Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
(Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 141.

Dissolved and particulate load in Danish water courses

BENT HASHOLT
Geographical Institute, University of Copenhagen, Copenhagen, Denmark

ABSTRACT Danish water courses can roughly be divided into two categories. In West Jutland, rivers drain towards the North Sea, flow mainly through outwash plains and low-relief moraines of Saale age, and exhibit rather low values of dissolved load. In the rest of the country water courses flow towards the Kattegat and the Baltic, drain mainly young morainic deposits, and have higher values of dissolved load but low particulate load. For selected rivers in each category, total load has been determined from measurements of bed, suspended and dissolved loads. Values of total denudation have also been evaluated.

Transport en solution et transport de particules dans les cours d'eau du Danemark

RESUME En première approximation, on peut diviser les cours d'eau du Danemark en deux catégories: ceux de l'Ouest du Jutland se jetant en Mer du Nord et drainant sandres et moraines du Saale. Ils sont caractérisés par un transport en solution à faibles concentrations. Pour le reste du Danemark les rivières parcourent les moraines de la glaciation Weichselienne pour se jeter dans le Kattegat et la Baltique. Le transport en solution est ici plus grand, tandis que le transport de particules est faible. Pour les deux catégories, des exemples sont donnés du transport total estimés à partir de mesures du charriage de fond, du transport en suspension et du transport en solution. L'érosion globale a finalement été évaluée.

INTRODUCTION

Denmark is a gently rolling lowland with a relative relief between 20-100 m and highest point 172 m a.m.s.l. During the Weichsel glaciation the southwestern part of Jutland (Jylland) (Fig.1) remained ice free and therefore displays landforms from the Saale glaciation, modified by periglacial processes. Between these landforms are extensive outwash plains from the last ice age. The eastern part of the country is mainly underlain by young morainic sands and clays, which become more clayey towards the east and give rise to a rather low but gently rolling relief. Due to the rise of sea level since the Weichsel glaciation, many low-lying valley bottoms are filled with peat or sediments of marine origin.

On the basis of the present relief and knowledge of the evolution of the landscape, low river load values might be expected. However, parent material of loose sediments, in combination with intensive farming, have influenced solutes in soil water and groundwater. About 70% of the country is farmland of which 95% is ploughed. Woods

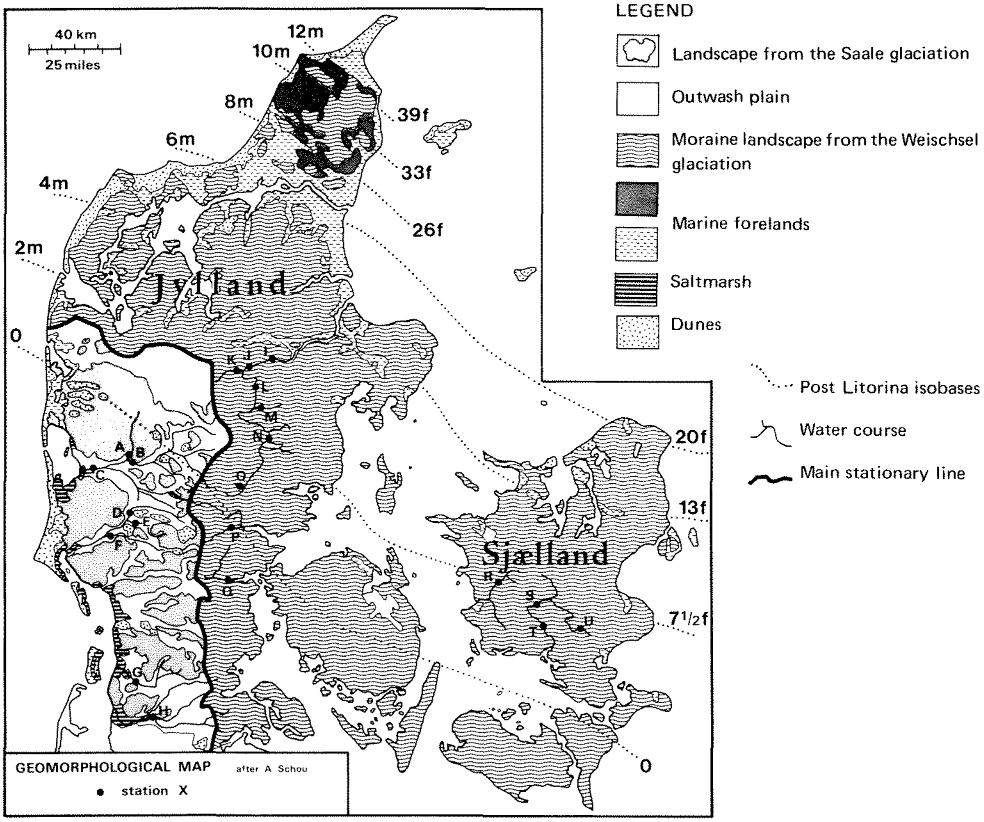

FIG.1 Location of sampling sites in relation to geomorphological features.

cover approximately 10% and the remainder comprises dunes, lakes and urban areas. The consumption of fertilizers, about 35 t km^{-2} of pure nutrients in 1980, has affected water quality. Moreover, accelerated erosion associated with intensive farming practices further complicates attempts to distinguish in river loads between the influence of man and other environmental factors. In the present study, an attempt has been made to determine the magnitude of dissolved and particulate load in water courses representative of typical Danish landscapes, and also to evaluate the net load and denudation, corrected for contributions from rainfall, fertilizers, and other sources.

METHODS

Most of the information on sediment load in Danish rivers originates from investigations for special purposes and not, as in many other countries, from routine data collection. Investigations have been mainly related to sedimentation problems induced in river reaches either by straightening associated with tile drainage and land reclamation or by damming for power production. Other studies have been undertaken to determine the transport of sediment-associated pollutants. The measuring methods adopted, therefore, depend on the scope of the individual investigation and are not always directly comparable. The author has mainly used the same investigation methods throughout the reports cited, but where results from other authors are cited, their methods are briefly described.

Field investigations

Water samples for determination of the dissolved, suspended, and wash load were usually collected in one-litre polyethylene bottles by means of a Swedish depth-integrating sampler (Nilsson, 1969). The unsampled zone was 8-10 cm. Simple dip sampling was employed to collect samples required for dissolved solids determination alone, and the same procedure was adopted for suspended solids samples when the water was turbulent, for example in rapids.

It was necessary in some investigations (Jacobsen, 1981) to carry out field analyses of HCO_3 and CO_3 because of their instability. The sampling frequency employed to determine dissolved load transport varied between weekly and monthly (Hasholt, 1972; Holm & Tuxen-Petersen, 1974). Jacobsen (1981) has studied the daily variations in dissolved load at a single station which demonstrate that monthly samples suffice for a reliable determination of the load of most ions, except for NO_3.

The most frequent sampling for suspended and wash load involved collection of 100-200 samples per year (Hasholt & Jacobsen, 1978; Hasholt, 1981). However, sampling programmes were designed to be most intensive at higher discharges and approximately 65% of the load is determined directly from daily samples. Daily values of transport have been derived from rating relationships between concentration and discharge which in turn are based on 10-15 water samples and associated simultaneous flow measurements taken monthly at a cross section (Hasholt, 1972). Additional samples were collected during flood conditions (Hasholt, 1977). In the work of Holm & Tuxen-Petersen (1974) discharge measurement and the collection of water samples was undertaken at approximately weekly intervals.

Bed load has been measured in different ways, and often two or more independent methods have been used simultaneously to secure reliable results. The techniques employed have involved measurements of resultant sedimentation (Hasholt, 1972; Høst-Madsen & Edens, 1974; Bartholdy *et al.*, 1982), pressure-difference samplers and dune tracking (Hasholt, 1972; Høst-Madsen & Edens, 1974; Hasholt & Jacobsen, 1978; Bartholdy *et al.*, 1982) and pit samplers (Holm & Tuxen-Petersen, 1974). Tracer methods have also been applied in individual cases (Hasholt, 1972; Thomsen, 1980). In addition sufficient hydraulic data have been collected to compute bed load by means of one or more sediment transport formulae.

Laboratory methods

Total dissolved solids content was derived from the concentrations of major ions, determined by standard methods for the analysis of drinking water (Jacobsen, 1981), and also from measurements of residue on evaporation and conductivity (Rainwater & Thatcher, 1960). In the study of Holm & Tuxen-Petersen (1974), suspended sediment was included in the residue on evaporation. Since 1975, suspended sediment concentrations of water samples have been determined by filtering through Whatman GF/F mass filters with a nominal retention diameter of 0.7 μm and afterwards through Millipore 0.22 μm membrane filters. The filters were dried at 65°C and later combusted at 500°C to separate inorganic and organic concentrations. Before 1975, paper filters and membrane filters with a retention diameter of about 1-2 μm were used. Laboratory procedures for the determination of bed load involved drying, weighing, and analysis of grain sizes.

Computational procedure

In detailed investigations (Hasholt & Jacobsen, 1978; Jacobsen, 1981), dissolved load is computed from daily values of discharge multiplied by concentration values for individual ions found by linear interpolation or cubic spline. In less detailed investigations, the computational procedure is adapted to the available data and employs relationships between load and discharge (Holm & Tuxen-Petersen, 1974).

The suspended load is found partly from clockwise relationships between concentrations and discharge and partly from linear interpolation when sufficient data are available (Hasholt & Jacobsen, 1978; Hasholt, 1981). In other cases, the field results have been used to establish relationships between discharge and concentration, or load. In some cases, relationships were computed separately for rising and for falling stages. The yearly transport values were then computed either from daily discharge values or from duration curves (Hasholt, 1972; Holm & Tuxen-Petersen, 1974; Bartholdy *et al.*, 1982).

Bed load was computed from discharge data by applying one or more of the transport formulae of Ackers & White (1973), Engelund & Hansen (1967), Engelund & Fredsøe (1976) and Thomsen (1982). Results are given in Høst-Madsen & Edens (1974); Hasholt & Jacobsen (1978), Bartholdy *et al.* (1982).

Reliability of results

With reference to the most detailed investigations, computation has shown standard errors of 3% on the yearly suspended load for the River Skjernå (Hasholt & Jacobsen, 1978) and 5.5-8.5% for the River Suså (Hasholt, 1981). Similar standard errors are to be expected in the detailed computations of dissolved load when comparing computed and measured values of concentrations (Jacobsen, 1981). Bed load values found by different methods may agree within 10% as shown by Bartholdy *et al.* (1982). It would be convenient if a standard error value could be specified for each of the results referenced in this paper. This is impossible, however, due to differences in field methods and computational procedures, and to lack of information about data reliability in some of the reports. In order to overcome this disadvantage, the author has divided the results into groups of different quality on the basis of experience (Table 1).

Recent investigations (Walling & Webb, 1981; Dickinson, 1981) show that, depending on computational procedure, the estimates of yearly suspended load may deviate by an order of magnitude from the true

TABLE 1 Reliability of load data

Dissolved load	*Suspended load*	*Bed load*
GROUP 1		
Chemical analysis of water samples, or both residue on evaporation and conductivity available. Sampling frequency: daily to monthly. Daily discharge records.	*100, or more, samples per year covering situations with extreme discharge values. Reliable correlation between concentration and discharge. Daily discharge records.*	*Reliable hydraulic data. Dune tracking and alternative methods. Significant correlation between bed load and discharge. Daily discharge records. Outlets of large lakes.*
Reliability: 5-10%	*Reliability: 5-10%*	*Reliability: 10-30%*
GROUP 2		
Chemical analysis less than monthly. Either residue on evaporation or conductivity more often than monthly. Missing discharge: Data computed from nearby streams.	*Sampling frequency weekly to monthly. Poorer correlation between concentration and discharge. Some discharge values from nearby streams.*	*Results based on hydraulic data and possibly on one measuring method. Poorer relationship between load and discharge.*
Reliability: 10-20%	*Reliability: 10-20%*	*Reliability: 30-100%*
GROUP 3		
Only residue on evaporation or conductivity. Sampling frequency: monthly or less. Discharge values: monthly or yearly.	*Data monthly or less. Discharge records: monthly or yearly.*	*Few measurements. Observational data on stream bed erosion and sedimentation.*
Reliability: errors may exceed 20%	*Reliability: errors may exceed 20%*	*Reliability: errors may exceed 100%*

values. Dickinson (1981) states that most methods underestimate the sediment load. In the author's detailed investigations, linear interpolation and moving rating curves have been employed together with a sampling frequency of more than once a week, and data reliability is comparable with Dickinson's values for a water course in environments similar to the Danish. As the results from the less detailed investigations accord reasonably well with those from the more detailed ones, it is believed that the load values discussed below are realistic within each quality group.

RESULTS

The main results are shown in Table 2, together with data concerning catchment characteristics. It is apparent that runoff values for the different years of computation lie within 10% of mean runoff ($\bar{R}$). Where data from subsequent years are available, it appears that dissolved load varies within 15% while discharge varies within 10% (Jacobsen, 1981). A comparable figure for suspended load is 43%, and this greater variability reflects the influence of stored suspended matter which is released after a dry period (Hasholt, 1981). The water courses A-H are situated in West Jutland, where dissolved load varies from 54 to 102 t km^{-2}year^{-1}. The values from sites D and F are known to be high because of waste water discharges from chemical industry. In comparison with the values from the eastern part of the country (I-U), which range from 63 to 148 t km^{-2}year^{-1}, the values from West Jutland are significantly lower. Suspended load

TABLE 2 River loads in selected Danish water courses

Location (see Fig.1)	Name of water course	Basin area (km^2)	Year of computation	Runoff R ($l\ s^{-1}\ km^{-2}$)	$R/\overline{R}$	Dissolved load ($t\ km^{-2}\ year^{-1}$)	Reliability class	Suspended and wash load ($t\ km^{-2}\ year^{-1}$)	Reliability class	Bed load ($t\ km^{-2}\ year^{-1}$)	Reliability class	Total load ($t\ km^{-2}\ year^{-1}$)
A	Vorgood Å	455	76,77	11.9	0.90	66	2	7.1	1	< 5	3	75
B	Skjernå	1056	76,77	11.9	0.90	68	2	7.4	1	9.9	1	85
C	Skjernå	2220	76,77	11.9	0.90	66	2	6.4	1	12.4	1	85
D	Grindsted Å	238	70,74,75	12.0	1	102	3	18.7	2	22.8	1	144
E	Ansager Å	138	70,74,75	12.0	1	54	2	9.5	2	19.7	1	83
F	Varde Å	598	74,75	12.3	1.03	81	2	9.4	2	< 1	3	91
G	Brede Å	292	68	12.2	1.08	70	3	6.2	3	14.7	1	91
H	Grønå	603	68,81	11.5	1	82	2	8.8	2	10.3	1	101
I	Gudenå	1787	74	11.7	0.95	78	2	3.4	2	< 1	2	81
J	Gudenå	1710	74	11.7	0.95	76	2	3.1	2	0	1	79
K	Tange Å	100	74	11.7	0.95	101	2	7.8	2	0.3	2	109
L	Gudenå	1454	74	11.7	0.95	78	2	2.9	2	< 1	2	82
M	Gjernå	115	74	11.7	0.95	81	2	4.4	2	-	-	≥ 85
N	Gudenå	1021	74	11.7	0.95	87	3	2.1	2	0	1	89
O	Mattrup Å	88	74	11.7	0.95	63	3	2.2	2	< 1	2	65
P	Vejle Å	206	75	17.3	0.98	115	3	-	-	-	-	> 115
Q	Kolding Å	90	75	16.3	0.98	148	3	-	-	-	-	> 148
R	Tude Å	148	70,71	5.6	1	101	2	5.4	3	< 1	3	106
S	Suså	601	78,79	6.3	0.94	117	1	5.6	1	< 1	3	123
T	Suså	753	78,79	6.7	0.93	116	1	1.2	1	0	1	117
U	Suså	42	78,79	8.4	0.89	135	1	7.7	3	< 1	3	143

values range in West Jutland between 6.2 and 18.7 t $km^{-2}year^{-1}$. The value from site D is again high, and probably reflects accelerated erosion due to pollution which has destroyed the bottom vegetation. The corresponding results from stations I to U are 7.8 to 1.2 t km^{-2} $year^{-1}$, or slightly lower. The low values in the main course of the River Gudenå and at station T in the River Suså reflect the occurrence of many lakes which trap most of the load from the upper reaches. Significant variation in bed load values is also apparent. In Jutland, the values vary from 5 to 22.8 t $km^{-2}year^{-1}$, while in the rest of the country they range from 0 to 1 t $km^{-2}year^{-1}$, and this difference may also be partly due to the distribution of lakes. The low value at station F is caused by dredging of bed load above the station, but the rather low load recorded at site A is probably a true value because this water course mainly drains moraines of Saale age, whereas the other water courses which flow westward drain outwash plains. Spatial variations in dissolved, suspended and bed loads to a certain extent counteract each other and values of total load are more uniform throughout the country than individual components (Table 2).

TABLE 3 Gross denudation rate and the percentage of total load by weight associated with load components

Location (see Fig.1)	*Dissolved load (mm $kyear^{-1}$)*	*% of total weight*	*Suspended wash load (mm $kyear^{-1}$)*	*% of total weight*	*Bed load (mm $kyear^{-1}$)*	*% of total weight*	*Total load (mm $kyear^{-1}$)*
A	25	84	5	9	<3	<7	33
B	27	80	5	9	7	12	39
E	22	65	6	11	13	24	41
H	33	81	6	9	7	10	46
J	30	96	2	4	0	0	32
O	25	97	1	3	<1	<1	27
S	47	95	4	5	<1	<1	52
T	46	99	1	1	0	0	47

Table 3 presents the gross denudation rate and the percentage of total load by weight associated with each load component. Density values of 1.5 and 2.5 t m^{-3} have been assumed for particulate and dissolved loads respectively. The denudation rate associated with the dissolved, suspended and bed loads ranges respectively between 22 and 47, 1 and 6, and 0 and 13 mm $kyear^{-1}$. Table 3 reveals that for all water courses the dissolved component accounts for the highest proportion of the total load, but particulate transport is relatively more important in West Jutland.

Table 4 shows the chemical composition of the dissolved load together with the composition of the suspended load. The results from the River Skjernå (station B) and the River Ansager Å (station E) are very similar except for the transport of Ca and SO_4, which is higher in the former basin because of drainage from bogs and abandoned browncoal pits. The transport values for the River Suså (station S) are quite different and, except for SiO_2, are mostly higher than in West Jutland. The greatest difference occurs in the transport of HCO_3 and Ca, and reflects weathering and wash out of

$CaCO_3$ from the morainic deposits of Zealand (Sjælland) which are rich in chalk. The rather low values of dissolved load, characteristic of West Jutland, are related to the presence of old till from which most of the chalk has been removed by a longer period of wash-out.

DISCUSSION AND CONCLUSIONS

As a basis for discussion of the denudational rate, a tentative "standard" dry-matter balance has been derived for Denmark (Fig.2) by weighting results from the cultivated area in relation to the area of the whole country. It is evident that human activities play a dominating role in the balance, since dry matter removed with crops is the greatest single element (Fig.2). The dry matter of crops contains much carbon as a result of photosynthesis, and it was considered more realistic to take the ash content as a measure of the actual removal. The latter also depends heavily on crop type.

TABLE 4 Load components (t $km^{-2} year^{-1}$*) for selected water courses*

Location (see Fig.1)	*Cl*	SO_4	HCO_3	NO_3	*Na*	*K*	*Mg*	*Ca*	SiO_2	*Rest*	*A*	*B*
B	9.9	18.1	13.5	3.9	5.6	1.4	1.5	10.8	4.0	∿0.4	5.1	2.3
E	9.9	8.3	14.2	4.2	4.7	1.3	1.2	6.7	4.5	<0.6	-	-
S	12.0	15.2	45.9	9.6	6.5	1.2	1.6	22.6	1.7	0.3	3.9	1.7

A: Inorganic suspended load.
B: Organic suspended load.

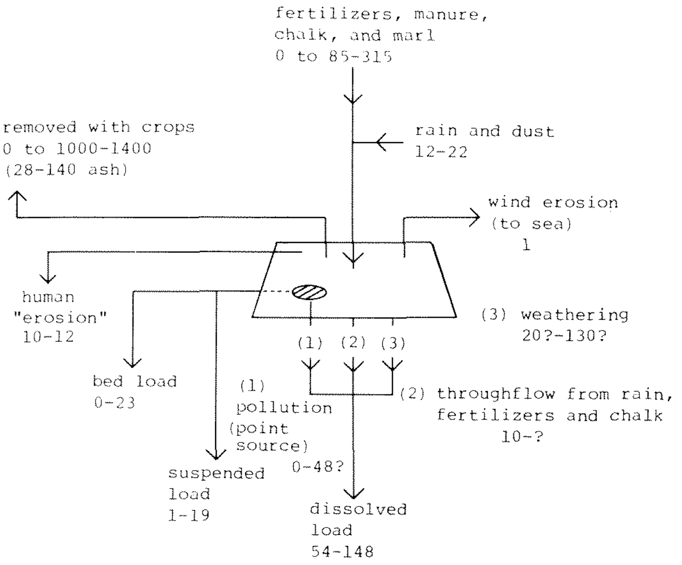

FIG.2 "Standard" dry-matter balance (t $km^{-2} year^{-1}$*). Ranges of individual elements are based on this investigation.*

Fertilizers (total weight), manure, chalk, and marl have also been incorporated in the balance and appropriate values have been taken from Statistics of Denmark (1981) and Venov (1982). This approach is clearly approximate because of the very different agricultural practices present in Denmark, although as a simple guide the need for fertilizers and chalk is highest in West Jutland. It is apparent that removal with crops and amount of fertilizer may balance each other out, but usually there will be a loss of NO_3 (Hansen, 1981). The term human "erosion" is applied here to material removed with sugar beets for sugar production, and for a single field this "erosion" alone may result in a denudational rate of about 100 mm kyear^{-1}. Wind erosion may occur in areas of intensive cultivation, and although generally of small net effect, Kuhlman (personal communication), it may be significant in parts of West Jutland. Pollution from point sources is difficult to evaluate, since the River Suså investigations hint at a contribution of less than 5 t km^{-2}year^{-1} (Jacobsen, 1981), but in extreme cases this can amount to about 50 t km^{-2}year^{-1}. The latter value has been estimated for the Grindsted Å by taking the dissolved load, which is influenced by pollutants from chemical industry, and subtracting the dissolved load of the unpolluted Ansager Å. In an area without human influence, rain and dust will be a major input of dissolved matter.

From the foregoing discussion it is obvious that the denudational rates reported in Table 3 are too high. While bed load and suspended load clearly contribute to the real denudational rate, only the weathering share of the dissolved load should be included. The values from Ansager Å can be considered to represent minimum denudation rates in West Jutland. Assuming dynamic equilibrium between rainfall (22 t km^{-2}year^{-1}) (Jørgensen, 1979) and throughflow, and assuming that throughflow of HCO_3, Cl, and NO_3 is about 10 t km^{-2} year^{-1}, the resulting estimate of dissolved load from weathering is 22 t km^{-2}year^{-1} and the corresponding denudational rate is about 30 mm kyear^{-1}. If the same line of reasoning is used for the Suså, contributions from rainfall (12 t km^{-2}year^{-1}) and throughflow (10 t km^{-2}year^{-1}) should be subtracted from the total dissolved load to give a denudational rate of about 45 mm kyear^{-1}.

It can be concluded that the dissolved component contributes the greatest part of total loads in Danish rivers, and this contribution is largest in the eastern part of the country in spite of lower runoff values. The particulate load may account for up to 35% of the total load in West Jutland. The main trends exhibited by load values are in good accordance with the geological background and the landscape evolution. However, it must be emphasized that the low values of particulate load found for eastern Denmark are partly due to lakes trapping the load. It can also be concluded that human activities make it difficult to obtain accurate values of net denudation rates.

ACKNOWLEDGEMENTS The author wishes to thank K.Simonsen for analysis of water samples, K.Winther for assistance in preparing the manuscript, A.Weng and J.Jønsson for preparing tables and figures, respectively. Thanks are also due to M.Pejrup, K.M.Jensen, and J.Jacobsen for valuable discussions.

REFERENCES

Ackers, P. & White, W.R. (1973) Sediment transport: New approach and analysis. *J. Hydraul. Div. ASCE 11*, 2041-2060.

Bartholdy, J., Hasholt, B. & Pejrup, M. (1982) Materiale-transport i Vidå-systemet. *Report to Sonderjyllands Amt. Skalling-Laboratoriet, Geogr. Inst., Copenhagen.*

Dickinson, W.T. (1981) Accuracy and precision of suspended sediment loads. In: *Erosion and Sediment Transport Measurement* (Proc. Florence Symp., June 1981), 195-202. IAHS Publ. no. 133.

Engelund, F. & Hansen, E. (1967) *A Monograph on Sediment Transport in Alluvial Streams.* Teknisk Forlag, Copenhagen.

Engelund, F. & Fredsøe, J. (1976) A sediment transport model for straight alluvial streams. *Nordic Hydrol.* 7, 293-306.

Hansen, B. (1981) Quantity and quality of tile-drain discharges in the Suså basin. *Report no. Suså H 19, Dansk Komité for Hydrol., Copenhagen.*

Hasholt, B. (1972) Materialevandringen og sedimentationen i Karlsgårde Sø og dens tilløb. *Geogr. Tidsskr.* 71, 54-90.

Hasholt, B. (1977) En undersøgelse af materialeaflejringer og sedimentationsforhold i Karlsgårde Sø. *Report no. 2. Mercury Investigations 1974-76, Skalling-Laboratoriet, Geogr. Inst., Copenhagen.*

Hasholt, B (1981) Concentration and transport of suspended material in the Suså-basin. *Report no. Suså H 14/15, Dansk Komité for Hydrol., Copenhagen.*

Hasholt, B. & Jacobsen, J. (1978) *Delprojekt 5, Skjernå-systemets vandkemi.* Geogr. Inst. and Danish Geol. Invest.

Holm, J.F. & Tuxen-Petersen, F. (1974) *Gudenåen 1974.* Lab. of Phys. Geogr., Geol. Inst., Univ. of Aarhus.

Høst-Madsen, M. & Edens, J.J. (1974) Sediment transport in Danish streams. *Nord. Hydrol. Conf. Papers* 1, 153-164, Copenhagen.

Jacobsen, J. (1981) Surface water chemistry and transport of dissolved matter in the Suså. *Report no. Suså H 16, Dansk Komité for Hydrol., Copenhagen.*

Jørgensen, V. (1979) Chemical composition of air and precipitation in Danish agricultural areas. *IHD in Denmark,* Copenhagen.

Nilsson, B. (1969) Development of a depth-integrating water sampler. *UNGI Report 2, Uppsala.*

Rainwater, F.H. & Thatcher, L.L. (1960) Methods for collection and analysis of water samples. *USGS Wat. Sup. Pap. 1454.*

Statistics of Denmark (1981) *Agricultural Statistics 1980.* Copenhagen.

Thomsen, T. (1980) The application of radioactive tracers for determination of bed-load transport in alluvial rivers. *Nordic Hydrol.* 11 (3/4), 133-144.

Thomsen, T. (1982) A modified sediment transport model for natural streams. *Nordic Hydrol.* 13, 79-92.

Venov, N. (1982) Grundforbedring. *Hedeselsk. Tidsskr.*

Walling, D.E. & Webb, B.W. (1981) The reliability of suspended sediment load data. In: *Erosion and Sediment Transport Measurement* (Proc. Florence Symp., June 1981), 177-194. IAHS Publ. no. 133.