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Deposition and Resuspension of Sediments in Near Bank Water Zones of the River Elbe

S. Prohaska\textsuperscript{a} and B. Westrich\textsuperscript{b}

\textsuperscript{a} Institute of Hydraulic Engineering, University of Stuttgart, Pfaffenwaldring 61, 70550 Stuttgart, Germany (sandra.prohaska@iws.uni-stuttgart.de)

\textsuperscript{b} Institute of Hydraulic Engineering, University of Stuttgart, Pfaffenwaldring 61, 70550 Stuttgart, Germany (bernhard.westrich@iws.uni-stuttgart.de)

Abstract: Catchment processes, such as spatially and temporally distributed rainfall, influence quantity and quality of river runoffs and thus, the transport of particulate sediments and associated contaminants in a river network. During flood events resuspension of contaminated sediments impacts the water quality and thus, it is important to determine the erosion probability of such deposits. The research is focused on the River Elbe deposits in groyne fields and their sediment dynamics. High percentage of contaminated deposits in the groyne fields originate from the tributary Mulde, which discharges high concentrations of arsenic and lead into the Elbe [Kraft, 2007]. Various hydrological scenarios were investigated for a 112 km long river reach of the Middle Elbe to predict the spatial distribution of the particulate suspended sediments and associated contaminants. The scenario results gave the estimation of erosion probability and pointed out the importance of the Mulde as the main contributor to the groyne field deposition and their potential source of contamination.

Keywords: river Elbe, transport modeling, suspended sediments, groyne fields.

1. INTRODUCTION

Describing the movement of suspended particulate matter in a river is important for ecological and water quality issues due to toxicity of adsorbed sediment bound contaminants. Numerical modeling of the suspended sediment transport contributes to better understanding of spatial and temporal distribution of ecologically interesting parameters, such as concentration in the water column, particulate deposition/erosion, deposited/eroded mass, etc. Fluvial hydraulics is the control mechanism of sediment transport. Therefore, modeling of different hydrological scenarios is a prerequisite for assessing ecological effects of toxicants to biodiversity. Various hydrological scenarios were applied to the River Elbe to predict the behavior of particulate suspended sediments and associated contaminants. The goal is to estimate the effect of the Elbe discharge on sedimentation and erosion in near bank groyne fields, and influence of a flood on dispersion and transport distance; and to determine the effect of contaminant inflow from tributaries and their spatial deposition in the Elbe. The scenarios results were used to estimate erosion probability as an important tool for decision making. The idea is to present a simple method to characterize the probability of erosion for contaminated sediment deposits in the groyne fields in terms of discharge probability.
2. HYDROLOGICAL SCENARIOS

The current research is focused on the Middle Elbe as a representative reach, for which the flow field is influenced by groyne structures on both river banks, see left panel of Fig. 1. The simulated domain extends from Wittenberg (km 214.1) to Magdeburg (km 326.6), comprising the influence of the tributaries Mulde (km 259.6) and Saale (km 290.7). The model used for numerical simulations is a 1D multi-strip model developed to predict the transport of suspended sediments in rivers trained by groynes [Prohaska and Westrich, 2006]. The model allows the subdivision of cross sections into three compartments in order to comprise the influence of groyne fields on flow and transport, refer to the right panel of Fig. 1.

Figure 1. Left panel: Middle Elbe and model area from Wittenberg to Magdeburg; right panel: Typical cross section of the River Elbe and simulated scenarios (I-IV) with model simplification and subdivision into strips.

The model parameters are listed in Tab. 1. The mass exchange parameter (ε), which accounts for the exchange of suspended sediments between adjacent strips, was measured in the laboratory, as well as the averaged sedimentation parameter (ξ). The geometry conditions and model parameters were kept constant during all simulations. In all simulations the discharge of the Saale had a constant value of 115 m³/s, and no suspended load. Therefore, the influence of the Saale was only by dilution, whereas the effect of a tributary on the transport processes was analyzed by the Mulde. Inflowing suspended sediment concentration and discharge in both the Elbe and the Mulde varied depending on the applied hydrological scenario. All input hydrographs are based on measured data. The model parameters are listed in Tab. 2.

Table 1. Model parameters for flow and transport used in the numerical simulations.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
<th>comment</th>
</tr>
</thead>
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<tr>
<td>n*</td>
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<td>m⁻¹/³ s</td>
<td>calibrated</td>
</tr>
<tr>
<td>n**</td>
<td>0.200</td>
<td>m⁻¹/³ s</td>
<td>calibrated</td>
</tr>
<tr>
<td>d₅₀</td>
<td>50</td>
<td>µm</td>
<td>measured</td>
</tr>
<tr>
<td>ξ</td>
<td>0.3</td>
<td>-</td>
<td>measured</td>
</tr>
<tr>
<td>ε</td>
<td>0.018</td>
<td>-</td>
<td>measured</td>
</tr>
<tr>
<td>τₑ,E*</td>
<td>14.88</td>
<td>Pa</td>
<td>measured</td>
</tr>
<tr>
<td>τₑ,E**</td>
<td>3.05</td>
<td>Pa</td>
<td>measured</td>
</tr>
</tbody>
</table>

*main channel; **side strip

Table 2. Hydrological scenarios with input data: discharge Q [m³/s], suspended sediment concentration [mg/l].

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Elbe Q</th>
<th>Elbe c</th>
<th>Mulde Q</th>
<th>Mulde c</th>
<th>Saale Q</th>
<th>Saale c</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>367</td>
<td>58</td>
<td>64</td>
<td>30</td>
<td>115</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>700</td>
<td>58</td>
<td>64</td>
<td>30</td>
<td>115</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>1790-3500</td>
<td>58-150</td>
<td>64</td>
<td>23</td>
<td>115</td>
<td>0</td>
</tr>
<tr>
<td>IV</td>
<td>367</td>
<td>0</td>
<td>61-150</td>
<td>30-60</td>
<td>115</td>
<td>0</td>
</tr>
</tbody>
</table>
Estimation of the main river effect on the contaminant sediment dynamics was performed focusing on different scenarios: (I) discharge that is smaller than erosive, (II) critical discharge at which erosion starts, (III) an extreme flood discharge, and (IV) the influence of a tributary on sediment deposition, see Tab. 2.

3. MODELING RESULTS

3.1 Constant discharge periods

In order to explore the long lasting deposition of contaminated sediments in groyne fields and whether erosion occurs in groyne fields for a flood of less than one year return period ($Q_{1}=876 \text{ m}^3/\text{s}$), numerical simulations of a mean discharge (scenario I) and small flood discharge with water level above groyne crests, but still lower than the bank elevation (scenario II) were performed. In both scenarios a constant inflow of suspended sediments in the Elbe was applied.

During 30 days (scenario I) around $367 \text{ m}^3/\text{day}$ of sediments were deposited in the groyne fields. In both the side strips there is a constant total sedimentation rate of about $172 \text{ t/day}$. The domain which is influenced by the Elbe sediment inflow is longer than the computational domain, i.e., small deposition in groyne fields still occurs 100 km downstream. In the upstream section of about 10 km the trapping effect of the near bank groyne field is very strong due to high lateral exchange with groyne fields. About 28% of total sediment inflow is deposited in groyne fields. Further downstream, at the Mulde mouth the deposition gradient again increases due to sediment inflow from the tributary.

![Figure 2. Longitudinal profiles after 4 days, scenario II: a) deposited and eroded mass of sediments per unit area of a side strip per day, for the left and b) right strip; c) cumulative mass of deposited sediments in both side strips in percentage of total sediment inflow; and d) suspended sediment concentration in the main channel.](image)

After four days of constant discharge of $700 \text{ m}^3/\text{s}$, around $83 \text{ m}^3/\text{day}$ of particulate sediments were deposited in the groyne fields. A deposition rate of $159 \text{ t/day}$ is smaller compared to the previous scenario I, due to increased discharge and erosion occurrence. Downstream of the Mulde mouth erosion occurs in some groyne fields, see Figs. 2a) and
b). However, the amount of eroded sediments is not big enough to influence the total mass balance. This is due to the fact that erosion occurs in only 1 % of all the groyne fields during the Elbe discharge of 700 m$^3$/s, which is considered as erosive discharge. As in the previous scenario I, the highest deposition occurs in the upstream section of the river (see Fig. 2d)) at the first 10 km. The deposition rate decreases nearly exponentially with increasing distance from the upstream model boundary, because of the relatively high lateral gradient dispersion of suspended sediments into the dead zones. In Fig. 2c) it is shown that around 25 % of the total sediment inflow was deposited in groyne fields over 4 days, which is somewhat smaller compared to the scenario I. The dilution by the Saale and decrease of the slope at km 290.7 is not clearly indicated due to small discharge increase after the Saale by 16 % only.

3.2 An Extreme Flood Event with Overbank Flow

Recently, severe precipitation for a number of days and snowmelt induced several extreme floods in the Elbe basin. These rare events, which occurred in summer 2002 and spring 2006, caused record water levels and worst flooding in the Elbe since the last 100 years. During the flood in 2002, transport characteristics have changed due to dyke breaching and top layers of fine sediments from groyne fields have been eroded [Baborowski et al., 2004; Schwartz, 2006]. Therefore, after the flood in 2002 many special measuring programmes were launched to assess sediments and pollutants. Assuming that top layers have been eroded and more resistant layers remained, less erosion could be expected if the same flood discharge occurs again. This was confirmed by measurements during the flood in spring 2006, i.e., in mass balance deposition was higher than erosion. The goal of the performed scenario is to determine transport characteristics of the Elbe during an extreme flood event (scenario III). A four days flood wave was applied starting with a discharge of 1790 m$^3$/s and reaching a peak of 3500 m$^3$/s, which corresponds to a 100 years return period flood. Inflow suspended sediment concentration follows the hydrograph.

![Figure 3](image)

Figure 3. Deposited and eroded sediment volume in the side strips along the 112 km river stretch, scenario III.

In both side strips erosion and deposition occur depending on geometrical and flow conditions, see Fig. 3. With increasing discharge deposition increases due to higher lateral dispersion. However, in some groyne fields erosion increases due to the increase of flow velocity in side strips itself. Maximum increase of both erosion and deposition rates (kg/day) occur during peak discharge. Afterwards, discharge decreases and consequently, erosion and deposition rates decrease as well.

The results show that both erosion and deposition are significantly higher compared to scenario II. The number of groyne fields with erosion is increased to 30 %, whereby 63 % of all groyne fields have deposition and 7 % show both deposition and erosion depending on time. The areas of erosion and deposition can be roughly estimated, refer to Fig. 4. In
the first 35 km mainly deposition takes place, whereby in the next 10 km erosion occurs until the Mulde mouth. Inflow suspended sediment concentration from the Mulde produces predominated deposition, which extend about 100 km downstream. At the end of the simulated river reach of 112 km, 33 % of the total inflow sediment mass was deposited. However, it is assumed that most of the sediments are deposited in flood plains. Keeping in mind the simplification made by the multi-strip model that side strips of the model comprise both the groyne fields and the flood plains, sediments in the groyne field might be eroded and deposited on flood plains. However, in total mass balance for the side strip deposition occurs.

The numerical estimation of the net deposition can be compared with the measurements during the spring flood in 2006, which had a maximum discharge of 3000 m$^3$/s at Rosslau (km 258) and lasted for 14 days. The inflow of suspended sediments from the Mulde and Saale was measured together with the suspended sediment concentration at Rosslau and Magdeburg (km 326.6). A robust estimate of total mass balance for the river stretch of 69 km indicated that a net deposition occurred during the flood, i.e., that 27 % of total sediment inflow was deposited in the domain, mainly on floodplains. In summary, the simulated extreme flood had the same peak discharge as the measured one and good agreement could be found.

**Figure 4.** Longitudinal profiles after 4 days, scenario III: a) deposited and eroded mass of sediments per unit area of a side strip per day, for the left and b) right strip; c) cumulative mass of deposited sediments in both side strips in percentage of total sediment inflow; and d) suspended sediment concentration in the main channel.

3.3 Impact of a Particulate Contaminant Load Associated with a Flood in the Tributary

The goal is to estimate the effect of particulate contaminant inflow from a tributary and its influence domain in the Elbe (scenario IV), excluding adsorption and degradation processes. Highly contaminated deposits in the groyne fields along the Elbe presumably originate from the tributary Mulde, which discharges high concentrations of arsenic and lead [Kraft, 2007]. Therefore, a hydrological flood scenario was applied on the Mulde in order to determine the effect and spatial extension of its influence with regard to potential deposition of particulate contaminant. It is important to emphasize that the 1D multi-strip
model cannot account for the lateral mixing in the main channel, which can be up to about 40 km in the case of a river trained by groynes [van Mazijk, 1996]. In the multi-strip model a tributary inflows into the main channel and a fully mixed situation occurs resulting in deposition in both side strips. In a reality, deposition would occur mainly in the left groyne fields until a fully mixed situation is reached.

A four days flood scenario was applied on the Mulde, starting with a mean discharge of 64 m³/s and reaching a peak discharge of 150 m³/s after one day. Water levels were below the groyne crests along 112 km of the Elbe reach, meaning that the contribution of the Mulde flood on the Elbe discharge was insufficient to cause overtopping of the groynes. Suspended sediment concentration from the Mulde follows the discharge hydrograph.

The results show that the flood produces an immediate deposition in groyne fields along the Elbe. Increased discharge in the Mulde increases the flow velocities in the Elbe main channel and thus, the lateral transport into the adjacent strip is higher and consequently the deposition in groyne fields. Deposition patterns follow the concentration decay in the main channel (Fig. 5) whereby higher suspended sediment concentration leads to a higher concentration difference between main channel and groyne fields and consequently to a higher deposition in side strips. At the end of the simulated river reach deposition in groyne fields is still taking place. The longitudinal dimension of the deposition process can be estimated on 90 km. Furthermore, the cumulative mass of deposited sediments in side strips (Fig. 5c) indicates that deposition ceases about 20 km downstream of the model boundary. It is important to emphasize that 44 % of the total sediment inflow is deposited in groyne fields at the end. In summary, the Mulde flood has an impact on deposition in groyne fields, which is relevant for contaminant management strategies.

Figure 5. Longitudinal profiles after 4 days, scenario IV: a) deposited and eroded mass of sediments per unit area of a side strip per day, for the left and b) right strip; c) cumulative mass of deposited sediments in both side strips in percentage of total sediment inflow; and d) suspended sediment concentration in the main channel.

3.4 Estimates of Erosion Probability

The results of the performed hydrologic scenarios allow an estimation of the erosion probability. The frequency of erosion can be easily derived from discharge hydrology by hydraulic flow model. The proposed method uses a cumulative frequency distribution of
the discharge, which correlates to the cumulative frequency of erosion in order to estimate the probability of erosion in groyne fields. The cumulative frequency curve at Wittenberg is obtained based on measurements from 1936 to 1995. However, data from the recent extreme flood events are not included.

Flow velocity and water depth in the main channel are significant hydraulic parameters to characterize the river flow, refer to Fig. 6. Therefore, the results are shown in terms of the main channel flow velocity and the water depth to enable a transfer of results to other rivers with similar characteristics. Erosion starts in some groyne fields at low main channel flow velocity and it increases with increasing flow velocity, see Fig. 6b). The results indicate that during the period of low discharge, i.e., with less than one year return period, erosion of groyne field sediments is low. Increased discharges produce higher and intensive erosion however, their probability of occurrence is lower. Although the analysis presented here is simplified, it clearly illustrates the large spatial and temporal variation of sedimentation and resuspension in groyne fields.

![Figure 6.](image)

Figure 6. Overview of significant hydraulic parameters for the whole investigated river stretch of 112 km at mean, high, and extremely high discharge: a) water flow depth and flow velocity in the main channel; b) erosion and deposition rates depending on main channel flow velocity; c) erosion and deposition rates for different discharges; and d) discharge probability curve at Wittenberg.

4. CONCLUSIONS AND REMEDIATION MEASURES

Typical hydrological scenarios were applied on the 112 km long river reach of the Middle Elbe to estimate the longitudinal distribution of particulate suspended sediments, erosion, and deposition. Erosion is governed by the Elbe discharge and starts at about 700 m³/s. Considerable erosion occurs during overbank flow, and increases with increasing discharge. The domain affected by deposition is greater for higher discharges. The number of groyne fields subject to erosion increases with increasing flood, whereas about 30% of inflow sediments are deposited in the near bank stagnant water bodies.
The Mulde flood strongly effects the deposition in the groyne fields along the Elbe. Keeping in mind the contaminant inflow discharged from the tributary, 44% of deposited sediments in groyne fields indicate severe potential pollution. The Mulde influence domain is estimated to approximately 90 km, which confirms that the tributary is the main contributor to the Elbe pollution. Even though, the calculations were performed in a conservative way neglecting adsorption and degradation processes, the presented approach gives an estimation of deposition of particulate contaminants.

The assessment of erosion probability is a complex issue that needs to involve the interaction of the physical, chemical and biological sediment properties together with hydraulic bed shear stress. The results presented here as an example, are a preliminary attempt to address the erosion probability.

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REFERENCES
Baborowski M., W. von Tümpling and K. Friese, Behaviour of suspended particulate matter (SPM) and selected trace metals during the 2002 summer flood in the River Elbe (Germany) at Magdeburg monitoring station. Hydrology and Earth System Sciences, 8, 135-150, 2004.