COMPREHENSIVE ASSESSMENT OF CONTAMINATED FLUVIAL SEDIMENTS – EROSION RISK AND ECOLOGICAL HAZARD

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ABSTRACT

A comprehensive assessment of contaminated aquatic sediments has to consider both sediment hydraulics and ecology. Since layers of contaminated sediments are often buried under less polluted deposits, the risk of erosion and the potential ecological impact have to be evaluated down to sediment depths of 1 m or more. In this paper, a strategy is presented that meets these requirements. This strategy comprises techniques of sediment sampling, non-intrusive density profiling, erosion measurement with depth and ecological assessment of sediments. Application of the proposed strategy to the Lauffen reservoir (River Neckar, Germany) indicates that there is a substantial risk for contaminated reservoir sediments to be eroded and transported downstream. The proposed strategy could serve as a powerful tool to assess hot spots of sediment contamination with respect to the need and urgency of remedial actions.

Keywords: contaminated sediments, risk assessment, erosion, ecological impact

INTRODUCTION

In the past, great quantities of pollutants were discharged into North American and Central European inland waters. Many of the emitted contaminants, such as trace metals and several organic micropollutants, predominantly sorbed to fine-grained particulate matter. The particles and the associated contaminants were deposited in regions of low turbulence. This led to the formation of highly polluted bottom sediments in harbors, groin fields and river reservoirs. In recent years, the emission of pollutants has been reduced drastically. As a consequence, the older contaminated sediments are, at present, frequently buried under less polluted younger deposits. Many sorbed contaminants are largely immobile within the anoxic sedimentary deposits. Hence, the polluted deposits often do not directly affect river water quality. However, the possible erosion and downstream transport of these contaminated sediments during major flood events could have a tremendous, long lasting negative impact on the fluvial ecosystem and the adjacent floodplains. Therefore, a comprehensive risk assessment of contaminated fluvial sediments has to consider both sediment hydraulics and the ecological risk. The objective of the present paper is, to lay out a strategy for such a comprehensive assessment of contaminated sediments. The proposed strategy will be applied to evaluate the risk arising from heavily polluted sediments in the Lauffen reservoir on the Neckar River in south-west Germany.

METHODOLOGY

Figure 1 gives a schematic overview of the proposed strategy. Its major feature is the parallel assessment of: (1) the erosion risk and (2) the potential ecological impact of the polluted sediments. Although contaminated deposits are frequently buried underneath unpolluted sediments, they can be reactivated during major flood events. Therefore, erodibility and sediment quality should be measured with sediment depth.

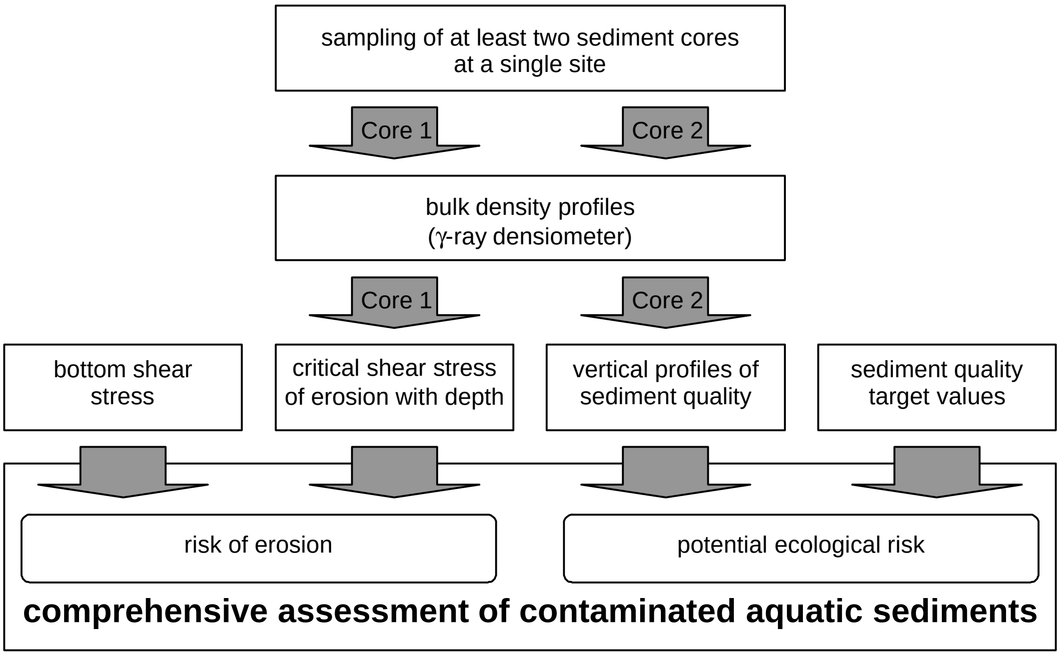

Fig. 1: Schematic of the assessment strategy.

SAMPLING

The strategy requires that at least two sediment cores are taken within close proximity to each other at each sampling site. Almost undisturbed sediment cores are obtained with cylindrical coring tubes - 1.5 m in length and 13.5 cm in diameter. The coring tubes are attached to poles of variable length, and then carefully pushed into the sediment bed from aboard a boat. In deeper waters divers can do the coring underwater. Immediately after retrieving a core, the bottom of the tube is sealed with a piston, that later serves to move the sediment material within the tube.

DENSITY PROFILING

River sediments are often very heterogeneous, with differences in layering and texture even on a small spatial scale. The bulk density of sedimentary deposits is mainly a function of the pore volume, and hence, of the material's grain size and its state of consolidation. Comparison of vertical density profiles of sediment cores taken at the same sampling site, therefore, allows to check whether the sedimentological layering within the sediment cores is similar. If this is the case, the results gained for one of the cores are also valid for the other one. In addition, the density profiles help to identify sections of relatively uniform grain size distribution within a core. Vertical profiles of bulk density of both cores are measured non-intrusively with a gamma-ray densiometer. The measurement is based on the attenuation of gamma rays passing the sediment in the sampling tubes. The magnitude of attenuation depends on the bulk density of the material passed. By vertically moving the densiometer along the sediment cores, bulk density profiles with a spatial resolution of less than 1 cm can be gained. For details on theory and application of the device see Dreher (1997).

RISK OF EROSION

Assessing the erosion risk requires knowledge of both the bottom shear stress in the river and the critical shear stress of sediment erosion. The bottom shear stresses in rivers can be determined numerically or experimentally, e.g. from velocity profiles. Looking at sediment contamination one usually is concerned with fine-grained, cohesive sediments. At present, for the erosion properties of these cohesive sediments no quantitative theory of universal validity exists. Therefore, their erosion behavior has to be determined experimentally. Using core 1, the critical shear stress of mass erosion is measured as a function of sediment depth with the SETEG-system. SETEG is a straight rectangular pressure duct, which allows to measure erosion of almost undisturbed sediments at shear stresses of up to 10 N m^{-2}. For details about the flume and its application see Kern et al. (in press). Comparison of bottom shear stresses in the river with the experimentally determined critical shear stresses of erosion allows to evaluate whether the sediments could be eroded. The erosion risk further depends on the frequency and duration of bottom shear stress exceeding the critical shear stress of erosion.

ECOLOGICAL RISK

To evaluate sediment quality with depth, core 2 is cut into sections. Almost uniformly textured sections are obtained, by cutting the core at depths of significant density changes. There are several different ways to assess sediment quality. The choice of an adequate method depends on the specific objective of the investigation. The sediment quality can be characterized by contaminant concentrations. Prior to the analysis of trace metals and organic micropollutants, coarse-grained material must be removed, to account for the grain size effect. In addition to determining contaminant concentrations, it is important to assess their bioavailability and toxicity under the chemical conditions in place, and in case of resuspension. The overall ecological impact of all sediment associated contaminants can be examined with bioassays; the effects of sediment resuspension by chemical and ecotoxicological analyses of sediment elutriates. The ecological risk is assessed by comparing the results of chemical analyses and bioassays with geochemical background concentrations and target values for sediment quality.

CASE STUDY: LAUFFEN RESERVOIR, RIVER NECKAR

STUDY SITE

The Lauffen reservoir is situated in the lock-regulated section of the River Neckar, just downstream of the confluence with the River Enz. Sediment pollution was mainly caused by a dye factory, that released great quantities of Cd into the River Enz until the mid 1970's. In subsequent years, a drastic reduction of heavy metal discharge led to a considerable improvement of sediment quality in upper sediment layers. Earlier investigations found a sudden increase of heavy metal concentrations with depth, separating younger deposits from older, highly polluted ones. However, this concentration leap appeared in different depths, and at some sites could not be detected at all [Kern & Westrich 1995]. Laboratory studies showed, that resuspension of contaminated sediments results in a chemical labilization or even the release of Cd. Accordingly, elutriates of buried sediments were found to be highly toxic. In the long term, sedimentation and erosion within the reservoir have been more or less in balance since the late 1970's. However, as was shown by echo sounding surveys, extreme flood events resulted in erosion depths of up to 70 cm [Kern & Westrich 1997]. An increase of flood probability, which is presently discussed as a possible consequence of climate change, may enhance sediment erosion. Hence, the question arises whether the old contaminated sediments now localized within Lauffen reservoir could be exposed, eroded and transported downstream. Therefore, we applied the strategy proposed above. In this investigation the aspect of erosion risk was emphasized, because sediment quality had already been investigated in detail.

RESULTS AND DISCUSSION

A total of 13 sediment cores from 5 different sampling sites within the Lauffen reservoir have been investigated. The measured density profiles indicate, that there is an immense spatial variability in the stratigraphic layering of the sediments. However, cores sampled at the same site show a similar layering, and thus, can be regarded as locally representative. 5 cores have been used to determine the critical shear stress of mass erosion ($\tau_{c,e}$) with depth. The experiments yielded a total of 150 values for $\tau_{c,e}$, ranging from 0.6 to 9.5 N m^{-2}. Trace metal concentrations in the grain size fraction < 20 µm have been analyzed as a function of depth in 4 cores. The results highlight the remarkable heterogeneity of metal pollution in the reservoir sediments. For example, in a total of 94 subsamples the Cd concentration varied from 0.8 to 105 mg kg^{-1}. In two of the investigated cores already the uppermost sections were highly contaminated. The other two cores did not reveal any significant heavy metal enrichment down to the sampling depths of 74 and 88 cm. This indicates, that contaminated sediments are located close to the sediment surface at some sites, whereas they are deeply buried beneath less contaminated deposits at other sites.

The results will be further illustrated using the data gained from a total of 5 sediment cores, all taken at the same sampling site at Neckar km 126.1. Vertical profiles of bulk density indicate, that the sedimentological layering of all 5 cores is similar (fig. 2A). Hence, the results gained for one of the cores are generally valid for the others, too. Higher bulk densities in the uppermost layer and below 80 cm can be attributed to a particle size effect (fig. 2A and 2B). The increasing bulk density between 20 and 50 cm rather seems to be due to sediment consolidation. The $\tau_{c,e}$- values are generally increasing with sediment depth (fig. 2C). However, this general tendency is overlapped by a high local variability of $\tau_{c,e}$. Sudden changes in $\tau_{c,e}$ are especially frequent between 20 and 50 cm. This is the region where also random changes in bulk density were measured. It is likely that the ongoing compaction of the sediments caused the local trapping of upward moving water and gas in this section. Trapped gas bubbles may result in sudden changes of bulk density and erosion stability.

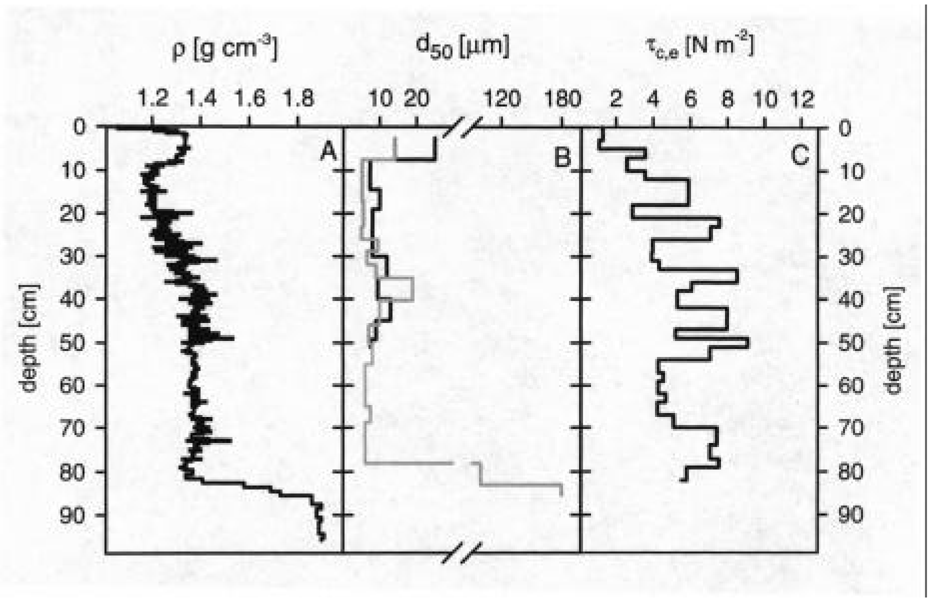

Fig. 2: Vertical profiles of: The range of bulk densities (5 cores, A); median grain size (B) and critical shear stress of mass erosion (C) for sediment cores from km 126.1.

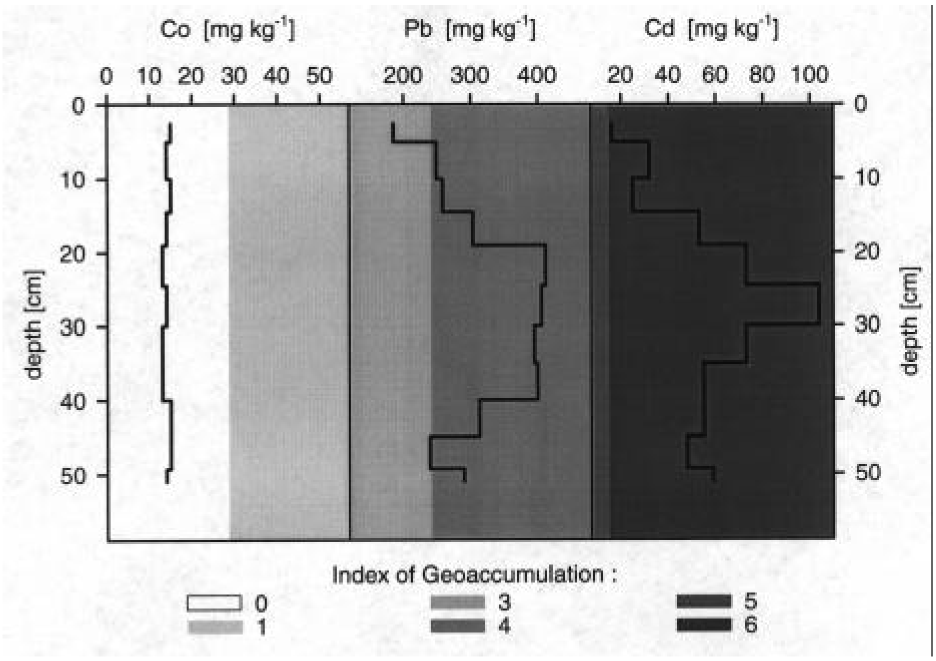

Fig. 3: Vertical concentration profiles of Co, Pb and Cd in the < 20 µm grain size fraction at km 126.1.

Figure 3 shows vertical concentration profiles of Co, which mainly originates from natural sources, and of the two anthropogenic heavy metals Cd and Pb. Co concentrations are in the range of the natural background and barely vary with depth. This clearly demonstrates the successful elimination of the grain size effect and the high quality of the analyses. In contrast, the concentrations of the anthropogenic heavy metals are highly variable. Maximum concentration of Cd is 105 mg kg^{-1}, and thus 350 times higher than the natural background value of 0.3 mg kg^{-1}. According to the “Index of Geoaccumulation” (e.g. Salomons & Förstner 1984), all subsamples can be classified as highly polluted with Cd. Pb concentrations reach a maximum of 412 mg kg^{-1}, which is about 20 times higher than the geochemical background of 20 mg kg^{-1}.

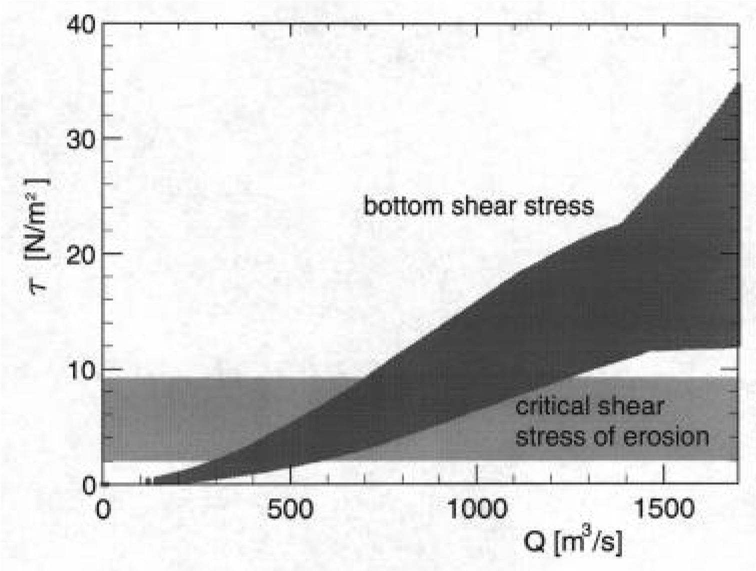

Fig. 4: Range of experimentally determined critical shear stress of mass erosion and range of bottom shear stress in Lauffen reservoir as a function of discharge.

To asses the risk of erosion, the range of measured $\tau_{c,e}$-values is compared with the range of bottom shear stresses (τ_0) present in the Lauffen reservoir (fig. 4). The bottom shear stress was determined with a numerical flow model. Figure 4 indicates, that up to a discharge of approximately 400 m^3 s^{-1}, which is five times the mean discharge of 80 m^3 s^{-1} at Lauffen, no erosion takes place. With discharge rising above 400 m^3 s^{-1} erosion starts. At discharges higher than 1100 m^3 s^{-1}, which corresponds to a flood with a return period of 5 years, all sediments can be eroded.

Based on the overall results, it can be stated that highly contaminated and supposedly toxic sediments are present close to the sediment surface, at least at some sites. Even though these sediments are old and well consolidated, they can be eroded during major flood events. However, other investigations have shown that the contaminated sediments within Lauffen reservoir are commonly buried in sediment depths of 20 to 100 cm. Whether these buried contaminated sediments will be eroded in the near future, strongly depends on the frequency of flood events.

CONCLUSIONS

Highly contaminated bottom sediments, that were often formed decades ago comprise a potential risk for the aquatic ecosystem. A sustainable water quality management thus requires the assessment of this environmental risk, to evaluate the need of remedial actions. However, for an adequate risk assessment of contaminated sediments both the risk of erosion and the potential ecological impact have to be evaluated. The strategy developed in this paper allows to consider sediment hydraulics and ecology. Hence, the proposed strategy can be used to comprehensively assess hot spots of sedimentary contamination. The results could lead to a classification of these hot spots with respect to the need and urgency of remedial actions.

ACKNOWLEDGEMENTS

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REFERENCES

Dreher, Th. (1997): Non Intrusive Measurement of Particle Concentration and Experimental Characterization of Sedimentation. Universität Stuttgart. Sonderforschungsbereich 404, Bericht 97/34.

Kern, U., Haag, I., Schürlein, V., Holzwarth, M., Westrich, B.: Ein Strömungskanal zur Ermittlung der tiefenabhängigen Erosionsstabilität von Gewässersedimenten: das SETEG-System. Wasserwirtschaft, in press (in German).

Kern, U., Westrich, B. (1995): Sediment Contamination by Heavy Metals in a Lock-Regulated Section of the River Neckar. Mar. Freshwater Res., 46, 101 – 106.

Kern, U., Westrich, B. (1997): Sediment Budget Analysis for River Reservoirs. Water, Air and Soil Poll., 99, 105 – 112.

Salomons, W., Förster, U. (1984): Metals in the Hydrocycle. Springer Verlag, Berlin.