Development of Deltas in Some Danish Watercourses

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Recurrent sedimentation has been observed in three watercourses in western Jutland where the slope of the water surface diminishes due to human intervention. The river bottom was surveyed by a scuba diver, the bedforms were described, and the grain-size distributions analysed. It is concluded that the sedimentation is due to the development of deltas.

Keywords: *Deltas, grain-size distributions, Danish watercourses*

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In order to improve the drainage conditions many Danish watercourses have been straigtened. In the alluvial streams of western Jutland with substantial bed load transport, a significant sedimentation may often be found in the lower reaches of straightened watercourses. The rivers discharging into the Wadden Sea are influenced by the tide and, to prevent inundation of the low-lying agricultural areas, the lower river stretches have in some places been endiked. Between the dikes sedimentation may occur, causing a rise in water-level, so the stability of the dikes will be threatened in case of storm floods. In a few Danish watercourses, dams with sluice gates have been built across the river valley to shunt the water to power stations. Above these dams, sedimentation may also be found.

The purpose of this investigation has been to study the nature of the sedimentation described above and, if possible, to predict its development.

Three watercourses were selected as case studies, because previous investigations had proved the presence of sedimentation. Besides, the earlier studies contain valuable data on the geometric and hydraulic properties of the selected watercourses: Varde Å, Brede Å, and Vidå. For location, see survey map, fig. 1.

The purpose of the newest field investigations was to collect supplementary data on bedforms and grain size and, moreover, to serve as a pilot study of the suitability of scuba-divers for investigations of river morphology.

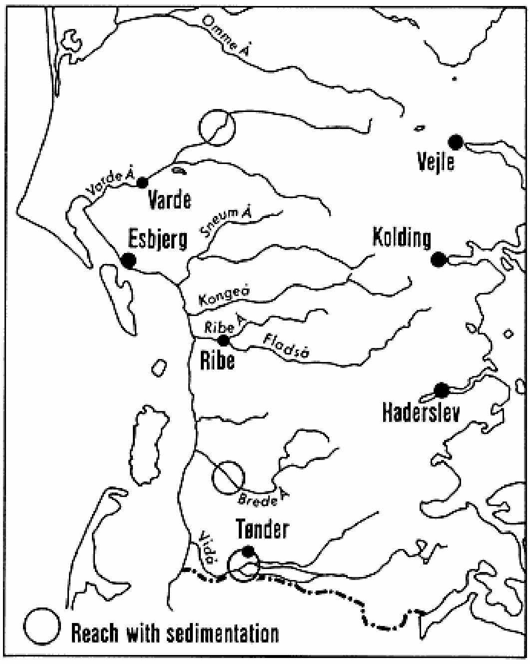

Fig. 1. Survey map with sedimentation area encircled.
Fig. 1. Oversigtskort med angivelse af sedimentationsområdet.

Methods

The purpose of previous investigations was to monitor the sedimentation and to determine the sediment transport in the watercourses leading to the sedimentation areas.

Surveys of length- and cross-profiles have been carried out and, in the most well described, the position of the profiles was fixed, so that exactly the same cross-section could be surveyed at different times (Bartholdy, Hasholt, and Pejrup, 1982).

The bed load was determined partly be means of a pressure difference sampler, developed by the Danish Heath Society, and partly by using the dune tracking method. In some cases, the field values were used to evaluate sediment transport formulas, f.inst. the formulas of Engelund and Hansen (1967) and Ackers and White (1973).

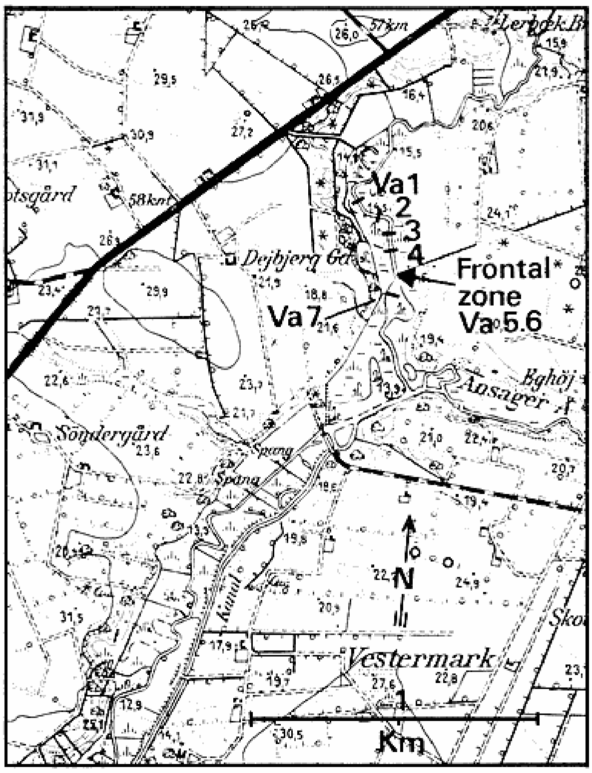

Fig. 2. The river Varde Å, sedimentation area. Location of sampling points approximate, because dredging has changed the outline of the watercourse.

Fig. 2. Varde Å, sedimentationsområde. Beliggenheden af prøvetagningspunkterne er omtrentlig, fordi oprensninger har ændret vandløbets omrids.

The suspended load was found by the EDI-method and measured by taking water samples with a Swedish depth-integrating water sampler (Nilsson, 1969).

The supplementary field work comprised visual descriptions of the bedforms, starting a short distance downstream the lower terminus of the sedimentation area, which is easily located. A scuba-diver classifies and measures the dimensions of the bedforms in the middle third of a cross-section spaced across the reach where sedimentation is abundant. It has also been attempted to photograph the bedforms with a Nikonex underwater camera.

The samples for the description of grain-size distributions were collected in the middle (thalweg) of the cross-sections in question by using a small cylindrical sampler (diameter: 3.2 cm and height: 3.0 cm) on the stoss side near the top of the single bedform to secure that the collected sediment represented grain sizes that actually move at the time of sampling. The grain size distributions were found by sieving with 1/4 Φ intervals after removal of organic matter with hydrogenperoxide. Mean, sorting, skewness and kurtosis were computed according to Folk and Ward (1957).

Results

Varde Å

The sedimentation area

The investigated area is situated 1-2 km upstream the diversion dam to the Karlsgårde waterpower station, fig. 2. The dam was constructed in 1945. About 20 years later sand had reached the inlet to the canal leading to the power station and, since then, the sand has been dredged roughly every second year to prevent closing of the canal. Each time a distance of about 1.5 km of the watercourse is deepened to a depth of about 2 m.

Previous investigations:

Investigations were carried out in 1969-70 and in 1974-76 (Hasholt 1972, 1974, and 1977). The slope of the water surface above the sedimentation area is about 6×10^{-4} m/m against 2×10^{-4} m/m in the canal to the power station. The mean annual discharge is approximately 2.7 m^3/sec. in the natural watercourse, and the corresponding depth is approximately 0.8 m. At the measuring station situated 5 km upstream the diversion dam the dominant bedform was dunes. At the same station the mean annual bed-load and suspended load were 23 t/km^2/year and 19 t/km^2/year, respectively.

Present investigation:

The investigation was carried out on April 20, 1983. Unfortunately the water was rather turbid for the season which was due to suspended sediment. The underwater photos taken were therefore of a very poor quality and have not been included. The location of the sample points is shown on fig. 2. At points 1-3 the bedforms were dunes with minor linguoid ripples on the crests. At point 4 the dunes were smaller, and gradually changed into linguoid ripples towards point 5 situated at the top of the »front« terminating the area of sedimentation. The front was approximately 0.6 m higher than the bottom just downstream and the water depth upstream the front was 0.6-0.8 m. The foreset showed weakly undulating small-scale ripples with back-flow ripples at the lower part, approximately 0.15 m above the bottom. At the bottomset (points 6 and 7) well-formed linguoid ripples were found. The grain-size characteristics are shown in table 1 and fig. 5.

It is seen that above the front the mean grain size varies between 352-598 μ, the sorting is moderate, and the skewness indicates a small deficiency of fine sediment. It is seen that the mean grain size below the front is significantly smaller and the skewness positive. A rather high value of kurtosis is found at point 7.

Brede Å

Sedimentation area

The investigated area is shown on fig. 3. The watercourse was straightened in 1956-60 in order to improve the

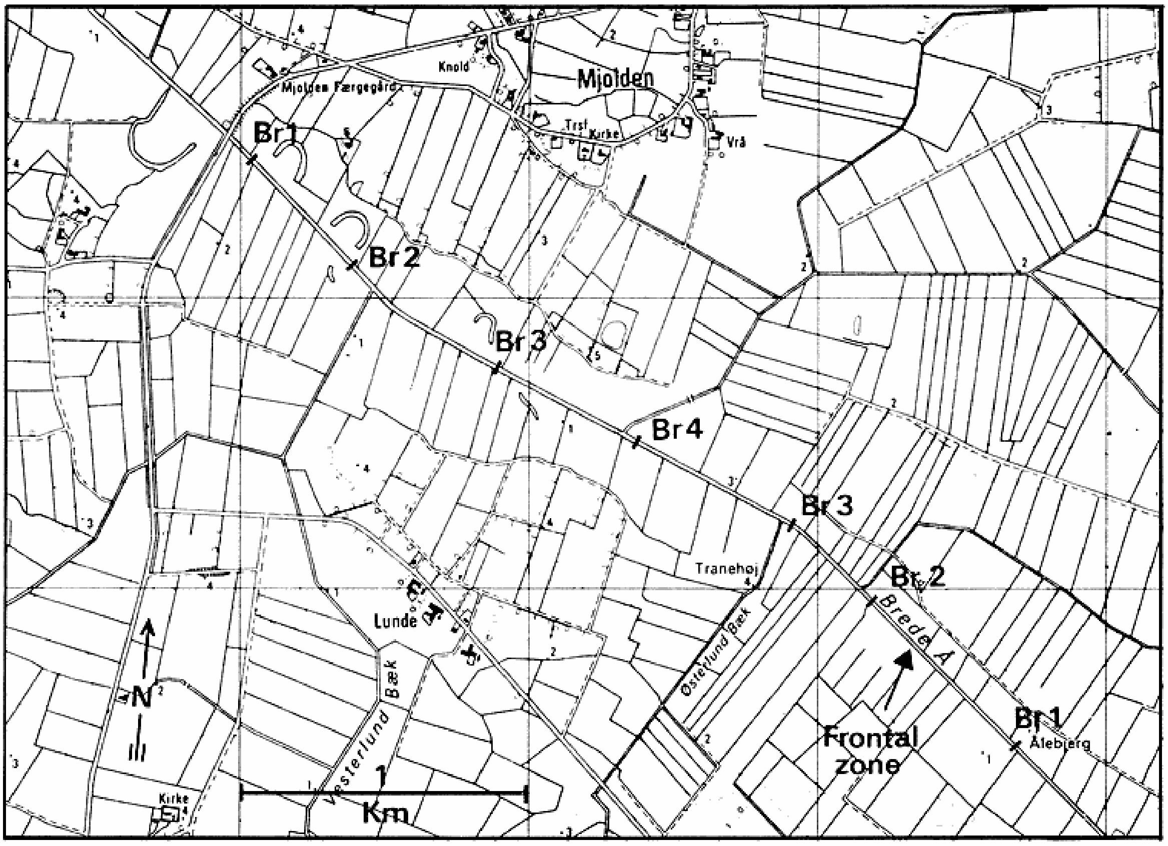

Fig. 3. The river Brede Å, sedimentation area with location of sampling points.

Fig. 3. Brede Å, sedimentationsområde med prøvetagningspunkter.

drainage conditions in the basin, but in the mid-sixties local farmers claimed that their farmland was inundated (fig. 3) rather often in winter and early spring. It proved that the bottom of the watercourse had become 0.5-1 m higher since the straightening due to sedimentation of sand. Since then, the area has been dredged frequently.

Previous investigations:
The sedimentation was investigated in 1968 by The Danish Heath Society and in 1969 by the author: Hasholt, (1969). The slope of the bottom immediately upstream the sedimentation area was originally 6×10^{-4} m/m, but a significant erosion reduced the slope to 4.7×10^{-4} m/m. Where the sedimentation was found, the slope originally varied from 5 to 3×10^{-4} m/m. After sedimentation the mean slope was 3.8×10^{-4} m/m. The slope of the water surface is often very small due to the closing of sluice gates during storms.

At the beginning of the investigated reach the mean annual discharge is about 3.1 m^3/sec., and in summertime the depth has been recorded to be 0.5 m. In July 1966 a »front« was located 1.4-1.6 km upstream the bridge at Mjolden. Bedforms were ripples at low discharges and dunes at high discharges, and mean annual bed load 15 t/km^2/year. The amount of accumulated sediment showed, however, that the transport values had been higher in the years immediately after the straightening of the watercourse.

Present investigation:
The investigation was carried out on April 18, 1983. The location of sample points is shown on fig. 3. The access to the watercourse is rather limited, and the exact location of the sedimentation was not known due to the dredging. The »front« was located approximately 3 km upstream the bridge at Mjolden. The foreset was not so well defined as in the case from Varde Å. At station 1, the bedforms were dunes with a height of 0.10-0.15 m, the water depth was about 0.85 m. Station 2 was located at the lower end of the foreset, the bedforms were linguoid ripples, and the depth was about 1 m.

The rest of the samples were taken from the bottomset. The bedforms were linguoid ripples with heights of 0.01 m and lengths of approximately 0.10 m; mud and sandless spots could be observed in between.

The grain-size parametres are shown in table 1 and fig.

6. The mean grain size upstream the front is 545 μ, the sorting is rather poor, and the skewness indicates that the amount of fine sediment is too small for a normal distribution. The grain size at the foreset is slightly smaller and the skewness still negative. The rest of the samples shows significantly smaller grain sizes, the skewness has become positive with values that indicate surplus of fine sediment. The kurtosis has rather high values indicating that the distribution originates from different populations.

Vidå

The sedimentation area

The investigated area is shown on fig. 4. In 1929 a large-scale land reclamation project was carried out. The watercourses were confined between dikes, and pumping stations hindered inundation of low-lying areas at high discharges. In the fifties, sedimentation was observed and, since then, dredging has frequently been made to protect the dikes against demolishing.

Previous investigations:

The watercourses were investigated by the Danish Heath Society (1968, 1970, 1979, and 1980) and by the Geographical Institute, University of Copenhagen, (Bartholdy et al., 1982). The slope of the water surface at the measuring stations upstream the study area varied between 2.5 to 3.5×10^{-4} m/m. The slope in the lower end is periodically smaller due to the tidal influence. The mean annual discharge is about 11 m^3/sec. and the corresponding depth about 1.2 m. Dunes were observed at high discharges in autumn and spring and ripples at low discharges during the summertime. In the lower part of the watercourse without sedimentation, the depth was 2-3 m. Here a fairly distinct »front« could be observed as well; in 1982 this was situated just below the bridge at Lægan. The grain-size analysis carried out by Bartholdy et al. (1982) showed mean values between 373 and 489 μ with moderate sorting and a slightly negative skewness at the upstream side of the front. The bed load was approximately 10 t/km^2/year. The investigations revealed that a substantial part, approx. 40%, of the sediment transported through the cross-sections at the measuring stations accumulates at the front, whereas the rest adds to the bottom level upstream.

The sediment was dredged late 1982.

Present investigation:

The investigation was carried out on April 19, 1983. The sample points are shown on fig. 4. The front was now located between station 7 and 8. The sight was very poor, approximately 0.2 m. The bedforms from station 1 to station 3 were dunes about 0.14 m high. At station 4, about 0.04 m high ripples could be observed. At stations 5, 6, and 7 linguoid ripples were found. Downstream the

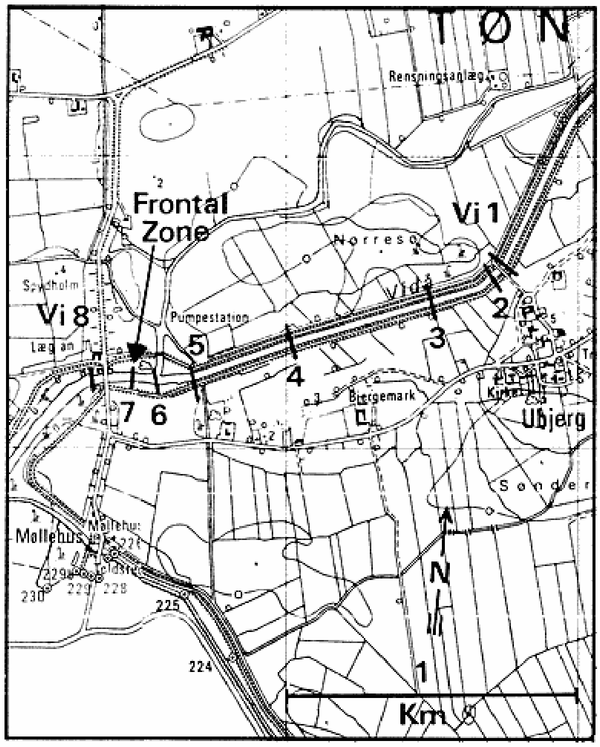

Fig. 4. The river Vidå, sedimentation area with location of sampling points.

Fig. 4. Vidå, sedimentationsområde med prøvetagningspunkter.

front, at station 8, only a small amount of sand was left, and the clay bottom had fresh traces of dredging. The depth upstream varied between 1.1 to 1.4 m in the sedimentation area, and at station 8 the depth was 2.4 m.

The grain-size parametres are shown in table 1 and fig. 7. The mean grain- size above the front varies between 319 and 433 μ which is slightly lower than mentioned above. The sorting is moderate, except for station 8 where it is poor. In the upstream end the skewness indicates absence of fine sediment, downstream the skewness is approximately 0 except at station 8, where there is a deficit of coarser grains. The variation in kurtosis is not significant.

Discussion and conclusions

The three watercourses show characteristic common features. They have all a significant sediment load which is dominated by bed-load, and sedimentation occurs where there is a substantial change in the slope. The sedimentation is seen to move downstream with a distinct frontal zone, besides there is some indication of a contemporary rising of the bottom upstream the frontal zone. The change in slope will cause a decreasing transport capacity, and the sequence of bedforms confirms this. The decreasing mean grain- size and the downstream variation in the skewness value from negative to positive confirmed, in

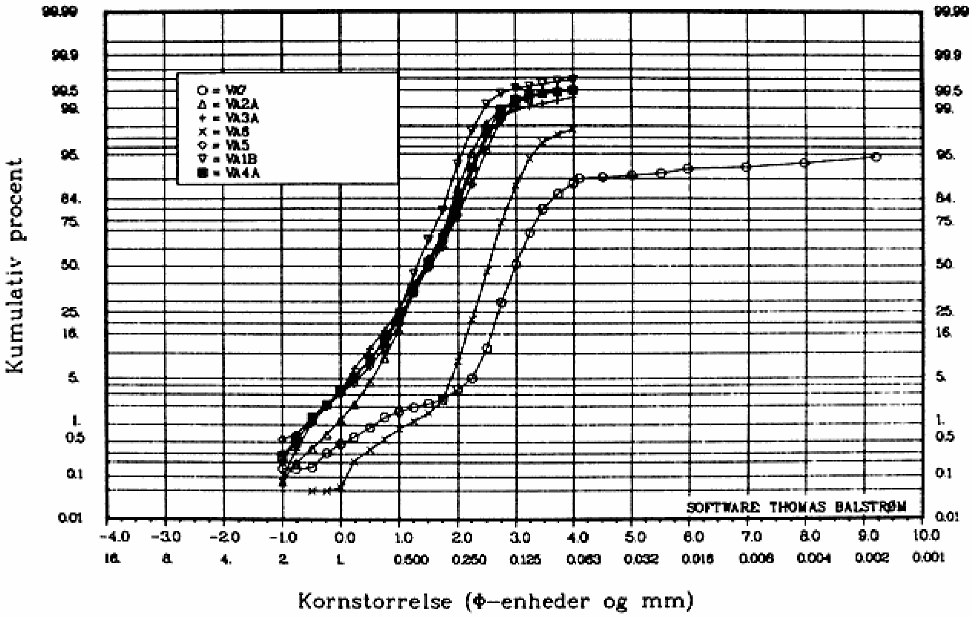

Fig. 5. The river Varde Å, selected grain-size distribution.
Fig. 5. Varde Å, udvalgte kornstørrelsesfordelinger.

addition, that there is a diminishing transport capacity downstream. Both parametres also evidence a selective transport (depending on the flow) so that only the finer grains are transported downstream the frontal zone. In Varde Å, where the frontal zone has been described most detailed, it was possible to distinguish between topset, foreset, and bottomset due to their characteristic bedforms.

The features mentioned above are found in connection with both natural deltas and deltas formed in flumes, cf. Harrison (1952), Jopling (1965), and Vincent (1966). It is therefore concluded that the sedimentation observed in all three watercourses actually is part of a delta and will act accordingly, a finding which will have some practical consequences. Formerly, it was assumed that the sediment was transported to, and accumulated at the frontal zone, and that after some time the river bed upstream would become stable, without further aggredation. If the river bed became stable at an acceptable level for the security of the dikes, no dredging would be necessary.

When, as found, the lower reaches of a watercourse are acting as a delta, however, the riverbed will not stabilize,

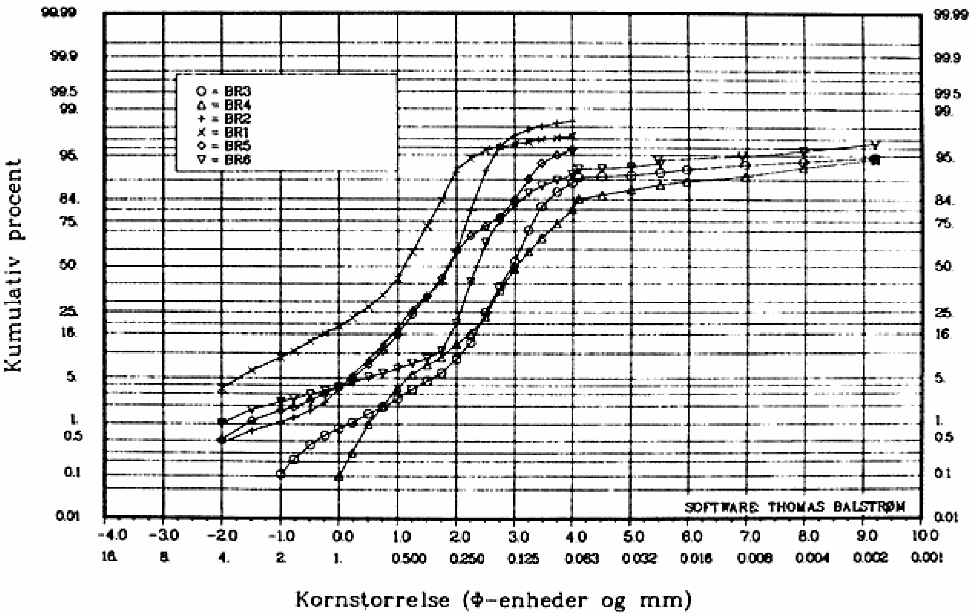

Fig. 6. The river Brede Å, selected grain-size distribution.
Fig. 6. Brede Å, udvalgte kornstørrelsesofrdelinger.

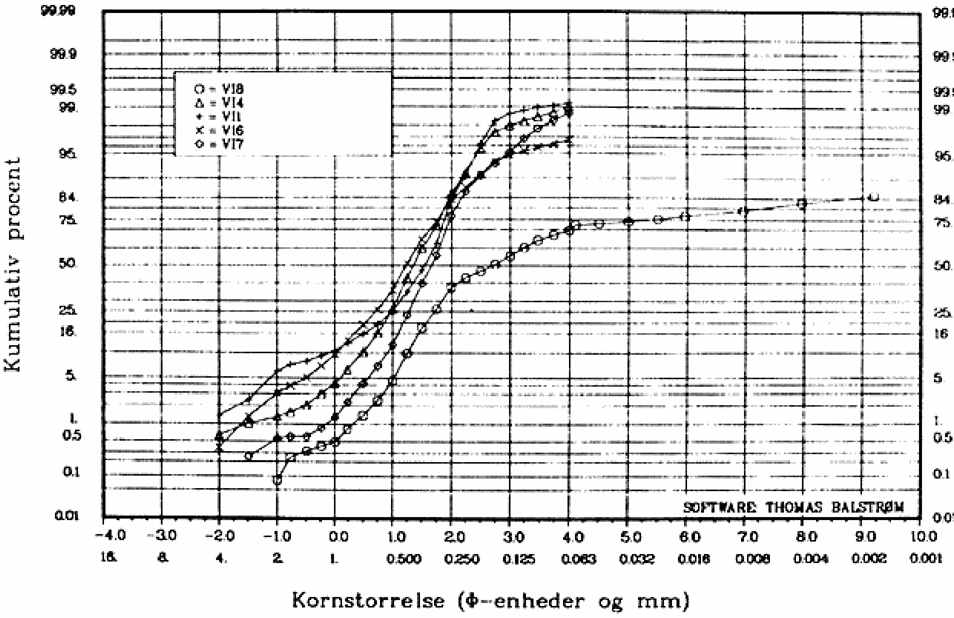

Fig. 7. The river Vida, selected grain-size distribution.
Fig. 7. Vidå, udvalgte kornstørrelsesfordelinger.

and, to maintain the watercourse, dredging will be necessary. This is most conveniently made by starting at the frontal zone and move upstream. Hereby the delta will be »transformed« into an earlier stage with a foreseeable development.

Indications of similar sedimentation conditions are known from other watercourses in western Jutland, and an understanding of their behaviour is essential when interventions are planned. As mentioned, suspended sediment hindered good photos to be taken, but another try will be made this summer. It is concluded that valuable information about bedforms, transport, and form-related sediment samples can be obtained by scuba-divers provided the current is not too strong.

Acknowledgements

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Resumé

Mange danske vandløb har været udsat for menneskelige indgreb i form af: reguleringer for at forbedre afvandingsforholdene, sikring af bredderne med diger for at hindre oversvømmelse samt opstemninger for at kunne udnytte vandkraften. Efter sådanne indgreb er der konstateret sedimentation på bestemte strækninger af nogle vandløb i Sydvestjylland. I Varde Å ses sedimentation opstrøms et stemmeværk, hvorfra vandet ledes til kraftværket ved Karlsgårde. I Brede Å er der sedimentation i det regulerede vandløb mellem Bredebro og Mjolden. I Vidåen sker sedimentationen i flodlejet mellem ådigerne syd for Tønder. De

Tabel 1

Prøve	Mz µ	Sd	SK	KG
Varde Å, 20/4-83				
Va 1b	404	.53	-.08	1.13
Va 2a	366	.51	-.03	.99
Va 3a	378	.68	-.14	.99
Va 4a	370	.62	-.13	1.09
Va 5	349	.64	-.06	1.03
Va 6	173	.40	.06	1.22
Va 7	119	1.39	.52	4.56
Brede Å, 18/4-83				
Br 1	545	1.11	-.37	1.41
Br 2	307	.73	-.37	1.04
Br 3	129	1.54	.34	4.00
Br 4	115	1.76	.36	2.81
Br 5	257	1.03	.12	1.06
Br 6	182	1.31	.35	4.01
Br 7	56	2.18	.54	1.72
Vidå, 19/4-83				
Vi 1	389	.91	-.43	1.61
Vi 2	343	.90	-.40	1.71
Vi 3	360	.51	-.02	1.04
Vi 4	390	.66	-.03	1.17
Vi 5	349	.84	.03	1.09
Vi 6	433	.97	.00	1.40
Vi 7	319	.63	.03	1.40
Vi 8	51	4.06	.71	1.64

Tab. 1. Grain size parameters.
Tab. 1. Kornstørrelsesparametre.

nævnte strækninger er dels vist på oversigtskortet fig. 1 og dels i detaljer i fig. 2-4. Sedimentprøver blev indsamlet i de pågældende vandløb af en svømmedykker, som også beskrev bundformerne. I alle vandløbene vandrer sedimentet ned mod en ret velafgrænset »front«, som forskydes i strømretningen. Samtidig er der indicier på en svag hævning af bunden opstrøms fronten. Sedimentanalyserne viser, at kornstørrelsen er ret ensartet oven for fronten, men svagt aftagende ned mod fronten. Nedenfor er kornstørrelsen væsentligt mindre. Skævhedsparameteren viser, at der er for lidt finkornet materiale oven for fronten i forhold til en normalfordeling, og den nedstrøms ændring mod positive værdier indicerer selektiv transport. Transportevnen aftager nedad som følge af ændringen i faldet. Bundformerne ændres fra banker længst oppe i vandløbene til rippler ned mod fronten.

I samtlige undersøgte vandløb viser sedimentationen træk, der er karakteristiske for naturlige delta-aflejringer, og det konkluderes derfor, at der er tale om en deltadannelse. Denne tolkning har betydning for vedligeholdelsen af vandløbene, idet denne mest hensigtsmæssigt foregår ved oprensning nedefra og etablering af sandfang. Endelig må det konstateres, at svømmedykkere med fordel kan udnyttes til prøvetagning og formbeskrivelse i vandløb.

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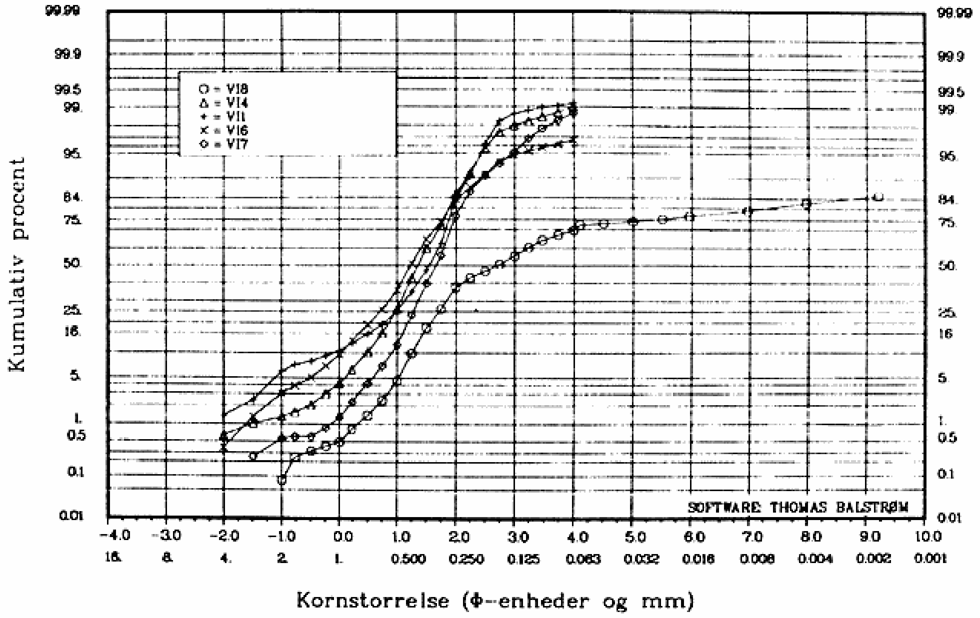

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Scuba-diver stud.scient. M. Binderup is thanked for her enthusiasm and endurance during the field work, K. Simonsen, Skalling-Laboratoriet, for her careful analysis of the sediment samples, and finally K. Winther for improving my English. Thanks are also due to M. Pejrup for valuable discussion.

Resumé

Mange danske vandløb har været udsat for menneskelige indgreb i form af: reguleringer for at forbedre afvandingsforholdene, sikring af bredderne med diger for at hindre oversvømmelse samt opstemninger for at kunne udnytte vandkraften. Efter sådanne indgreb er der konstateret sedimentation på bestemte strækninger af nogle vandløb i Sydvestjylland. I Varde Å ses sedimentation opstrøms et stemmeværk, hvorfra vandet ledes til kraftværket ved Karlsgårde. I Brede Å er der sedimentation i det regulerede vandløb mellem Bredebro og Mjolden. I Vidåen sker sedimentationen i flodlejet mellem ådigerne syd for Tønder. De

Tabel 1

Prøve	Mz µ	Sd	SK	KG
Varde Å, 20/4-83				
Va 1b	404	.53	-.08	1.13
Va 2a	366	.51	-.03	.99
Va 3a	378	.68	-.14	.99
Va 4a	370	.62	-.13	1.09
Va 5	349	.64	-.06	1.03
Va 6	173	.40	.06	1.22
Va 7	119	1.39	.52	4.56
Brede Å, 18/4-83				
Br 1	545	1.11	-.37	1.41
Br 2	307	.73	-.37	1.04
Br 3	129	1.54	.34	4.00
Br 4	115	1.76	.36	2.81
Br 5	257	1.03	.12	1.06
Br 6	182	1.31	.35	4.01
Br 7	56	2.18	.54	1.72
Vidå, 19/4-83				
Vi 1	389	.91	-.43	1.61
Vi 2	343	.90	-.40	1.71
Vi 3	360	.51	-.02	1.04
Vi 4	390	.66	-.03	1.17
Vi 5	349	.84	.03	1.09
Vi 6	433	.97	.00	1.40
Vi 7	319	.63	.03	1.40
Vi 8	51	4.06	.71	1.64

Tab. 1. Grain size parameters.
Tab. 1. Kornstorrelsesparametre.