Sediment monitoring and sediment management in the Rhine River

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Abstract Long-term records of permanent monitoring stations on the Rhine River are an excellent base from which to quantify the input of suspended sediment from the large tributaries and to estimate the effect of impounding on the sediment budget of the Upper Rhine. The decrease of suspended load downstream of the Iffezheim barrage is clearly related to the completion of the impoundment chain in the 1970s. Recently about 100 000 t of fine-grained sediments were dredged in the backwater of the Iffezheim barrage and relocated downstream into the free flowing river. Due to a comprehensive monitoring programme, the impact of this measure on sediment concentration could be traced downstream over tens of kilometres. Furthermore, the effect of a very high sediment input due to an extreme precipitation event in Switzerland in August 2005 was analysed in detail. A preliminary attempt to reconstruct the propagation of the sediment wave has brought new insight into the sedimentation processes along the Upper Rhine and helps to understand the potential effects of climate changes on the suspended load of the Rhine River.

Key words climate change; contaminated sediments; dredging; sedimentation; suspended load

INTRODUCTION

The Rhine River is the most important inland waterway of Europe connecting Switzerland, western Germany and eastern France with the North Sea. Although bed load management is an important task in the free flowing section of the river (Goelz, 2004), this paper focuses on the problems created by suspended solids and their fine grained deposits. Sedimentation in the impounded section of the Upper Rhine causes rising of bed and water levels. To ensure high flood discharge and the security of the dykes, the sediments have to be removed from time to time. Dredging and disposal, however, are a major problem as the sediments are contaminated by hexachlorobenzene (HCB). As has been shown by Witt *et al*. (2003), there is also the risk of remobilization of highly contaminated sediments during high floods. In the future, due to climate change, the frequency and magnitude of high floods could increase (Asselman, 1997) and might influence sedimentation in the impounded section. Thus the development of strategies both to reduce dredging of sediments and to dispose them in an ecologically friendly and economically acceptable manner is one of the important tasks of sediment management on the Rhine waterway. To achieve these goals, the behaviour of the suspended load when entering, passing, and leaving the impounded section has to be studied. As a first step this has been done by evaluating the data of the permanent measuring stations for suspended load and by detailed monitoring of a flood event and of a major dredging exercise at the Iffezheim barrage.

HYDROLOGICAL REGIME AND ENGINEERING HISTORY

The hydrological conditions in the Rhine basin are described comprehensively in the monograph “*Le bassin du Rhin—Das Rheingebiet*” (CHR, 1977). The southern Upper Rhine is characterized by high discharges in early summer, caused by snowmelt and precipitation in the Alps. Owing to the influence of the large tributaries, Neckar, Main and Mosel, the discharge maximum shifts more and more to the semi-annual winter period. The mean discharge at Maxau is 1270 $m^3 s^{-1}$ and the maximum discharge is 4550 $m^3 s^{-1}$. The resulting low *HHQ*/*MNQ* ratio (highest/mean low water) is due to the damping effects of the Perialpine lakes, especially Lake Constance, and the training of the Jura River. Up to the 18th century the Upper Rhine was a natural river with a braiding tendency in the southern part and large meanders in the northern half. The first major anthropogenic impact was the channalization of Tulla in the first half of the 19th century, creating a uniform, straightened and fixed channel accompanied for some distance by flood dykes. In the second half of the 19th century the channalized river was trained by groynes to fix the alternating bars and to establish a defined thalweg for navigation. After World War I the French began to build a long side canal (Grand Canal d’Alsace) with four impoundments beginning downstream of Basel and ending near Breisach. The next four impoundments were constructed by diverting the river by an artificial loop for the locks and the hydropower station (the so-called loop-solution). The last two barrages, Gambsheim (1974) and Iffezheim (1977), cross the whole river as one structure. They consist of two locks, a dam, the hydropower station and a flexible weir. The two impoundments are laterally bordered by high dykes between which the whole flow of the river has to be discharged.

LONG-TERM MONITORING OF SUSPENDED SEDIMENT

Suspended sediment transport along the Rhine River has been monitored over more than three decades at 11 permanent stations by taking a 5 L water sample at a defined measuring point every working day. Suspended sediment concentration is determined by filtering the sample and weighing the solid residue. The influence of the tributaries and the retention effect of the impoundment-chain of the Upper Rhine on the suspended sediment budget of the river can best be seen in the longitudinal section of the annual suspended load (Fig. 1). The Rhine River leaves Lake Constance at km 0 nearly devoid of sediments. The first major sediment input comes from the Aare River draining the central Swiss Alps, the Swiss midlands and part of the Jura chain. Although only small tributaries join the Rhine within the next 70 km downstream to Basel (km 170) the annual suspended load increases by about 0.5 Mt to about 1.5 Mt. Passing the impoundment chain between Basel and Iffezheim, the southern Upper Rhine appears to lose about 300 000 t of suspended sediment by backwater deposition. The actual loss must, however, be significantly higher, because some smaller tributaries draining the Black Forest and the Vosges enter the main stream between Basel and Maxau. As shown by previous petrographic investigations, the Alsatian waste water channel supplies a considerable amount of suspended solids originating from the French potash mining industry (Goelz, 1990). Further downstream the influence of the

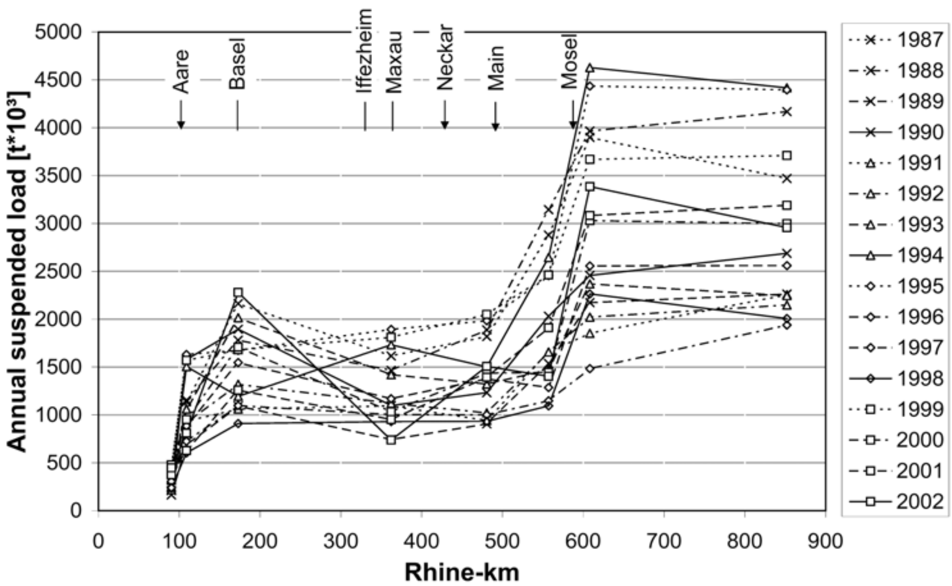


Fig. 1 Longitudinal section of the annual suspended load along the Rhine River.

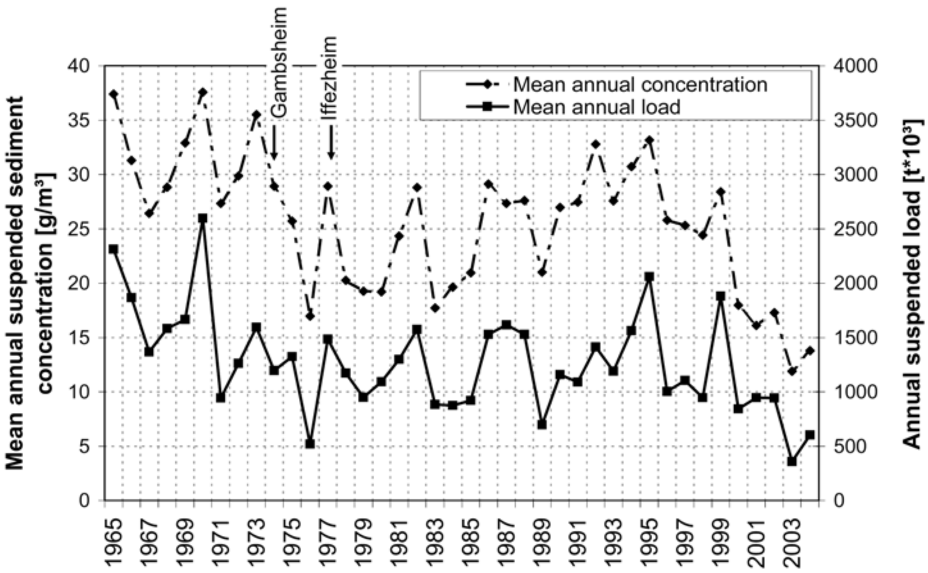


Fig. 2 Mean annual suspended load and mean annual concentration at station Maxau (Rhine-km 362.3).

River Neckar is rather modest, whereas the Rivers Main, Nahe, Lahn, and especially the Mosel cause a doubling of suspended load by about 1.5–3 Mt on average. Down to the German–Dutch border (Rhine-km 865), the suspended load remains nearly constant. It is of interest to take a closer look at the monitoring station of Maxau.

Maxau is one of the oldest stations and is located some 25 km downstream of the Iffezheim barrage. Monitoring of suspended load started in 1965, i.e. 9 and 12 years, respectively, before the barrages of Gambsheim and Iffezheim were put into operation. From Fig. 2 it is evident that both suspended sediment concentration and suspended load dropped by about 25% after the construction of the barrages. Considering the

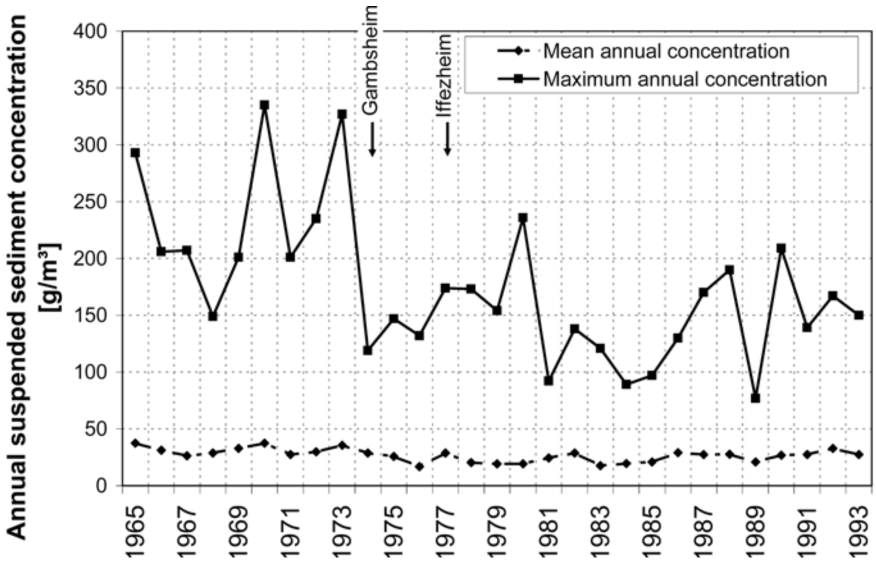


Fig. 3 Mean and maximum annual sediment concentration at station Maxau.

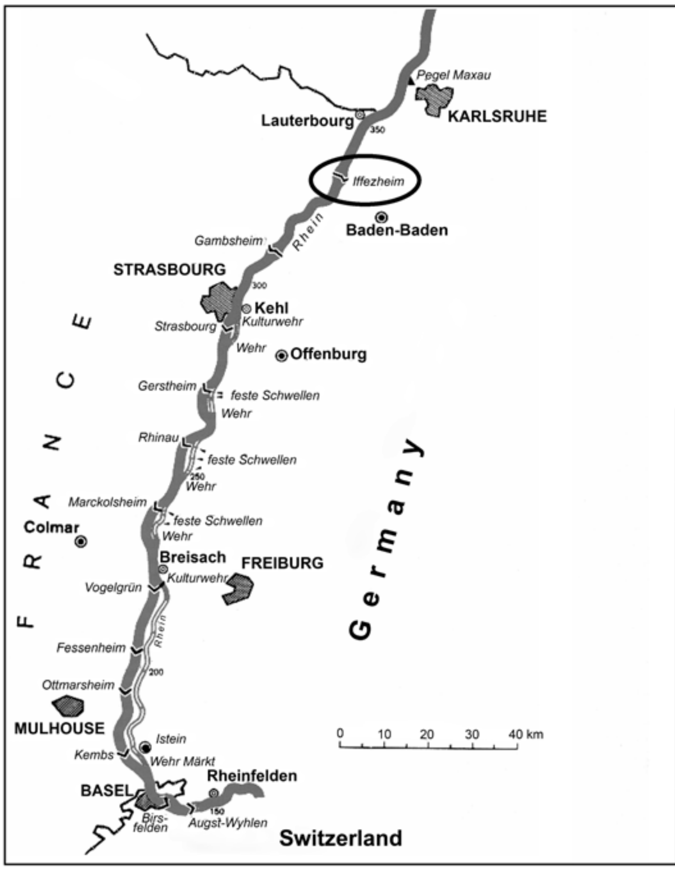
variation of the maximum suspended sediment concentration in Fig. 3, the damping effect of the two impoundments before and after closure of the dams is evident.

DREDGING AND RELOCATION OF SEDIMENTS

Dredging activities on the Upper Rhine are mainly concentrated on the sediment accumulations upstream of the weirs and on those forming in the outlet channels of the hydropower stations. Figure 4 gives an overview of the annual amounts of dredged material during the last 15 years (Ritz, 2005). Within the group of the first eight barrages, which are all situated inside canals and do not impound the main channel, the annual volume of dredged material amounted to 100 000 m^3 $year^{-1}$ in former years. Now it has been reduced to about 50 000 m^3 $year^{-1}$ by allowing a further narrowing of the cross-sections (Schittly, 2005, personal communication). About 160 000 m^3 are dredged at Iffezheim and 70 000 m^3 at Gambsheim; hence, about 85% of the total dredging volume are assigned to these two impoundments.

In the years after construction the dredging volumes of the two final barrages were considerably higher, but could be reduced by building moles in the backwater, serving on the one hand as hydraulic structures, and on the other hand as disposal sites for the dredged material. Meanwhile the capacity of these disposal sites, as well as the capacity of an additional mole in the tailwater of the Iffezheim barrage, is nearly depleted. Depending on hydrology it must be expected that every year about 150 000–200 000 m^3 of fine-grained sediment settle in the backwater of the Iffezheim barrage and have to be dredged to guarantee the safety of the dams and the discharge of floods. A further reduction of sedimentation by changing the weir operating mode was investigated, but could not be implemented because the area of sedimentation is too far away from the main hydraulic influence of the weir.

As all other dredged material handling options (e.g. treatment of dredged material, land disposal) would cost significantly more, the German Water and Navigation



Barrages "Oberrhein"	Annual dredging volume [m³/a] (1991-2004)
Kembs	5.500
Ottmarsheim	2.000
Fessenheim	2.000
Vogelgrün	6.000
Markolsheim	6.500
Rhinau	5.500
Gerstheim	5.000
Strasbourg	7.300
Gambsheim	68.000
Iffezheim	160.000

Fig. 4 Survey map of the impoundments at the Upper Rhine and annual amounts of dredged sediment between 1991 and 2004 (Ritz, 2005).

Authorities decided to relocate the dredged material downstream by flushing it through a pipeline across the barrage into the free-flowing river where the separated flows from the ship-locks, the power station and the weir channel converge (Huber & Polschinski, 2004).

From the chemical point of view, there is currently still a major problem left from the past. During the period 1960–1985, large amounts of hexachlorobenzene (HCB), released by illegal emissions, had been discharged into the Rhine. Although the main emitter of HCB has meanwhile reduced its inputs to negligible levels for many years now, HCB-contaminated sediments are still present in the impoundments and move downstream when they are resuspended by floods or mobilized by dredging operations (Koethe *et al*., 2004). Thus contamination of freshly settled sediments in the backwater of the Iffezheim barrage is the result of mixing of recent, relatively clean, suspended matter with remobilized old, contaminated sediments. The detailed transport mechanisms of the HCB load from one barrage to the next and finally to Iffezheim are very complex and are not fully understood yet.

The relocation of some 100 000 m^3 of fine grained sediments within some months has never been practised at the Rhine before, but it was clear that this measure would increase the concentration of suspended matter in the Rhine downstream of the Iffezheim barrage over many kilometres and for a long period. The river itself transports naturally some 1.2 Mt of suspended matter per year (see Fig. 1) but during flood events, some 500 000 t can be moved within only a few days, which leads to much higher concentrations of suspended sediment. Consequently, the river system and its biocoenoses are “accustomed” to high sediment discharges. Therefore, the scheduled sediment monitoring programme had to consider the situation that increased concentrations of suspended matter would prevail over months. This means that monitoring activities were concentrated, on the one hand, on the morphological responses in ecologically sensitive areas like groyne fields, side channels etc. and, on the other hand, on the dispersion of suspended solids in the river channel.

The distribution patterns of suspended solids were determined at selected cross-profiles before, during, and after the relocation operation. The influence of the relocation on sediment distribution is shown in Fig. 5 for a cross-section located some 100 m downstream of the pipeline outlet. Altogether suspended sediment concentrations were measured at 13 cross-sections between Iffezheim (km 334) and Worms (km 444) by means of sampling, turbidity measurements and Acoustic Doppler Current Profiling (ADCP). Additional information was provided by the daily records of the permanent measuring stations.

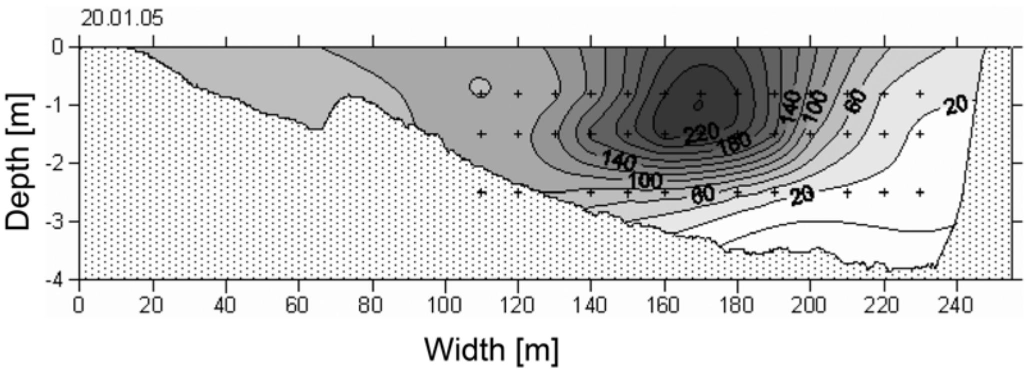


Fig. 5 Distribution of suspended material, g m^{-3}, in a cross section downstream of the relocation site.

The longitudinal section of Fig. 6 shows the range of cross-sectional averaged suspended sediment concentrations, measured during the relocation phase, in comparison to the long-term average concentration for similar discharge situations at roughly 1000 $m^3 s^{-1}$. Close to the relocation point, the concentration varies considerably due to changes of the flushing mode and to variations of discharge. Further downstream dispersion effects contribute to homogeneity and the variation of concentration becomes smaller.

The strong decline of suspended sediment concentration within the first 20–30 km cannot be ascribed to dispersion and dilution effects but must be explained by temporary deposition because suspended sediment loads decrease by the same range. Concerning the fine grained nature of the relocated material and the high flow velocity of the Upper Rhine, the risk of settling of large amounts of sediment in the channel can be excluded, but it was expected that suspended solids might drift into groyne fields, bayous, harbour basins etc. Sediment sampling subsequent to the relocation measure

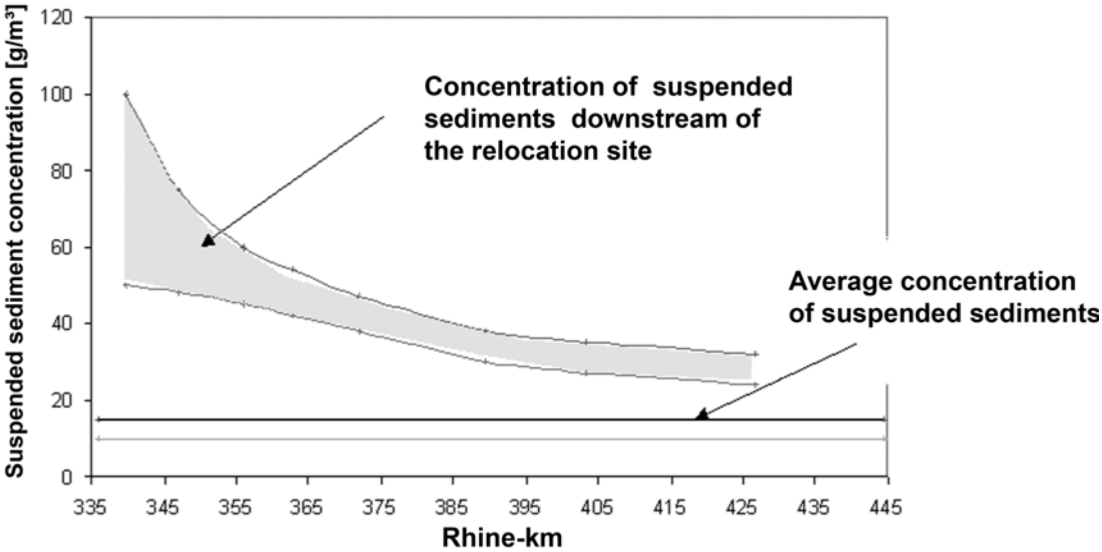


Fig. 6 Longitudinal distribution of mean suspended sediment concentration (g m^{-3}) downstream of the relocation site.

confirmed that most of the fine sediment, which had been temporarily stored in such areas, was resuspended again by increasing discharge and transported further downstream. The temporal resolution of the turbidity records enabled calculation of the propagation velocity of distinct turbidity peaks and lead to approx. 4 km h^{-1} as the characteristic transport velocity for suspended sediment at discharges lower than the long-term mean discharge (*MQ*). This is in good agreement with the flow velocities determined by Van Mazijk (1996) by using a dye tracer ten years ago.

FLOOD EVENT OF AUGUST 2005

The extreme rainfall in the Swiss Alps during 19–22 August 2005 and the associated heavy soil erosion induced a very strong increase of suspended sediment concentration in the tributaries, in the lakes but also in the main river. The concentration measured on 23 August at the station of Weil/Basel amounted to 2689 mg L^{-1}, which was the highest concentration ever measured there since the beginning of records in 1973. With the aid of the records of the permanent measuring stations along the Rhine and some supplementary recordings from turbidity sensors, the propagation of the turbidity peaks could be followed from Lake Constance down to the Dutch border. Between Weil/Basel and Koblenz the mean velocity of the suspended sediment wave was 6 km h^{-1} both within the impounded upper reach and in the subsequent free-flowing section. The flood wave with the highest discharge of around 3000 m^3 s^{-1} (at Weil/Basel slightly greater and at Koblenz slightly less, see Fig. 8) propagated with the same velocity of approx. 6 km h^{-1} downstream but the centroid of the turbidity cloud lagged typically some hours behind the discharge peak. The peak sediment concentration decreased within a few days, whereas the decline of the discharge took more than one week.

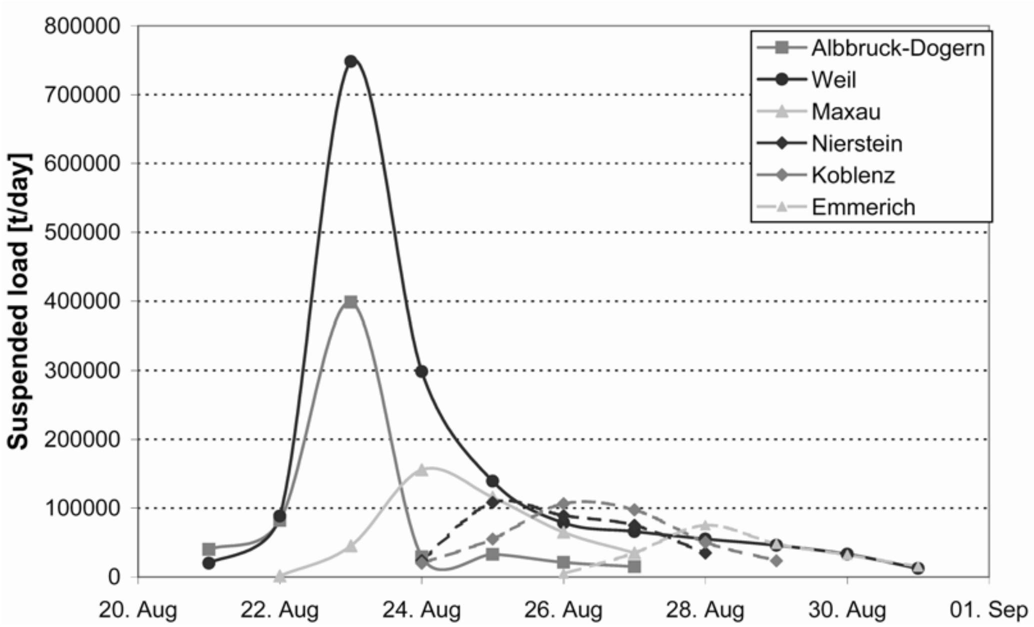


Fig. 7 Suspended load at the permanent monitoring stations during the flood event of August 2005.

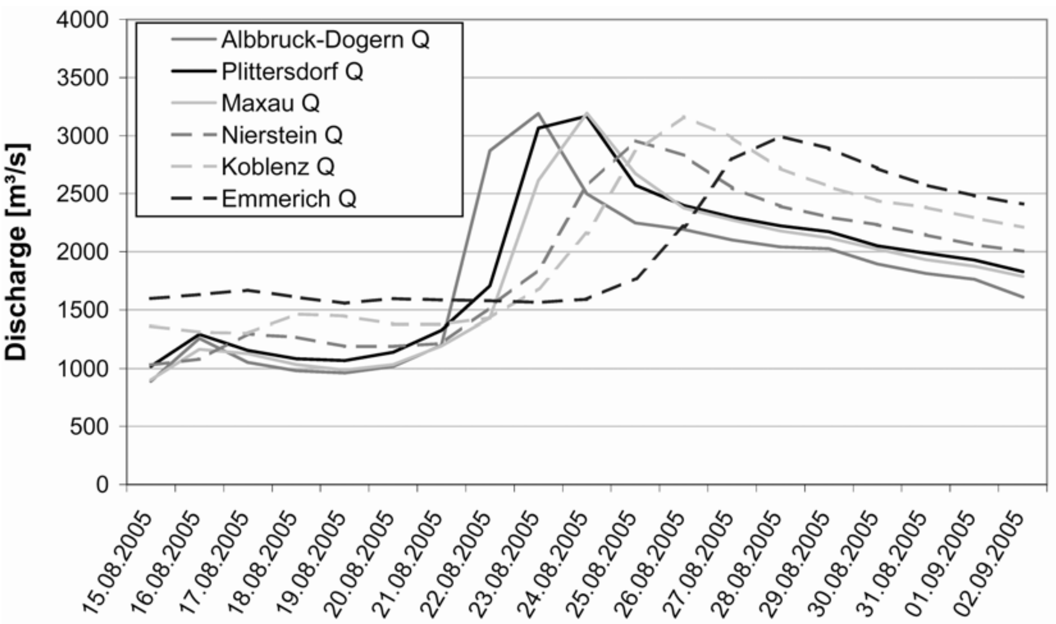


Fig. 8 Discharge at the monitoring stations during the flood event of August 2005.

The extreme precipitation event was due to a so-called Vb weather situation (Schmid *et al*., 2005). Aside from the discussion whether the more frequent appearance of such weather conditions is a consequence of climatic change, there is no doubt that the short but extreme event caused an extreme input of suspended sediment into the river system. Besides Weil/Basel, another two permanent monitoring stations recorded maximum values of turbidity or sediment concentration, respectively. Since sampling at some stations is discontinued on Saturday and Sunday, the graph in Fig. 7 contains curves that are partly fitted in order to give an overall impression of the suspended sediment transport in the Rhine River between Switzerland and the Netherlands during the August 2005 event.

A large amount of sediment must have disappeared in the impounded section of the Upper Rhine, as the deficit between the stations of Weil/Basel and Maxau amounts to about 1 Mt of suspended sediment. It is not plausible that this mass has been deposited in the impoundments alone, in fact part of the sediment load might have been stored in the so-called "Restrhein", on the flood plain and the accompanying bayou system. Downstream of the impounded sections the suspended load decreases further. At first sight this seems surprising, because normally the suspended load increases significantly on its way down to the Netherlands (see Fig. 1). However, in this special case, none of the numerous tributaries to the Rhine downstream of Basel offered either noticeable additional discharge or an appreciable sediment input. A kind of "frozen" sediment wave moved downstream with a quasi-steady profile and with a maximum discharge peak being only slightly reduced.

CONCLUSIONS

The permanent monitoring stations for suspended load provide an important database for the understanding of suspended sediment transport and sedimentation processes along the Rhine River. From the analysis of the prominent flood event of August 2005 it is concluded that sedimentation in the impounded reach is related to high discharge events rather than to mean or low discharge conditions. This is indicated by the strong reduction of suspended sediment load when the flood wave passes the impounded section. Although at flood stage part of the suspended load enters the "Restrhein" and might be stored on the flood plain and in the accompanying bayou system, considerable amounts of sediment are deposited in the impoundments of Gambsheim and Iffezheim. Both the long-term records at Maxau and the dredging statistics substantiate that the backwaters of the barrages Gambsheim, and especially Iffezheim, are important sediment traps, which considerably reduce the suspended load in the subsequent free-flowing section. Looking at the potential influence of climate change on sedimentation, it has to be considered that global climate change affects the frequency and intensity of extreme events (Kempe & Krahe, 2005). Given that precipitation events such as that of August 2005 will occur more frequently in future, the rate of sedimentation in the impounded section of the Upper Rhine might increase considerably, necessitating enhanced dredging activities in the backwaters of the Iffezheim and Gambsheim barrages.

To secure high flood discharge and the stability of the dykes in the impounded section of the Upper Rhine, about 200 000 t of fine grained sediments have to be dredged and relocated every year. Because of the contamination of the dredged material, relocation within the channel is problematic and has already caused some political disturbances. Monitoring of suspended sediment transport during the relocation of 100 000 m^3 of fine grained sediments from the backwater of the Iffezheim barrage into the free-flowing river proved that, despite the temporary storing of sediments in groyne fields and side channels, no permanent silting affected the riverine ecosystem.

To increase knowledge about transfer, storing, remobilization and mixing of sediments along the chain of impoundments, especially in the backwaters of the Gambsheim and Iffezheim barrages, two additional measuring stations for suspended sediment should be installed between Basel and Maxau. Furthermore, the passage of suspended sediments during high floods has to be studied in detail and connected with the results of the chemical monitoring and echo-soundings carried out before and after the floods. Together with the data of the dredging and dumping activities, it should be possible to establish a detailed sediment balance of the impounded section, which serves as the basis for improved sediment management along the southern Upper Rhine.

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