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A new semi-quantitative tracer approach for the validation of a two-dimensional sediment transport model

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ABSTRACT

Validation of hydrodynamic two-dimensional (2D) sediment transport models is often difficult, because of their high demands for spatially distributed sediment deposition data. Therefore, the objective of this study is to introduce a new method for the validation of distributed hydrodynamic sediment transport models, which relies on the linear relationship between sedimentation and heavy metal concentration in the topsoil of riverine floodplains. The tracer method was tested in the heavily contaminated 45 km^2 large floodplains of River Mulde near Bitterfeld (Germany), using 129 topsoil concentrations of cadmium (Cd), zinc (Zn), and arsenic (As). Sediment deposition during flood events was simulated using the hydrodynamic and sediment transport model Telemac2D. A monotonic increase in median heavy metal concentrations with increasing sediment deposition classes was found by comparing simulated sediment deposition classes to associated heavy metal concentrations of the topsoil. These findings were confirmed for Cd, Zn, and As for more than three sediment deposition classes. Results of correlation analyses indicate highly significant linear positive relationships between heavy metal concentrations and sediment deposition. The proposed method is easy to apply, and time-consuming event-based measurements are not required, because of the use of time-integrated measurements of topsoil heavy metal concentrations. The new method enables the user to evaluate the validity of 2D sediment transport models at least in a semi-quantitative manner, by comparing given heavy metal concentrations of the topsoil of active floodplains to simulated sediment deposition.

Introduction

Two-dimensional (2D) models of computational fluid dynamics (CFD) with high spatial resolutions are commonly applied to riverine floodplains with different landscape structures (e.g. ditches, oxbows, plateaus, steep escarpments), in order to facilitate the quantification of sediment deposition (Schröder et al., 2005; Bates et al., 1998; Nicholas and Walling, 1998). Deposits of fine sediment are linked to high spatial variations of hydromorphometry (Baborowski et al., 2007). Therefore, there is a high demand of data availability for calibration and validation of spatially distributed sediment transport models (Spencer et al., 2011). For the calibration and validation of transport models, sedimentation rates can be determined by means of sediment traps that are deployed prior to hydrological events, such as extreme floods. After the event, quantity and quality of the sediment thus sampled can be evaluated. In addition, these sediment trap samples can be related to sedimentary records and thus tested for their representativeness of the actual sedimentation (Krüger et al., 2006; Asselman and Middelkoop, 1995; Büttner et al., 2006). Sediment trap exposures deliver net sedimentation during events. Disadvantages of this method are high logistic efforts and its highly limited representativeness in time and space.

Tracer techniques are alternatives for validating transport models at least in small areas, where logistic demand is low. Artificial materials can be used as tracers that mimic the behavior of natural fine sediment and its characteristic behavior in suspension, such as flocculation. Spencer et al. (2011) used holmium as particulate tracer. By means of samples taken from the flooded area, the integrity of the CFD model applied can be tested by comparing the spatial distribution of the tracer with model results. Due to high costs, this procedure can only be performed in small areas. Fallout radionuclide tracers such as ^{137}Cs or ^{210}Pb enable event-based determinations of medial sedimentation rates (Nicholas and Walling, 1998; He and Walling, 1998; Walling and He, 1997). However, this method is time-consuming due to measurement techniques required to ascertain the necessary horizontal and vertical resolutions of the river bottom samples. Therefore, deployments of radionuclides are limited to small floodplains.

In central Europe particulate heavy metal concentrations in riverine suspended matter increased considerably at the end of the 19th century

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because of beginning industrialization and expanding mining activities (Schönfelder et al., 2009). Therefore, heavy metal concentrations in floodplain soils are often elevated compared to natural background conditions, especially in highly industrialized regions like e.g. the study area near Bitterfeld in central Germany. Due to export of contaminated sediments during flood events, many alluvial meadows bordering on waterways and rivers were contaminated with heavy metals, such as arsenic (As), zinc (Zn) and cadmium (Cd) (Beurskens et al., 1994; Fleit and Lakatos, 2003; Zachmann et al., 2013). They can be used to estimate floodplain sedimentation rates by comparing the concentration profiles in the floodplain soils with the chronology of metal pollution of the sediments. Various studies have demonstrated that trace metals may provide a useful dating method for the reconstruction of floodplain sedimentation rates over several decades (Knox, 1987, 1989; Bogen et al., 1992; Middelkoop, 2002). For example, Bogen et al. (1992) give an overview of such studies in Western Europe including heavy metals, such as copper (Cu), lead (Pb) and Zn as tracers for calculating sediment deposition rates. However, the application of heavy metal soil profiles for validating spatially distributed CFD models is restricted to 2D sediment transport models.

Overall, the existing calibration and validation methods of sediment transport models, such as sediment traps and tracer techniques require high logistic effort for large model areas. Therefore this study introduces a new procedure for the validation of spatially distributed CFD models simulating the transport of cohesive sediments, which makes use of the relationship between sedimentation rates and heavy metal concentrations in the top layer of floodplain soils. By means of the application of a 2D CFD model, the suitability of the procedure proposed in this study can be revealed for large alluvial floodplains. This new method can be supplemented by event-based field methods measuring deposition, such as sediment mat exposures, to optimize the validation of the transport simulations.

Material and methods

Study site and test data

The region of Bitterfeld and Wolfen is situated in the Federal State Saxony-Anhalt in the central eastern part of Germany (Fig. 1). Since the beginning of industrialization in the 19th century, Bitterfeld experienced severe pollution by local chemical industries, open lignite pits in the lower- and ore mining in the upper-catchment of the river system Mulde. Highly polluted residual sedimentary records, originating from periodic As and heavy metal exports during high floods of the river Vereinigte Mulde, are evenly distributed within the floodplain, whereas other pollutants, such as persistent organic pollutants (e.g. hexachlorocyclohexane (HCH)), dioxins, and mercury, are locally enriched in the vicinity of former and present chemical industries (Franke et al., 2005; Barth et al., 2007; Schulz et al., 2009). In August 2002, River Mulde experienced a flood disaster due to heavy rainfall in the Ore Mountains upstream of Bitterfeld over the upper catchment of River Elbe. The town area of Bitterfeld and several villages situated in the floodplain of River Mulde around Bitterfeld were inundated and thus contaminated with pollutants as mentioned above from upstream areas and autochthonous sources.

Model setup

High-resolution spatial surface data derived from a laser scan survey have been used to establish a mesh grid with about 100,000 finite elements with a spatial resolution between 10 m in urban areas and 25 m in agricultural areas for the study site (total area of 45.0 km^2, Fig. 1). Triangles were used to construct the domain mesh. The elevation of the model area ranges between 57 m a.s.l. in downstream parts north of the village Raguhn to 118 m a.s.l. in upstream parts west of the Mulde Reservoir. The model area includes the eastern part of the town Bitterfeld, as well as the villages Jessnitz and Raguhn, but mostly consists of agricultural areas in the former floodplain of River Vereinigte Mulde. For model simulations, default values for settling velocity, as well critical sedimentation and erosion velocities were implemented. The time step was set to dt = 10 s. A value of 1.6 g cm^{-3} was taken for wet sediment density.

Field measurements

Measurements of suspended sediment concentrations and sedimentation rates during the extreme flood in August do not exist. Therefore for model testing two different data sets were used. i) For the calibration of the boundary conditions (suspended matter concentrations), sediment traps were exposed at five locations with four to seven replicates each in the former floodplain of River Vereinigte Mulde during the fluvial high water in March 2006 (Fig. 1). The sediment traps used have been described by Krüger et al. (2006). Artificial lawn mats revealed a rough upper surface, imitating the surface of unsealed areas. After the end of inundation of the mats, all sediments were collected from the mats. Sediment samples were dried and subsequently weighed, to determine dry weight of captured particulate matter. The range of values was between 202 and 646 gm^{-2} (Krüger et al., 2006). ii) For spatially distributed model validation data of 126 soil samples on contaminations of the topsoil of the floodplains, such as heavy metal concentrations were available. These data comprise As, Zn, and Cd concentrations measured in 1992 and 1993 (Fig. 1) and Table 1). These point data were interpolated to raster data by a geo-statistical procedure using orthogonal and isotropic Kriging (Schulz et al., 2009). Concentrations of the three elements tended to be highest in close vicinity and lowest in great distances to the main channel, but this spatial pattern was statistically not confirmed.

Model system Telemac2D

In the study at hand, the 2D Finite Element model system Telemac2D was applied, which consists of a hydrodynamic (Telemac-2D), a transport (Subief-2D), and a water quality module (wq2subief). A detailed description of Telemac-2D is given elsewhere (Hervouet, 2007; Hervouet and van Haren, 1996).

Flow and sediment transport modeling

For the flood event in August 2002 with a peak flow of 2140 m^3 s^{-1} and an estimated return period of 200 years, the hydraulic module of Telemac-2D was calibrated using satellite images, aerial photographs (Haase et al., 2004) and measured high water marks at some locations in urban areas. The friction values (Strickler values) used in the hydraulic model were spatially distributed, and derived from color infrared (CIR) views and from a map of habitat types from 1992, supplied by the Regional Agency of Environmental Protection Saxony-Anhalt (Schulz et al., 2009). The friction values were selected minimizing the root mean square error (RMSE) between measured and modeled surface water levels. The Strickler values used as input data were varied with a uniform distribution in the floodplain (25–33 m$^{1/3}$/s) and river (30–38 m$^{1/3}$/s). For sediment transport modeling the calibrated hydraulic model was used to simulate the 2006 flood event, which had a peak flow of 597 m^3 s^{-1} and a return period of 10 years (Schulz et al., 2009).

Statistical analyses

Bivariate canonical correlation analyses were performed between untreated raw data of concentrations of As, Cd and Zn and sediment deposition. Prior to correlation analyses, input variables should have been tested for normal distribution applying Kolmogorov–Smirnov tests for normality. However, it was assumed that at least one input variable was non-normally distributed. Therefore, tests for normality were omitted and for correlation analyses, the rank correlation coefficient Spearman-rho was used, which is applicable to both normally and