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A new approach to investigate the interactions between sediment transport and ecotoxicological processes during flood events

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Abstract

Extreme hydrodynamic events such as flood events or dredging activities bear the risk of eroding sediments in rivers, reservoirs, harbour basins or estuaries. One of the key concerns associated with these erosion processes is the re-mobilisation of sediment-bound pollutants in highly contaminated sediments. To date, much research has been conducted to characterise flow and sediment processes associated with hydrological events such as floods. Furthermore, there is a large body of literature describing the interaction of contaminants associated with particulate matter to aquatic biota. However, there is little knowledge regarding interactions between hydro-sedimentological and ecotoxicological processes. Understanding of the ecotoxicological consequences and associated risks to aquatic wildlife associated with hydraulic events can provide critical information to regulatory bodies or managing authorities. Specifically, it will aid in assessing risks associated with current management practices and will aid in developing more sustainable future management practices for waterways or harbours. Therefore, a combined experimental methodology between hydraulic engineers and ecotoxicologists was developed to investigate the ecological and toxicological relevance of sediment re-suspension and transport during erosion. An overview of this methodology is given in the present paper.

Keywords: annular flume, contamination, ecotoxicology, floods, hydromechanics, sediment

Introduction

The objective of the Floodsearch project - which is funded by the Excellence Initiative of the German Federal and State Governments - is to combine the traditionally separated disciplines of hydraulic engineering and ecotoxicology in a single experimental approach in order to investigate the bioavailability and hazard potential of sediment-bound contaminants to aquatic organisms under simulated flood conditions. Depending on the flow velocity, sediments can either be eroded from or settle down in high and low flow sections in rivers, reservoirs and in harbour basins, respectively. In industrialised regions rivers and estuaries often contain large volumes of old cohesive sediments that can be polluted with toxic agents. Thus, the deposited sediments become a potential risk for the environment due to their ability to bind contaminants [1-3]. The behaviour of such contaminated materials during extreme hydraulic events is of particular interest because toxic fractions of eroded and newly suspended material can be re-suspended, and thus, become bioavailable in the water column again. Former investigations (cf. [4-6]) confirmed the bioavailability of previously immobilised particle-bound contaminants and concluded that re-suspension of sediments may have a major impact on aquatic biota. Unfortunately, no research is available combining hydraulic stresses, sedimentological response and resulting bioavailability of re-suspended contaminated sediments.

The Floodsearch project combines hydraulic and ecotoxicological (hydro-toxicological) methodologies in a

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joint experimental study [7]. The interaction of hydraulic processes, contaminated sediments and aquatic organisms is investigated under controlled laboratory conditions. The main advantage of these experiments is the simulation of the important processes in a single model set-up (hydraulic processes, sediment erosion, transport and deposition, bioavailability of the sediment bound contaminants and the ecotoxicological effectiveness in both *in vitro* and *in vivo* systems) (Figure 1). Therefore, this methodology presents considerable advantages for a better understanding and description of the relevant processes and interactions in the field.

Experimental set-up and test programme

One of the primary objectives of the Floodsearch project was to characterise re-suspended particle-bound contaminants in the water layer under simulated flood conditions, and to assess the ecotoxicological relevance of these re-suspended contaminants. This was done using an annular flume (Figure 2), adapted such that it enabled the exposure of fish under controlled environmental conditions [8]. In particular, the instrumentation to control environmental variables (water cooling, oxygen supply, etc.) and associated parameters (e.g., pH, temperature, etc.) was an important add-on for the project [8].

Two different series of experiments were carried out to investigate the impact of contaminated and re-suspended sediments on the test organism, rainbow trout (*Oncorhynchus mykiss*). One test series was conducted with organisms whereas the other test series was accomplished without fish. Every test with fish was performed with 15 individuals. Therefore, the impact of the sediments on fish was measurable. All experiments were performed under controlled hydraulic and sedimentological conditions. Artificial, multi-fractional sediment was used in each experiment. This sediment was composed of 5% peat, 20% kaolinite, 75% silica sand and 30% water [9]. A mixture of the following polycyclic aromatic hydrocarbons (PAH) was added to spike the sediments: pyrene (4.1 mg kg^{-1}), phenanthrene (5.0 mg kg^{-1}), chrysene (3.3 mg kg^{-1}) and benzo[*a*]pyrene (8.3 mg kg^{-1}). A total amount of about 700 kg artificial sediment was prepared for the experiments in the annular flume and half of the sediment was spiked with the above-described PAHs. This approach was intended to provide a standardised substrate with well-defined concentrations of the model substances. Recovery of PAHs by

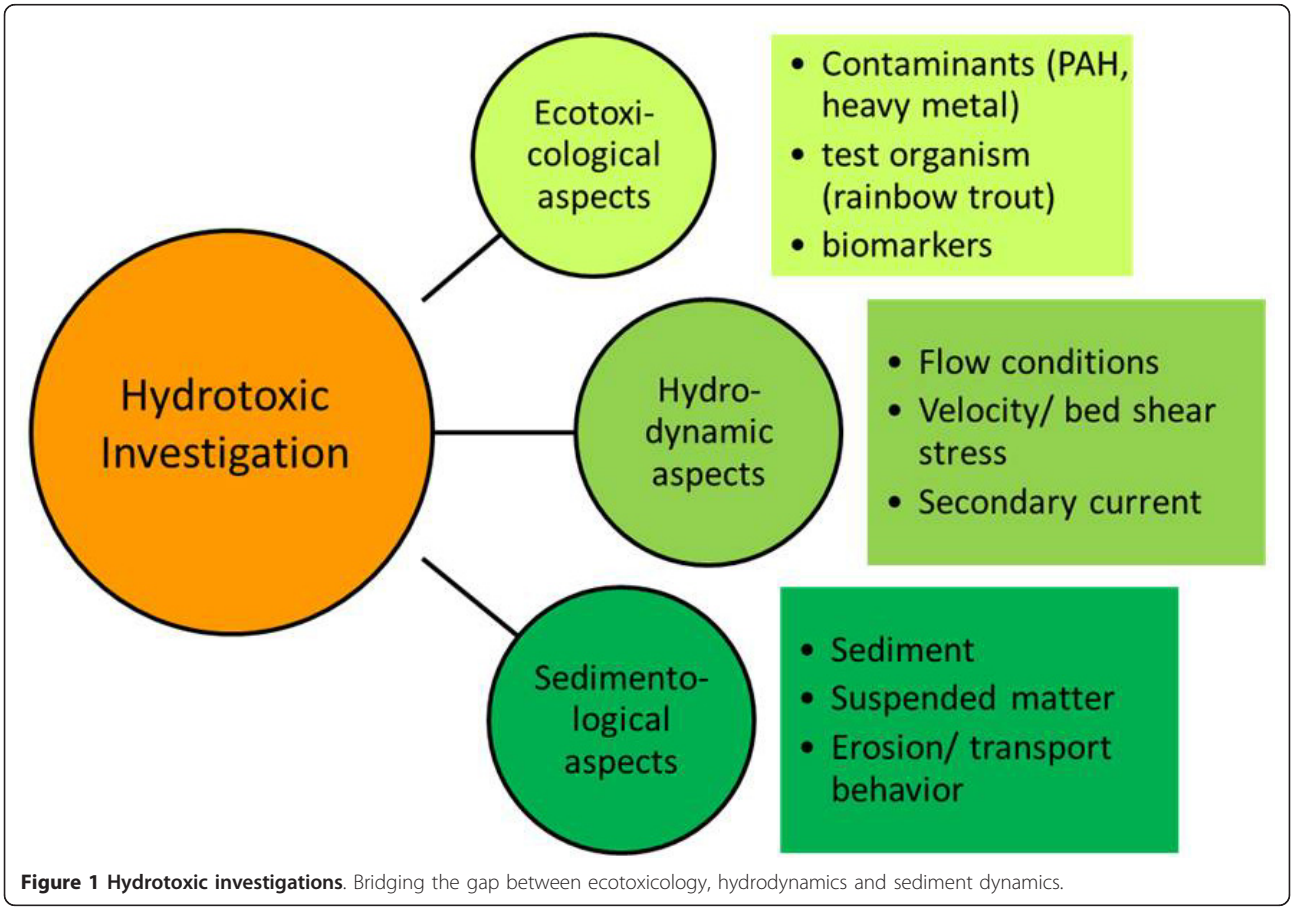

Figure 1 Hydrotoxic investigations. Bridging the gap between ecotoxicology, hydrodynamics and sediment dynamics.

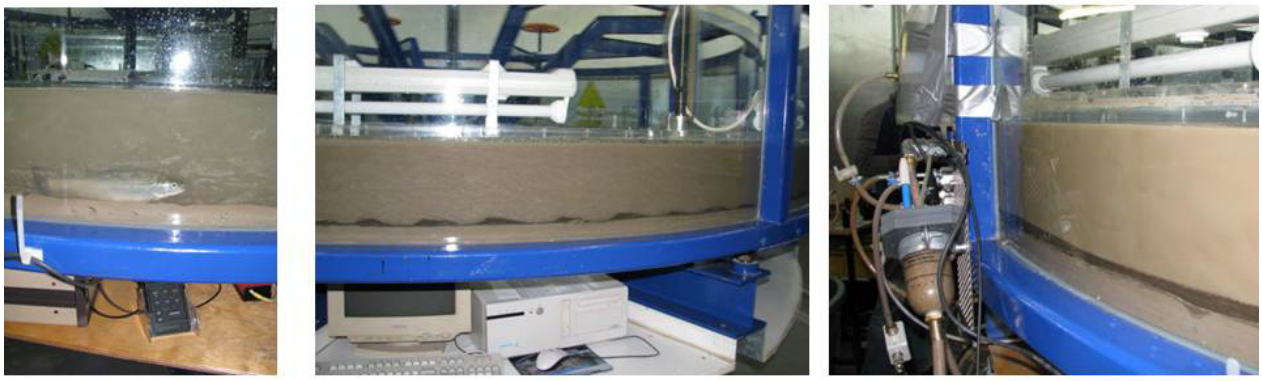

Figure 2 Annular flume. The annular flume at the laboratory of the Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Germany (left, rainbow trout; middle, formation of ripples; right, instrumentation to control environmental parameters).

instrumental chemical analyses ranged from 52% to 74%. After introducing sediment into the annular flume, it was carefully overlaid by water and consolidated for 3 days according to Schweim [10].

A flood curve was simulated according to the German DIN standard 4049-3 [11] resulting in a test duration of 5 days, a maximum velocity of 0.38 m/s and a maximum bed shear stress of τ = 0.40 N/m^2. Figure 2 depicts the evolution of the sediment movement during the simulated flood event. The model set-up and the environmental test conditions are described in more detail in [8].

Experimental results

Two types of experimental data were collected during the course of the tests described here. First, hydraulic, sedimentological and chemical parameters were collected to characterise the environmental conditions during the experiments. During the entire test duration the following physico-chemical parameters were logged and analysed. The mean oxygen content was C_{O_2} = 8.52 mg/l, the mean temperature was T = 12.66°C and the mean pH was pH 7.64. Measurements of physico-chemical water parameters demonstrated that a stable environment was established for the model organism, which represented one of the major challenges of this proof-of-concept study.

The characterization of sedimentological parameters resulted in critical bed shear stresses and temporal variations of suspended particulate matter (SPM). The concentration of SPM depends on the shear stress, sediment components, storage time of the sediment, and presence or absence of fish. Furthermore, the water content, the capacity of exchangeable cations, the organic matter and additional variables are responsible for erodibility of cohesive sediment [8]. The maximum concentration of SPM was 18.50 g/l. The critical shear stress is a measure for the initiation of erosion and is determined from the slope of the concentration progress during the flood event [8].The detailed results are described in detail in [8].

Second, a number of different biological endpoints were analysed at the end of the experiment to assess the impact of the flood event and associated re-suspension of contaminants on the test organism and to identify suitable endpoints for future studies. Biological endpoints measured included biochemical markers (7-ethoxyresorufin-*O*-deethylase, glutathione-*S*-transferase and catalase activity, lipid peroxidation), gene expression analyses (quantitative real-time RT-PCR), determination of cytochrome P450 1A1 (CYP1A1) protein content, chemical analysis of metabolites in bile (1-hydroxypyrene, 1-hydroxyphenanthrene and 3-hydroxybenzo[*a*]pyrene; Figure 3), and the micronucleus test with peripheral erythrocytes, a definite marker for chromosome damage. These biological endpoints are described in Brinkmann et al. 2010 [12].

There were no significant changes in any of the enzyme measurement endpoints following the exposure to particle-bound contaminants. In contrast, the micronucleus frequency was significantly (4.3-fold greater than controls) increased after exposure of trout to PAHs contaminated re-suspended sediments in the annular flume. The most sensitive biomarker to PAH exposure was the biliary concentration of PAH metabolites, demonstrating the uptake of particle-bound pollutants.

In contrast to the *in vivo* measurements, spiked sediments showed significantly elevated EROD induction compared to control sediments in an *in vitro* assay using the permanent cell-line RTL-W1. With bio-TEQs of approximately 900 pg g^{-1}, spiked sediments were within the range of activities that were reported in other studies investigating contaminated sediments in German river systems. Discrepancies between *in vivo* and *in vitro*

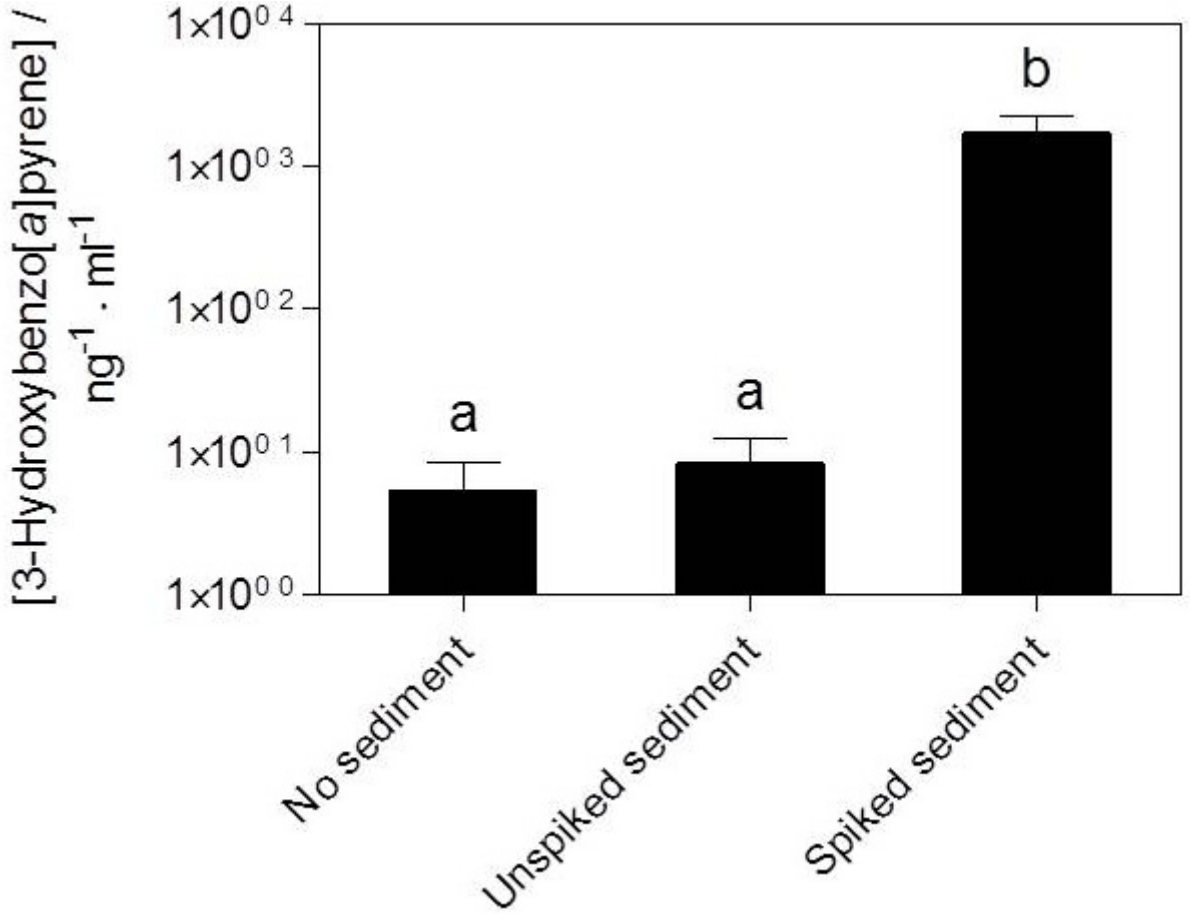

Figure 3 Concentration of PAH-metabolites 3-hydroxybenzo[*a*]pyren in bile of sediment exposed rainbow trouts in the annular flume. Reference [12].

EROD induction may be attributed to the short exposure to contaminated sediment (5 days), as well as to metabolization effects of low PAH concentrations.

Conclusions and outlook

During the Floodsearch project the feasibility of combining hydrodynamical with ecotoxicological approaches was clearly demonstrated. This new interdisciplinary approach represents a powerful and promising tool to improve our understanding of interactions between hydraulic stresses, sediment dynamics, sediment-bound contaminants and exposed aquatic organisms. The objective of the ongoing research is to extend and improve the current experimental design based on the knowledge of the presented proof-of-concept study [13]. During the next phase, natural and artificial contaminated sediments will be tested in the annular flume under varying environmental conditions (turbidity, pH, currents, sediments, aquatic organisms). The annular flume will be modified and extended to meet these challenges (e.g., new temperature control). The processes resulting in the transfer of pollutants from sediments to aquatic organisms will be investigated in more detail and uptake kinetics of particle-bound contaminants will be researched.

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Authors' contributions
HS and HH developed the concept of this article. HS, MB, CC, RMF, SUG, MH, SH, UK, GL, SR, AS and HH contributed equally to the content of the article and gave their final approval. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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