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Physiologically-based toxicokinetic models help identifying the key factors affecting contaminant uptake during flood events

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ABSTRACT

As a consequence of global climate change, we will be likely facing an increasing frequency and intensity of flood events. Thus, the ecotoxicological relevance of sediment re-suspension is of growing concern. It is vital to understand contaminant uptake from suspended sediments and relate it to effects in aquatic biota. Here we report on a computational study that utilizes a physiologically based toxicokinetic model to predict uptake, metabolism and excretion of sediment-borne pyrene in rainbow trout (*Oncorhynchus mykiss*). To this end, data from two experimental studies were compared with the model predictions: (a) batch re-suspension experiments with constant concentration of suspended particulate matter at two different temperatures (12 and 24 °C), and (b) simulated flood events in an annular flume. The model predicted both the final concentrations and the kinetics of 1-hydroxypyrene secretion into the gall bladder of exposed rainbow trout well. We were able to show that exhaustive exercise during exposure in simulated flood events can lead to increased levels of biliary metabolites and identified cardiac output and effective respiratory volume as the two most important factors for contaminant uptake. The results of our study clearly demonstrate the relevance and the necessity to investigate uptake of contaminants from suspended sediments under realistic exposure scenarios.

1. Introduction

As a consequence of global climate change, it has been predicted that both frequency and intensity of flood events will likely increase in the coming decades (Ikeda et al., 2005; Kay et al., 2006; Solomon et al., 2007). Apart from the direct hydrological implications of floods that pose a risk to humans and aquatic ecosystems, the re-suspension of historically polluted sediment layers is of great concern. Contaminants that are immobilized in the sediment bed under regular flow regimes may be re-mobilized during floods and in this way become available for uptake by aquatic organisms (Ahlf et al., 2002; Hollert et al., 2007). In light of the multitude of stressors that can act on aquatic biota apart from sediment contamination (e.g. temperature, suspended particulate matter (SPM; Pepelnik et al., 2004), hypoxia (BFG, 2008), increased current or changes in oxidation/reduction potential and pH-conditions (Calmano et al., 1993)) it is obvious that the reactions will differ significantly from those of biota exposed under standardized laboratory conditions (Mesa, 1994). In this context, it is of prime importance to fully understand the physiological

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processes and confounding factors during exposure to multiple stressors in fish in order to derive robust information on contaminant exposure (Forbes et al., 2006; Hallare et al., 2011). Until recently, however, only scarce laboratory methods were available that allowed environmental scientists to systematically investigate the reaction of exposed fish under flood-like conditions.

Apart from studies in which fish were exposed in containers with a sediment bed (e.g. Fragoso et al., 2006; van Geest et al., 2011), many researchers used electric pumps or repeatedly added sediment slurries to generate sediment suspensions (e.g. Ellis et al., 2002; Jürgens et al., 2009; Nendza, 2002). Both approaches allow only for investigating the effects under conditions with no flow or with a defined amount of SPM. Not represented are (a) the elevated directional flow velocity and (b) the SPM and flow dynamics, i.e. the temporal changes during a flood event (Dong et al., 2013). A first attempt to provide a better experimental approach for such studies was made by an interdisciplinary project (Wölz et al., 2009). In this work, an annular flume, i.e. a circular channel that is typically used for erosion and deposition studies, was used to expose rainbow trout (*Oncorhynchus mykiss*) under flood-like conditions. Today, the project is completed and a number of experiments and substudies were conducted (Brinkmann et al., 2010, 2013; Cofalla et al., 2012; Schüttrumpf et al., 2011). In order to verify our knowledge about the processes during sediment re-suspension and to provide a valuable tool for sediment management, i.e. desorption of contaminants from sediment particles and subsequent uptake and metabolism in rainbow trout, a suitable modeling approach had to be identified.

Here we report on a study in which the equilibrium partitioning (EqP) model (Di Toro et al., 1991) and an extended multi-compartmental physiologically based toxicokinetic (PBTK) model (Nichols et al., 1990) were used to predict uptake, metabolism and excretion of sediment-borne pyrene in rainbow trout. For this purpose, we used data from experimental studies that focused on re-suspension of contaminated natural sediments and compared the results with the model predictions. One study described the uptake and effects of sediment-borne PAHs in batch re-suspension experiments, where pumps were used to maintain a constant suspended particulate matter concentration (Brinkmann et al., 2013). Sediment was sampled from the river Rhine (Koblenz-Ehrenbreitstein, Germany) and rainbow trout were exposed at 12 (optimum temperature) and 24 °C (temperature stress). In the second study, fish were exposed under simulated flood conditions in an annular flume (Hudjetz et al., 2013). Most relevant environmental parameters, including the increased flow velocity, were combined in this exposure scenario. Sediments used in this study comprised the one from Ehrenbreitstein, a second from the river Moselle (Stadtbredimus-Palzem, Luxembourg) and third a mixture (1:1, dw/dw) of both. Although both studies partly used the same sediment from the river Rhine, the resulting biomarker data differed significantly between both exposure scenarios. Based on a literature research, a number of factors were identified that increase during physical exercise as a result of increased flow velocities and might be the reason for the observed differences. We hypothesize that uptake of contaminants from sediments can be drastically altered by physical exercise. Furthermore, we wanted to test if PBTK models are suitable tools to predict the differences if the following factors were implemented: (a) biotransformation rate, (b) cardiac output, and (c) effective respiratory volume. Last, a sensitivity analysis was performed in order to determine the most sensitive factors influencing biliary metabolite concentrations during physical exercise and their impact on bioaccumulation parameters (bioconcentration factor, time to equilibrium) was evaluated.

2. Materials and methods

2.1. Background

In the present study, we attempted to compare experimentally measured 1-hydroxpyrene concentrations in the bile of fish following exposure to sediment suspensions with concentrations that were modeled by use of a sediment desorption model and a PBTK model. The experimental data used to evaluate the model performance was previously published in Brinkmann et al. (2013) and Hudjetz et al. (2013). In order to make the modeling process more transparent, the experimental techniques will be briefly described. For the full experimental procedures, please refer to the original publications.

2.2. Experimental data

2.2.1. Experimental series A

These experiments have been conducted and previously published by Brinkmann et al. (2013). Briefly, juvenile rainbow trout were exposed to suspensions of sediment from the river Rhine. Experiments were conducted at two different final temperatures (approximately 12 and 24 °C) in 750 L glass fiber-reinforced plastic containers. Submersible pumps with a flow-through of 6000 L h^{-1} were used to constantly suspend the sediments at a nominal concentration of 10 g L^{-1}. Tanks were aerated at a rate of approximately 25 L min^{-1}. In each of the two experiments, physicochemical water parameters, concentrations of PAHs in SPM, and biliary metabolites in exposed fish ($n = 10$ per sampling point) were measured after 1, 2, 4, 6, 8, or 12 days and in untreated control animals. Due to mortality, only $n = 4$ animals were assessed in the 24 °C treatment. While the temperature was held constant at 11.9 ± 0.3 °C in the cooled experiment, temperature increased during four days from 20 °C to 23.8 ± 0.5 °C in the uncooled experiment (23.0 ± 1.9 °C, average temperature during complete experiment). Dissolved oxygen concentration was 10.5 ± 0.2 mg L^{-1} in the 12 °C experiment. In contrast, concentrations of dissolved oxygen decreased to concentrations as low as 6.5 mg L^{-1} in the 24 °C experiment during the first four days of the experiment and then averaged at 7.6 ± 0.4 mg L^{-1}. The final weight and standard length of experimental fish was 58 ± 23 g and 161 ± 19 mm, respectively.

2.2.2. Experimental series B

The experiments have been conducted and previously published by Hudjetz et al. (2013). Briefly, juvenile rainbow trout were exposed to suspensions of sediments from the river Rhine and the river Moselle under varying bed shear stress regimes. Experiments were conducted in an annular flume, i.e. a circular channel (width 0.25 m, inner radius 1.5 m, outer radius 1.75 m) with a coaxial lid. Channel and lid were rotated in opposite directions to generate an endless and stationary flow (Spork et al., 1995). During the 7 days experimental program, bed shear stress was increased up to a maximum of 0.4 N m^{-2} in 0.05 N m^{-2} increments, which corresponded to a maximum flow velocity of 0.38 m s^{-1} (Cofalla et al., 2011). The flume was aerated with a membrane pump. Fish were exposed at a constant ambient temperature of 14.6 ± 0.2 °C and a light-dark period of 12 h.

Three experiments that varied regarding sediment contamination level were conducted: (1) with sediment from the river Rhine (Ehrenbreitstein, EBR), (2) a mixture (1:1, dw/dw) of both EBR and sediment from the river Moselle (Stadtbredimus-Palzem, Luxembourg, PZ) and (3) the undiluted PZ sediment. In each of the experiments, physicochemical water parameters (temperature, dissolved oxygen, electric conductivity, pH, turbidity) were logged at an interval of 60 s by calibrated instruments and water samples for gravimetric determination of suspended particulate