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Combined sediment desorption and bioconcentration model to predict levels of dioxin-like chemicals in fish

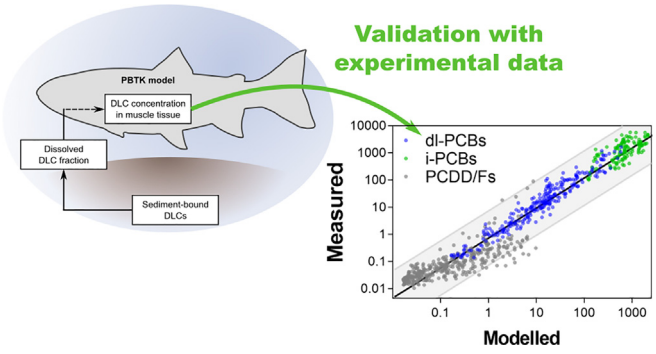
Markus Brinkmann [a,b,c,*], Jacob D. Ouellet [d], Markus Zennegg [e], Sebastian Buchinger [f], Georg Reifferscheid [f], Henner Hollert [d,g,h,**]

[a] School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Canada
[b] Toxicology Centre, University of Saskatchewan, Saskatoon, Canada
[c] Global Institute for Water Security, University of Saskatchewan, Saskatoon, Canada
[d] Goethe University Frankfurt, Department of Evolutionary Ecology and Environmental Toxicology, Max-von-Laue-Str. 13, 60438 Frankfurt am Main, Germany
[e] Swiss Federal Institute for Materials Science and Technology, Laboratory for Advanced Analytical Technologies, Dübendorf, Switzerland
[f] Federal Institute of Hydrology, Department G3: Biochemistry and Ecotoxicology, Koblenz, Germany
[g] State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing, China
[h] Key Laboratory of Yangtze Water Environment, Ministry of Education, Tongji University, Shanghai, China

HIGHLIGHTS

- A coupled sediment desorption and toxicokinetic model for fish was developed.
- Bioconcentration resulting from sediment resuspension was accurately predicted.
- Predictions generally differed less than 10-fold from measured values.
- The model showed an excellent global coefficient of determination of 0.95.

GRAPHICAL ABSTRACT



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ABSTRACT

Flooding and other sediment disturbances can lead to increases in sediment resuspension. In this context, it is of central importance to understand the kinetics of release from these sediments and the uptake of pollutants, such as polychlorinated biphenyls (PCBs) and polychlorinated dioxins and furans (PCDD/Fs), into aquatic organisms. In the present study, we parameterized a sediment desorption model based on experimentally determined rapidly-desorbing fractions of dioxin-like chemicals (DLCs). We coupled this desorption model with a physiologically-based toxicokinetic model for rainbow trout. This combined model was used to predict DLC concentrations in the muscle of exposed fish. The performance of this model was evaluated using a previously published dataset on DLC uptake from sediment suspensions during simulated re-suspension events. Predictions generally differed less than 10-fold from measured values, and the model showed a good global coefficient of determination (R^2) of 0.95. The root mean squared error (RMSE) for PCBs was 0.31 log units and 0.53 *log* units for PCDD/Fs. The results of our study demonstrate that the prediction of bioconcentration and related risk to fish resulting from sediment resuspension can be accurately predicted using coupled desorption and toxicokinetic models.

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* Correspondence to: M. Brinkmann, School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Canada.
** Correspondence to: H. Hollert, Goethe University Frankfurt, Department of Evolutionary Ecology and Environmental Toxicology, Max-von-Laue-Str. 13, 60438 Frankfurt am Main, Germany.
E-mail addresses: markus.brinkmann@usask.ca (M. Brinkmann), hollert@bio.uni-frankfurt.de (H. Hollert).

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1. Introduction

The frequency and intensity of flood events are increasing as a consequence of global climate change (Hollert et al., 2000). In addition to the direct damage that floods cause on infrastructure and ecosystems, re-suspension of contaminated sediments and the remobilization of sediment-bound pollutants are a concern (Hollert et al., 2007). Previous studies have demonstrated that flood events can increase bioavailability of various priority chemicals, including polyaromatic hydrocarbons and plant protection products (Hollert et al., 2009). Of particular concern are dioxin-like chemicals (DLCs), such as polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-dioxins and -furans (PCDD/Fs) (Wölz et al., 2008). Because of their physicochemical properties, DLCs are not degraded readily by abiotic factors or sediment microorganisms, and due to their high lipophilicity, they tend to accumulate in sediments and biota (Weber et al., 2008; Spagnoli and Skinner, 1977; La Rocca and Mantovani, 2006). Furthermore, DLCs have been shown to cause a wide range of toxic effects in exposed organisms, including immunotoxicity, neurotoxicity, hepatotoxicity, reproductive toxicity and some types of cancer (Denison and Heath-Pagliuso, 1998; Denison and Nagy, 2003; Brouwer et al., 1995; Van den Berg et al., 1998; Poland and Knutson, 1982; Giesy et al., 1994). Although partitioning of DLCs between environmental compartments has been studied extensively (Vandermarken et al., 2018), quantitative kinetic models for the uptake of sediment-borne DLCs in fish are currently lacking.

Previous studies have used a variety of approaches to predict bioaccumulation of sediment-borne chemicals from sediments, including bioaccumulation factors (van der Oost et al., 2003), biota-sediment accumulation factors (Ankley et al., 1992), food-web accumulation models (Gobas and Arnot, 2010; Arnot and Gobas, 2004; Thomann et al., 1992), and one-compartment models (Moermond et al., 2004; Hendriks et al., 2001). Many of these approaches, however, are not necessarily suitable to predict concentrations in aquatic organisms under the rapidly changing conditions of flood events, or they are limited in their representation of individual tissues. To overcome these limitations, we previously described a coupled model that consisted of an equilibrium partitioning (EqP) model for PAHs (Di Toro et al., 1991) that made use of calculated partitioning coefficients and measured total concentrations, and a physiologically based toxicokinetic (PBTK) model (Nichols et al., 1990). We used this combined model to predict uptake and metabolism of the sediment-borne PAH pyrene in rainbow trout (Brinkmann et al., 2014a). The model showed very good performance and good agreement between measured and modeled values. However, DLCs often show highly variable desorption kinetics (Van Geest et al., 2011), and the total concentration of various DLCs is a poor indicator of the overall bioavailability of these chemicals (Eichbaum et al., 2016).

To overcome these limitations, our study aimed to experimentally determine the rapidly desorbing fraction of several DLCs in sediments from the rivers Rhine and Elbe in Germany. Here, we defined the rapidly desorbing fraction operationally as the fraction of DLCs that readily desorbs from sediments within ten days and is retained in Tenax® TA beads as the adsorbent. The sediments used in the present study were previously investigated for their toxicological effects on rainbow trout (*Oncorhynchus mykiss*) in a large-scale resuspension study (Brinkmann et al., 2015a). The resulting rapidly desorbing fractions, along with measured total concentrations of DLCs, were used as input for the coupled EqP and PBTK model described in Brinkmann et al. (2014a). Predicted concentrations of DLCs in the muscle of exposed fish were verified using measured concentrations.

Overall, the approach presented here is a powerful method to estimate potential uptake of DLCs and effects in exposed biota, which will be of high relevance and benefit to the risk assessment of historically contaminated sediments.

2. Materials and methods

2.1. Study design

The rapidly desorbing fractions of several DLCs of concern were determined in sediments from the rivers Rhine and Elbe in Germany using Tenax® TA beads as the adsorbent. The sediments used in the present study have been previously investigated for their toxicological effects on rainbow trout (Brinkmann et al., 2015a). The resulting rapidly desorbing fractions, along with measured total concentrations of DLCs, were used as input for the coupled EqP and PBTK model described in Brinkmann et al. (2014a). Predicted concentrations of DLCs in the muscle of exposed fish were verified using measured levels reported in the Brinkmann et al. (2015a) study, and the predictive power of the model was estimated (Fig. 1).

2.2. Description of sediment samples and available chemical data

The sediments used throughout the present study were previously described in Brinkmann et al. (2015a). Briefly, sediments were collected from the rivers Rhine and Elbe. The locations were chosen to be representative of varying levels of contamination. These were lowest in Ehrenbreitstein (Rhine, Koblenz, Germany), greater in Prossen (Elbe, Germany), and greatest in Zollelbe sediments (Elbe, Magdeburg, Germany). The levels of various DLCs (and other priority contaminants) in these sediments were previously measured and were readily available for the present study (Brinkmann et al., 2015a). Furthermore, these sediments represent a range of fluvial systems with respect to the sediment particle size and organic carbon content (Heininger et al., 2007; Feiler et al., 2013), and they have been extensively characterized regarding their toxicological potential (Eichbaum et al., 2016; Brinkmann et al., 2015a; Heininger et al., 2007; Hudjetz et al., 2014; Brinkmann et al., 2013; Marth et al., 1999; Eichbaum et al., 2013; Eichbaum et al., 2014).

2.3. Determination of sediment desorption rates of DLCs

The Tenax® desorption experiment was performed in 100-mL amber glass bottles sealed with PTFE-lined caps. Prior to the extraction, Tenax® TA beads were rinsed three times with each of ultrapure water, acetone, and finally *n*-hexane at a volume of 10 mL per gram of Tenax®. The cleaned Tenax® was dried overnight at 75 °C. PTFE gauze bags were filled with 3.0 g of Tenax® to minimize the loss of the beads during the collection at the end of the exposure. The Tenax®-containing gauze bags were added to individual 100-mL amber glass bottles which contained 5.0 g d.w. equivalents of native sediment from one of the sampling locations (either Ehrenbreitstein, Prossen, and Zollelbe), 350 mL ultrapure water and 5.0 mg mercury chloride to prevent microbial degradation. Each desorption experiment, in addition to a blank sample containing no sediment, was performed in duplicate. The bottles were sealed and placed on a shaker set to 125 rpm at a temperature of 20 °C. Following a 10-d extraction period, the Tenax®-containing gauze bags were collected, wrapped loosely in aluminum foil and air-dried in a fume hood prior to extraction and chemical analysis. The 10-d extraction period was chosen to mimic the conditions in the Brinkmann et al. (2015a) study, where sediment suspensions were exchanged every 10 days during the 90-day exposure period.

Dried Tenax® beads were extracted with acetone/*n*-hexane (1:1) for 16 h using a mini-soxhlet extractor. The extracts were purified using a Dextech-plus automated dioxin and PCB clean-up system (LCTech, Obertaufkirchen, Germany). The quantitative determination of PCBs and PCDD/Fs in the purified Tenax® TA extracts was achieved by electron ionization high-resolution mass spectrometry (GC/EI–HRMS), carried out on a MAT 95 mass spectrometer (Thermo Finnigan MAT, Bremen, Germany), coupled to a gas chromatograph Trace GC ultra 2000 (Thermo Fisher Scientific, Waltham, MA, USA) equipped

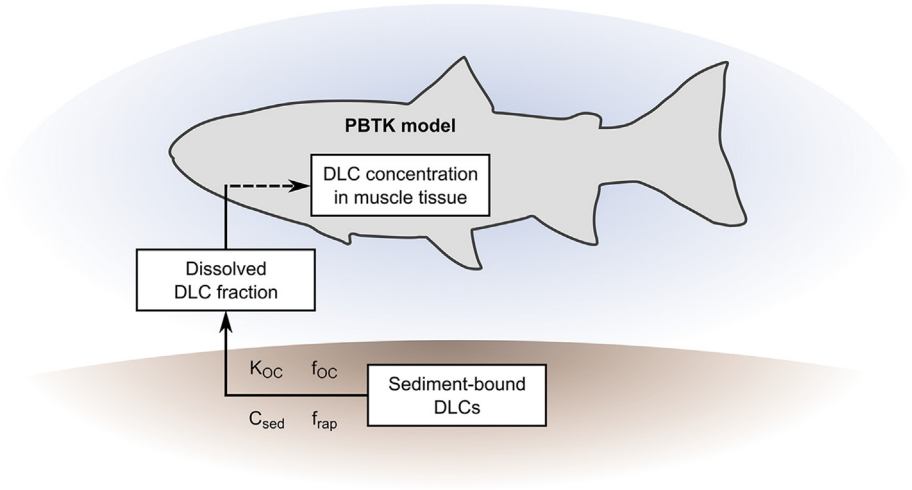

Fig. 1. Conceptional depiction of the combined sediment desorption (EqP) and PBTK model. K_{OC}: organic carbon-water partitioning coefficient, f_{OC}: organic carbon fraction, C_{sed}: total DLC concentration in sediment, f_{rap}: rapidly desorbing DLC fraction.

with a Triplus AS autosampler (Thermo Fisher Scientific), as described in Brinkmann et al. (2015a). The rapidly desorbing fraction of DLCs f_{rap} (dimensionless) was determined by dividing the chemical amount of DLCs that was extracted using the Tenax® method by the chemical amount of DLCs extracted using exhaustive pressurized liquid extraction (PLE) as reported in the Brinkmann et al. (2015a) study.

2.4. EqP model

The dispersion of organic chemicals in aquatic systems is often described using equilibrium partitioning (EqP) models (Di Toro et al., 1991). Organic carbon-water partition coefficients K_{oc} (L kg^{-1} organic carbon) (Burgess et al., 2003) were calculated for each DLC using the US-EPA software KOCWIN and are listed in Supplementary Table S1 (US EPA, 2013). Aqueous exposure concentrations of DLCs were calculated using Eq. (1), where C_{water} (μg L^{-1}) was the aqueous concentration of each DLC, $C_{sediment}$ (μg kg^{-1} dry mass) was the measured total concentration of each DLC in the sediment, K_{oc} (L kg^{-1} organic carbon) was the organic carbon-water partition coefficient, f_{oc} (dimensionless) was the measured organic carbon content of sediments, and f_{rap} (dimensionless) was the rapidly desorbing fraction of DLCs as determined in the present study. Measured total sediment concentrations and organic carbon contents of sediments were previously published and readily available for the present study (Brinkmann et al., 2015a).

$$C_{water} = \frac{C_{sediment} \cdot f_{rap}}{K_{OC} \cdot f_{OC}} \quad (1)$$

2.5. PBTK model

A multi-compartment PBTK model for rainbow trout developed initially by Nichols et al. (1990), with modifications by Stadnicka et al. (2012) and Brinkmann et al. (2014b), was re-implemented in the open-source software Jupyter® Notebook (www.jupyter.org, version 5.5.0) in the programming language Python™ (Python Software Foundation, Delaware, USA, version 3.6.5). Six different compartments (blood, fat, liver, kidney, richly perfused tissues, and poorly perfused tissues) were explicitly represented in the model. The model has been previously shown to be capable of accurately predicting the internal concentrations of neutral organic chemicals across 23 single chemicals (39 data points total), with 95% of all datapoints lying within ten-fold difference from measured values (Brinkmann et al., 2014b).

2.6. Statistical analysis of model performance

The model performance was evaluated using measured DLC concentrations in the muscle of rainbow trout exposed to suspensions of contaminated sediments from Brinkmann et al. (2015a) No new animal experiments were conducted within the present study. We used a total number of 770 data points from the Brinkmann et al. study, which comprised the concentrations of 35 DLCs across 22 different treatments in which fish were exposed for 7, 14, 30, 60 or 90 days to various mixtures of the three previously described sediments (EBR, ZE, PR) from the rivers Rhine and Elbe.

For each of these 770 data points, an individual PBTK model run was conducted based on the following input parameters: log Kow of the DLC, exposure time, the aqueous concentration of the DLC predicted by the EqP model, measured dissolved oxygen concentration, measured temperature, and measured fish weight. Exposure time, water temperature, dissolved oxygen concentration, as well as the weight of the fish was set to match the experimental data (see Supplementary Table S2), while aqueous exposure concentrations were predicted using the EqP model.

The model performance was quantified using the log root mean squared error (RMSE), as well as the coefficient of determination (R^2). The full set of model inputs is provided in the supplemental material (Supplemental Table S1).

3. Results and discussion

3.1. Sediment desorption of DLCs and rapidly desorbing fractions

The rapidly desorbing fractions of the DLCs studied in this research were investigated using infinite sink desorption studies using Tenax® TA as the sorbent.

The desorbed fractions of PCDD/Fs were generally small, and due to the low concentrations of these chemicals in the sediments, they were frequently below the detection limit. The average rapidly desorbing fraction of PCDD/Fs was very small, with 0.675% of the total PCDD/F sediment concentration. To account for the somewhat different physicochemical properties of PCDD/Fs, with log K_{ow} values ranging from 6.53 to 8.60, we used the slope of the regression line of *log* K_{ow} values versus F_{rap} for PCBs to establish a reasonable relationship between *log* K_{ow} and F_{rap} for PCDD/Fs (Table 1). These findings are in line with previous studies, where the rapidly desorbing fractions of PCDD/Fs in highly contaminated river sediments from Finland ranged from 0.8 to 8% (Sormunen et al., 2008).

Table 1
Total sediment concentrations of various polychlorinated dioxins and furans (PCDD/F) congeners in sediments from Ehrenbreitstein (EBR), Zollelbe (ZE) and Prossen (PR), as well as the average rapidly desorbing fraction of PCDD/Fs across the three sediments.

Chemical	Total sediment concentrations (dw)[a]			Rapidly desorbing fraction $f_{rap}(-)$
	EBR (ng kg^{-1})	ZE (ng kg^{-1})	PR (ng kg^{-1})	
2,3,7,8-TCDD	0.32	13.9	1.36	9.29E-03
1,2,3,7,8-PeCDD	0.62	19.4	1.50	1.06E-02
1,2,3,4,7,8-HxCDD	1.60	9.80	0.80	8.25E-04
1,2,3,6,7,8-HxCDD	2.84	32.5	1.60	8.25E-04
1,2,3,7,8,9-HxCDD	3.41	25.2	2.50	8.25E-04
1,2,3,4,6,7,8-HpCDD	57.4	327	29.2	1.16E-03
OctaCDD	707	2590	231	1.16E-03
2,3,7,8-TCDF	4.62	162	9.82	1.16E-02
1,2,3,7,8-PeCDF	2.35	179	6.48	1.06E-02
2,3,4,7,8-PeCDF	2.71	63.6	6.39	8.27E-03
1,2,3,4,7,8-HxCDF	8.93	523	12.1	1.16E-03
1,2,3,6,7,8-HxCDF	4.81	445	15.5	1.16E-03
2,3,4,6,7,8-HxCDF	1.62	50.8	2.70	1.16E-03
1,2,3,7,8,9-HxCDF	0.30	71.8	0.80	2.69E-03
1,2,3,4,6,7,8-HpCDF	17.9	1200	26.2	1.16E-03
1,2,3,4,7,8,9-HpCDF	3.80	420	5.20	1.16E-03
OctaCDF	73.0	4550	65.0	1.16E-03

[a] Data from Brinkmann et al. (2015a).

The desorbed fractions of PCBs were larger compared to those of PCDD/Fs, and due to the greater concentrations of these chemicals in the sediments, chemical-specific rapidly desorbing fractions could be calculated (Table 2). The rapidly desorbing fraction of PCBs ranged from 0.116% for PCB 81 to 7.50% for PCB 28. Again, these findings are comparable with those of previous studies, where the rapidly desorbing fractions of total PCBs ranged from 7.7 to 90% (Mackenbach et al., 2014). Generally, smaller rapidly desorbing fractions were found for sediments with lower PCB concentrations, such as the ones investigated in the present study. Rapidly desorbing fractions were considerably greater in sediments from the Hudson River, USA, that contained PCB concentrations that were up to 1000-fold greater compared to those found in our samples (Carroll et al., 1994). The same was true when the sediments were spiked with PCBs, which apparently led to significantly weaker binding of the chemicals to sediment particles (Cornelissen et al., 1997).

Table 2
Total sediment concentrations of various polychlorinated biphenyl (PCB) congeners in sediments from Ehrenbreitstein (EBR), Zollelbe (ZE) and Prossen (PR), as well as the chemical-specific rapidly desorbing fractions of PCBs, averaged across the three sediments.

Chemical	Total sediment concentrations (dw)[a]			Rapidly desorbing fraction $f_{rap}(-)$
	EBR (ng kg^{-1})	ZE (ng kg^{-1})	PR (ng kg^{-1})	
PCB 77	230	1000	368	4.40E-03
PCB 81	3.40	30.90	14.2	1.16E-03
PCB 126	25.3	59.00	25.3	1.79E-02
PCB 169	3.40	13.20	4.50	1.00E-02
PCB 105	393	2240	552	4.56E-03
PCB 114	25.5	127	26.0	4.74E-02
PCB 118	1240	9480	2850	1.54E-02
PCB 123	25.6	190	30.0	4.55E-02
PCB 156	447	2640	1200	4.01E-03
PCB 157	63.3	356	350	8.01E-03
PCB 167	207	1220	555	2.41E-03
PCB 189	59.0	474	256	4.63E-03
PCB 28	1010	8240	4270	7.50E-02
PCB 52	1080	8850	2990	7.44E-02
PCB 101	4110	11900	5800	2.27E-02
PCB 138	4270	23200	9060	6.37E-03
PCB 153	7000	28200	16600	4.75E-03
PCB 180	4290	20600	13400	1.57E-03

[a] Data from Brinkmann et al. (2015a).

3.2. Predictive power of the coupled EqP and PBTK model

The predictive performance of the coupled EqP and PBTK model based on a previously published dataset on DLC uptake from sediment suspensions during simulated re-suspension events was very good. Model predictions generally differed less than 10-fold from measured values (Fig. 2). The model showed a very good global coefficient of determination (R^2) of 0.95. The root mean squared error (RMSE) for PCBs was 0.31 log units and 0.53 *log* units for PCDD/Fs, spanning almost five orders of magnitude in sediment concentrations, and six orders of magnitude in internal concentrations in fish (Fig. 2).

These results are comparable to previous modeling efforts for single chemicals, e.g., the PAH pyrene, where biliary concentrations of pyrene in sediment-exposed rainbow trout could be accurately predicted (Brinkmann et al., 2014a). Furthermore, the predictive power of our coupled EqP and PBTK model did not appear to be inferior to PBTK models that use aqueous exposure concentrations as inputs; for these models, RMSEs ranged from 0.28 log units in European eels to 0.44 in zebrafish, 0.66 in rainbow trout, and 1.0 *log* units in fathead minnows (Stadnicka et al., 2012; Brinkmann et al., 2016; Brinkmann et al., 2015b)

These findings suggest strongly that the underlying physicochemical desorption processes have been accurately captured by means of the modified EqP model that encompasses measured values for the rapidly desorbing chemical fraction. These findings are in line with a multitude of previous studies that employed simpler bioaccumulation models but also accounted for the bioavailable and rapidly desorbing chemical fractions through Tenax® desorption assays, as reviewed in Lydy et al. (2015).

3.3. Potentials and limitations of the proposed methodology

In the present study, we demonstrated that our combined EqP and PBTK model was capable of accurately predicting the uptake of sediment-borne PCBs and PCDD/Fs in rainbow trout. This model takes not only total sediment concentrations into consideration, but also accounts for the differential bioavailability of DLCs. These advances will

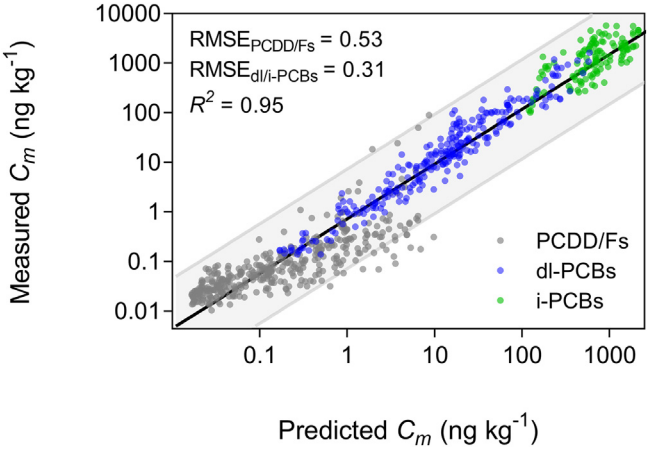

Fig. 2. Relationship between measured and predicted internal concentrations in the muscle tissue of rainbow trout (*Oncorhynchus mykiss*). The solid black line represents the regression line, while the shaded area indicates the interval of 10-fold deviation from the regression line. Gray points are data for polychlorinated dibenzo-*p*-dioxins and furans (PCDD/Fs), while blue and green points are data for dioxin-like and indicator polychlorinated biphenyls (dl-PCBs and i-PCBs), respectively. The root mean squared error (RMSE) for both PCDD/Fs and PCBs, as well as the overall coefficient of determination (R^2), are provided for reference.

be beneficial for the application of this model in sediment risk assessment under dynamic exposure scenarios, e.g., during flood events or as a result of global climate change. We are confident that this approach will be useful for the management of sediments regarding the prediction of the bioaccumulation potential of DLCs or prioritization of potential future remediation measures (Kwok et al., 2013).

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143891.

CRediT authorship contribution statement

Markus Brinkmann: Conceptualization, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Jacob D. Ouellet:** Investigation, Data curation, Writing - review & editing. **Markus Zennegg:** Investigation, Data curation, Writing - review & editing. **Sebastian Buchinger:** Validation, Data curation, Writing - review & editing. **Georg Reifferscheid:** Supervision, Funding acquisition, Project administration, Writing - review & editing. **Henner Hollert:** Supervision, Funding acquisition, Project administration, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ankley, G.T., Cook, P.M., Carlson, A.R., Call, D.J., Swenson, J.A., Corcoran, H.F., Hoke, R.A., 1992. Bioaccumulation of PCBs from sediments by oligochaetes and fishes: comparison of laboratory and field studies. Can. J. Fish. Aquat. Sci. 49 (10), 2080–2085.

Arnot, J.A., Gobas, F.A.P.C., 2004. A food web bioaccumulation model for organic chemicals in aquatic ecosystems. Environ. Toxicol. Chem. 23 (10), 2343–2355.

Brinkmann, M., Hudjetz, S., Kammann, U., Hennig, M., Kuckelkorn, J., Chinoraks, M., Cofalla, C., Wiseman, S., Giesy, J.P., Schäffer, A., Hecker, M., Wölz, J., Schüttrumpf, H., Hollert, H., 2013. How flood events affect rainbow trout: evidence of a biomarker cascade in rainbow trout after exposure to PAH contaminated sediment suspensions. Aquat. Toxicol. 128-129, 13–24.

Brinkmann, M.; Eichbaum, K.; Kammann, U.; Hudjetz, S.; Cofalla, C.; Buchinger, S.; Reifferscheid, G.; Schüttrumpf, H.; Preuss, T.; Hollert, H., Physiologically-based toxicokinetic models help identifying the key factors affecting contaminant uptake during flood events. Aquat. Toxicol. 2014a, 152, (0), 38–46.

Brinkmann, M., Eichbaum, K., Buchinger, S., Reifferscheid, G., Bui, T., Schäffer, A., Hollert, H., Preuss, T.G., 2014b. Understanding receptor-mediated effects in rainbow trout: in vitro–in vivo extrapolation using physiologically based toxicokinetic models. Environmental Science & Technology 48 (6), 3303–3309.

Brinkmann, M., Eichbaum, K., Reininghaus, M., Koglin, S., Kammann, U., Baumann, L., Segner, H., Zennegg, M., Buchinger, S., Reifferscheid, G., Hollert, H., 2015a. Towards science-based sediment quality standards – effects of field-collected sediments in rainbow trout (*Oncorhynchus mykiss*). Aquat. Toxicol. 166, 50–62.

Brinkmann, M., Freese, M., Pohlmann, J.D., Kammann, U., Preuss, T.G., Buchinger, S., Reifferscheid, G., Beiermeister, A., Hanel, R., Hollert, H., 2015b. A physiologically based toxicokinetic (PBTK) model for moderately hydrophobic organic chemicals in the European eel (Anguilla anguilla). Sci. Total Environ. 536, 279–287.

Brinkmann, M., Schlechtriem, C., Reininghaus, M., Eichbaum, K., Buchinger, S., Reifferscheid, G., Hollert, H., Preuss, T.G., 2016. Cross-species extrapolation of uptake and disposition of neutral organic chemicals in fish using a multispecies physiologically-based toxicokinetic model framework. Environmental Science & Technology 50 (4), 1914–1923.

Brouwer, A., Ahlborg, U.G., Van den Berg, M., Birnbaum, L.S., Ruud Boersma, E., Bosveld, B., Denison, M.S., Earl Gray, L., Hagmar, L., Holene, E., Huisman, M., Jacobson, S.W., Jacobson, J.L., Koopman-Esseboom, C., Koppe, J.G., Kulig, B.M., Morse, D.C., Muckle, G., Peterson, R.E., Sauer, P.J.J., Seegal, R.F., Smits-Van Prooije, A.E., Touwen, B.C.L., Weisglas-Kuperus, N., Winneke, G., 1995. Functional aspects of developmental toxicity of polyhalogenated aromatic hydrocarbons in experimental animals and human infants. Eur. J. Pharmacol. Environ. Toxicol. Pharm. 293 (1), 1–40.

Burgess, R.M., Ahrens, M.J., Hickey, C.W., Den Besten, P., Den Hulscher, D., Van Hattum, B., Meador, J.P., Douben, P.E.T., 2003. An overview of the partitioning and bioavailability of PAHs in sediments and soils. In: Douben, P.E.T. (Ed.), PAHs: An Ecotoxicological Perspective. John Wiley & Sons Ltd., Chichester, England, p. 99.

Carroll, K.M., Harkness, M.R., Bracco, A.A., Balcarcel, R.R., 1994. Application of a permeant/polymer diffusional model to the desorption of polychlorinated biphenyls from Hudson River sediments. Environmental Science & Technology 28 (2), 253–258.

Cornelissen, G., van Noort, P.C.M., Govers, H.A.J., 1997. Desorption kinetics of chlorobenzenes, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls: sediment extraction with Tenax® and effects of contact time and solute hydrophobicity. Environ. Toxicol. Chem. 16 (7), 1351–1357.

Denison, M.S., Heath-Pagliuso, S., 1998. The Ah receptor: a regulator of the biochemical and toxicological actions of structurally diverse chemicals. Bull. Environ. ContamToxicol. 61 (5), 557–568.

Denison, M.S., Nagy, S.R., 2003. Activation of the aryl hydrocarbon receptor by structurally diverse exogenous and endogenous chemicals. Annu. Rev. PharmacolToxicol. 43 (1), 309–334.

Di Toro, D.M., Zarba, C.S., Hansen, D.J., Berry, W.J., Swartz, R.C., Cowan, C.E., Pavlou, S.P., Allen, H.E., Thomas, N.A., Paquin, P.R., 1991. Technical basis for establishing sediment quality criteria for nonionic organic chemicals using equilibrium partitioning. Environ. Toxicol. Chem. 10 (12), 1541–1583.

Eichbaum, K., Brinkmann, M., Buchinger, S., Hecker, M., Engwall, M., van Bavel, B., Reifferscheid, G., Hollert, H., 2013. The dioRAMA project: assessment of dioxin-like activity in sediments and fish (Rutilus rutilus) in support of the ecotoxicological characterization of sediments. J. Soils Sediments 13 (4), 770–774.

Eichbaum, K.; Brinkmann, M.; Buchinger, S.; Reifferscheid, G.; Hecker, M.; Giesy, J. P.; Engwall, M.; van Bavel, B.; Hollert, H., In vitro bioassays for detecting dioxin-like activity — application potentials and limits of detection, a review. *Sci.* Total Environ. 2014, 487, (0), 37–48.

Eichbaum, K., Brinkmann, M., Nuesser, L., Buchinger, S., Reifferscheid, G., Codling, G., Jones, P., Giesy, J.P., Hecker, M., Hollert, H., 2016. Bioanalytical and instrumental screening of the uptake of sediment-borne, dioxin-like compounds in roach (Rutilus rutilus). Environ. Sci. Pollut. Res. 1–15.

Feiler, U., Höss, S., Ahlf, W., Gilberg, D., Hollert, H., Meller, M., Hammers-Wirtz, M., Neumann-Hensel, H., Ottermanns, R., Seiler, T.-B., Spira, D., Heininger, P., 2013. Sediment contact tests as a tool for the assessment of sediment quality in German waters. Environ. Toxicol. Chem. 32 (1), 144–155.

Giesy, Ludmig, J.P., Tillitt, D.E., 1994. Embryolethality and deformities in colonial, fish-eating, water birds of the Great Lakes region - assessing causality. Environ. Sci. Technol. 28, 128A–135A.

Gobas, F.A.P.C., Arnot, J.A., 2010. Food web bioaccumulation model for polychlorinated biphenyls in San Francisco Bay, California, USA. Environ. Toxicol. Chem. 29 (6), 1385–1395.

Heininger, P., Höss, S., Claus, E., Pelzer, J., Traunspurger, W., 2007. Nematode communities in contaminated river sediments. Environ. Pollut. 146 (1), 64–76.

Hendriks, A.J., van der Linde, A., Cornelissen, G., Sijm, D.T.H.M., 2001. The power of size. 1. Rate constants and equilibrium ratios for accumulation of organic substances related to octanol-water partition ratio and species weight. Environ. Toxicol. Chem. 20 (7), 1399–1420.

Hollert, H., Dürr, M., Erdinger, L., Braunbeck, T., 2000. Cytotoxicity of settling particulate matter (SPM) and sediments of the Neckar river (Germany) during a winter flood. Environ Toxicol and Chem 19, 528–534.

Hollert, H., Dürr, M., Haag, I., Wölz, J., Hilscherova, K., Blaha, L., Gerbersdorf, S.U., 2007. Influence of hydrodynamics on sediment ecotoxicity. In: Westrich, B., Förster, U. (Eds.), Sediment Dynamics and Pollutant Mobility in Rivers. Springer, Heidelberg, pp. 401–416.

Hollert, H., Ernst, M., Seiler, T.-B., Wölz, J., Braunbeck, T., Kosmehl, T., Keiter, S., Grund, S., Ahlf, W., Erdinger, L., Dürr, M., 2009. Strategien zur Sedimentbewertung – ein Überblick Umweltwiss Schadst Forsch 21 (2), 160–176.

Hudjetz, S., Herrmann, H., Cofalla, C., Brinkmann, M., Kammann, U., Schäffer, A., Schüttrumpf, H., Hollert, H., 2014. An attempt to assess the relevance of flood events—biomarker response of rainbow trout exposed to resuspended natural sediments in an annular flume. Environ. Sci. Pollut. Res. 21 (24), 13744–13757.

Kwok, C.K., Liang, Y., Leung, S.Y., Wang, H., Dong, Y.H., Young, L., Giesy, J.P., Wong, M.H., 2013. Biota–sediment accumulation factor (BSAF), bioaccumulation factor (BAF), and contaminant levels in prey fish to indicate the extent of PAHs and OCPs contamination in eggs of waterbirds. Environ. Sci. Pollut. Res. 20 (12), 8425–8434.

La Rocca, C., Mantovani, A., 2006. From environment to food: the case of PCB. Ann Ist Super Sanita 42 (4), 410.

Lydy, M.J., Harwood, A.D., Nutile, S.A., Landrum, P.F., 2015. Tenax extraction of sediments to estimate desorption and bioavailability of hydrophobic contaminants: a literature review. *Integr. Environ. Assess.* Manage. 11 (2), 208–220.

Mackenbach, E.M., Harwood, A.D., Mills, M.A., Landrum, P.F., Lydy, M.J., 2014. Application of a tenax model to assess bioavailability of polychlorinated biphenyls in field sediments. Environ. Toxicol. Chem. 33 (2), 286–292.

Marth, P., Schramm, K.-W., Martens, D., Oxynos, K., Schmitzer, J., Kettrup, A., 1999. Distribution of chlorinated hydrocarbons in different ecosystems in Germany. Int. J. Environ. Anal. Chem. 75 (1–2), 229–249.

Moermond, C.T.A., Roozen, F.C.J.M., Zwolsman, J.J.G., Koelmans, A.A., 2004. Uptake of sediment-bound bioavailable polychlorobiphenyls by benthivorous carp (*Cyprinus carpio*). Environmental Science & Technology 38 (17), 4503–4509.

Nichols, J.W., McKim, J.M., Andersen, M.E., Gargas, M.L., Clewell Iii, H.J., Erickson, R.J., 1990. A physiologically based toxicokinetic model for the uptake and disposition of waterborne organic chemicals in fish. Toxicol. Appl. Pharmacol. 106 (3), 433–447.

Poland, A., Knutson, J.C., 1982. 2,3,7,8-tetrachlorodibenzo-*p*-dioxin and related halogenated aromatic hydrocarbons: examination of the mechanism of toxicity. Annu. Rev. Pharmacol. Toxicol. 22, 517–554.

Sormunen, A.J., Koistinen, J., Leppänen, M.T., Kukkonen, J.V.K., 2008. Desorption of sediment-associated polychlorinated dibenzo-p-dioxins, dibenzofurans, diphenyl ethers and hydroxydiphenyl ethers from contaminated sediment. Chemosphere 72 (1), 1–7.

Spagnoli, J.J., Skinner, L.C., 1977. PCB's in fish from selected waters of New York State. Pestic. monit. j. 11 (2), 69–87.

Stadnicka, J., Schirmer, K., Ashauer, R., 2012. Predicting concentrations of organic chemicals in fish by using toxicokinetic models. *Environ. Sci.* Technol. 46 (6), 3273–3280.

Thomann, R.V., Connolly, J.P., Parkerton, T.F., 1992. An equilibrium model of organic chemical accumulation in aquatic food webs with sediment interaction. Environ. Toxicol. Chem. 11 (5), 615–629.

US EPA, 2013. Estimation Programs Interface Suite™ for Microsoft® Windows, v 4.11. United States Environmental Protection Agency, Washington, DC, USA.

Van den Berg, M., Birnbaum, L., Bosveld, A.T., Brunström, B., Cook, P., Feeley, M., Giesy, J.P., Hanberg, A., Hasegawa, R., Kennedy, S.W., Kubiak, T., Larsen, J.C., van Leeuwen, F.X., Liem, A.K., Nolt, C., Peterson, R.E., Poellinger, L., Safe, S., Schrenk, D., Tillitt, D., Tysklind, M., Younes, M., Waern, F., Zacharewski, T., 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. Environ. Health Perspect. 106, 12.

van der Oost, R., Beyer, J., Vermeulen, N.P.E., 2003. Fish bioaccumulation and biomarkers in environmental risk assessment: a review. Environ. Toxicol. Pharmacol. 13 (2), 57–149.

Van Geest, J.L., Mackay, D., Poirier, D.G., Sibley, P.K., Solomon, K.R., 2011. Accumulation and depuration of polychlorinated biphenyls from field-collected sediment in three freshwater organisms. Environmental Science & Technology 45 (16), 7011–7018.

Vandermarken, T., Gao, Y., Baeyens, W., Denison, M.S., Croes, K., 2018. Dioxins, furans and dioxin-like PCBs in sediment samples and suspended particulate matter from the Scheldt estuary and the North Sea coast: comparison of CALUX concentration levels in historical and recent samples. Sci. Total Environ. 626, 109–116.

Weber, R., Gaus, C., Tysklind, M., Johnston, P., Forter, M., Hollert, H., Heinisch, E., Holoubek, I., Lloyd-Smith, M., Masunaga, S., Moccarelli, P., Santillo, D., Seike, N., Symons, R., Torres, J., Verta, M., Varbelow, G., Vijgen, J., Watson, A., Costner, P., Woelz, J., Wycisk, P., Zennegg, M., 2008. Dioxin- and POP-contaminated sites—contemporary and future relevance and challenges. Environ. Sci. Pollut. Res. 15 (5), 363–393.

Wölz, J., Engwall, M., Maletz, S., Olsman Takner, H., Bavel, B., Kammann, U., Klempt, M., Weber, R., Braunbeck, T., Hollert, H., 2008. Changes in toxicity and Ah receptor agonist activity of suspended particulate matter during flood events at the rivers Neckar and Rhine — a mass balance approach using in vitro methods and chemical analysis. Environ. Sci. Pollut. Res. 15 (7), 536–553.