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Transport of phosphorus, wash load and suspended sediment in the River Varde Å in southwest Jutland, Denmark

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Abstract Total phosphorus (TP) concentrations, suspended sediment concentrations (SSC) and wash load have been measured at three river monitoring stations in the River Varde Å system since 1998. This provides the possibility of studying the link between SSC and wash load and concentrations of TP. Transport rates of TP, suspended sediment and wash load at the three stations, calculated using rating curves, indicate the dependence of TP transport on the transport of suspended sediment and wash load. Two stations are located on tributaries flowing upstream of the third station located at a weir at the end of a small impoundment. Transport rates at the upstream stations were 57% higher for suspended sediment and 27% higher for wash load than at the downstream station, while transport of TP was the same. This indicates that phosphorus is transported adhered to the finest grain size fractions that do not deposit in the impoundment.

Key words Denmark; phosphorus transport; rating curve; river system; River Varde Å; sediment transport; suspended sediment; wash load

INTRODUCTION

The transport of phosphorus has been studied in the central part of the River Varde Å system, through a monitoring programme started in 1998. The transport of suspended sediment and wash load has been studied at the same locations since 1969 (Hasholt & Madeyski, 1998). The monitoring programme gives the possibility of studying the connections between transport of phosphorus and the transport of water, suspended sediment and wash load. It is well known that phosphorus, to some extent, is transported adhered to suspended particles, e.g. Kronvang *et al.* (1997). It could also be argued that phosphorus is transported adhered to the finest particles in transportation because of electrical surface bounding, and therefore will be transported by wash load rather than suspended sediment.

STUDY AREA

The River Varde Å system is located in southwest Denmark (Fig. 1). The catchment area is 1090 km^2 and the average water discharge at the river mouth is 16.00 m^3 s^{-1} (Ovesen *et al.*, 2000) (Table 1). The river is an alluvial lowland river; it has three main tributaries, of which two are considered here, the River Grindsted Å and the River Ansager Å (Fig. 1). The monitoring stations are located in the central part of the river system, where the River Grindsted Å and the River Ansager Å meet and become the River Varde Å. Shortly downstream of the confluence the River Varde Å is split into the River Gammel (Old) Varde Å and the Ansager, at a dammed site, where the water is directed to the River Gammel

Table 1 Mean annual discharge and catchment areas for three river stations in the River Varde Å system.

	River Ansager Å Lavborg Bridge	River Varde/Grindsted Å Mølby Bro	Ansager Canal Ansager Weir
Discharge mean annual ($m^3 s^{-1}$)	2.04*	3.39	5.19
Catchment area (km^2)	131*	238†	439‡

*(Ovesen *et al.*, 2000) †(Hasholt, 1983) ‡(Hasholt, 1972).

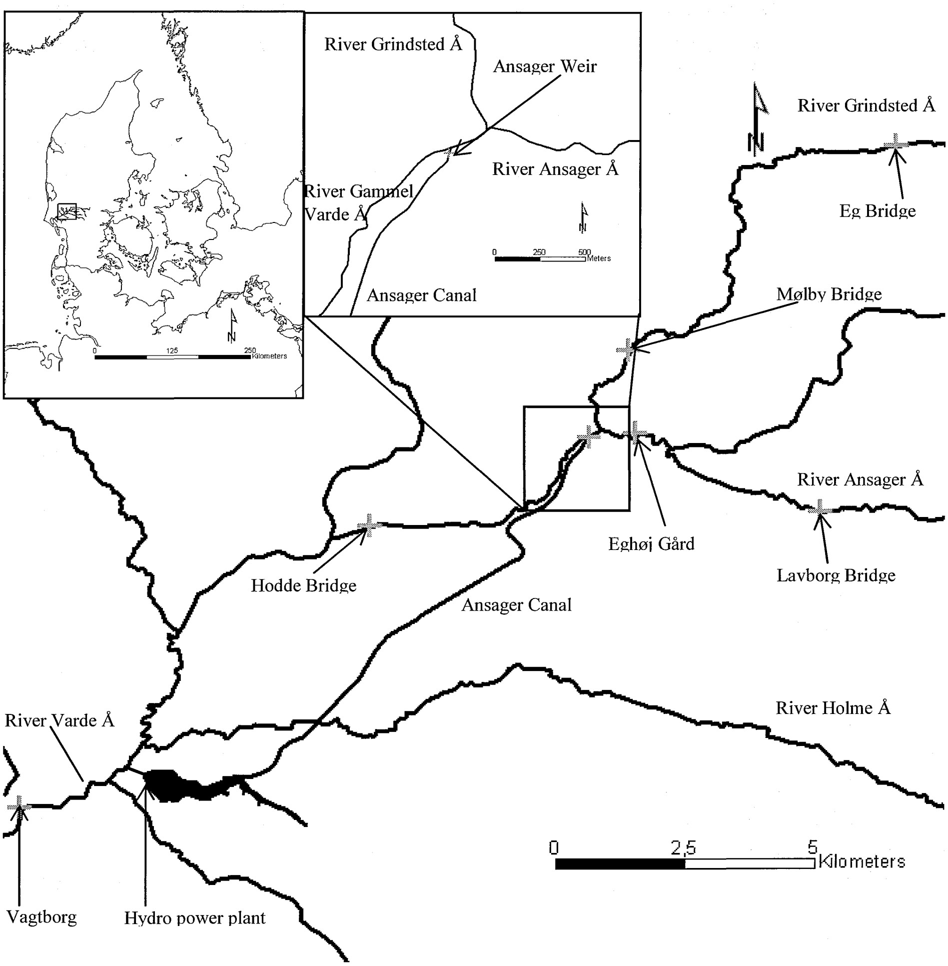

Fig. 1 Map of the study area showing the drainage network and river stations.

Varde Å and the Ansager Canal over two weirs. There is a small impoundment upstream of the dam. One monitoring station is located on the River Ansager Å at Lavborg Bridge and another is located on the River Grindsted Å at Mølby Bridge (Fig. 1). The third monitoring station is located downstream of the confluence at the weir between the impoundment and the Ansager Canal. Most of the water from the River Varde Å enters the Ansager Canal which feeds a hydropower plant. A minor part of the water is still supplied to the natural stream channel, the River Gammel Varde Å (Fig. 1).

Discharges at the Ansager Weir on the Ansager Canal are calculated using *Q*/*Q* relations between the stations at Eg Bridge and Mølby Bridge on the River Grindsted Å and at Lavborg Bridge and Enghøj Gård on the River Ansager Å (Fig. 1). Then the following expression is used $Q_{\text{Mølby Bridge}} + Q_{\text{Enghøj Gård}} - Q_{\text{Hodde Bridge}} = Q_{\text{Ansager Weir}}$, (Fig. 1). Discharge from the Ansager canal at the Ansager Weir are only calculated for the period 5 May 1994–31 December 2002 because of a lack of data from the previous period. The method of calculating the discharge at Mølby Bridge is given above. Discharge at Lavborg Bridge is obtained from a permanent gauging station at that location. Mean annual precipitation in the catchment between 1 January 1990 and 31 January 2001 is about 875 mm year^{-1}. Geomorphologically the catchment mainly consists of sandy outwash plains from the Weichsel glaciations, and older sandy moraine landscapes from the Sahle glaciations, the most easterly parts of the catchment consists of younger moraines from the Weichsel glaciations (Smed, 1978).

METHOD

Samples of suspended sediment have been collected using a depth integrating water sampler (Nilson, 1969) at all stations approximately once a month since 1969 (Hasholt & Madeyski, 1998). Data from 1983–1984 are missing. During 1987 additional samples were collected on days with high discharges. Samples of suspended sediment collected just beneath the water surface using the depth integrating water sampler, have been collected since 1980 at the same time as the suspended sediment samples: these samples provide an estimate of wash load. Since November 1990 water samples were also collected 1–3 times a day using an ISCO 2700 automatic water sampler (ISCO, 1988) at Lavborg Bridge on the River Ansager Å. The ISCO samples water approximately 50 cm above the bed.

In the laboratory total suspended sediment concentrations (SSC) and wash load were determined in two ways. Before 1975 sediment concentrations were determined by filtering water samples through OOH paper filters with a retention diameter of 1–2 µm. Since 1975 Whatman GF/F filters with a retention diameter of 0.7 µm have been used. Filters were dried for at least 3 h at 60°C; after drying filters were weighed after resting for 20 min at room temperature. Water samples were analysed for total phosphorus concentrations using a standard photometric method (Dansk standard, 1985)

A rating curve approach for modelling the transport of suspended sediment as a function of discharge was used, because more sophisticated approaches such as the rising/falling limb approach and the duration curve approach did not significantly improve the modelling results. Suspended sediment concentration rating curves were calculated for the three monitoring stations as a function of water discharge. At the River Ansager Å rating curves were calculated for both manually and automatically collected samples. The difference in transport rates calculated on the basis of manually and automatically collected samples were used to calculate a correction factor for correcting the transport rates from the manually collected samples. The correction factor was calculated by adjusting the mean annual transport given by the rating curve to the mean annual transport given by the automatically sampled data, at the monitoring station at River Ansager Å, Lavborg Bridge. Total phosphorus concentrations were modelled using three kinds of rating curves: those derived by using water discharge, SSC and wash load as the predictors.

RESULTS AND DISCUSSION

Transport of suspended sediment, wash load and phosphorus are modelled and the dependence of phosphorus transport to SSC and wash load concentrations is described.

Suspended sediment

Rating curves for the total SSC, measured by the depth integrating sampler and the ISCO automatic sampler as a function of discharge, were calculated. The rating curves are power functions fitted by a standard least square technique (Table 2). Mean annual transport rates of suspended sediment were calculated using the rating curve functions for the manually collected samples and water discharge for the period 1 January 1995 to 31 December 2002 (Table 2). Estimates of suspended sediment transport obtained by rating curves tend to underestimate the transport in comparison with estimates made by high frequency sampling (Ferguson, 1986; Phillips *et al.*, 1999; Asselman, 2000). At the Ansager Å River station measurements were made 1–3 times a day by the ISCO sampler in the period determining suspended sediment transport. The transport rate estimated by the high frequency sampling method is calculated using mean daily water discharges. A correction factor is applied to the mean annual transport determined by the rating curve approach, giving the corrected mean annual transport. Correction factor:1285 t year^{-1}/1100 t year^{-1} = 1.17. The correction factor is multiplied by the mean annual transport thereby giving the mean annual corrected transport, (Table 2). The correction factor was used at the three monitoring stations.

At the River Ansager Å station suspended sediment yields were previously found to be 7 t km^{-2} year^{-1} (Hasholt & Madeyski, 1998). The transport rates indicate that the area between the two upstream stations and the Ansager Canal station is a deposition area for suspended sediment. A part of the suspended sediment transported in that part of the River Varde Å upstream of Ansager Canal is transported to the River Gammel Varde Å. No direct measurements of this transport exists but it is expected to be much smaller than the transport to the Ansager Canal because of a much smaller discharge to the River Gammel Varde Å. Deposition of suspended sediment would be expected at the impounding upstream of the weirs of the Ansager Canal and the River Gammel Varde Å. Approximately 57% of the

Table 2 Rating curves of total suspended sediment concentration (SSC) as a function of dischange (Q), based on depth integrated samples and samples collected automatically by an ISCO sampler. Mean annual transport rates and corrected mean annual transport rates.

River & station	Number of samples (n)	R^2	Function	Mean annual transport		Mean annual corrected transport	
				(t year^{-1})	(t km^{-2} year^{-1})	(t year^{-1})	(t km^{-2} year^{-1})
River Ansager Å, Lavborg Bridge	390	0.30	SSC = 5.488 $Q^{1.256}$	1100	8.4	1285	9.8
River Grindsted Å, Mølby Bridge	397	0.24	SSC = 5.471 $Q^{1.140}$	2800	11.8	3270	13.7
River Ansager Canal, Ansager Weir	104	0.36	SSC = 3.861 $Q^{0.528}$	1660	3.8	1940	4.4
River Ansager Å, Lavborg Bridge ISCO	5153	0.30	SSC = 5.321 $Q^{0.965}$	1285	9.8	–	–

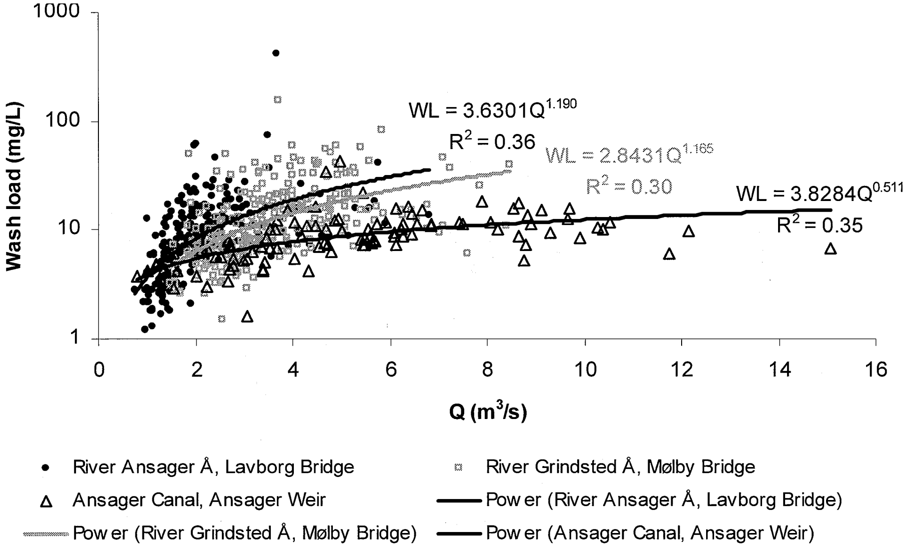

Fig. 2 Rating curves of concentrations of wash load as a function of water discharge (Q), at three stations at the River Varde Å system. WL is wash load concentration.

sediment transported through the two upstream stations is not transported through the station at the Ansager Canal (Table 2).

Wash load

Wash load concentrations are collected from all three monitoring stations. Rating curves have been calculated for the three monitoring stations (Fig. 2).

The rating curves given in Fig. 2, and discharge from the period 1 January 1995 to 31 December 2002 were used to calculate mean annual transport rates which are as follows:

River Ansager Å at Lavborg Bridge, 675 t year^{-1}, 5.2 t km^{-2} year^{-1};
River Grindsted Å at Mølby Bridge, 1500 t year^{-1}, 6.3 t km^{-2} year^{-1};
Ansager Canal at Ansager Weir, 1590 t year^{-1}, 3.6 t km^{-2} year^{-1}.

The sum of the transport rates of the two upstream stations on the River Ansager Å and the River Grindsted Å are approximately 27% higher than at the downstream station on the Ansager Canal. This also indicates that sediment is deposited between the stations. For suspended sediment 57% is deposited between the stations, because it holds fractions of coarser grains from suspended bed load, which is deposited in the impounded water.

Phosphorous

Measurements of total phosphorus concentrations have been made at the three stations. At the River Grindsted Å and the Ansager Canal measurements have been made since May 1998 and at the River Ansager Å since the beginning of 1999. Samples have been collected at the same dates as sediment samples. Rating curves have been made for the relationship

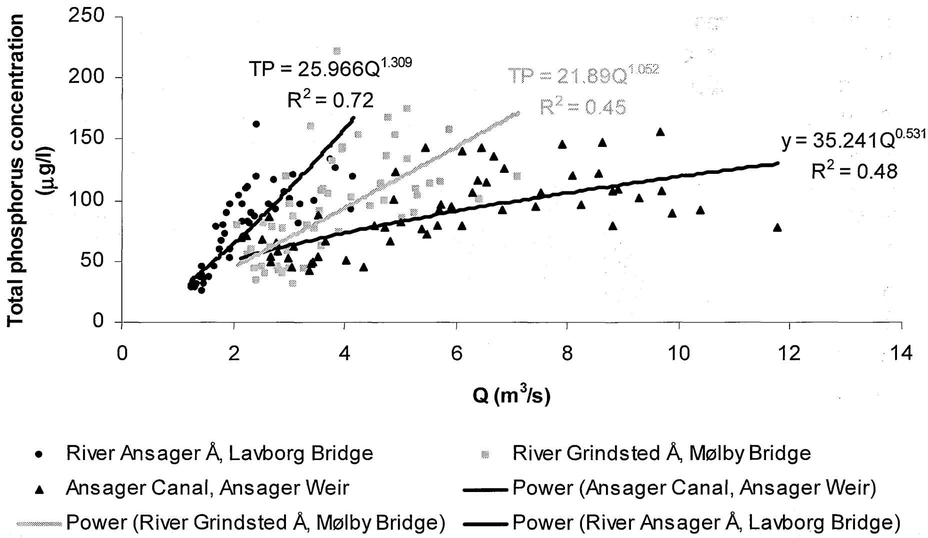

Fig. 3 Rating curves of Total Phosphorus concentrations (TP) as a function of water discharge (Q) at three stations at the River Varde Å system.

Table 3 Total phosphorous concentrations (P_{total}) as a function of suspended sediment concentrations (SSC) and wash load (WL).

River	Samples *n*	SSC R^2	Function	Wash load concentration R^2	Function
River Ansager Å, Lavborg Bridge	47	0.82	P_{total}=18.185 $SSC^{0.623}$	0.86	P_{total}=15.236 $WL^{0.75}$
River Grindsted Å, Mølby Bridge	53	0.58	P_{total}=23.048 $SSC^{0.497}$	0.69	P_{total}=39.603 $WL^{0.51}$
Ansager Canal, Ansager Weir	57	0.86	P_{total}=20.003 $SSC^{0.659}$	0.83	P_{total}=21.303 $WL^{0.64}$

between total phosphorus and discharge (Fig. 3). Relatively large differences are seen in the constants of the three power functions (Fig. 3). The two upstream stations have higher power values, reflecting a higher degree of response to changes in discharge, but also reflecting the fact that the discharge is higher at the downstream station while the total phosphorus concentration is in-between the values of the two upstream stations. Total phosphorus concentrations are better correlated to discharges at the station on the River Ansager Å, than the other two stations.

It has been shown that phosphorus is, to a large extent, transported through fluvial systems adhered to suspended particles (Kronvang *et al.*, 1997). Sediment sampled just beneath the water surface has a smaller grain size than depth integrated samples because the latter samples contain a part of the suspended bed load. Phosphorus is adhered to the smallest grain sizes because of electrical bounding. Phosphorus may then be transported with wash load rather than with total suspended sediment. The influence of the suspended sediment and wash load on total phosphorus concentrations are seen in Table 3.

On average wash load has a better correlation with total phosphorus than suspended sediment, but no clear trend is seen (Table 3). The small difference between the two functions for the Ansager Canal possibly reflects the deposition of the coarsest suspended particles in the impoundment just upstream of the weir (Table 3). The effect of this is that the transports, measured as suspended sediment and as wash load over the weir, to a great extent consists of the same particle size fractions.

Rating curves predicting total phosphorus concentrations can be developed from water discharge, SSC and wash load. Mean annual transport rates of phosphorus are calculated using water discharge rating curves for the three stations. For comparison, a mean annual transport rate is calculated for River Ansager Å at Lavborg Bridge, by a rating curve using SSC, measured by the automatic ISCO sampler, as the input value. Mean annual transport rates of phosphorus derived by water discharge rating curves are:

River Ansager Å at Lavborg Bridge, 5.5 t $year^{-1}$, 42.0 kg km^{-2} $year^{-1}$;
River Grindsted Å at Mølby Bridge, 9.8 t $year^{-1}$, 41.2 kg km^{-2} $year^{-1}$;
Ansager Canal at Ansager Weir, 15.2 t $year^{-1}$, 34.6 kg km^{-2} $year^{-1}$.

Mean annual transport rates derived by SSC rating curve are:
River Ansager Å at Lavborg Bridge, 9.0 t $year^{-1}$, 68.7 kg km^{-2} $year^{-1}$.

Transport of total phosphorus calculated by water discharge indicates that phosphorus is not accumulated between the two upstream stations and the Ansager Canal to the same extent as suspended sediment and wash load. The transport through the upstream stations are 9.8 t $year^{-1}$ + 5.5 t $year^{-1}$ = 15.3 t $year^{-1}$ and 15.2 t $year^{-1}$ through the station at the Ansager Canal. Comparison between phosphorus transport rates at the River Ansager Å at Lavborg Bridge, calculated by water discharge and SSC indicates that the transport rate calculated by water discharge is underestimated. The transport rate calculated by SSC is approximately 64% higher than the transport rate calculated by water discharge. The calculated values indicate that phosphorus is not deposited in the area.

Comparisons can be made for the transport of phosphorus to measurements of transport made by the Ribe Amt County (Jepsen *et al.*, 2003). For the River Varde Å at Vagtborg (Fig. 1) the Ribe Amt County had a transport rate of 36.787 t $year^{-1}$ for 2002, and, with the catchment area at Vagtborg being 814 km^2, this gives 45.2 kg km^{-2} (Fig. 1). At the River Grindsted Å the equivalent number is 44.8 kg km^{-2}; for the River Ansager Å it is 46.7 kg km^{-2} and at the Ansager Canal it is 39.0 kg km^{-2}. All values are seen to be of approximately the same size, indicating that the observed transport rates are of the right magnitude. It is also indicated that using SSC, which has a much higher R^2 value with total phosphorus concentrations than that found for water discharge, could produce a considerably different and perhaps more reliable estimate of transport rates.

It is seen by the above, that the transport of phosphorus is less influenced by deposition in the impoundment upstream of the Ansager Weir than the transport of wash load and especially suspended sediment. This indicates that phosphorus is transported with only the finest sediment particles, which are not deposited in the impounding area. Modelling of phosphorus concentrations using SSC is therefore more site-specific than using wash load. It could, therefore, be argued that wash load is more appropriate in modelling phosphorus concentrations in river systems than SSC, because SSC is highly influenced by the location of deposition areas.

CONCLUSIONS

It can be concluded that phosphorus is transported adhered to fine grain size particles in the wash load transport fraction. It may also be concluded that the transport of phosphorus is not affected by the passage of the river flow through an area of impounded water. The transport rates of suspended sediment is reduced by 57% and the transport of wash load is reduced by 27%, by passing through the impounded area. It was found that total phosphorus concentrations are well correlated with SSC and wash load, and poorly correlated with water discharge. Transport rates of total phosphorus calculated using SSC as the predictor at the River Ansager Å gives a 64% higher transport rate than using water discharge as the predictor. If possible, SSC or wash load concentrations should be used instead of water discharge as the predictor of total phosphorus concentrations.

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