

Varde Å's estuarium tilføres materiale både fra oplandet i form af bed-load og suspenderet materiale og fra Ho Bugt i form af flokkuleret, finkornet suspensionsmateriale.

Ved målinger 12 km opstrøms for Varde Ås munding fandtes overensstemmelse mellem suspensionskriteriet $W_c = 0.8{\cdot}U'_f$ (Engelund 1973), og det fine knæk på kornstørrelsesfordelingskurven (log/sandsynligheds plot). Endvidere fandtes, at der i en »normal« situation tilføres mindre and 5% af den samlede suspenderede transport i form af egentlig suspenderet bed-load materiale, resten udgøres af wash load.

Målinger foretaget i en springtids-situation viste, at estuariets competance falder drastisk i området fra 7.5-3.0 km opstrøms for mundingen, og at dette berører kornstørrelser, der dagligt tilføres estuariet. Competancefaldet bevirker en opkoncentrering af grovkornede partikler og aflejring af channel bars i det nævnte område. Bed-load materialet, der transporteres gennem området, blandes med finkornet materiale fra Ho Bugt og transporteres videre gennem estuariet til aflejring på en barre kystværts for mundingen.

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REFERENCES

Bartholdy, J. (1979): »Sedimenttransport i Varde Å's Estuarium«, Dept. of Georg., Univ. of Copenhagen; report to the Danish Ministery of Environment.

Bartholdy, J. (1980): »Sediment Transport in the Varde Å Estuary, West Denmark«. In press.

Biggs, R. B. (1970): »Sources and distribution of suspended sediment in northern Cheasapeak Bay«. Marine Geology, 9, 3: 187-201.

Cameron, W. M. og Pricthard, D. W. (1963): »Estuaries« in »The Sea«. ed. by M. N. Hill.

Det Danske Hedeselskabs kulturtekniske afdelings hydrometiske undersøgelser: 7. beretning.

Dyer, K. R. (1973): »Estuaries: A Physical Introduction«.

Einstein, H. A. (1950): »The Bed-load function for sediment transportation in open channel flows«, Tech. Bull. No. 1026, Sept. 1950, U.S. Dept. of Agriculture, Soil Cons. Service, Washington, D. C.

Engelund, F. A. (1964): »Flow resistance and hydraulic radius«. Acta Pol. Scan.

Engelund, F. A. og Hansen, E. (1972): »A Monograph on sediment transport in alluvial streams«.

Engelund, F. A. og Christensen, L. (1969): »Lagdelte inhomogene væskers hydraulik«.

Engelund, F. A. (1973): »Steady transport of moderately graded sediment«. Prog. Rept. 29, D.T.H.

Engelund, F. A. og Pedersen, F. B. (1974): »Hydraulik«.

Engelund, F. A. og Fredsøe, J. (1976): »A sediment transport model for straight alluvial channels«, Nordic Hydrology, 7.

Folk, R. L. og Ward, C. W. (1957): »Brazo River bar: A study in the significance of grain size parameters«, Journ. of Sed. Pet. 27, 1.

Gry, H. (1942): »Das Wattenmeer bei Skallingen«, Folia Geographica Danica. II, 1. København.

Guy, H. P., Simons, D. B. and Richardson, E. V. (1966): »Summary of Alluvial Channel Data From Flume Experiments, 1956-61«. Geol. Surv. Prof. Pap. 462-I.

Hasholt, B. (1968): »En undersøgelse af hydrologiske forhold i den nedre del af Brede Å lavningen«; internal report.

Hasholt, B. (1972): »Materialevandringen i Karlsgårde Sø og dens tilløb«. Geografisk Tidsskrift, 71.

Hasholt, B. (1976): »Varde Å - Hydrologi og Materialetransport i Vestjyske Vandløb« i »Topografisk Atlas Danmark« ed. by Jensen, R. H. and Jensen, K. M.

Hasholt, B. (1978): »En undersøgelse af materialeaflejringer og sedimentationsforhold i Karlsgåde Sø«. Ribe Amtsråd.

Hjulstrøm, F. (1935): »Studies of the morphological activity of rivers as illustrated by the river Fyris«. Bull. inst. Univ. Uppsala 25.

Horrer, P. L. (1976): »Methods and devices for measuring currents« i »Estuaries«, ed. by Lauf, G. H.

Inglis, C. C. og Allen, F. H. (1957): »The regime of the Thames estuary as affected by currents, salinities and river flow«. Proc. Inst. Civil. Eng. 7

Jacobsen, N. K. (1964): »Træk af Tøndermarskens naturgeografi med særlig henblik på morfogenesen«. Folia Geographica Danica. VII, 1.

Jacobsen, N. K. (1976): »Skallingen - Naturens laboratorium for klit, marsk og vade« i »Topografisk Atlas Danmark«, ed. by Jensen, R. H. and Jensen, K. M.

Leopold, L. B. og Maddock, T. (1953): »The hydraulic geometry of stream channels and some physiographic implications«. U.S. Geol. Surv. Prof. Paper 252.

Lüneburg, H., Schaumann, K. og Wellershaues, S. (1975): »Physiographie des Weser-Ästuars (Deutsche Bucht)«. Veröff. Inst. Meeresforsch. Bremerh. 15.

Lyshede, J. M. (1955): »Hydrologic Studies of Danish Water Courses«. Folia Geographia Danica VI. København.

Myrick, R. M. og Leopold, L. B. (1963): »Hydraulic Geometry of a small Tidal Estuary«. U.S. Geol. Sur. Prof. Paper 422-B.

Middleton, G. V. (1976): »Hydraulic interpretation of sand size distributions«. Jour. of Geol. 84.

Pedersen, K. og Hasholt, B. (1978): »Forekomst og transport af kviksølv i det fysiske miljø«. Report to Ribe Amtsråd.

Pejrup, M. (1979): »Sedimenttransport og hydrografi i Ho Bugt«, Dept. of Geogr., Univ. of Copenhagen; internal report.

Pejrup, M. (1980): »The turbidity maximum in the northern part of Ho Bay«. Geografisk Tidskr. 80.

Postma, H. (1967): »Sediment transport and sedimentation in the estuarine environment« i »Estuaries«, ed. by Lauff, G. H.

Raudkivi, A. J. (1976): »Loose Boundary Hudraulics«. 2nd ed.

Report No. 12 (1958): »Some fundamentals of particle size analysis«. Subcommittee on Sedimentation. US Government Printing Office.

Sagoe, K.-M. O. and Visher G. S. (1977): »Population breaks in grain-size distributions of sand - a theoretical model«. Jour.Sed.-Pet., 47, 1: 285-310.

Visher, G. S. (1969): »Grain Size distributions and depositional processes«. Jour. of Sed. Pet. 39, 3.

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tinct inflection points. One near 0.75 Φ (0.59 mm) and another near 2.4 Φ (0.19 mm). Measurements show that the fine inflection point is in agreement with the actual dynamic conditions separating bed load and suspended load.

2. Based on data from Report No. 12, Subcommittee on Sedimentation (1957), the following equation has been constructed:

$$W_T = W_{20} (1 + (20\text{-}T) (8.3\ 10^{-3} + 6.8\ 10^{-3}\ \ln(W_{20}))) \quad (1)$$

The equation predicts the fall velocity W_T at a given temperature T ($10°C < T < 20°C$), from the fall velocity at 20°C W_{20} ($2\ 10^{-3}$ m/s $< W_{20} < 2.5\ 10^{-1}$ m/s).

3. In »normal« situations, less than 5% of the total, suspended material supplied to Varde Å estuary from the drainage area consists of suspended bed load material, the rest is wash load.

4. In the channel reach from 7.5-3.0 km upstream from the estuary mouth, there is a drastic decrease in competence. In a normal spring-tide situation this decrease is affecting particle sizes present in the bed load supplied from the drainage area.

5. The bed load transport through the estuary is affected by the decreasing competence; resulting in a mean grain size maximum about 4 km upstream from the estuary mouth, and, in the same region, development of channel bars which tend to narrow the cross section of the estuary. The bed load material escaping this region is mingled with fine-grained, flocculated material, and with this transported farther for deposition at a submerged bar just outside the estuary mouth.

6. At flood-tide, the inflowing water is part of a turbidity maximum in the northern part of Ho Bugt. At high-tide slack water, the suspended material deposits inside the estuary. During ebb-tide, it is resuspended and the estuary bottom is »washed clean«. At the end of the ebb period, the estuary is filled with relatively pure fresh water from the drainage area.

7. Organic matter reacts much weaker upon flocculation in salt water than minerogene material does. In estuaries, this difference may lead to selective sedimentation of minerogene material, whereas the organic material easier escapes to the ocean.

8. The upper part of the estuary is narrowing very quickly giving it a pronounced funnel shape. The exponent b in the regime formula $W = aQ^b$ was determined to 1.6, which is high compared with the expected value between 0.7 and 0.9. This non-equilibrium state is believed to be a result of the rising sea level and the relatively new sheltering effect of the peninsula Skallingen.

LIST OF SYMBOLS

a	reference level above the bottom; empirically determined multiplicator
b	empirically determined exponent
C_{wa}	concentration of wash load
C_y	concentration of suspended material at level y above the bottom
d	mean fall diameter
D	depth
g	accelleration of gravity
I_o	water surface gradient (energy gradient)
kg	kurtosis
M	Manning number
m_z	mean grain size
qs	transport rate of suspended bed load material
qwa	transport rate of wash load material
R_d	Reynold's number for grains with the diameter d
sk	skewness
T	temperature
U_f	friction velocity
U'_f	friction velocity left after form drag correction
V	mean velocity over depth
W	fall velocity; channel width
W_c	critical fall velocity before suspension
W_T	fall velocity in pure water at temperature T
Z	$w/\kappa \cdot U'_f$ exponent
κ	V. Kármán's constant
σ	standard deviation
θ	Shield's parameter
θc	critical Shield's parameter before transport
τ	bed shear stress

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