Impact of projected climate change on transport of cohesive sediments and particle-bound contaminants in the impounded section of the Upper Rhine River

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Abstract Some climate projections for Germany indicate both increased flood frequencies and severities, which may lead to a re-mobilization of contaminated sediments in rivers. The project „Risks due to cohesive sediments“ is part of the recently established departmental research program KLIWAS (2009-2013) by the German Federal Ministry of Transport, Building and Urban Affairs. The project aims to analyse the impact of climate change on both sediment yield and sediment quality for optimising sediment management. Within the scope of this research project, sediment dynamics and contaminant transport in the Upper Rhine River between Weil and Iffezheim (impounded reach, km 170 to 340) are analysed by means of field and laboratory studies and numerical models. The methodology of the field studies and the numerical modelling is discussed in this paper.

Keywords climate change; sediment transport; contaminant transport; numerical simulation; field study

INTRODUCTION

In future, due to climate change, the frequency and magnitude of high floods in German rivers could increase and may lead to a re-mobilization of contaminated sediments. The project „Risks due to cohesive sediments“ is part of the recently established departmental research program KLIWAS (2009-2013) by the German Federal Ministry of Transport, Building and Urban Affairs. The project aims to analyse the impact of climate change on both sediment yield and sediment quality for optimizing sediment management. Within the scope of this research project, sediment dynamics and contaminant transport in the Upper Rhine River between Weil and Iffezheim (impounded reach, km 170 to 340) are analysed by means of field and laboratory studies and numerical models. The study focuses on determining potential risks by the erosion and relocation of contaminated cohesive sediments from and within impounded river reaches by climate change. We also aim to evaluate the influence of changes in maintenance strategies such as adjusted dredging periods or modes of operation of the barrages.

Field studies comprise chemical and sedimentological analyses of sediment samples from both suspended and deposited sediments. The scope of the field studies and the different methodological concepts are explained in this paper. The data from the field studies are complemented by laboratory experiments on the sorption of site-specific contaminants and on transport mechanisms of cohesive sediments.

These data sets are used as input data and to calibrate and validate numerical models of sediment and contaminant transport. Based on projections of climatic conditions, the model systems’ response to climate changes will be determined and evaluated. Simulations including different management strategies will enable governmental and other affected institutions to adapt to the impacts of climate change.

Study site

The catchment of the Upper Rhine River (area ca. 50000 km²) includes the Alpine Rhine and High Rhine catchments (Figure 1). Sediment loads in the river are affected by Lake Constance, by the river Aare and by a total of 21 impoundments along the High Rhine and the Upper Rhine. While Lake Constance and the impoundments mainly act as sediment traps, the river Aare is an important tributary of both flow and sediment load.

The study reach (cf. Fig. 1) of the Upper Rhine was strongly modified by river regulation. Along this reach, ten impoundments govern flow and sediment transport. Construction of the Great Alsace Canal and the barrages began in the late 1920s. Four

Fig. 1 Catchment of the Upper Rhine River. The study focuses on the highlighted (red) section of the Upper Rhine River.

impoundments are located in the Great Alsace Canal (Kembs, Ottmarsheim, Fessenheim, Vogelgrün). Another four impoundments are situated in lateral canals to which most of the river water is routed at these sections (Marckolsheim, Rhinau, Gerstheim, Straßbourg). Further downstream, two impoundments are built on-stream (Gambsheim, Iffezheim). Operation of the water power plant at the last barrage at Iffezheim started in 1978. Overall sedimentation rates in the impoundments along the Upper Rhine are estimated by average annual dredging volumes to amount to approximately 320000 m^3a^{-1} (Polschinski *et al.*, 2008).

During the 1970s and 1980s, hexachlorobenzene (HCB) was emitted to the High Rhine by chemical effluents. Although the emission was terminated in the early 1990s, contaminated sediments within the impoundments still pose a threat to the environment as contaminants re-enter the river load by remobilized sediments during flood events.

METHODOLOGY

Links between climate and transport of contaminated sediments exist on different levels:

1) **Sediment yield:** Input rates of sediment into rivers depend on soil erosion rates among other things. Climate change may affect soil erosion by varying rainfall intensities or by changes in land cover. The impact of changed rainfall intensities and distributions on sediment delivery rates into the river channel will be accounted for by modelling soil erosion in response to different climate projections with the help of a PESERA model (Kirkby *et al.*, 2008).
2) **Transport conditions:** Changes in discharges (seasonal distribution or frequency of high/low flow conditions) influence hydraulic conditions within the river channel. Those changes in hydraulic characteristics will affect sediment loads (deposition and erosion rates), which may in turn result in bed level changes that re-affect the hydraulics.
3) **Chemical or biological ambient conditions:** Other factors that relate to sediment and contaminant transport may as well be affected by climate change. Increasing water temperature may for example lead to increased algae bloom resulting in higher loads of suspended matter and an increase in algal toxins. The partitioning of contaminants is also dependent on water temperature which may lead to higher loads of dissolved contaminants. However, effects caused by changes in water temperature or biogenic effects that are related to sediment and contaminant transport are not considered within the scope of this research project.

Numerical Modelling

The numerical simulation of projected loads of sediments and contaminants reflecting the first two aspects mentioned above is realised by several different models on different scales. Long-term simulations with respect to the impact of projected climate change are carried out within a multi-model ensemble based on IPCC emission scenarios that includes global climate models, regional climate models, hydrologic catchment models, and hydraulic models. Projected hydrologic conditions derived within this model chain serve as input data to a soil erosion model and several transport models.

Figure 2 illustrates the different levels of modelling sediments and contaminants within the Upper Rhine catchment. On the catchment scale, soil erosion is modelled by means of the PESERA model (Kirkby *et al.*, 2008). Several different projections of hydro-meteorological conditions are used to calculate projected rates of soil erosion. The study aims to determine the span of changes in sediment yield due to climatic changes. Possible changes in future land use and agricultural technology are not taken into account.
Results of the PESERA model are used to assess changes in sediment yield.
Aside from projections of the hydrologic boundary conditions such as the river discharges, these are important input data to the long-term sediment transport

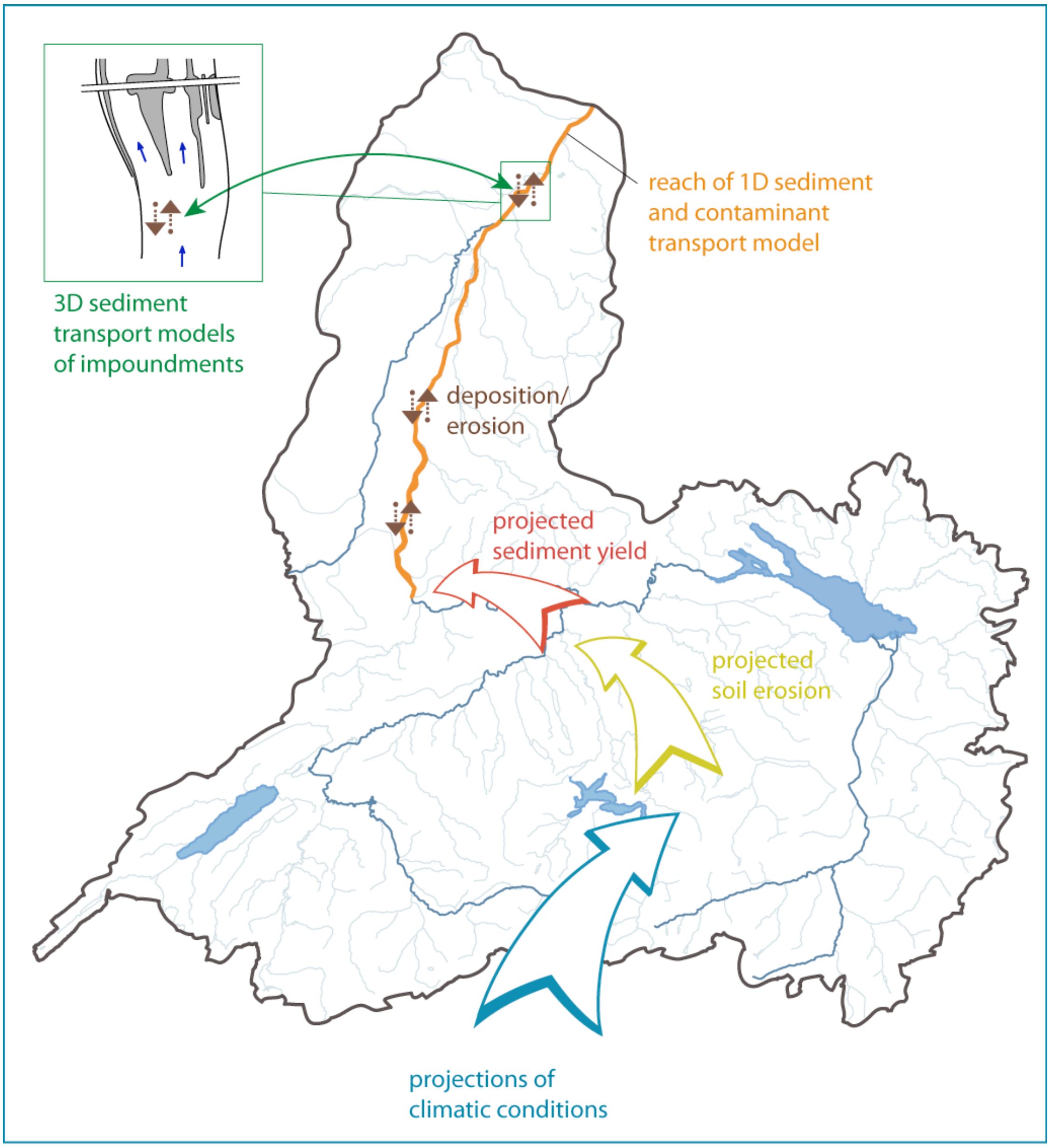

Fig. 2 Catchment of the Upper Rhine River. Illustration of the modelling layers concerning the sediment budget within the catchment.

simulations. Long-term simulations of the sediment and contaminant budget of the Upper Rhine reach as indicated in Fig. 2 are carried out by means of a 1D hydraulic model using the SOBEK-River software developed at Deltares. Near the barrages, where flow characteristics evidently are multidimensional and where sediment dynamics is most intense, the 3D model SSIIM (Olsen, 2009) is used. The 3D simulations comprise reaches of a few kilometres only and relatively short periods of time. Direct coupling of the 1D and 3D models is unfeasible because the 3D simulations are expensive in terms of computational time. Therefore, it is the overall effects in terms of sediment transport at the barrages that are transferred from SSIIM to the 1D SOBEK model.

Field data are used for the calibration and validation of numerical transport models.

Field Study of Sediment and Contaminant Transport Situation

The status quo of both sediment and contaminant transport is monitored at a number of locations along the Upper Rhine River (cf. Fig. 3). Concentrations of suspended sediments are determined by bucket samples at three measurement stations that have been in operation for more than 30 years. From these measurement stations, we get time series of weekday samples of suspended sediment concentrations. Recently, these discrete samples are being complemented by time-continuous turbidity measurements at four locations and one acoustic probe. As all those monitoring techniques only give information on sediment concentrations at one point, additional cross-sectional measurements by Acoustic Doppler Current Profiler (ADCP) are carried out. Typically, ADCP is used to measure flow velocities in cross-sections. As echo intensities of the sound wave emitted by the ADCP correlate to suspended sediment concentrations, ADCP data also give information on the cross-sectional distribution of sediment concentrations and loads.

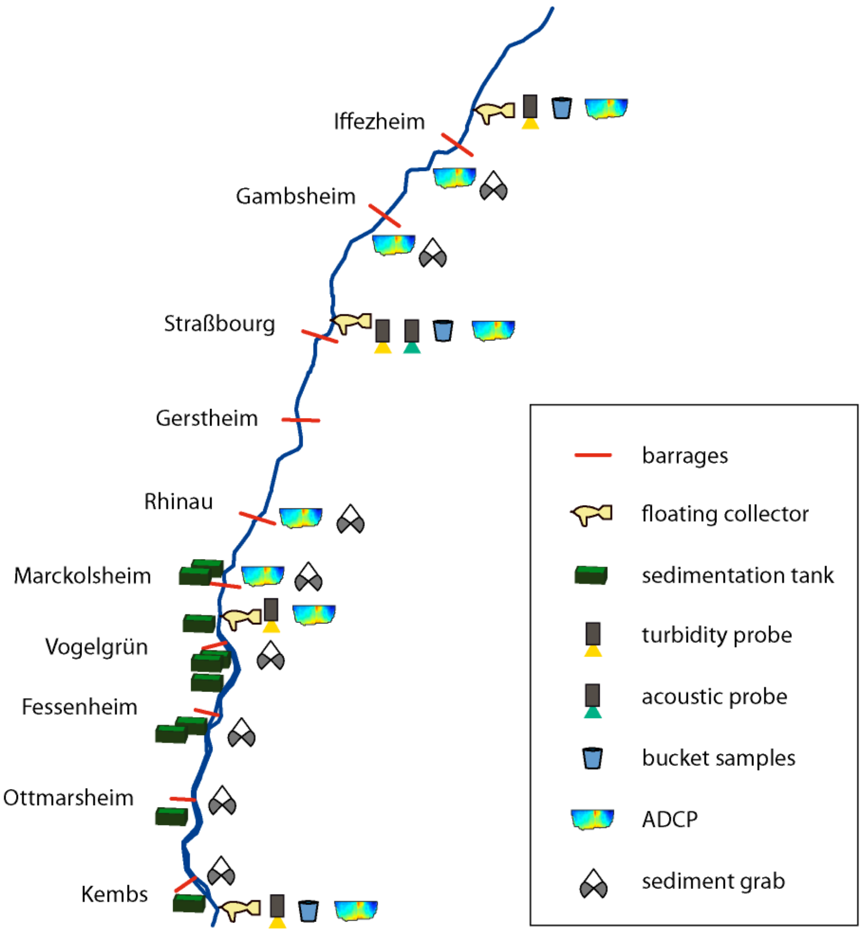

Fig. 3 Impounded section of the Upper Rhine River. Sediment monitoring techniques.

Contaminant transport is studied by analysing samples of suspended and deposited sediments. Two different collectors are used to collect suspended sediment samples: a box-shaped sedimentation tank and a more streamlined floating collector. Both use baffle plates inside the corpus to reduce flow velocities and increase sedimentation in the sample container. They collect integrating samples over two to four weeks and are known to favour coarser grain sizes. The data from these collectors are complemented by centrifuge samples at stations near the upstream and downstream end of the considered river reach (not shown in Fig. 3). Centrifuge samples are believed to better represent the actual grain size distribution of the suspended river sediments, sampling is usually done on a bi-weekly frequency. In-situ investigations of suspended grain sizes will be carried out with the aid of a microscope-optical system to evaluate the collected samples. All sediment samples – both from suspension and from deposited sediments within the impoundments – are analysed for a range of organic contaminants with a special focus on HCB which plays the most prominent role as pollutant at the Upper Rhine River.

The data from the field studies are complemented by laboratory experiments on the sorption of HCB and on transport mechanisms of the cohesive sediments. Sorption experiments provide information on partition coefficients and sorption rates to site-specific sediments and co-sorbates. On the one hand, this is important to gain further insight into the Upper Rhine system. On the other hand, these values are needed to calibrate numerical models.

CONCLUSIONS

In this paper, the methodology to determine the impact of climate change on the transport of contaminated sediments within the impounded section of the Upper Rhine River is presented. Prerequisite to this aim are sufficiently long time series of field measurements of key parameters to calibrate and validate numerical models. In order to model projected transport conditions, models need to be able to properly reproduce the corresponding physical processes, but also to be sufficiently simple to carry out a set of long-term simulations within a reasonable period of time. To this aim, a combination of a complex 3D model for special application near the barrages together with a simpler 1D model for modelling the sediment and contaminant budget of the whole reach were chosen.

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