The Structure, Function and Management Implications of Fluvial Sedimentary Systems (Proceedings of an international symposium held at Alice Springs, Australia, September 2002). IAHS Publ. no. 276, 2002.

Effective discharge for heavy metal deposition on the lower River Rhine flood plains

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Abstract The present study addresses the effective discharge for heavy metal transport and deposition on the lower Rhine flood plains, as the product of stage-dependent sediment trapping efficiency of the flood plain, discharge frequency, suspended sediment concentration in the river, and metal concentration in the sediment. This type of analysis is essential for evaluation of the effects of landscaping measures along the lower River Rhine on overbank flow and deposition of sediment and sediment-associated pollutants on the flood plain. Effective discharges for metal deposition depend on the flood plain topography, and vary from slightly in excess of bankfull for low areas that experience frequent flooding of fine sediments, to much larger than bankfull for distal parts of flood plains behind minor embankments.

Key words flood plain; heavy metals; sediment trapping; effective discharge; Rhine River

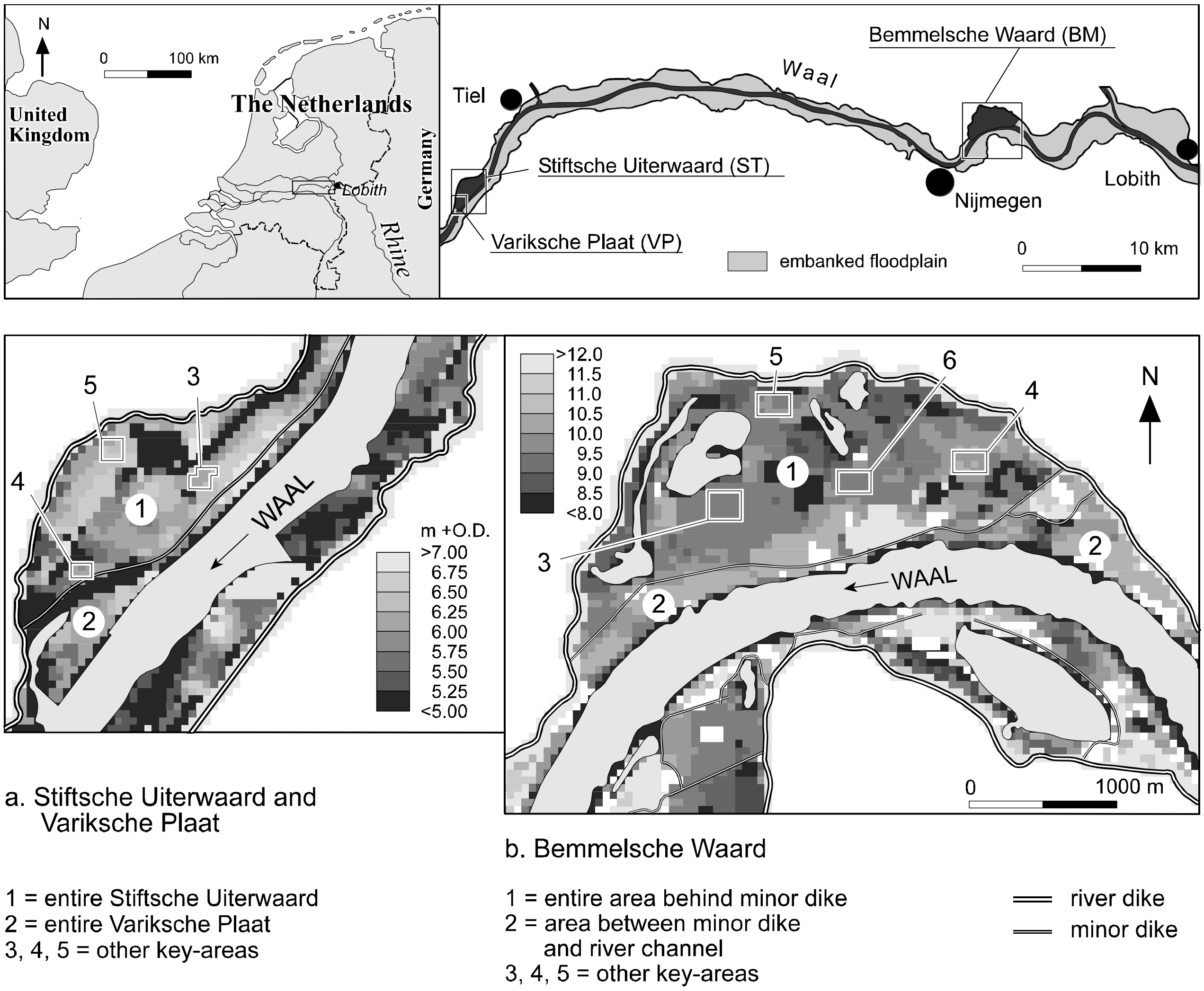
INTRODUCTION

Due to deposition of contaminated overbank sediments over many years, the embanked flood plains of the lower River Rhine in The Netherlands contain large amounts of heavy metals (Middelkoop, 1997; 2000). Although various surveys have been made on the present-day metal pollution of the lower Rhine flood plain, little progress has been achieved on the prediction of future deposition of pollutants, and on the analysis of the spatial distribution and magnitude–frequency relationship of pollutant deposition. Such analyses are essential for evaluation of the effectiveness of ongoing projects for ecological restoration and improvement of the discharge capacity of the lower River Rhine. Landscaping measures involved in these projects include lowering the flood plain surface, removing minor embankments, and excavating side channels (Silva *et al.*, 2000), which may greatly affect overbank flow and deposition of sediment and sediment-associated pollutants on the flood plain. For this purpose, the effective discharge (after Andrews, 1980) for heavy metal deposition may be a useful concept. In the present study, the factors determining this effective discharge are examined for the lower Rhine River flood plains. The results are compared with the effective discharge for in-channel metal transport.

CONCEPT AND METHODS

Study area

Effective discharges for metal deposition were determined for three flood plain sections along the Waal, the largest distributary of the lower Rhine River in The



a. Stiftsche Uiterwaard and Varikische Plaat

b. Bemmelsche Waard

1 = entire Stiftsche Uiterwaard
2 = entire Varikische Plaat
3, 4, 5 = other key-areas

1 = entire area behind minor dike
2 = area between minor dike and river channel
3, 4, 5 = other key-areas

river dike
minor dike

Fig. 1 Location of the study area.

Netherlands: the Bemmelsche Waard (BM), the Stiftsche Uiterwaard (ST) and the Varikische Plaat (VP) (Fig. 1). The Varikische Plaat is a lowlying flood plain section that is inundated 3 or 4 times per year. The Stiftsche Uiterwaard is protected from low floods by a 0.5–1 m high embankment, and is inundated, on average, once a year. At the time of sampling, the Varikische Plaat and parts of the Stiftsche Uiterwaard had a natural relief with depressions from partly in-filled secondary channels. The Bemmelsche Waard is protected from low-magnitude floods by a 3-m-high embankment. Consequently, average inundation frequency is 0.8 times per year. This area has been levelled.

Effective discharge for heavy metal deposition

Following Andrews (1980), the discharge which, in the long term, deposits the greatest amount of metals is considered the effective discharge for metal deposition at a certain flood plain site. The effective discharge for metal deposition was assessed by the following sequence of factors: (a) the sediment trapping capability of the flood plains; (b) the frequency distribution of the Rhine discharge; (c) suspended sediment concentration; and (d) heavy metal concentration in the suspended load. The product of these factors results in a metal deposition curve, which can have a different shape at different places on the flood plain. The shape of the curve indicates how the total annual metal deposition is distributed over different discharges. The curve peaks at the effective discharge for metal deposition. If there is a broad peak over a wide discharge range, there is no effective discharge. The area below the curve equals the total annual metal deposition.

All parameters and relationships used here were measured at or constructed for the Lobith gauging station on the River Rhine at the Dutch–German border.

Sediment trapping capability of the flood plain

The sediment trapping capability (STC) of a flood plain section is determined by the local sediment deposition rate that occurs at a certain river discharge for a standard suspended sediment concentration in the river. The deposition rates plotted against river discharge make up a STC curve (STCC) that describes how deposition due to sediment trapping varies with river discharge, regardless of the frequency of occurrence of discharge or suspended sediment concentration in the river. Consequently, differences in STCCs are only determined by flood plain topography.

Sediment trapping capability curves were determined using the GIS-embedded sedimentation model SEDIFLUX (Middelkoop & Van der Perk, 1998). This raster-based model calculates sediment deposition on flood plains for given steady-state conditions of river flow and concentration of the suspended load in the main river channel. Standardized sediment deposition rates, $S_{st,a}$ (kg m^{-2} day^{-1}), were calculated for characteristic water flow patterns over the three study areas, resulting from different discharges Q_a in the River Rhine, using a standard sediment concentration C_{st} in the Rhine equal to 100 mg l^{-1}. By plotting these standardized deposition rates for key sites within the investigated flood plain sections against river discharge, STCCs were obtained (Fig. 2(a), (b)).

Discharge frequencies and suspended sediment concentrations in the Rhine River

Discharge frequencies were determined using a record of daily discharges observed over the period, 1901–1995. Following Asselman (2000), the average value of the relationship between discharge and suspended sediment concentration was determined empirically using a sediment rating curve in the form of a power function with the addition of a constant term:

$$C = p + aQ^b$$

where C is suspended sediment concentration (mg l^{-1}), Q is discharge (m^3 s^{-1}), and p, a and b are regression coefficients. The regression parameters were determined by fitting the function on discharges and sediment concentrations measured during the period 1975–1990.

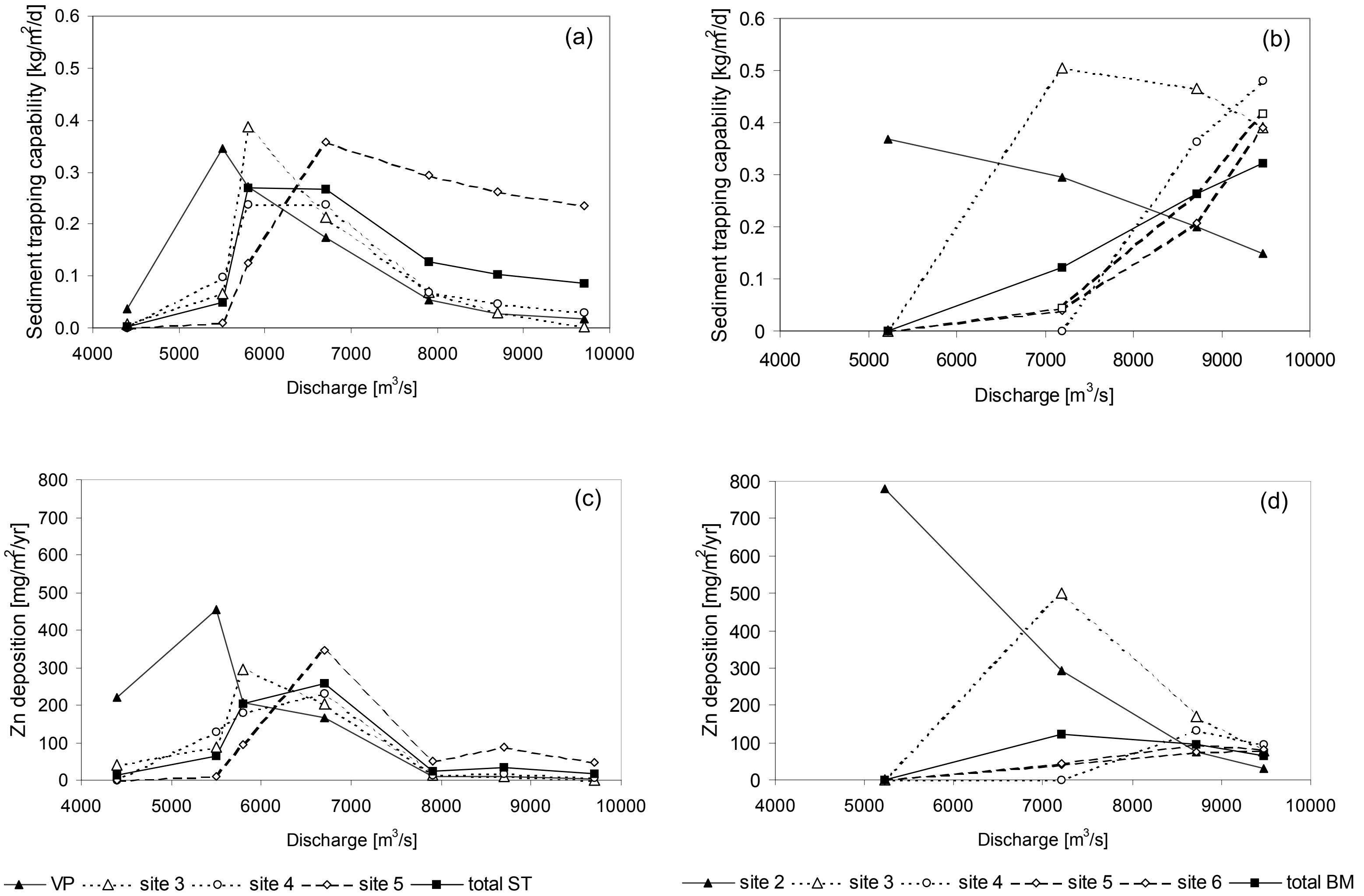


Fig. 2 Sediment trapping capability curves for the VP and ST sections (a) and BM section (b); zinc deposition curves for the VP and ST sections (c) and BM section (d).

Metal concentrations in suspended sediment

A record of bi-weekly measurements of heavy metal concentrations in the suspended sediment was available for the period 1992–1994. The average decrease in metal concentrations in the suspended load with increasing discharge was determined empirically by means of fitting a regression function of metal concentrations on discharge. The Zn and Cd data were fitted by an inverse function $M = a_m + b_m/Q$, where M is heavy metal concentration in the suspended load (mg kg^{-1}), Q is water discharge (m^3 s^{-1}), and a_m and b_m are regression coefficients. The best fit for Pb and Cu was obtained by using an exponential version of this function:

$$M = \exp(a_m + b_m/Q)$$

Effective discharge for metal transport

For comparison with the effective discharges for metal *deposition* on flood plains, the effective discharge for metal *transport* through the Rhine River was also calculated. This was done by multiplication of discharge by its associated duration, sediment concentration and metal concentration in the sediment. The effective discharge for metal transport is the discharge at which the resulting curve peaks.

RESULTS

Sediment trapping capabilities

The sediment trapping capability curves shown in Fig. 2(a) and (b) demonstrate that the ST and VP sections are more effective in trapping sediment at lower discharges than the BM section. The STC of low flood plain sections that are not protected by an embankment (VP and BM site 2) is highest at relatively low discharge (5500 m^3 s^{-1}). At higher discharge, current velocities become so fast that most sediment is conveyed over the flood plain without settling. The embankment bordering the ST section protects this area from minor floods, which causes the STCCs to peak at 6000–7000 m^3 s^{-1}. In the distal area behind the relatively high embankment of the BM section, sediment trapping becomes increasingly efficient at higher discharge (Fig. 2(b), sites 4, 5 and 6). This is because, due to this embankment, the BM section becomes inundated only at high discharge. But, even under conditions of extremely high discharge, the embankment drastically reduces flow velocity of the overbank flow, such that suspended sediment can still settle. The effective discharges are summarized in Table 1.

Discharge frequencies and sediment concentrations

The discharge frequency curve is given in Fig. 3. The same figure also shows the suspended sediment rating curve fitted to the observations. Suspended sediment

Table 1 Average annual deposition rates of sediment and heavy metals, and effective discharge for deposition at different sites within the investigated flood plain sections.

Flood plain section	Sediment ($kg\ m^{-2}\ year^{-1}$)	Zn ($mg\ m^{-2}\ year^{-1}$)	Cd ($mg\ m^{-2}\ year^{-1}$)	Pb ($mg\ m^{-2}\ year^{-1}$)	Cu ($mg\ m^{-2}\ year^{-1}$)	Q_{eff} ($m^3\ s^{-1}$)
Total BM	1.09	218	0.71	45	36	7200
2	3.40	1149	5.99	240	190	5220
3	2.37	675	5.21	142	114	7200
4	1.01	137	4.43	32	26	8720
5	0.85	120	5.38	29	24	8720
6	0.99	146	6.46	35	29	8720
Total ST	1.93	609	2.10	127	101	6700
VP	2.66	1072	3.78	222	176	5500
3	1.96	651	2.25	135	107	5800
4	1.78	572	1.97	119	94	6700
5	2.08	624	2.14	132	106	6700

concentrations in the lower Rhine are generally greater when river discharge is high. However, sediment concentrations during high flows are variable, due to sediment exhaustion during the course of the high-water season (winter–early spring), and due to hysteresis effects during the course of a flood (Asselman, 1997).

The scatter plots of Zn and Pb concentrations in the suspended sediment against the discharge and the regression lines are given in Fig. 4. Metal concentrations are highly variable when discharge is below about 4000 $m^3\ s^{-1}$. Although few measurements are available for high discharges, the results indicate that when discharge exceeds 4000 $m^3\ s^{-1}$, metal concentrations decrease to about one-half to two-thirds of the concentrations during low flow, and show less variation.

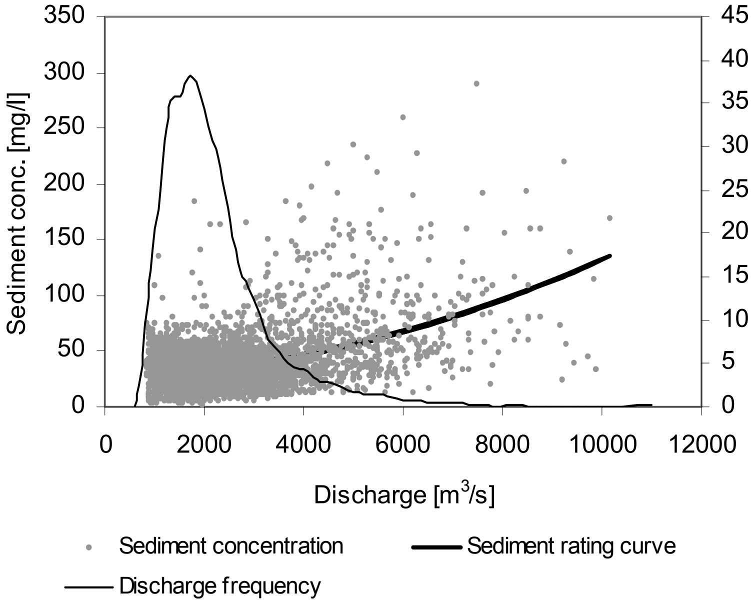


Fig. 3 Frequency distribution of water discharge, suspended sediment concentrations and sediment rating curve of the lower Rhine River.

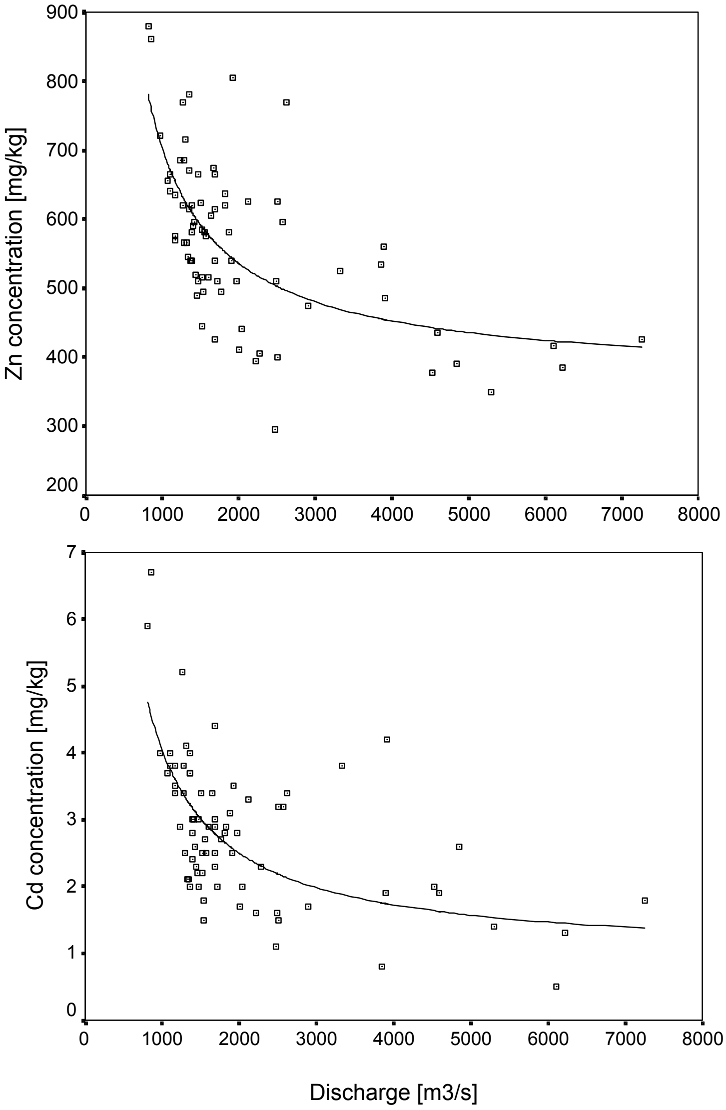


Fig. 4 Metal concentrations in the suspended sediment in the lower Rhine River and their respective regression lines.

Effective discharge for metal deposition

The metal deposition curves are given in Fig. 2(c) and (d). The STC and metal deposition curves for the ST section show the same trends, and peak in the range between 6000 and 7000 $m^3 s^{-1}$. For the BM section, however, the curves are different (Fig. 2(b), (d)): while the STCC strongly increases with discharge (Fig. 2(b)) the increase for the metal deposition is only moderate (Fig. 2(d)). The broad peak for the total BM area indicates that there is no clear effective discharge. Apparently, the high trapping capabilities of the BM sites and high sediment concentrations in the river at high discharge cannot completely outweigh the infrequent occurrence of these discharges. Still, the effective discharges for metal and sediment deposition are the same (Table 1).

The results show that the spatial variation in effective discharge for metal deposition is mainly controlled by the combination of varying sediment trapping capabilities and discharge frequencies. Metal concentrations in the sediment show little variation at high discharge when overbank flooding occurs, and hence have little effect on the spatial distribution of effective discharge for metal deposition.

When the results are compared to the zinc transport curve given in Fig. 5, it becomes apparent that most metal transport occurs during discharges of about 1900 $m^3 s^{-1}$. For sediment transport, the effective discharge is 2350 $m^3 s^{-1}$ (Asselman, 1997). The difference is due to a decrease in metal concentrations stronger than the increase in sediment concentration at increasing water discharge. Lower discharges, therefore, are relatively more important for heavy metal transport than sediment transport.

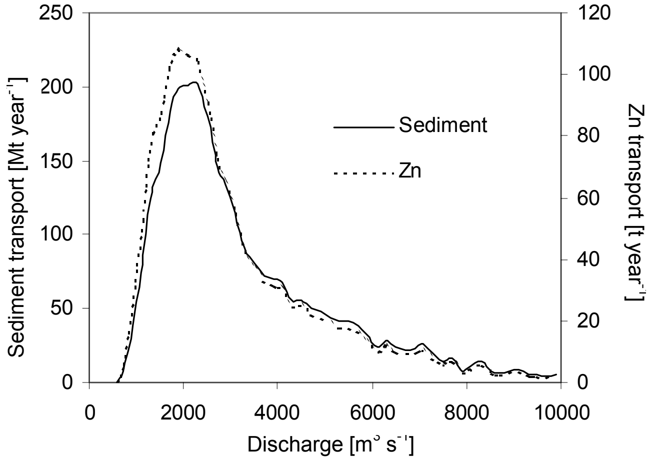


Fig. 5 Transport of suspended sediment and zinc in the Rhine River at varying discharges.

DISCUSSION AND CONCLUSIONS

The effective discharge for heavy metal deposition is an adequate measure of the trapping efficiency of various flood plain sections for sediment-associated heavy metals. The calculation of the effective discharge is relatively straightforward for rivers that are regularly monitored for discharge, suspended sediment concentration, and heavy metal concentration of the suspended sediment. However, the effective discharges calculated here do not account for hysteresis in suspended sediment and heavy metal concentrations during high discharge events, as these could not be determined from the available bi-weekly monitoring data. The reported effective discharges mainly apply for metals bound to the fine silt and clay fractions deposited in the central parts of the flood plain sections. However, metal deposition in sand sheets deposited on the river banks may considerably contribute to the total metal deposition, despite the relatively low heavy metal concentrations in these coarse-grained sediments (Middelkoop, 2000). Besides, spatial variation in deposition of different grain sizes on flood plains was not considered here but may be important due to preferential binding effects.

Flood plain topography not only determines the deposition rate of heavy metals, but also the effective discharge during which most of the deposition occurs. On lowlying flood plain sections that experience frequent flooding, the trapping efficiency of sediment-associated heavy metals is high. This implies that river restoration projects that result in lowering of the flood plain surface and/or removing minor embankments cause a considerable enhancement of heavy metal deposition. This occurs because it leads to an extension of inundation duration and results in sediment deposition during low discharge, when sediment is more polluted than sediment deposited during high discharge.

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