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Model based sediment quality management on river basin scale

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Abstract:

Contaminated sediment mobility plays an important role in river engineering and water resources management. Numerical models are powerful tools to be used for analysis, prediction and remediation issues in sediment management. Erosion stability plays a key role for contaminated sediment mobility assessment. Experimental investigations on erosion stability of undisturbed sediments reveal a large spatial variability of sediment properties. A 1-d and a 2-d numerical transport model is applied to analyse erosion and sedimentation processes of contaminated sediments in the Upper River Rhine reservoirs and in the river Elbe focussing on the effect of the near bank low flowing water zones.

Keywords: sediment, erosion, contaminants, samples, modelling.

1. INTRODUCTION

Sediments play an important role in river engineering, water quality management and river rehabilitation. In the past, rivers have been regulated for navigation, hydropower and flood protection by building different structures such as weirs, dams and river training works which have great influence on the sediment transport behaviour. In industrialized countries, many river sediments are contaminated by heavy metals and organic substances due to municipal and industrial waste water discharge [Förstner et al., 2005]. Contaminated sediment deposits can be found in low flowing or stagnant adjacent water bodies such as near bank so called groyne fields, harbours, dead arms, flood plains and retention reservoirs as well. Most deposits are subject to resuspension and long distance transport by erosive flood events with wide spread impact on the aquatic ecosystem. Therefore, a risk based sediment management is required which accounts for the probability of contaminant mobilization by erosive discharge events and the impact on the environment.

Because of the complex interaction of hydrological, hydrodynamic, sedimentological and biochemical processes an interdisciplinary approach on a river basin scale is required to provide basic information for a sustainable sediment management including remediation measures and decision support [Westrich and Förstner, 2007].

2. INTEGRATED RISK ASSESSMENT

Referring to the EU-Water Frame Work Directive a sustainable sediment management is required to improve the ecological status of surface water bodies by reducing the risk of adverse impact and ecological damage due to toxicants. A comprehensive risk assessment should be based on an interdisciplinary approach to cope with various processes on different space and time scale. Management strategies must provide solutions on local, regional and river basin scale. Since each catchment has its characteristic pattern in terms of water use and pollution the remediation concept must be site and catchment specific.

Floods play a dominant role in sediment erosion risk assessment because of their extreme erosion capacity followed by large scale dispersion and uncontrolled immission. Hence, older most highly contaminated sediments in deeper layers can be resuspended and redeposited in yet uncontaminated water bodies or on flood plains. In this context the sediment erosion stability turns out a key factor as it controls the mobility and contaminant mass flux and hence, allows to estimate the total amount of released contaminants by flood events. Erosion probability can be determined by combining the statistics of the hydrodynamic bed shear stress based on discharge hydrology and the sediment specific erosion resistance.

Resuspended fine sediments are often transported over a long distance through the river network while simultaneously different interacting processes are going on such as: mixing with bed material; dilution or additional loading by tributaries, point sources or erosion; fractional sedimentation; ad-/ desorption of pollutants; repartitioning of pollutants and, finally biochemical transformation and degradation.

3. TRANSPORT AND EXPOSURE MODELLING

Numerical models allow to integrate processes of different scale in space and time. Physically based numerical models are useful tools to describe the pathway and fate of contaminants in rivers and to quantify the relationship between emission and immission. Moreover, predictive numerical models can also be used for a risk reduction analysis by investigating the effect of alternative remediation measures and providing basic information for a cost-benefit analysis. Hydrological scenario modelling produces data on intensity and duration of immission which can be used for further statistical modelling of a dose-effect relationship. Consistent field data of extreme events are very poor and hence, contaminant transport model calibration and validation are subject to high uncertainty However, neglecting biochemical transformation and degradation processes an engineering approach with conservative assumptions can be made for a preliminary study focussing on hydrological and hydraulic issues related to erosion, transport and deposition of particulate contaminants

To describe long-term and large scale transport processes one-dimensional models have been proven useful. A 1-d multi-strip model was developed aiming to describe the erosion, dispersion and deposition dynamics of fine suspended sediments for regulated rivers with typical training works such as near bank groyne fields. The total river cross section is subdivided into three compartments: main channel, adjacent groyne fields on the left and right bank and flood plains, respectively [Prohaska and Westrich, 2006]. The set of 1-d transport equations for the strips are coupled by dispersive and advective exchange terms. For water levels below the crest of the structure the water body is considered a dead water zone with homogeneous suspended sediment concentration. Because of the complex flow and transport processes inside the groyne area the exchange coefficients are measured by laboratory experiments, confirmed by a 2-d flow and transport model [Jacoub, 2004] and implemented into the 1-d model strip model as an engineering approach.

4. SEDIMENT DATA

Sediment input data have different quality in terms of accuracy and density in space and time. To reduce the model uncertainty due to great variability of sediment properties several samples must be taken at the site of interest The application of a contaminated sediment transport model requires a comprehensive data base comprising physical, chemical and biological parameters such as: critical shear stress for erosion and deposition [Gerbersdorf et al., 2004], erosive and depositional mass flux for sediments and contaminants, particle fall velocities, sorption parameters, kinetic parameters for transformation and degradation processes. The spatial distribution of erodability and contamination including depth profiles plays a key role for predicting the total mass of eroded sediments and contaminants. In Fig. 1 representative depth profiles of some samples of typical groyne fields of the river Elbe are depicted showing the spatial and temporal variability of the critical erosion shear stress. Samples from another site reveal a typical pattern, meaning that deeper layers are highly polluted whereas the upper layers are less polluted due to reduction of river pollution in recent years (Fig. 2). Numerical Monte Carlo simulations based on the statistics of critical erosion shear stress and erosion rate coefficients have shown the influence on the expected value and the variance of the total mass of sediments eroded by a flood [Li, 2004].

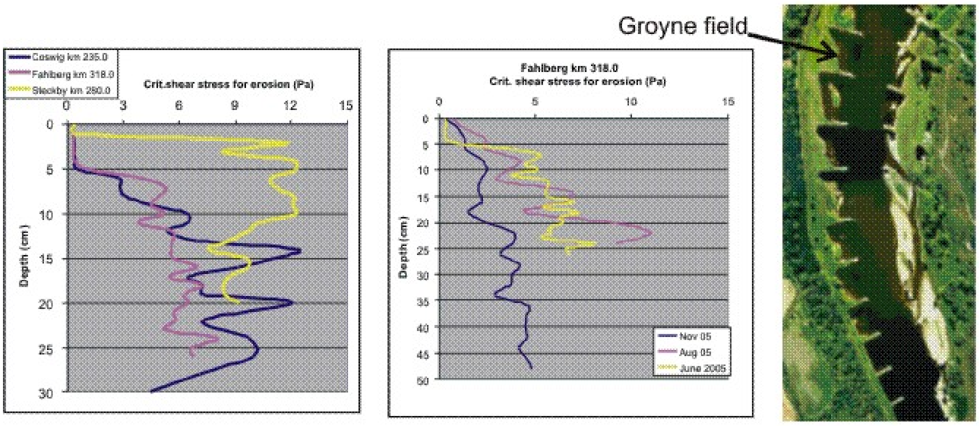


Figure 1. Spatial and seasonal variation of critical erosion shear stress: groyne fields of the river Elbe at Coswig, Fahlberg and Steckby [Jancke et al., 2006].

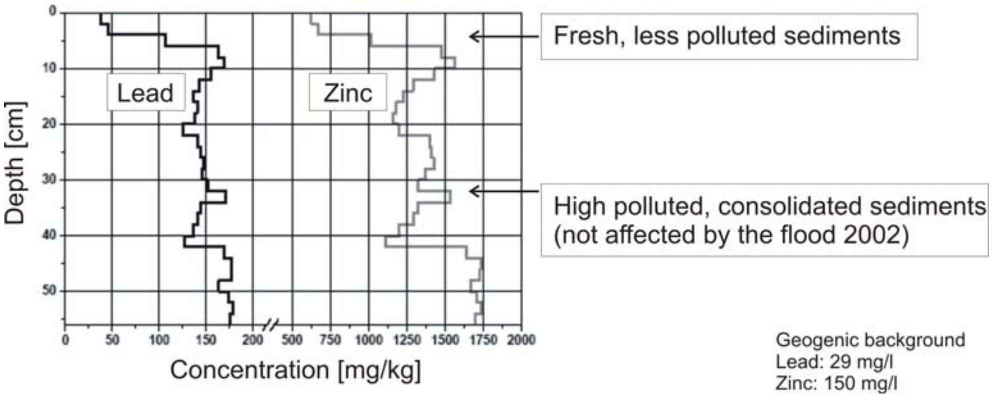
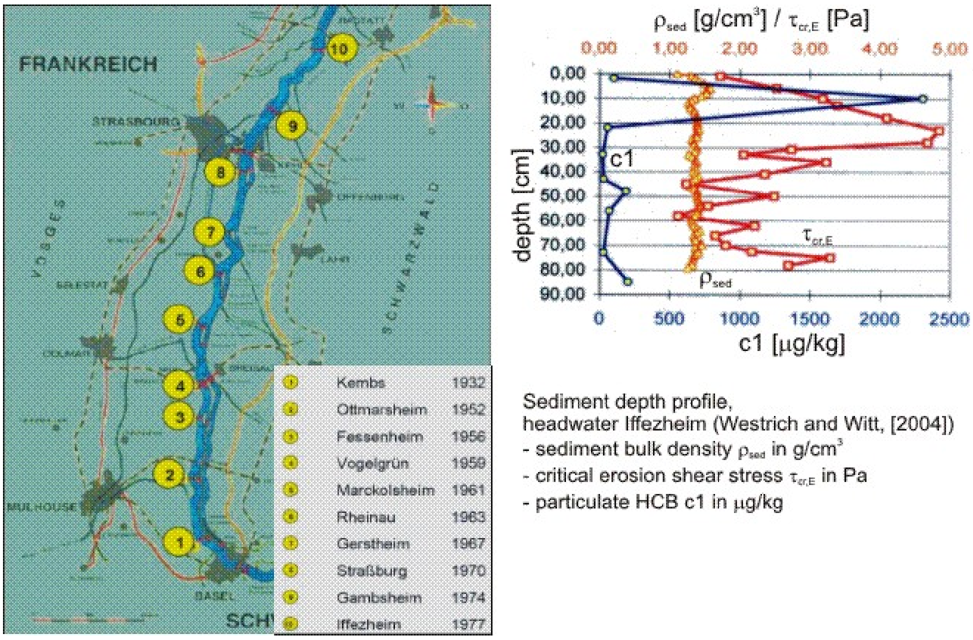


Figure 2. Depth profile of lead and zinc concentration, Elbe km 420,9 [Schwartz and Kozerski, 2004].

5. MODEL APPLICATION

5.1 Hot spots in the headwaters at the Upper River Rhine hydropower stations

The headwaters of the hydropower stations at the Upper River Rhine (built in the years 1961 to 1977) are considered to be one of the most important depots of contaminants in terms of toxicity and total amount in the Rhine catchment (Fig. 3). The headwater area shows characteristic sedimentation pattern as depending on the arrangement of the hydropower, the spillway section and the ship lock. The objective was to estimate the total mass of eroded particulate HCB (Hexachlorobenzene) during the flood in 1999 in a retrospective manner. Each of the six reservoirs was investigated to estimate the mass of eroded HCB and to quantify the cumulative contribution of each reservoir to the total particulate HCB load released to the Lower River Rhine and monitored at the German/Dutch border. Unfortunately, prior to the flood no data on deposited sediments were available. The river discharge hydrograph, the suspended sediment outflow concentration and the associated daily HCB load through the turbine section were given and used as boundary conditions.



Sediment depth profile,
headwater Iffezheim (Westrich and Witt, [2004])
- sediment bulk density ρ_{sed} in g/cm^3
- critical erosion shear stress $\tau_{cr,E}$ in Pa
- particulate HCB c1 in µg/kg

Figure 3. Layout of the hydropower stations at the Upper River Rhine, with a representative sediment core analysis.

Despite the extensive post-flood field investigation at the upstream station Marckolsheim the uncertainty of the calculated eroded particulate HCB was unsurprisingly high. The main reason was the small number of sediment samples, and the high spatial variability of sediment erodability and contaminant content of the post-flood samples (Fig. 3). The estimated eroded mass of HCB during the flood ranges from 2.4 to 17 kg with an average of 5 kg (Table 1). The computed values are beyond the ICPR (International Commission for the Protection of river Rhine) target value of 1.3 kg referring to a maximum permissible sediment contamination of 40 µg/kg for HCB [Jacoub, 2004].

Table 1. Particulate contaminant mass eroded during the flood in 1999 in the headwater of the lower six hydropower stations at the Upper River Rhine [Jacoub, 2004].

hydropower station reservoir	contaminated area (10^3 m^2)	particulate HCB (kg)	specific HCB mass content (g/m^2)	uncertainty assessment
Marckolsheim	54	5	0.11	underestimated
Rheinau	13	10	0.08	estimated
Gerstheim	178	14	0.08	plausible
Strasbourg	230	23	0.10	plausible
Gambsheim	68	6	0.09	highly underestimated
Iffezheim	36	3	0.08	highly underestimated
Total		61 (145 measured)		highly underestimated

According to the numerical results of the investigated reservoirs the total mass of HCB mobilized during the flood in all six reservoirs mounts up to some 61 kg which must be considered an underestimation because of the fact that the computation was performed based on contamination data which were measured after the flood and averaged over the erosion depth of about 0,1m. Beside the numerical results, it is evident that the measured value of 145 kg HCB must be considered too low because the samples were taken in front of the turbines (right side river branch with discharge capacity of 1050 m^3/s) instead in the main stream through the weir branch (with discharge of 2900 m^3/s) and hence, the measurements can only capture a fraction of the total load.

4.2 Sediment dynamics in the near bank water zones of the River Elbe

The study aims at modelling the effect of the near bank river training works, so called groyne fields, on the transport dynamics of suspended sediments and particulate pollutants for different hydrological scenarios of the Elbe catchment. The interaction between the groyne fields and the main channel was investigated over a 112 km long stretch of the river Elbe to describe sedimentation during low flow periods and erosion during high discharge periods. The study includes the contribution of two major tributaries to the potential pollution of the main channel sediments (Fig. 4). To provide the lateral exchange coefficient and the overall sedimentation coefficient of the groyne field for the 1-d modelling laboratory experiments were performed. In addition, to provide high spatial resolution a depth averaged 2-d model for detailed local investigation of sedimentation, erosion processes in the groyne fields of a 50 km long inner section was applied and used to support and underline the 1-d model results. The 2-d model was partly calibrated on and applied to the extreme flood event of August 2002 as shown by the following results.

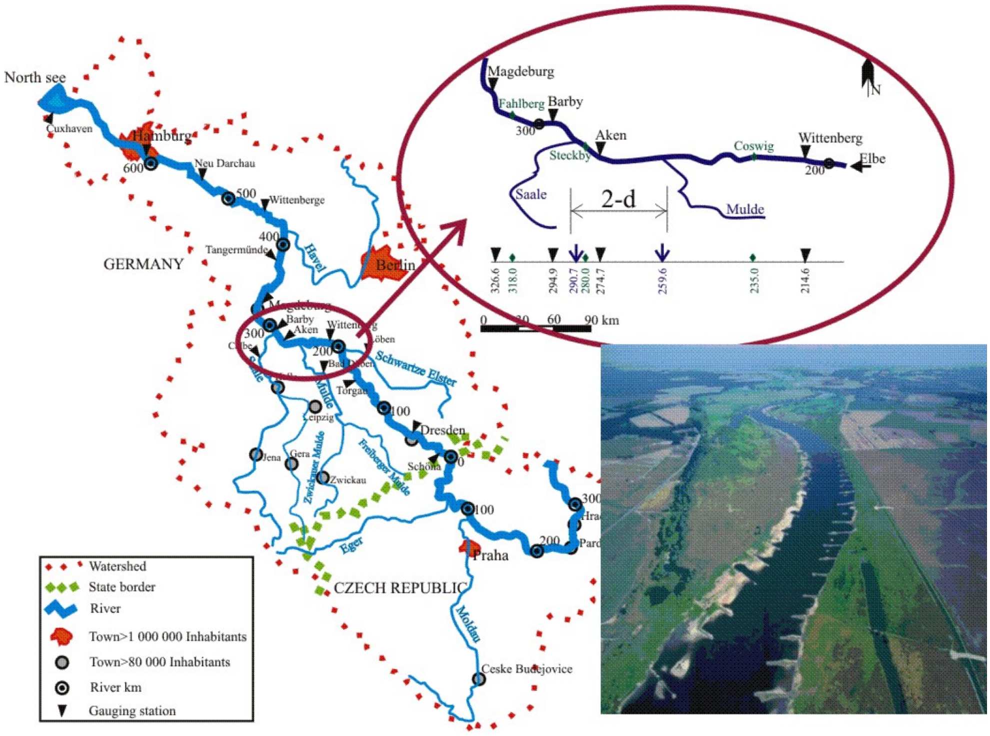


Figure 4. River Elbe catchment with a 112 km long section for numerical model investigation on the effect of groyne fields on the transport dynamics.

During the low discharge periods, from 1-st to 10-th August 2002, the river discharge was about 220 m^3/s with small flow velocities up to 0.8 m/s. Suspended sediments are in part deposited in the groyne fields (Fig. 5). The local sedimentation rates vary between about 5 x 10^{-5} – 5 x 10^{-6} kg/m^{2}s. High sedimentation occurs in the groyne fields and at the mouths of the tributaries Mulde and Saale as compared to the main channel. At the flood peak with Q=3965 m^3/s at 19-th August 2002, the flow velocities mounted up to 2.2 m/s and erosion mainly occurred in the groyne fields. The water depth on the flood plains is about 2.5 m and the velocity about 1.4 m/s. Due to high flow resistance of the river training works the maximum flow velocity near the banks is in the range of 0.8-0.9 m/s. The inflowing suspended sediment concentration at the upstream boundary increases to its maximum value of 0.096 kg/m^3. The maximum concentration reaches a value of 0.11 kg/m^3 in the groyne fields due to erosion (Fig. 5).

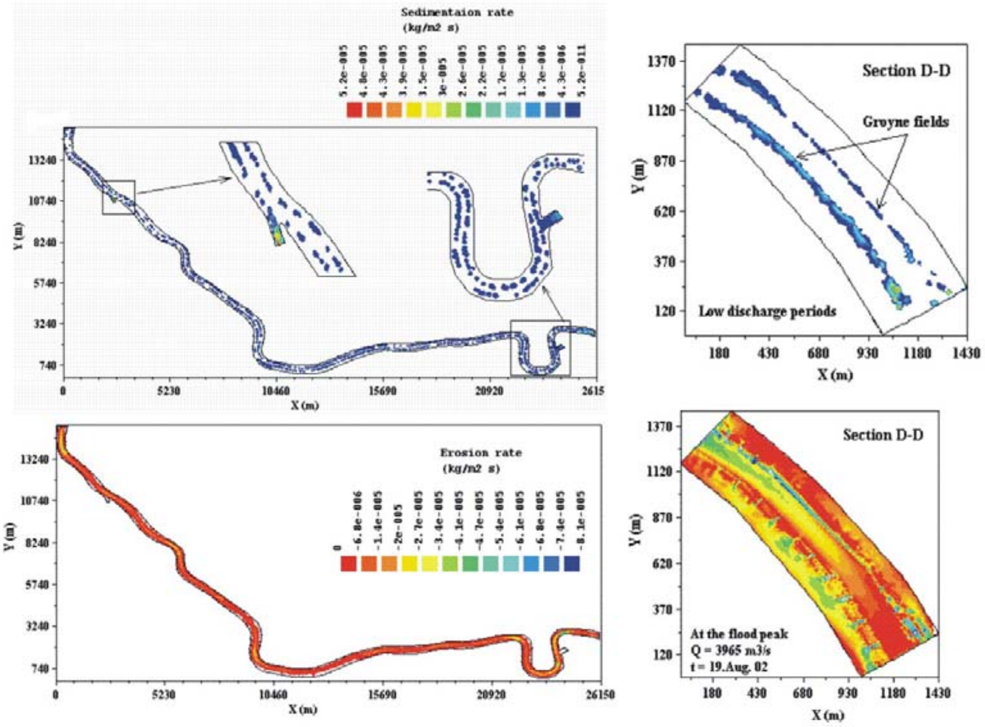


Figure 5. Numerical results: sedimentation and erosion in the groyne fields of the 50 km section embedded in the 112 km section of the 1-d model [Jacoub and Westrich, 2006].

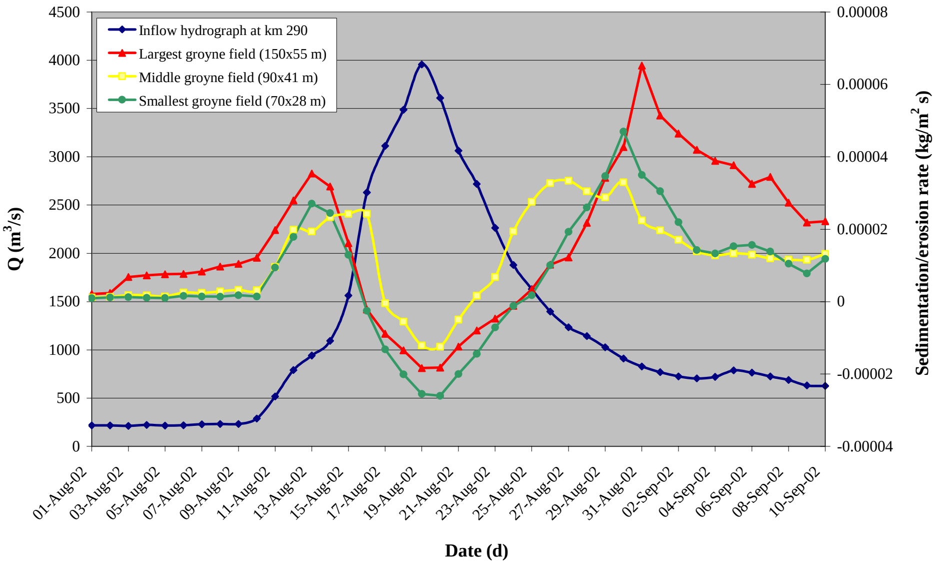


Figure 6. Spatially averaged sedimentation and erosion rates in three different types of groyne fields during the flood in August 2002 [Jacoub and Westrich, 2006].

Erosion rates also vary by an order of magnitude, i.e. from 7 x 10^{-6} – 7 x 10^{-5} kg/m^{2}s. The average erosion depth in the groyne fields varies from 0.004-0.02 m depending on time as well as size, shape and inclination angle of the groyne structure to the flow direction. The transport dynamics is clearly illustrated by the discharge controlled alternating sedimentation and erosion processes as shown by the model results in Fig. 6.

The 1-d strip model was used to investigate the long range sedimentation and erosion dynamics for selected hydrological scenarios. The results show the influence of a typical flood event in the catchment of the major polluter Mulde depicted in Fig. 7 as: (a) the longitudinal development of the spatially averaged deposition rate D in kg/m^{2}d in the left groyne fields, (c) the cumulative deposition in the groyne field approaching about 45% of the total input, and (d) the nearly exponential decrease of suspended matter concentration in the main channel with the dilution effect of the lower tributary Saale. The suspended sediment concentrations both in the main channel C_{mainch} and the adjacent groyne fields C_{gf} are larger but still proportional

$$c_{gf} = \alpha \cdot c_{main\ ch}$$

$$\alpha = \frac{1}{1 + \dfrac{\xi \, v_s \, b}{\varepsilon \, u \, h}}$$

(ξ = sedimentation coefficient, ε = exchange coefficient, b = groyne width, h = water depth, u = main channel flow velocity) however, the depositional adaptation length is significantly shorter in nature compared to the 1-d results. However, the total amount of deposited sediments in not affected by the 1-d approach. Despite the fact that the 1-d strip model is a simplified approach it shows the function of the groyne fields as sinks and sources of deposits and the influence of tributaries. The scenario of a 100 years flood event shows that about 33 % of the total inflowing suspended sediments are deposited on the flood plains, which is a reasonable figure compared to 27 % resulting from the mass balance of the spring flood in 2006 over a river section of 69 km as evaluated by Krüger and Jancke (not published).

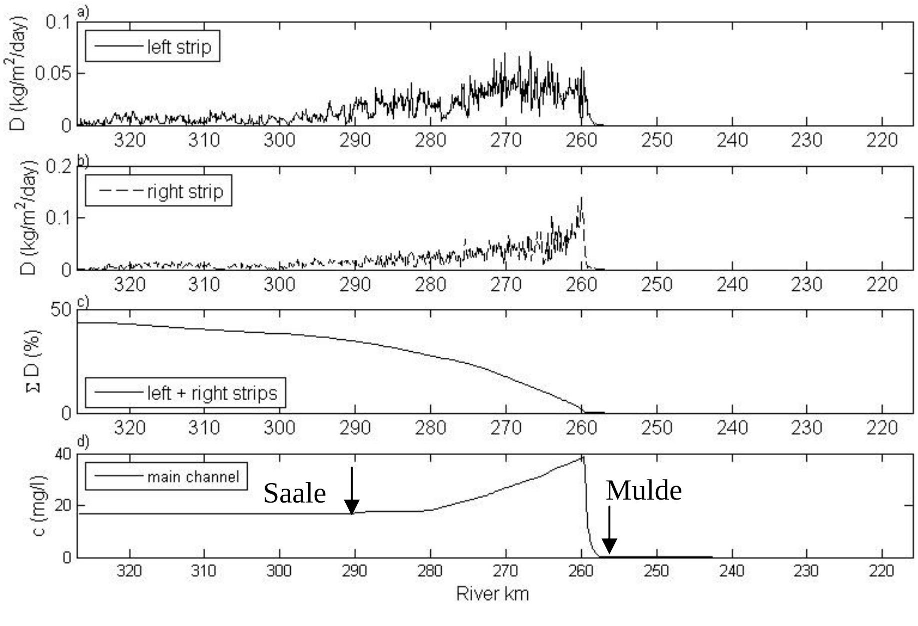


Figure 7. Longitudinal development of sediment deposition in the groyne fields due to input from the tributary Mulde and the dilution due to Saale [Westrich and Prohaska, 2008].

5. CONCLUSIONS

Numerical models are useful tools to investigate sediment associated pollutant transport processes in natural rivers, navigational channels and backwaters. Erosion, dispersion and deposition of mobilized sediments can be predicted on river basin scale as basic information for an environmental risk assessment. Field measurements are required to capture the large spatial variability of both sediment properties and contaminant inventory and to improve the quality of the model predictions towards risk assessment and efficiency of remediation measures. Contaminated sediment transport models allow to bridge the gap between emission and immission issues as required by the EU Water Framework Directive WFD. Numerical models provide basic information for a site specific risk assessment by tracing mobilized hot spots and localizing pollutant sources. They can also be used by stakeholders and decision makers, e.g. water authorities, water and environmental engineers, to establish a risk based sediment management at the catchment scale.

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REFERENCES

Förstner, U., S. Heise, R. Schwartz, B. Westrich and W. Ahlf, Historical Contaminated Sediments and soils at the river Rhine basin scale, *Journal of Soils and Sediments* 4(4) 247-260, 2005.

Gerbersdorf, S., T. Jancke, and B. Westrich, Physico-chemical and biological sediment properties determining erosion resistance of contaminated sediments - Temporal and vertical pattern at the Lauffen reservoir river Neckar, Germany, *LIMNOLOGIA*, 35, 132-144, 2004.

Jacoub, G., Development of a 2-D Numerical Module for Particulate Contaminant Transport in Flood Retention Reservoirs and Impounded Rivers, Ph.D. thesis, University of Stuttgart, Heft 133, ISBN 3-933761-36-0, 2004.

Jacoub, G., and B. Westrich, Modelling transport dynamics of contaminated sediments in the headwater of a hydropower plant at the Upper river Rhine, *Acta hydrochimica and hydrobiologica*, 3 (3), 2006.

Jancke, T., S. Prohaska, and B. Westrich, Analysis and evaluation of data on river morphology, to identify sedimentation and erosion areas, MODELKEY scientific report, 2006.

Li, C.C., Deterministisch-stochastisches Berechnungskonzept zur Beurteilung der Auswirkungen erosiver Hochwasserereignisse in Flussstauhaltungen, Ph.D. thesis (in German), Universität Stuttgart Mitteilungen, Heft 129, ISBN 3-933761-32-8, 2004.

Prohaska S., and B. Westrich, One-dimensional multi-strip transport model for long distance sediment transport in navigation channels, case study the River Elbe, paper presented at 23. Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management, Belgrade, Serbia, August, 2006.

Schwartz, R., and H.P. Kozerski, Bestimmung des Gefahrenpotenzials feinkörniger Buhnenfeldsedimente für die Wasser- und Schwebstoffqualität der Elbe sowie den Stoffeintrag in Auen, In: Geller et al. (Eds): *Schadstoffbelastung nach dem Elbe-Hochwasser 2002*, UFZ, Magdeburg, 2004.

Westrich B., and U. Förstner, *Sediment Dynamics and Pollutant Mobility in Rivers – an interdisciplinary approach*, Springer, Heidelberg, 2007.

Westrich, B., and S. Prohaska, Exposure modelling aiming at the prediction of spatial distribution of deposited particulate key toxicants for different hydrological scenarios of the River Elbe and its tributaries, MODELKEY scientific report, 2008.