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Original Research Article

Numerical modeling of heavily polluted fine-grained sediments remobilization in northern Czech Republic

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ABSTRACT

The northern part of the Czech Republic is regarded as significantly polluted by antecedent or ongoing heavy industrial production mainly concentrated in the riparian zones of the Elbe River and its tributaries. Toxic pollutants tend to persist in the environment for a long time bound with fine-grained sediments. Nevertheless, a high-flow event can induce a remobilization of those deposits and lead to secondary pollution of downstream aquatic ecosystems. Numerical modeling was used as a tool for remobilization probability assessment under local hydrodynamic conditions within 113 km of Elbe and Bílina river beds and riparian zones. The assessment was based on statistical evaluation of causal discharge, the actual discharge observed at the evaluated cross section at the time of remobilization defined as significant erosion of observed sediment depositions. MIKE modeling software by DHI was used with different levels of horizontal plan schematization according to site-specific flow conditions and available data sources. MIKE 11 and MIKE 21 were used for Bílina River and MIKE 21 C was used for the Elbe River. Sediment transport was calculated simultaneously with hydrodynamic simulation of the unsteady synthetic boundary conditions based on observed flood properties (MIKE 21 C, MIKE 21 MT). Remobilization assessment of Bílina River sediment was based on the shear stress map evaluation verified with the results obtained by 2D model of the experimental site. The study contributes to risk-based assessment of polluted sediment management of the Elbe and extends the current scope of remobilization prediction within a reasonable timeframe using a numerical modeling method.

1. Introduction

Fine-grained particles (<0.063 mm) originating from rock denudation, biological processes, dust fallout, untreated sewage, and industrial waste play an important role in the Elbe's aquatic ecosystems (Borovec, 1995). While coarse sediment is derived mostly from channel erosion, fine-grained sediment can originate from arable

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land wash or occasionally from industrial or mining activities (Jánský et al., 2013). Although according to Aksoy and Kavvas (2005) only a small portion of sediment ultimately reaches the stream and can be transported during short, occasional periods of high-flow events, Haddadchi et al. (2013) state that 70–85% of sediment transported as suspended load originates from surface erosion. Contaminated sediment layers resulting from long-lasting deposition (Förstner et al., 2004) trapped in abandoned channels (Büttner et al., 2006) or other calm, slack water zones are considered to be potential hot spots of pollution because of the risk of mobilization under erosive hydraulic conditions (Jacoub and Westrich, 2006). The majority of the material is transported during high-flow river activity. Sediments are mobilized and accumulated according to local flow conditions once these exceed threshold values (e.g., critical shear stress for erosion τ_c and deposition τ_{cd}). According to Buzek (2000), a Moravian high-flow event observed in 1997 with a 100-year return period (RP) transported 51% of total recorded material suspended within the monitored period of 23 years. Schwartz (2006) reported reduction by 60% of long-term deposition in one middle Elbe groyne field as a consequence of a flood event in 2002. Although trends in sediment transportation under the influence of climate and land-use changes have been studied by numerous authors (Janský et al., 2010; Kliment, 2005; Cai et al., 2012; Walling and Fang, 2003), particular flow conditions for local remobilization require long-term observation or model assessment as an enhanced prediction tool.

According to van der Veen et al. (2006), under socialism (1950–1990) the Elbe was one of the most polluted rivers in Europe. The pollution was caused by heavy metals and organic contaminants from industrial and communal untreated sewage. Although water quality has improved significantly, sediment pollution still represents an important threat to the Elbe's aquatic ecosystems. According to Förstner et al. (2004) and Langhammer (2007), even though the Bílina River contributes almost insignificantly to Elbe water discharge (on average 6.5 $m^3 s^{-1}$ at the Bílina's confluence with the Elbe versus the Elbe's total 312 $m^3 s^{-1}$ at the German border), it has a significant impact on downstream water quality. Toxic matter together with cohesively acting fine particles forms a unity that can long persist in a riparian ecosystem (Droppo et al., 2009; Pores, 2009; Grabowski et al., 2011). Among other pollutants, heavy metals are regarded as being of special interest when bound to particles with low probability of degradation (Zeng et al., 2013). Once remobilized, toxin-bound fine-grained particles can be transported long distances in the form of wash load when shear velocity u^* greatly exceeds particle settling velocity w_s (Komar, 1988). Wash load contaminated particles can cause secondary pollution by desorption of the pollutant in the water environment (Segura et al., 2006). According to Borovec (1995), the coarser silt fraction (0.02–0.063 mm) may be enriched by pollutants as well due to the black and brown coating generated after a particle's long resistance in a single location. The qualitative properties of Elbe sediment have been described in several studies (Heininger et al., 2003; Rudiš et al., 2008; Schwartz, 2006).

Developments in hydroinformatics enable rapid implementation of theoretical sediment transport concepts with fine spatial and time distribution within a numerical modeling approach. Nevertheless, the entrainment of cohesive sediments, which is the main subject of this study, remains poorly understood due to its great complexity. In addition to appropriately describing sediment transport, the problem of sufficiently accurate flow parameter calculation plays a crucial role as it is a prerequisite for determining values for hydrodynamic variables used as the basis for sediment transport modeling, such as flow velocity, water depth and shear stress (Guerrero and Lamberti, 2013). According to Kiat et al. (2008), Simpson and Castelltort (2006) and Yang et al. (2004), flow and sediment transport should be simulated simultaneously as they significantly affect one another. Hardy (2013) has reviewed the current state of the art of process-based sediment transport modeling on different levels of flow schematization. The complex modeling system is extremely sensitive to the appropriate setting of parameters which, due to a lack of monitoring data, often must be estimated according to experience and corrected within a calibration process (Büttner et al., 2006; Jacoub and Westrich, 2006).

The present study continues on the topic of Elbe sediment remobilization as discussed by, for example, Heise et al. (2008), Kerner (2007), Rudiš (2000) and Schwartz (2006). It provides new knowledge of the Elbe fluvial system by implementing complex numerical hydrodynamic and sediment transport modeling as a tool for assessing remobilization risk. The main aims of the study are to (i) evaluate the probability of fine-grained, heavily polluted sediment remobilization at selected sites on the Upper Elbe and its left tributary the Bílina regarded as the main pollution sources; and (ii) discuss environmental aspects of the results thus obtained. In comparison with previous studies, an advantage lies in the ability to explore all expected hydrologic conditions while using RP as the main comparative parameter. Knowledge can thus be extrapolated beyond experience.

2. Materials and methods

With its total catchment area of 144,055 km^2, the Elbe River is an important European watercourse. The source and upper-middle course are located within the Czech Republic, where it drains an area of 48,750 km^2 (equal to 68% of the country). Fragments of the basin are located in Austria and Poland, but the largest part of the basin lies within Germany's borders. Average discharge at Hřensko (chainage 726.6 km), where the Elbe leaves the Czech Republic is 308 $m^3 s^{-1}$, while at the North Sea estuary the Elbe's discharge is more than double that amount, at 716 $m^3 s^{-1}$ under average runoff conditions. This study was conducted on the Elbe River reach between upstream chainage 965 km and Hřensko as well as on the Bílina River, left tributary (in the interval from upstream chainage 55 km to its confluence with the Elbe). The latter is regarded as one of the most polluted rivers in the Czech Republic (Langhammer, 2010; Přibylová et al., 2006) and a significant contributor to the overall water quality of the