

The Feature

Historical Contaminated Sediments and Soils at the River Basin Scale Examples from the Elbe River Catchment Area

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Abstract

Background, Aims, and Scope. Data from the Elbe River and its tributaries indicate, despite extensive improvement in water quality during the last 15 years, that the respective sediment situation of many priority pollutants has not reached an acceptable level. For the coming decades, risks for downstream sites and stakeholders will persist, mainly due to secondary sources originating from historical pollution of soils and sediments in the catchment area. In practice, a catchment-wide assessment of historical contaminated soil and sediment should apply a three-step approach: (i) Identification of substances of concern (s.o.c.) and their classification into 'hazard classes of compounds'; (ii) identification of areas of concern (a.o.c.) and their classification into 'hazard classes of sites'; (iii) identification of areas of risk (a.o.r.) and their assessment relative to each other with regard to the probability of polluting the sediments in the downstream reaches. The conversion of this concept has to consider the underlying philosophy of the EU Water Framework Directive, particularly with respect to the analysis and monitoring of priority substances in solid matrices. However, major deficiencies are still in the assessment and prognosis of resuspension processes, and potential approaches to fill this gap are described both in theory and from examples of the Elbe River.

Methods. The sediment stability testing facilities consist of a unique triple set developed by innovative experimental laboratory and field research. The instrumental facilities consisting of a tube corer and a pressurized channel allow one to measure not only the onset of erosion (critical bed shear stress), but also the erosion rate for different sediment layers. Undisturbed sediment samples were taken from contaminated sites, e.g. in near-bank groyne fields and floodplains, using (i) core sampler (diameter 14 cm, length 150 cm) for sediment erodibility depth profiling and (ii) box sampler (30*70 cm² top view area, 28 cm depth) for comparing and upscaling the results from the laboratory to the field. Sediment properties such as grain size spectrum (laser beam attenuation), water and gas content were analyzed by a non-intrusive, high frequency, capacity measurement method and bulk density by γ -ray.

Results and Discussion. Sediment core samples from flooded areas in the Middle Elbe indicate, that, except from the uppermost 5 cm and at a depth of from 47 to 48 cm, where the critical shear stress is very low (0.5 Pa), the critical bottom shear stress is between 1.2 Pa and 3.4 Pa, i.e. at a moderate level. Major reasons for the distinct heterogeneity of the erosion stability are differences in consolidation processes, grain size distribution and in the composition of stabilizing exudates in the individual sediment layers. Similar to the erosion stability depth profile, the metal data exhibit short-range heterogeneities; the variations in the individual layers can be explained by different proportions of fine grained components and by an improvement of suspended matter quality in the course of time.

A comparison of the metal contents of embanked alluvial soils and unembanked alluvial areas suggests the following causal chain: Recent floodplain areas at low mean water levels exhibiting high concentrations of organic carbon represent the most highly contaminated sites. On the other hand, insignificant pollution has occurred on alluvial areas, which were embanked already at pre-industrial times. In the case of flood events, due to the combination of flooding probability and flow conditions, the most favorable conditions for the deposition of nutrient- and contaminant-rich suspended particulate matter are found in the low level depressions with low current.

Within a typical river section of 1 km length in the lower middle Elbe, the groyne fields are recognized as dominant, slack-water zones containing the following nutrient and trace metal loads (reference year 2001, anthropogenic proportions): 287 t organic carbon, 17.6 t phosphorous, 17.4 t nitrogen, and 16.7 t sulfur; 8.6 t zinc, 1.1 t copper, 0.9 t lead, 0.4 t chromium, and 0.2 t nickel, respectively. The estimated nutrient and pollutant loads, deposited on the floodplains and in the river course, clearly demonstrate the specific sink function of both sites. At the same time, however, the results suggest, in contrast to the deposits in the floodplains, that sediments within the river course may partly be remobilized. This means that the long-term sink function can at least temporarily become a significant source character, involving the hazard of a substantial deterioration of the downstream sections of the river basin.

Conclusions and Outlook. In view of the findings of relative low erosion stabilities of groyne field sediments and, in particular, after the extreme Elbe flood from August 2002, a prime question relates to the remobilization risks of these sediments typically enriched in contaminants and nutrients. The combined view on substances, areas and processes of concern in the Elbe catchment – with special emphasis on historical contamination of floodplain soils and sediments, as well as on groyne field sediments, as significant secondary sources of pollution – is a typical example for the holistic river basin approach of the European Water Framework Directive (WFD), both with respect to assessment of ecological risks and the development of remediation measures. In the latter respect, recent developments in 'soft' (geochemical and biological) techniques on contaminated soils and sediments, both with respect to policy aspects as well as to technical developments have led to a stimulation of in-situ remediation options, such as sub-aqueous depots, active capping, and application of natural attenuation processes. Limited financial resources require a direction of investments to those sites with the highest efficiencies in risk reduction. Establishing a rough sediment dynamic model, building on tributary/Elbe dilution factors, sedimentation data, suspended particulate matter monitoring data as well as calculations of long-term costs and benefits, based on risk management, could be essential steps in a basin wide river management.

Keywords: Catchment area; dredged material; erosion stability; floodplain; groyne field; heavy metals; hydraulic processes; monitoring; natural attenuation; priority substances; remobilization; resuspension; risk assessment; secondary sources; sediment management; Water Framework Directive (EU-WFD)

1 Introduction

Sediments and soils function as sinks for ongoing releases from many sources; these include wet and dry fallout from air emissions, runoff from farms, solid and dissolved inputs from mines, discharges from landfills, industrial plants, and sewage-treatment plants. Therefore, even if water quality improves, sediment and floodplain soil contamination will remain a 'legacy of the past'.

The owners of large 'sediment traps', such as the big ports, mostly at the end of navigable rivers, are put at a disadvantage as they have to pay the expenses of all former, actual and future shortcomings in emission control within their entire catchment areas. Therefore, it is a matter of 'hydro solidarity' – as Salomons (2004) has called it – "to achieve a full upstream/downstream integration of monitoring, stakeholder consultation, models and expert systems that can link basin pressures to transfers, across various administrative and/or political boundaries, and between the various land users, water users and other stakeholders." With regard to the complex problem of historical contaminated sediments and soils at the catchment scale, scientists and engineers can contribute to integration process in three ways:

- Sediment and soil should be managed together. Soil-specific research issues relate to the fate of sediment-associated contaminants when sediment is deposited upland and a better understanding of the impact on ground water, water and soil ecosystems; long-term, integrated research to determine the sediment transport process at the river basin scale has to consider land and water use and hydrological (climate) change (Brils et al. 2004). Soils and sediments are composed of essentially the same matrices, they receive similar pollutant inputs, major interactive processes between dissolved and solid constituents may just differ in intensity (Förstner 2002), and quality criteria assessment for soils and sediments become closer when these protocols are increasingly based on biological information (Ahlf et al. 2002a).
- Characteristic dynamic features of sediment-related processes in rivers include dramatic effects of storm water events on particle transport, rapid and far-reaching effects of sulfide oxidation during resuspension, and biological accumulation and potential release of toxic chemicals. Both for establishing sediment-related quality objectives and for developing and implementing technical problem solutions a set of practical process knowledge is needed that uses a wide range of simulation techniques as well as models in different spatial and temporal scales (e.g. SEDYMO-Project; Förstner 2004a). Hydraulic processes form the primary input factors for the large-scale dispersion of historical contaminated sediments. Unlike problems related to conventional polluted sites, the risks here are primarily connected with the depositing of contaminated solids on soils in downstream regions. Therefore, sediment physical parameters and techniques form the basis for any risk assessment in this field. In addition, sediment quality approaches should include experimental designs for the study of chemical and biological effects during erosion and deposition¹.

¹ Apart from the risk in terms of its impact downstream, there is the in-situ risk of sediments, e.g. as substrates for benthic communities and, for example, fish fry in situ.

- A basin-scale framework for sediment management should be comprised of two principal levels of decision-making: the first for basin-scale evaluation (site prioritization) and the second for site-specific assessment (risk ranking; Apitz and White 2003). Prioritization, among others, needs the development of appropriate indicators for sediment mobility at a catchment scale and determination of the sediment dynamics and budget in a river (Heise et al. 2003; Babut et al. 2005). In practice, a catchment-wide assessment of historical contaminated soil and sediment should apply a three-step approach (Heise et al. 2004): (i) Identification of substances of concern (s.o.c.) and their classification into 'hazard classes of compounds'; (ii) identification of areas of concern (a.o.c.) and their classification into 'hazard classes of sites'; (iii) identification of areas of risk through consideration of erosion and transport processes (a.o.r.) and their assessment relative to each other with regard to the probability of polluting the sediments in the downstream reaches.

The conversion of the latter concept has to consider the philosophy of the EU Water Framework Directive (WFD), particularly with respect to the analysis and monitoring of priority substances in solid matrices (Section 2). Assessment and prognosis of resuspension processes, and their effects on the dispersion of particle-associated contaminants, is beyond the scope of the official WFD monitoring programs (Article 8, implementation until 2006); a pragmatic approach for estimating flood-derived inputs of suspended particulate matter will be presented in Section 3.

In the following section, Section 4, the 'three-step approach' with special emphasis on 'erosion stability' and 'secondary sources of contaminants' is described from examples of the Elbe River and its main tributaries. The Elbe basin comprises characteristic point sources such as the mining districts of Thuringia and Saxony as well as other areas of concern for the resuspension of historical contaminations like damming stages in the Czech Republic, and in the lowland area of the Elbe River in Germany, the groyne fields and the large-scale flood plains. The latter two represent typical features in the middle section of the Elbe River and an in-depth knowledge of the combined geochemical and hydraulic processes in these areas is the key for the sustainable sediment management (SSM, Anonymous 2004a), both with respect to the measures within the catchment area (Section 5) and for the management of dredged material in Hamburg harbor (Section 6).

2 Sediment Quality Assessment at the Catchment Scale

The Conceptual Basin Model for risk assessment, as presented by Apitz and White (2003), balances the mass flow of particles and contaminants, screening level assessment of sediment quality data, and base-scale objectives, e.g. for source control (local historical, remote historical, active point sources, quasi-diffuse sources, non-point sources). However, no indication has been given so far concerning what type of measurements is needed and how to combine the various sets of quality and quantity data. This section refers to actual discussion of the advisory group for the implementation of the Water Framework Directive (WFD), in particular with respect to the definition of sources for priority substances and the needs for analytical quality control, both related to sediments.

2.1 Definition of sources for priority (hazardous) substances

Risk due to erosion of contaminated sediments and their potential impacts downstream and subsequently in deltaic and coastal regions is not covered by existing regulations. Existing regulations are focused on local impacts of the re-location of contaminated sediments and do not take the whole catchment into account. On the other hand, the WFD, which focuses on the catchment scale, does not explicitly mention sediments nor sediment quality and quantity. However, the strategies against chemical pollution of surface waters (WFD article 16), i.e. implementation of monitoring programs until 2006 and establishment of the program of measures until 2009, have to consider sediment quality at the catchment scale. With respect to the latter date, already the first step – screening of all generic sources that can result in releases of priority substances and priority hazardous substances – will include the specific source/pathway 'historical pollution from sediment'.

In the process of implementing emission control of priority substances, some key terms – discharges, emissions, installations, and losses – are defined in article 2 WFD. For example, the 'emission limit values' for substances shall normally apply at the point where the emissions leave the installation, dilution being disregarded when determining them. The term 'sources' is not defined in article 2 of the WFD, but, with regard to indirect releases into the water, 'losses' could include any intentional or unintentional release or transfer of priority substances, other than discharges, emissions or the result of accidents, directly or indirectly into surface waters as defined under Article 2(1) of Directive 2000/60/EC.

2.2 Types and quality of chemical sediment data

In the framework of an integrated, decision-making process, a systematic approach is needed starting with a critical examination to establish whether environmental measurements provide a suitable basis for monitoring and other assessment strategies. From a practical view, three categories of risk assessment for contaminated sediments can be distinguished:

- Memory effect, mainly in dated sediment cores from lakes, reservoirs and marine basins, as historical records reflecting variations of pollution intensities in a catchment area.
- Life support, i.e. sediment as ecological, social and economic value, as an essential part of the aquatic ecosystem by forming a variety of habitats and environments. A system approach is needed comprising biotests and effect-integrating measurements due to the inefficiency of chemical analysis in the assessment of complex contamination.
- Secondary source, mobilization of contaminated particles and release of contaminants after natural or artificial resuspension of sediments.

In the decision-making process, *memory effects* are applied both on source material, e.g. historically contaminated sediment areas, and target sediments, i.e. for the assessment of concentration trends for critical substances, for example in harbor sediments. *Ecological effects* are assessed or estimated from the target sediments. *Resuspension effects* are estimated

from source materials and this information forms the input term for the transport calculations, which will eventually lead to a prognosis of both mass deposition rates and trends of pollutant concentration in downstream reaches, e.g. harbors and coastal areas.

With regard of the application of chemical sediment data, major problem areas have been identified and discussed by the European thematic framework 'Metropolis' (Metrology in Support of Precautionary Sciences and Sustainable Development Policies; Anon. 2004b), e.g. lack of harmonization of the procedures applied by laboratories, lack of representativeness and a lack of 'traceability': The latter concept implies that measurement data are linked to stated references through an unbroken chain of comparison, all with stated uncertainties (Quevauviller 2004).

2.2.1 Surveillance investigations and monitoring

The schematic overview in Fig. 1 indicates, for *surveillance investigations*, that a basic sequence of measurements consists of three steps, which can be considered as an unbroken chain of comparison, i.e. either reference materials (RM) are applied or standardized, well-documented procedures (Doc).

Sediment monitoring and, in particular, the assessment of bioavailability, is still based on less well-documented procedures (except for sequential extraction of heavy metals and phosphorous in sediments, where certified reference materials can be applied; Quevauviller 2002). In the implementation of monitoring programs in the Water Framework Directive (WFD Article 8, 2006), 'whole water' analyses were selected as the only relevant matrix for compliance checking of the environmental quality standard (EQS) for priority substances other than metals. However, as recommended by the Scientific Committee on Toxicity, Ecotoxicity and Environment (CSTEE plenary meeting of 28 May 2004) monitoring programs for lipophilic substances should be focused on biota and possibly on sediment. As the number of chemicals selected as priority substances is very limited, the CSTEE strongly recommend producing the required ecotoxicological information for supporting sound quality standards at least for these substances.

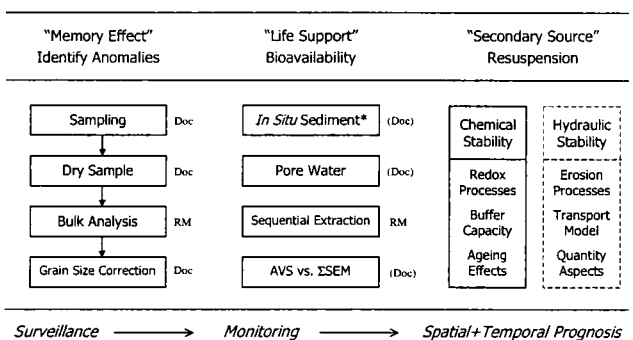


Fig. 1: Schematic overview on traceability aspects of chemical sediment analysis (for details see Förstner 2004b). RM = Reference Material; Doc = Documented Procedure; AVS/ΣSEM = Acid Volatile Sulfide/Sum of Simultaneously Extractable Metals (DiToro et al. 1990); *Wet Sample: Sub-sampling for tests under oxygen-free atmosphere (pore water, sequential extraction, etc.)

2.2.2 Resuspension – secondary source

In a dynamic system, this assessment should include not just those materials that are currently sediments, but also materials such as soils, mine tailings, etc. that can reasonably be expected to become part of the sediment cycle during the lifetime of a management approach (Apitz & White 2003).

Sampling. For both erosion risk and chemical mobilization risk studies, the chains of comparison are broken at early stages of sampling and sample preparation (see Fig. 1). Sampling of flood plain soils and sediments is affected by strong granulometric and compositional heterogeneities arising from the wide spectrum of flow velocities at which the sediments were eroded, transported and deposited. These heterogeneities can be reduced by subsequent normalization procedures; however, the overall comparability of the samples will be significantly lower than in the applications described for surveillance and monitoring tasks. Sampling and sample preparation of in situ sediments primary have to avoid any modification of labile phases, in particular, the access of oxygen, which will inevitably change redox-sensitive minerals such as metal sulfides (Hong et al. 1994). For physical sediment property analysis, especially for erosion tests, undisturbed samples should be taken so as to ensure in situ conditions with respect to the sediment matrix and gas content.

Uncertainties regarding the interpretation of findings from chemical mobilization studies mainly arise from the fact that the reliability of chemical analyses proper are masked by large variabilities of influencing factors such as anoxic sediment/porewater extraction and all types of ageing processes within the deposited sediment. On the other hand, the study of 'new' sediment parameters like the buffer capacity will significantly increase the knowledge base for long-term predictions on in-situ pollutant mobility.

In total, however, the largest uncertainties will arise when the chemical data are combined with hydraulic stability data (see Fig. 1). When calculating the mass of contaminated sediments released by flood events, the spatial variability of the erosion-related sediment parameters and the associated particulate concentration of sediments, especially with sediment depth, must be taken into account. The variability of both the physical and chemical parameters with depth in many cases has proved to be much larger than the horizontal variability. Consequently, the statistical range of results for the resuspension of contaminated sediments will be considerably high in reality. The more that processes are involved on the pathway along the river course, the higher the variance of the transport quantities involved and the larger the gap between the best and worst case assumption for the sediment management at the downstream end.

3 Erosion and Transport Processes

In most cases, contaminated sediments have very small particle size of less than 20 micrometer, they exhibit cohesive properties and high sorption capacity reflected by the partitioning coefficient K_d (Kern 1997). Those fine particles are characterized by high sediment-specific, interparticle binding forces which are enhanced by natural consolidation and influenced

by diagenetic processes, river water chemistry and sediment biology. For example, several historical sediment deposits in the Rhine river basin are known as highly contaminated and must be considered as a severe latent hazard for the river ecosystem, because of their toxic potential (Witt et al. 2003).

3.1 Sediment erosion stability

As for the contaminated sediment, resuspension risk, the sediment erosion stability is the key issue because of the triggering effect of hydrodynamic erosion which controls the contaminant mass flux and, therefore, the initial concentration, the exposure conditions and the subsequent chemical and biological processes in the water body. Despite several research activities on sediment stability we have only a weak understanding as to which physical, chemical and biological parameters are relevant and to what extent they influence the sediment stability (Gerbersdorf et al. 2004, Haag and Westrich 2001). The evaluation and comparison of experimental data on cohesive sediment erosion show that there is no simple correlation between sediment properties and critical bed shear stress for erosion. Sediment samples from the river Neckar (Haag and Westrich 2001) show a reasonable correlation between sediment grain size smaller than 20 micrometer, water content and extracellular polymer substances (EPS). However, more intensive recent investigations on sediments from different sites, i.e. river Rhine, Neckar and Elbe, revealed a complex feature of sediment erosion stability in terms of seasonal and spatial pattern. By applying the principle component analysis, major components influencing the sediment stability could be identified such as water content, bulk density, clay content, TOC, CEC, colloidal and CER-extractable carbohydrates as well as proteins as part of the EPS (Gerbersdorf et al. 2004). By the correlation analysis some interaction of physical, chemical and biological factors could be detected such as algal and bacterial biomass with water content, particle size, liquid limits, TOC and bulk density, but a conclusive generic description of cohesive sediment erosion processes is not yet possible because of the limited number of analyzed sediment types.

3.2 Erosion stability test procedure

The sediment stability testing facilities consist of a unique triple set developed by innovative experimental laboratory and field research. The instrumental facilities allow one to measure not only the critical bed shear stress for erosion, but also the erosion rate for different sediment layers, using a special pressurized channel. The mobile, flume-like, calibrated, testing equipment facilitates the simulation of local erosive events by applying high, near bed flow velocities and bed shear stress, respectively. The unique combination of laboratory and in situ experiments enables one to upscale and transfer sediment erosion and sedimentation criteria to nature, which is an essential prerequisite for numerical modeling of natural processes. In addition, it facilitates the collection of freshly eroded particles for sedimentological (grain size, etc.), geochemical and/or biological analysis on site.

As the river flow and transport conditions vary in space and time, sediments must be sampled at selected sites with regard to the local flow pattern (groyne fields, harbors, headwa-

ters) lateral mixing processes and contaminant point sources from municipal or industrial waste water plants. Undisturbed sediment samples can be taken from contaminated sites, e.g. in near bank groyne fields, harbors, headwaters and reservoirs, using appropriate and recently-developed techniques: (1) core sampler (diameter 14 cm, length 150 cm) inserted in the pressurized channel for sediment erodibility depth profiling, (2) box sampler (30*70 cm² top view area, 28 cm depth) for comparing and upscaling the results to the field.

The objective is to analyze physical sediment properties such as grain size spectrum, water and gas content by a non-intrusive high frequency capacity measurement method, bulk density by γ -ray, to specify the depth profile of critical erosion shear stress as a key parameter which then, must be linked to the discharge which is hydrologically specified by its occurrence probability or statistical return period. In addition, the erosion rate as another key parameter can be quantified through laboratory experiments by applying the extended SETEG system called SEDCIA (Sediment Erosion Detection by Computer aided Image Analysis, Witt and Westrich 2003) and through the recently developed mobile in situ erosion stability testing facility EROMOB (30*70 cm²), which produces almost natural turbulent flow conditions at the sediment surface (Westrich and Schmid 2004).

For the sediments in the upper Rhine river reservoirs, especially upstream of the Marckolsheim hydro power station, a critical erosion shear stress between 2–8 Pa (N/m²) and a erosion rate between 0.0001 and 0.011 (g/cm² sec) could be found and finally used for the numerical prediction of particulate mass of HCB eroded during the 1999 flood event as shown by Witt (2004). With the sediment corer, parallel samples can be taken for chemical and eventually biological sediment parameter profiling. As a more simple method, a calibrated Cohesive Strength Meter can be applied and used for rough investigation and intercomparison (de Deckere et al. 2001). Beside the physical sediment properties, the contamination level is subject to a great variability both in space and time, which has to be taken into account when estimating and predicting the transport behavior and the environmental impact of particulate contaminants in the fluvial system. In most cases there is no information available about the depth profile of sediment contamination which in connection to the erosion parameter is an important parameter for any erosion induced contaminant mass flux calculation. To provide the input data for a 1-d (COSMOS, Westrich et al. 1999) or 2-d (TELEMAC-CTM SUBIEF 2d, Jacoub 2004) numerical transport model field and laboratory measurements must be conducted. As not enough field data are available for a geostatistical evaluation or an accurate extra- / interpolation the contaminated sediment bodies must be explored in three dimensions (surface and depth) to get a complete picture of the hotspots which is necessary for modelling the total mass of contaminants resuspended by an erosive event.

The difficulties and uncertainties associated with the prediction of erosive mass flux of sediment bound contaminants released from historically contaminated sites has been investigated by Li (2004) based on data of the river Neckar. The results confirm the predominant influence of the peak

discharge and duration of a flood event and the spatial variability of the critical shear stress and the erosion rate as well. This can be illustrated by the attempt to quantify the concentration and total mass of particulate HCB released from the river Rhine reservoir Iffezheim during the flood event in May 1999. The data base of the post flood contamination of the remaining reservoir sediments was quite poor so that different assumptions on local bed shear stress and sediment contamination depth profile had to be made resulting in a large spreading of the resuspended contaminants calculated by a 2-d numerical flow model (Witt 2004).

3.3 Transport and sedimentation of resuspended sediments

After erosion, sedimentation of contaminated sediments is likely to occur in low flowing areas such as large reservoirs, flood plains, stagnant water bodies like inland harbors and groyne fields. Sedimentation of fine suspended material is primarily dominated by the bed shear stress, the flow velocity and flow depth, the fall velocity and concentration of the contaminated fraction and the microstructure of the river bed and the flood plains, respectively (Juraschek and Westrich 1985). From the hydraulic point of view one can simply conclude that the flow velocity is the key parameter for sedimentation control. Up to now there is nearly no quantitative description of fractional sedimentation possible under natural conditions encountering on flood plains with different land use. Large flood plain areas very often show low flow velocities and hence, are subject to temporary or final sedimentation of particulate contaminants.

An example has been presented by Schwartz (2001) for the recent floodplain areas of the middle Elbe River at Lenzen (Brandenburg – River-km 837.0 to 850.0), where the following average flood derived inputs of suspended particulate matter (SPM) were determined by means of artificial grass mats in relation to the mean water level (MWL) of the River Elbe: In the lower areas (< 1.0 m MWL), the mean input of SPM was 2000–4000 g/m²/a; in the intermediate areas (1.0–2.0 m MWL), the SPM-input was reduced to 500–1500 g/m²/a, due to the smaller flooding probability in combination with the then increased overflow velocity. At the highest levels (> 2.0 m MWL), which are flooded on an average only during 20 days per year, an input of SPM of 200–500 g/m²/a has been found. As a consequence, floodplain soils in the extreme case (drainless depression, flooding probability > 80 days/a) will receive an annual input of 1600–3200 kg/ha/a organic carbon, 150–300 kg/ha/a nitrogen, 60–120 kg/kg/a phosphorous and 45–90 kg/ha/a sulfur, and – anthropogenic proportion only – of 20,200–40,400 g/ha/a zinc, 2640–5280 g/ha/a lead, 2500–5000 g/ha/a copper, 580–1165 g/ha/a arsenic, 480–960 g/ha/a chromium, 160–320 g/ha/a nickel, 145–290 g/ha/a cadmium and 106–212 g/ha/a mercury (Schwartz 2001).

Transport, mixing and sedimentation in the river system is a complex process varying both in space and time. If sedimentation in the main river, e.g. the river Rhine itself or one of its tributaries, can be neglected the maximum concentration depending on the lateral and longitudinal dispersion due to mixing with low flowing or stagnant water bodies

can be effected only. However, if the contaminated sediment erosion source strength is constant over some time, the maximum concentration of the resuspended contaminants will not be affected unless there are tributaries.

Tributaries always have an influence on the concentration and also on the total mass of contaminants if there is an additional input to the main river. As a first approach, this effect can be described by applying the simple mixing equation in the following way (Eq. 1)

$$C_1 * Q_1 + C_{trib} * Q_{trib} = C_{mix} * (Q_1 + Q_{trib}) \quad (1)$$

with

C_1 is the product of $C_{particulate\ matter\ main\ river}$ (mg/kg) * $C_{total\ suspended\ sediment\ main\ river}$ (mg/l)

and, in a similar way, with

$C_{trib} Q_1$ (m³/s) means discharge in the main river, Q_{trib} in the tributary of course.

This assumption can be applied only if the particulate contaminants are restricted to the grain size fraction smaller than 20 micrometer and the total suspended sediment grain size distribution of both the rivers, that is the tributary and the receiving river, is unchanged. Because of a lack of data, no evidence can be given that this assumption is justified.

The mixing approach assumes a complete mixing of the contaminated fraction at the point of confluence in the main river and the joining tributary as well. In case of measurements taken in a contaminated plume with lateral concentration gradients, the concentration profile must be known to allow the evaluation for the mass balance by integration of the product of local concentration and flow velocity. If the mixing approach is acceptable, it has to be applied at each point of confluence along the main river until the last tributary is reached. Knowing the residence time and specifying some reaction and degradation processes, the final concentration at the destination, that is, for example, the port of Hamburg, can be estimated.

4 Sediment Management for the Elbe River

4.1 The approach

A management of contaminated sediment should be based on scientific information. Although economical and societal conditions are also taken into account for the final site-specific management, we will focus on the scientific requirements for a risk management. For the Elbe, these comprise at least²:

- An inventory of the kind of substances that are of concern in the Elbe Basin as compared to quality standards;
- the sources of these substances, and their location ('Areas of concern');

- the potential erosion risk of these areas in terms of resuspension;
- information on sediment/suspended matter dynamics that enable the calculation of dilution/sedimentation processes, current velocity, discharges, and suspended matter concentrations.

As sediments are considered the 'memory of the river', information on historical uses and contamination of the river have been shown to be helpful in identifying areas of concern in a basin. After assessing the available information, site prioritization of contaminated or contaminating areas could be carried out. Some details on the information that is available for the Elbe River, and which could be used for sediment management, are given below.

4.2 Substances and areas of concern with regard to Elbe sediments

Inorganic substances that are of concern along the Elbe basin comprise arsenic and the heavy metals cadmium, mercury, lead and zinc (Table 1). According to the LAWA³-system, they cause parts of the Elbe to be assigned to the highest contamination class IV. With the exception of lead, which is of least concern for the Elbe and only shows increased levels in parts of the Mulde and the Saale, all heavy metals as well as organic substances like PCB, HCH, dioxins, DDT and HCB show highest concentrations in the sediments around Magdeburg, sometimes even further upstream, and those of Hamburg (Prange et al. 2000).

With regard to industrial point sources, the following production processes are of concern: chemical and pharmaceutical industry, paper industry, metal and electro industry, leather and fur producing industry, glass and ceramic industry, textile industry and mining (Prange et al. 2000). The largest brown coal mining area was the 'Mitteldeutsches Revier' between the two mountainous regions 'Harz' and 'Erzgebirge'. Next to the energy sources, a dense concentration of chemical industry settled in the area along the Saale and the Mulde Rivers, tributaries of the Elbe. During the last 20 years, most of the industrial plants closed down and mining activities stopped. Production and use of fertilizers, application of manures and intensive farming decreased in this area, while the efficiency of waste water treatment improved. As a consequence, heavy metal emissions from point sources (industry and waste water treatment plants) to the Elbe catchment area have decreased by 80 to 90 percent between 1985 and 1999. Emissions from diffuse sources, although less extreme, also declined significantly: 40 to 80% in urban areas and 50 to 80% in rural areas (Vink 2002). Emissions in legacies of the past, such as disposal sites and areas where the accumulation of contaminated sediments present a risk, were seen to have decreased as well.

In the Czech Republic and Germany, 33 important sites with contaminated material and 15 disposal sites have been identi-

² See also Babut et al. (2005): Prioritization at catchment scale, risk ranking at local scale. In: Heise S (ed) 'Sediment Risk Management and Communication' (2005).

³ LAWA – Länderarbeitsgemeinschaft Wasser (Länder Working Group for Water).

Table 1: Substances of concern, their historic sources and current areas of concern in the Elbe River, compiled from (Spott and Becker 2000, Prange et al. 2000)

Substance of concern	Historical sources	Areas of concern
Arsenic (As)	Browncoal mining	Mulde
Cadmium (Cd)	Browncoal mining Smelting processes Metal processing	Mulde (Havel) (Elbe downstream of Magdeburg)
Copper (Cu)	Artificial silk production	Elbe
	Copper-processing industry	Saale
Mercury (Hg)	Chlor-alkali electrolysis (amalgamation process)	Saale Mulde downstream of Bitterfeld
Lead (Pb)	Mining Smelters	Saale Freiberger Mulde
Zinc (Zn)	Industrial and municipal wastewater Mining industry Smelters	Saale Mulde Weiße Elster Havel (Elbe downstream of Magdeburg)
Halogenated organic compounds (AOX)	Pulp and paper mills (Mulde)	Mulde Saale
Trichloromethane	Chemical industry, Pulp and paper mill waste water	Mulde
Insecticides e.g. DDT, γ -HCH	Production facilities	Bilina (CR), Mulde
Hexachlorobenzene	Chemical industry	Karlsberg & Luznice (disposal sites) Bilina (CR)
PCB	Chemical industry	Bilina (CR), Mulde, Saale, Weiße Elster
PAH	By-product during incomplete incineration of organic material	Schwarze Elster Mulde

fied with extensive soil pollution and groundwater risk. Highest pollution potentials are situated near Bitterfeld-Wolfen, Magdeburg-Rothensee, Buna and Leuna.

With a decline of primary point sources in the Elbe Basin, the relative contribution of secondary sources, such as historic contaminated sediments, to the environmental risk increases and, hence, the importance of these sources in the effort to achieve a long-term improvement of Elbe River quality increases as well. Secondary sources of contamination are legacies of the industrial and mining activities in this area: Rising groundwater leads to drainage of leachates from former coal and ore mines. Disposal sites of industrial waste lie in areas prone to flooding, as has been shown during the flood in 2002 (Geller et al. 2004). In previous industrially-used regions, untreated waste waters have contaminated vast areas like the 20,000 tons of sediment in the Spittelwasser creek, heavily polluted with toxic and ecotoxic compounds including polychlorinated dibenzo-*p*-dioxins and furans (Hille et al. 1992, Brack et al. 2002), polychlorinated naphthalenes (Brack et al. 2003), heterocyclic polyaromatic compounds (Brack and Schirmer. 2003), organotin compounds (Kuballa et al. 1995), N-phenyl-2-naphthylamine and several pesticides (Popp et al. 1994, Brack et al. 1999).

As listed in Table 1, tributaries of highest concern with regard to contaminated sediment are the rivers Saale and Mulde with their tributaries, and the Bilina in the Czech Republic, where the industrial plant Spol-Chemie is located. The Bilina

only has an average discharge of 5 m³/s at the confluence with the Elbe, but has a significant impact on the Elbe quality due to its high contamination. Compared to Bilina, the rivers Mulde and Saale contribute much higher volumes to the Elbe River (73 and 115 m³/s, respectively), which has a discharge of 315 m³/s at the Czech-German border (Prange et al. 2000). The Saale is the river that under usual conditions transports most contaminants into the Elbe. Even at normal flow conditions, suspended matter of the Elbe shows increased levels above the target threshold of class II, LAWA-classification, with the heavy metals of cadmium, copper, mercury, zinc and, to a low degree, lead. A study from 1998 showed that chromium and copper, as the only ones from the 7 prioritized heavy metals, reached their target values due to legacies of the past (Prange et al. 2000).

Ecotoxicological studies, that were carried out in 1995 and 1996 with 5 biotests, assigned all Elbe sediments to toxicity classes 4 and 5 out of 5 classes (1: no toxicity shown; to 5: high toxicity in 3 or more test systems) (Fig. 2) also identified the Middle Elbe as the one with highest toxicity classes, while the toxicity at several sites below Hamburg is reduced to class 2 due to dilution effects during incoming tides (Heise et al. 2000). Major toxicants accumulated in sediments of the Spittelwasser creek as one of the major sources of pollution in the River Elbe have been identified by effect-directed analysis on the basis of toxic responses in various biotests (Brack et al. 1999, Brack et al. 2002, Brack and Schirmer 2003).

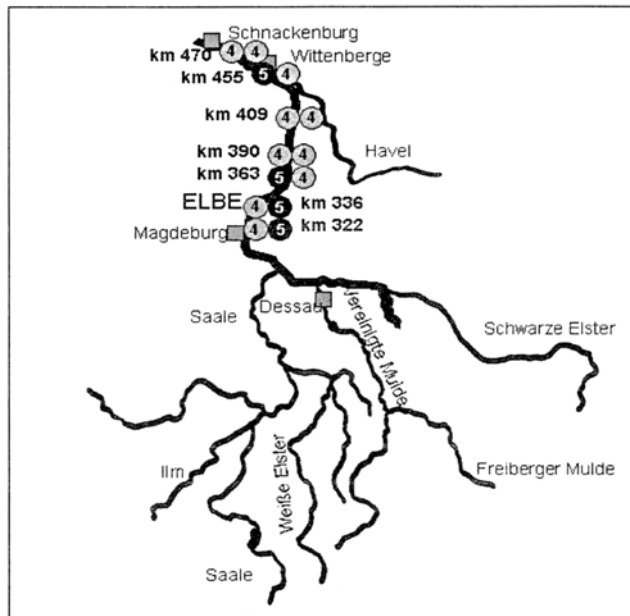


Fig. 2: Map of the Middle Elbe, indicating the tributaries Mulde, Saale and Havel, and showing the ecotoxicological classes (classes 4 and 5 only) of 1995 and 1996

The risks due to historic contaminated sediments becomes more pronounced during flood events as they resuspend deeper and mostly higher contaminated material, therewith facilitating remobilization of contaminants. The results of the project 'pollution level after the Elbe Flood 2002'⁴ showed that considerable loads of contaminants, especially heavy metals (Hg, Cd, and Co) and arsenic, became remobilized and transported downstream, increasing the contaminant concentration in fluvial and riverine sediments in the Mulde tributary, and below the Mulde confluence in the Elbe River. Regularly flooded areas, the fluvial alluvium, below Mulde and Saale up to Geesthacht, are highly contaminated with dioxins and mercury. Legacies from the industrial chemical production sites in the area of Bitterfeld have led to complex contaminant mixtures with unknown ecological effects. Especially below the Mulde impounding reservoir, which has a high retention capacity, contaminant concentration was first relatively low, but then increased drastically (after) the confluence of the highly dioxin-contaminated creek Spittelwasser (Götz et al 1998). Ecotoxicological studies that have been carried out in the scope of the ad-hoc project 'Elbe flood 2002' have supported the chemical analyses and reported all investigated sediments as 'problematic' (Knöchel and Ockenfeld 2004).

Ecotoxicological tests (Ahlf and Gratzner, 1999) on freshly deposited material, that were carried out after the flood of 2002, showed an increased toxicity, although the contamination was less than before the flood – due to dilution and retention events upstream. The bioavailability of the contaminants in the material that was eventually deposited,

⁴ Original title: 'Schadstoffbelastung nach dem Elbe-Hochwasser 2002', funded by the German Ministry of Education and Research (BMBF) Final Report June 2004, 462 pp. ISBN 3-00-013615-0.

though, seemed to have been changed relative to space (Heininger et al. 2003). The geochemical mechanism is not identified, but it was previously described that a natural dilution of contaminated sediments with silt could enhance bioavailability of pollutants and consequently toxic effects (Ahlf et al. 2002b).

In order to assess environmental risks, derived from contaminated sediments, tests on effects should therewith be performed to cover potential changes in bioavailabilities during transport processes. This seems to be especially true for recently sedimented material, which, in addition, is prone to resuspension due to its low critical erosion thresholds. The specified layer is exactly the habitat where benthic organisms are living. The recommendation for an assessment strategy use an integrated hierarchical approach combining toxicological, chemical and ecological information to assess and evaluate the quality of sediments (Ahlf et al. 2002c). Examining adverse effects could contribute to a better understanding of geochemical changes due to transport processes and will lead to a trend analysis of ecological sediment quality.

4.3 Erosion stability of Elbe sediments

A measure for the mechanical-physical stability is the critical erosion shear stress, which reflects the critical shear stress at the sediment-water interface on the start of erosive processes. This parameter was studied on several sediment-cores taken from flooded areas in the Middle Elbe, at River-km 787.9, a few km upstream from Wittenberge close to the village of Havelberg. The data presented here stem from a sediment core from the center of a groyne field. Fig. 3 shows the bottom shear stress (Pa in N/m²) needed for sediment remobilization in dependency on sediment depth (Schwartz and Kozerski 2004).

Major reasons for the distinct heterogeneity of the erosion stability are differences in consolidation processes, grain size distribution and in the composition of stabilizing exudates in the individual sediment layers. Except for the uppermost 5 cm and at a depth of 47 to 48 cm, where the critical shear stress is very low (0.5 Pa), the critical bottom shear stress in the studied sediment profile is between 1.2 Pa and 3.4 Pa, i.e. at a moderate level.

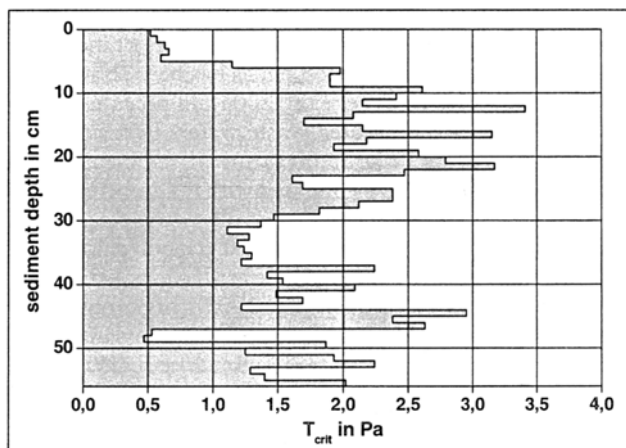


Fig. 3: Sediment depth profile of the critical bottom shear stress in a groyne field sediment core from the River Elbe near Havelberg

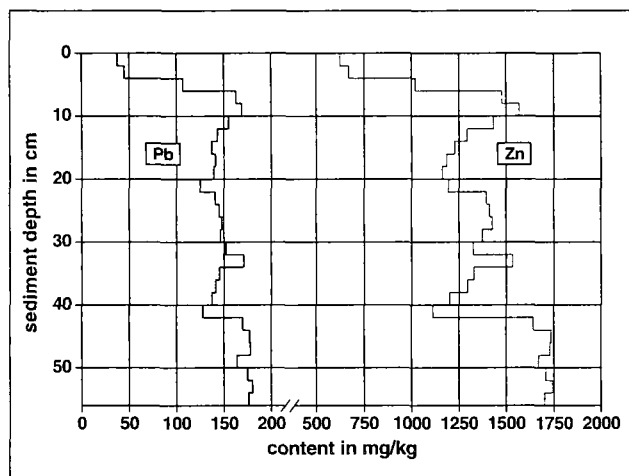


Fig. 4: Sediment depth profile of the lead and zinc content in a groyne field sediment core from the River Elbe nearby Havelberg

Fig. 4 shows the trace metal depth profiles of lead and zinc in a sediment core taken in the immediate vicinity and at the same period of time as the sediment core used for erosion stability studies (see Fig. 3). Similar to the erosion-stability depth profile, the metal data exhibit short-range heterogeneities; in this case, however, within three distinct concentration levels. The variations in the individual layers can be explained by different proportions of fine grained components and by an improvement of suspended matter quality in the course of time. In particular, at the beginning of the 1990s, a significant amendment of water and sediment quality has been observed (Schwartz et al. 1999). However, if the metal depth profiles of Figure 4 are normalized to the fraction <math>< 20 \mu\text{m}</math>, it becomes obvious that these values are still strongly surpassing the natural background values for sediments (at the catchment scale; Krüger et al. 1999) of 22 mg/kg for lead and 103 mg/kg for zinc.

In view of the findings of relatively low erosion stabilities of groyne field sediments and, in particular, after the extreme Elbe flood of August 2002, a prime question relates to the

remobilization risks of these sediments typically enriched in contaminants and nutrients. The extent of flood-induced remobilization is shown by two snapshots (Fig. 5) on the occurrence and distribution of sediments derived from suspended matter in a typical groyne field of the middle Elbe river at Havelberg (River-km 785.0). The length amounts to 70 m of the upstream groyne, and to 45 m of the downstream one. The distance between the upstream and downstream groyne root totals 83 m, which corresponds to a total groyne field area of 4770 m².

Fig. 5 indicates that the largest sediment depots occur in the center of the groyne field, caused by the low average flow velocity below 10 cm/s in this range (Schwartz and Kozerski 2003). The left part of Figure 5 shows the situation immediately before the extreme flood at the Elbe river of August 2002 and the right part of Fig. 5 refers to the situation nine months after this flood event. While approximately 340 m³ sediments were detected on an area of 970 m² in July 2002, both the areal extension and volume of sediment was reduced after the flood to about 620 m² and approximately 130 m³; i.e. a decrease of the sediment depots of nearly 60% took place. This means that approx. 200 m³ nutrient- and pollutant-rich sediment, derived from suspended matter, has been mobilized from this one groyne field and has either been transferred downstream or has been transferred to the adjacent, recent, flood plain areas.

4.4 Floodplains as sinks and secondary sources for contaminants

Floodplain soils in their composition reflect the former geological and pedological processes and, due to the periodical material inputs, they form a memory of the pollution history in the catchment area. In particular, floodplain soils of the Elbe River downstream from the mouth of the Saale and Mulde tributaries are significantly contaminated by inorganic and organic pollutants (Friese et al. 2000). In this section 4.4, therefore, the function of floodplain soils as sinks and potential secondary sources are treated in more detail.

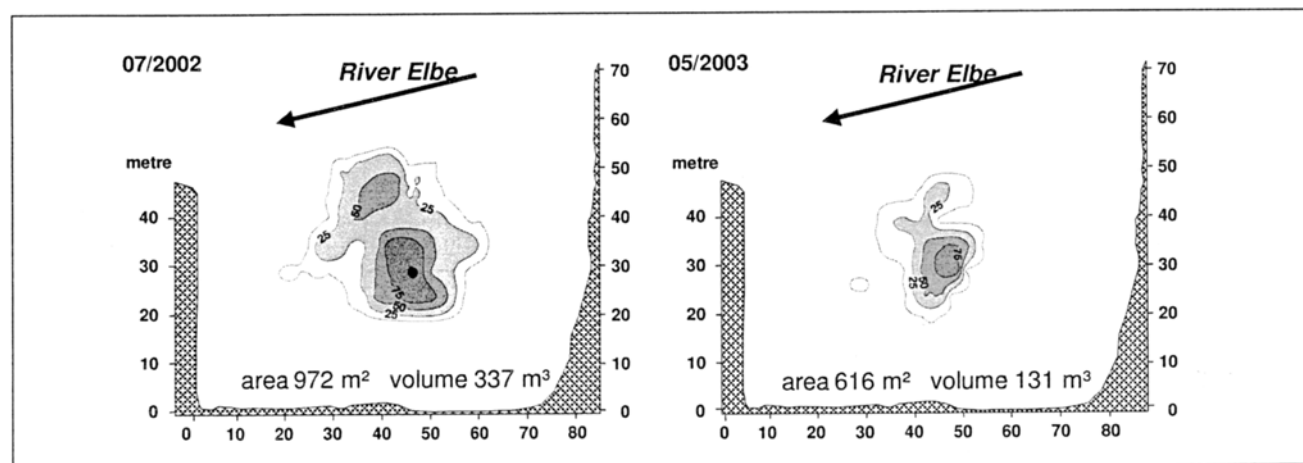


Fig. 5: Shape and depth of the mud layer (in cm) in the left-hand groyne field of the River Elbe near Havelberg, before and after the extreme flood of 2002

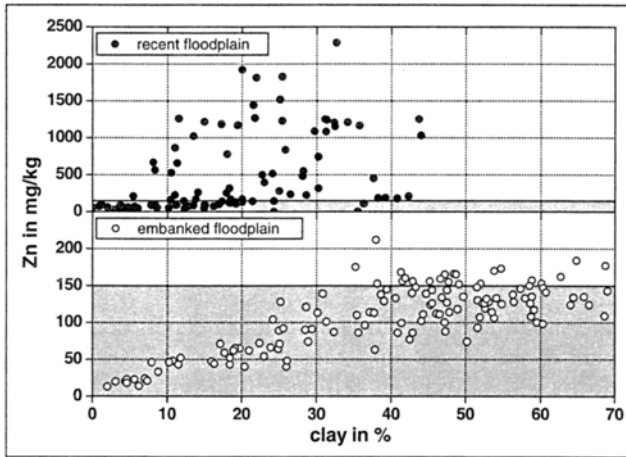


Fig. 6: Zinc content versus clay content in the recent and embanked floodplain from the River Elbe near Wittenberge (gray hatching: catchment-based, geogenic, element background level)

Fig. 6 shows the ratio between zinc concentrations and clay contents in the recent inundation floodplain of the middle Elbe river in the region of Lenzen (River-km 838.5 to 849.5) and in another floodplain area of this region, which, however, has been embanked since the 13th century. Obviously, the zinc contents of embanked alluvial soils are predominantly geogenic and the mean concentrations of fine-grained samples coincide with the catchment-related background values for alluvial clays of 150 mg/kg zinc, as determined by Krüger et al. (1999); there is a close correlation to the clay content ($r^2 = 0.896$, $n = 134$, $p < 0.0001$). On the other hand, zinc concentrations in samples from the non-embanked alluvial areas do not exhibit significant correlation with the clay content ($r^2 = 0.429$, $n = 215$, $p < 0.0001$) and these zinc contents are surpassing the geogenic background values partly by more than tenfold.

A comparison between the zinc concentrations and the contents of organic carbon of samples from outside and inside the embanked areas of the middle Elbe river from River-km 838.5 and 849.5 (Fig. 7) indicates, in the non-embanked swampable areas, that increasing zinc concentrations clearly coincide with increasing contents of organic carbon ($r^2 = 0.782$, $n = 263$, $p < 0.0001$). Obviously, there is a simultaneous deposition of organic substances and of zinc sorbed to these materials. In the embanked areas, on the other hand, there is no further increase of zinc concentrations at organic substance contents above 1.0% ($r^2 = 0.417$, $n = 366$, $p < 0.0001$). Apart from few exceptions, the element-specific background values of 150 mg/kg zinc is not surpassed in these areas. From the different behavior, it can be concluded that the organic substances in the embanked areas are nearly exclusively of autochthonous origin, while the flood-related allochthonous proportion of organic material predominates in the samples of the unembanked alluvial areas.

Fig. 8 relates the zinc concentrations of alluvial soils and sediments to the long-term mean water level (MWL, see Section 4.2) of the same Elbe river section. While the zinc concentrations generally increase with decreasing relative water level, there is no statistically significant correlation between the two parameters. However, it can be seen that

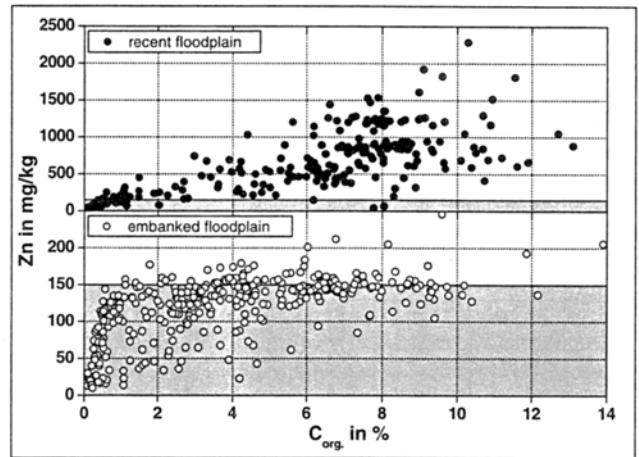


Fig. 7: Zinc content versus organic carbon content in the recent and embanked floodplain from the River Elbe near Wittenberge (gray hatching: catchment-based, geogenic, element background level)

zinc concentrations of more than 250 mg/kg do not occur at mean water levels higher than 2.0 m; conversely, zinc concentrations above 1000 mg/kg are restricted to mean water levels < 1.0 (see Fig. 8).

In summary, the results from Figures 6 to 8, with zinc as a general measure for inorganic and organic contamination of the floodplain soils in the middle Elbe river region, can suggest the following causal chain: Recent floodplain areas, at low mean water levels and low current during inundation exhibiting high concentrations of organic carbon, represent the most highly contaminated sites. On the other hand, only insignificant pollution has occurred on alluvial areas, which were embanked already at pre-industrial times

In the case of flood events, due to the combination of flooding probability and flow conditions, the most favorable conditions for the deposition of nutrient- and contaminant-rich, suspended particulate matter are found in the low level, drainless depressions (see Section 3.3). Channels at similar water levels, due to stronger flow velocities, receive significantly less flood-induced inputs of suspended particulate matter and their associated nutrient and pollutant loads. As

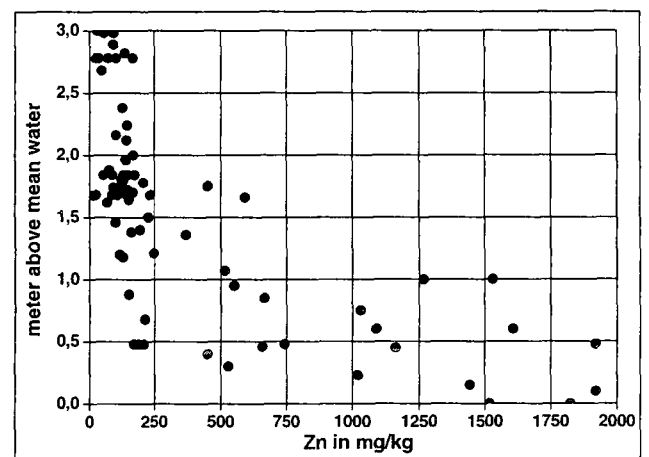


Fig. 8: Zinc content depending on the relative altitude of alluvial soils from the recent floodplain of the River Elbe near Wittenberge

a consequence, recent floodplain soils and sediments show small-scale heterogeneous pollution patterns. Therefore, assessment of the pollution status of floodplains requires detailed pedologic mapping with respect to the association of individual soil types and differentiation of geomorphological units (Schwartz 2001).

Subsequently, in order to demonstrate the extent of anthropogenic inputs of nutrients and pollutants into the floodplain areas of the lower middle Elbe river (River-km 790.0 to 952.9), extrapolations will be made with regard to the main sedimentation areas, based on numerous point data. Discrimination between natural and anthropogenic inputs is made on the basis of element-specific background values for the individual catchment areas (Krüger et al. 1999). Calculations of the anthropogenic nutrient and pollutants loads in the slack waters of the Elbe river near Havelberg (Brandenburg) are based on the data of Schwartz and Kozerski (2003). Data for the recent floodplain areas immediately along the river course at Pevestorf (Lower Saxony) have been assembled by Miehlisch (1994).

Within a typical river section of 1 km length of the lower middle Elbe, the groyne fields, as dominant slack water zones, contained the following nutrient and trace metal loads (reference year 2001, anthropogenic proportions): 287 t organic carbon, 17.6 t phosphorous, 17.4 t nitrogen, and 16.7 t sulfur; 8.6 t zinc, 1.1 t copper, 0.9 t lead, 0.4 t chromium, and 0.2 t nickel, respectively. Metal loads of floodplain deposits, typical as well for selected river sections of the Elbe, were calculated for 1.0 ha area and 1.0 m soil depth as follows (reference year 1994, anthropogenic proportions): 2.5 t zinc, 0.5 t lead, 0.4 t copper, 0.3 t arsenic, 0.02 t cadmium and 0.01 t nickel.

The listed nutrient and pollutant loads, deposited on the floodplains and in the river course, clearly demonstrate the specific sink function of both sites. At the same time, however, the results of Section 4.3 suggest, in contrast to the deposits in the floodplains, that sediments within the river course may be remobilized in part. This means that the long-term sink function can, at least temporarily, become a significant source character, involving the hazard of a substantial deterioration of the downstream sections of the river basin.

5 Problem Assessment and Potential Solutions in the Elbe River Catchment Area

The combined view of substances, areas and processes of concern in the Elbe catchment – with special emphasis on the historical contamination of floodplain soils and sediments as well as on groyne field sediments as significant secondary sources of pollution – is a typical example for the holistic river basin approach of the European Water Framework Directive (WFD), both with respect to assessment of ecological risks and the development of remediation measures.

5.1 Examples for large-scale screening and detailed measurements

A river basin-wide sediment assessment should, at first, perform inventories of interim depots with the catchment area,

i.e. underground and surficial mining residues, river-dams, lock reservoirs (Förstner 2003) and – as emphasized in the present study – flood plain and groyne field sediments. With respect to the latter, examples from the Elbe River suggest that large-scale screening of the relative risk can be based on hydraulic measurements of the mean water levels and current velocities during inundation (Section 4.4). Examples of a basin-wide assessment can be found in the final report of the coordinated ad-hoc project on the assessment of risk potentials at the Elbe and Mulde rivers after the flood of August 2002 (Geller et al. 2004), e.g. non-target screening of organic pollutants (Franke et al. 2004), longitudinal profiles based on analyses of suspended particulate matter (Pepelnik et al. 2004) and colloid-bound metals as indicators of specific sources in the catchment area (Baborowski et al. 2004).

Detailed measurements for critical sites can apply the wider spectrum of laboratory and in-situ erosion stability tests (Section 3.2). In the framework of the before-mentioned, ad-hoc project, the study of erosion stability on sediment core profiles (example in Fig. 3) was combined with analyses of the acid neutralizing capacity, providing a first indication on the heavy metal mobility in the grain matrix relative to the (bio-)chemical processes, which can form acidity (Kersten and Förstner 1991). The flood plain-profile from the Middle Elbe river exhibits a relatively high acid neutralizing capacity, and it can be expected that relocation processes involving oxidation of sulfide minerals will not induce long-term problems with respect to the mobility of heavy metals (Förstner and Jacobs 2004). Such effects, however, should be respected in the relative low-carbonate Elbe sediments, as has been demonstrated from erosion experiments on sediments from the Hamburg-Harburg inner harbor (Fengler et al. 1999).

Both for risk assessment and problem solutions at the river basin scale, self-solidifying effects on sediments and soils in floodplains merit special attention. Following an initial study on natural attenuation mechanisms in the Spittelwasser region (Förstner et al. 2001; see Section 5.2), a recent project in the framework of the coordinated program on 'Controlled natural retention and degradation of pollutants during remediation of contaminated groundwater and soils' investigates physical, chemical and biological techniques to quantify non-destructive, 'intrinsic'-bonding mechanisms which, apart from chemical processes, involve an enhanced mechanical consolidation of soil and sediment components by compaction, loss of water and mineral precipitations in the pore space, and may induce a quite essential reduction of the reactivity of solid matrices (Schwartz et al. 2004).

5.2 Remediation techniques at the river basin scale

In the future, remediation methodology as well will be seen in the context of sustainable sediment management. Recent developments in 'soft' (geochemical and biological) techniques on contaminated soils and sediments, both with respect to policy aspects as to technical developments have led to a stimulation of in-situ remediation options. 'Geochemical engineering' (Salomons and Förstner 1988) applies

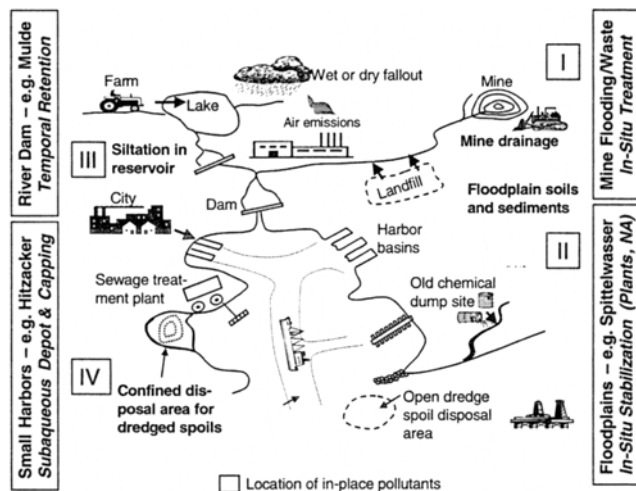


Fig. 9: Sediment contamination in a river catchment area (after Shea 1988) and proposals for treatment methodologies in the Elbe River basin (see text)

principles such as stabilization, solidification, and other forms of long-term, self-containing barriers to determine the mobilization and biological availability of critical pollutants. Fig. 9 gives examples for such techniques on a catchment scale.

Predominantly in the upper and middle course of river systems, sediments are affected by contamination sources like wastewater, mine water from flooded mines and atmospheric deposition. Measures at the source are particularly important and may include an improvement of traditional wastewater purification, but also more approaches for in-situ treatment of highly contaminated effluents such as introducing active barriers (fly ash, red mud, tree bark, etc.) into ore mines to prevent heavy metal dispersion during flooding (Zoumis et al. 2000).

From an initial example of the Spittelwasser case comparison (Anon 2000) in a 60 km² flood plain of the upper Elbe River, it has been shown that problem solutions for such areas deserve a thorough consideration of legal and socio-economic aspects. Until now quantitative data of the effects of ageing and natural attenuation on sediment and pollutant stability are scarce and the conceptual basis of practical applications still has to be developed (Joziassse and Van der Gun 2000). However, it is quite obvious that any problem solution strategy in situations, where traditional remediation procedures become economically unacceptable, either due to the large volume of dredged material or because sediment-bound contaminants are dispersed in a hardly predictable manner, has to be based on natural processes that simultaneously consider both the chemical demobilization and the reduction of mechanical erodibility⁵.

In the course of the river and its tributaries, natural or man-made depressions can be used for the storage of contaminated sediments. A typical example is the Mulde reservoir

⁵ The Sediments Remediation Action Team of the Remediation Technologies Development Forum (RTDF) has published a series of downloadable draft papers on the weight-of-evidence approach for evaluating the use of monitored natural recovery (MNR; <http://www.rtdf.org/public/sediment/mnrpapers.htm>; Davis et al. 2004, Erickson et al. 2004).

(~ 6 km² area, ~ 120 million m³ water) in the Elbe River system, which was created in 1975, when a 10 km section of the river was displaced in order to get access to a lignite coal area. Retention is approx. 50% of the sediment-bound cadmium discharge of the Elbe River and it has been predicted that this type of sediment trap could last for 500 to 1000 years (Zerling et al. 2001).

In the center of today's sediment management, there is a science-based technology for the final storage of sediments – called 'subaquatic depot'. The EU Landfill Directive does not refer to waste disposal below the groundwater level (Anonymous 1999), and here the two most promising conditions for a sediment depot can be found: (i) a permanent anoxic milieu to guarantee extremely low solubility of metals, (ii) base layers of compacted fine-grained sediments which prevent the advective transport of contaminants to the groundwater (Anonymous 1998, 2002). Together with advanced geochemical and transport modeling, such deposits offer the most cost-effective and sustainable problem solutions for dredged sediments. In the convoy of this technology – flagship is the Dutch 'De Slufter' depot – innovative sediment-specific applications are developing, for example techniques for active capping to safeguard both depot and in-situ contamination against pollutant release into the surface water. Actually, there are 16 sites of depots for harbor sediment in The Netherlands, most of them at near coast sites. The preparation work before construction is between 4 and 7 years. Filling for the smaller depots will take place within 5 years, for the larger ones within 20 year. Cost estimations for construction, operation and aftercare are between 5 and 10 Euro per m³ (Anonymous 2002).

Application of a combined sub-aquatic depot and active capping technology can be considered for small yachting harbors. For the Hitzacker/Elbe harbor site, a draft approval has been made which involves the excavation of approx. 10,000 m³ fine grained, polluted sediments from the harbor area and their sub-aquatic deposition close to the site, in a communication channel between the Elbe River and the harbor (Förstner 2003). Active capping of the sediment depot will include natural zeolite additives and monitoring of the site will be performed using dialysis sampler and diffusional gradient technique probes (Jacobs 2003).

6 Conclusions

Data from the Elbe River and its tributaries indicate, despite extensive improvement in water quality during the last 15 years, that the respective sediment situation of many priority pollutants has not changed to an acceptable level. Mercury, cadmium and zinc concentrations in suspended matter and sediment still have to be classified as 'increased to a very high contamination'. Regarding the coming decades, it can be predicted, despite significant reductions in industrial emissions, that risks for downstream sites and stakeholders will persist, mainly due to secondary sources originating from historical pollution of soils and sediments in the catchment area. As evidenced from data in the present study, this type of contamination seems to be specifically associated with sediments which undergo a frequent resuspension-

depositioning cycle such as in groyne fields along the Elbe River. In addition, ecotoxicological effects of freshly deposited material can differ significantly compared with aged material, and such experience should be taken into account when assessing the ecological risk of resuspended material.

Limited spatial resources downstream of the Elbe require a long-term reduction of contaminant levels in order to reduce the volume of dredged material that has to be disposed of on land. Limited financial resources require a direction of investments to those sites with the highest efficiencies in risk reduction. Establishing a rough sediment dynamic model, building on tributary/Elbe dilution factors, sedimentation data, suspended, particulate-matter monitoring data and integrating a higher number of data on critical erosion thresholds that exist today, it should be possible to achieve a scientific site prioritization with detailed answers about what risks could be reduced by applying methods to a specific site. Calculations of long-term costs and benefits, based on risk management, could be an essential step in a basin-wide river management. These calculations could indicate, when considering an investment in measures upstream, that a reduction of the volume of contaminated material may even be profitable for stakeholders downstream. On the other hand, a risk reduction of a certain contaminant could be pointless since it would not definitely lead to a reduction in environmental risk or to a decrease of material, that needs to be disposed of on land in a costly manner.

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