

CRITICAL REVIEW

View Article Online
View Journal | View Issue



Cite this: *Environ. Sci.: Processes Impacts*, 2018, 20, 58

Environmental fate and exposure models: advances and challenges in 21st century chemical risk assessment

Antonio Di Guardo, ^a Todd Gouin, ^b Matthew MacLeod ^c and Martin Scheringer ^{*de}

Environmental fate and exposure models are a powerful means to integrate information on chemicals, their partitioning and degradation behaviour, the environmental scenario and the emissions in order to compile a picture of chemical distribution and fluxes in the multimedia environment. A 1995 pioneering book, resulting from a series of workshops among model developers and users, reported the main advantages and identified needs for research in the field of multimedia fate models. Considerable efforts were devoted to their improvement in the past 25 years and many aspects were refined; notably the inclusion of nanomaterials among the modelled substances, the development of models at different spatial and temporal scales, the estimation of chemical properties and emission data, the incorporation of additional environmental media and processes, the integration of sensitivity and uncertainty analysis in the simulations. However, some challenging issues remain and require research efforts and attention: the need of methods to estimate partition coefficients for polar and ionizable chemical in the environment, a better description of bioavailability in different environments as well as the requirement of injecting more ecological realism in exposure predictions to account for the diversity of ecosystem structures and functions in risk assessment. Finally, to transfer new scientific developments into the realm of regulatory risk assessment, we propose the formation of expert groups that compare, discuss and recommend model modifications and updates and help develop practical tools for risk assessment.

Received 27th November 2017
Accepted 20th December 2017

DOI: 10.1039/c7em00568g

rsc.li/espi

Environmental significance

Multimedia environmental fate models are regularly employed in the risk assessment of chemicals. They historically evolved from simple approaches to more refined and integrated modeling tools, often provided as part of a tiered strategy. Much work has been devoted to improving various aspects at the process and environmental description levels, but some issues need further research and model development, such as the capability to properly simulate the behaviour of polar and ionizable chemicals in the environment, the bioavailability of chemicals in aquatic and terrestrial environments, and variability in time and space to account for more ecological relevance. At the same time, it is important to avoid "paralysis by analysis" and develop practical tools for regulatory risk assessment that are fit for purpose. We propose the formation of expert groups to address this task.

1. Introduction: evolution and current status of fate and exposure modeling

Assessing the environmental fate and exposure of chemicals used in commerce is a challenging but critical part of assessing the risks associated with their production, use and release.

Environmental fate and exposure models play an important role in the chemical assessment process, and when coupled with monitoring data, can provide reliable information about the exposure of humans and the environment to chemicals.¹

Over the last three decades, the development and application of environmental fate models has been facilitated by a repeating pattern of co-operation between model developers and users in *ad hoc* working groups. In 1994, workshops were organized by the Society of Environmental Toxicology and Chemistry (SETAC) at Leuven, Belgium (April, 1994) and later at Denver, Colorado (November, 1994). These two workshops brought together 30 model users and developers to discuss the application of environmental fate and exposure models; to evaluate their performance; to provide guidance on their use; and to make recommendations on how the models could be improved to

^aDepartment of Science and High Technology, University of Insubria, Via Valleggio 11, 22100 Como, Italy

^bTG Environmental Research, Sharnbrook, MK44 1PL, UK

^cDepartment of Environmental Science and Analytical Chemistry (ACES), Stockholm University, Svante Arrhenius väg 8, SE-11418 Stockholm, Sweden

^dInstitute for Chemical and Bioengineering, ETH Zürich, Vladimir-Prelog-Weg 1, 8093 Zürich, Switzerland. E-mail: scheringer@chem.ethz.ch

^eRECETOX, Masaryk University, 625 00 Brno, Czech Republic



broaden their acceptability and encourage their use.² Seven years later, an OECD/UNEP Workshop was organized in Ottawa, Canada (October, 2001), to assess the utility of multimedia fate models for estimating overall environmental persistence and long-range transport of chemicals in the context of assessing potential persistent organic pollutants (POPs) and/or persistent, bioaccumulative and toxic substances (PBTs). The Ottawa workshop marked the beginning of a period of activity by a working group of model developers and users (the OECD Expert Group on Multimedia Modeling) that led to the publication of a model comparison study,³ recommendations for assessing persistence and long-range transport with models⁴ and a consensus model, the OECD Overall Persistence and Long-range Transport Modeling Tool (The OECD Tool⁵). In 2013 a working group jointly organized by the three Scientific committees of the European Commission, DG SANCO (SCHER, SCHENIR, SCCS),⁶ published the scientific opinion “Addressing the New Challenges for Risk Assessment” in which a number of opportunities to improve exposure models to increase their ecological realism and predictive ability for the growing number of chemical classes on the market were identified. Some of the fate and exposure assessment challenges from the scientific opinion were reported by Di Guardo and Hermens.⁷

Most recently, the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) organized a workshop on environmental fate and exposure models in Brussels, Belgium (May, 2017). Following the format of previous workshops, the ECETOC workshop brought together users and developers of environmental fate models. At this workshop, industry scientists and regulators who conduct chemical hazard assessments using PBT criteria, and risk assessments for industrial chemicals, pharmaceuticals, biocides and agricultural chemicals, came together to review current standards of practice in exposure modeling and to identify key challenges for addressing 21st century needs in chemical hazard and risk assessment. The authors of this review article have been active in many of the workshops summarized above, and all participated at the recent ECETOC workshop. This review article summarizes key observations from the workshop, with a particular emphasis on how advances in environmental fate models over the last 20 years have addressed the challenges identified in the 1994 workshops, and to identify the primary needs to further advance the models.

Environmental fate models provide a framework to assemble a quantitative and mechanistic description of the sources of chemicals to the environment, and the pathways they follow en-route to their ultimate degradation or irreversible sequestration. Fate models can be integrated with, or loosely-coupled to, multi-pathway exposure models that describe the transfer of chemicals from the environment into the food and water ingested by humans, and water and soil that directly contacts the human skin.⁸ Models are currently heavily relied upon to assess chemical hazard, exposure and risk, and to formulate chemical management strategies. But models did not always occupy such a strong position as scientific and policy support tools.

One of the main outputs of the modeling workshops that were held in the 1990s was a report by Cowan *et al.*² that

identified a number of research areas that required attention in order to strengthen the utility of models as scientific and decision-support tools. Cowan *et al.*² recognized that the models were powerful conceptual tools capable of characterizing and quantifying the sources, environmental pathways, and exposure routes for chemicals used in commerce. And, they recognized the importance of identifying and quantifying the uncertainty and variability associated with a model's description of these processes. The following five key areas were identified as requiring attention by Cowan *et al.*² in 1995:

(1) Clear classification of chemicals that are within the domain of applicability of models; chemical properties and degradation half-lives and their variability with temperature; emission data, including background environmental concentrations;

(2) Model algorithms and parameterization to increase the fidelity of the model's descriptions of the real environment within the bulk compartments of air, water, soil and sediment that were generally included in models at the time, and to extend the models to describe additional compartments such as vegetation and ice/snow; additionally, the need to develop data sets to describe inter-media transfer coefficients in a variety of environmental scenarios; among the other areas to improve were sub-models for chemical fate in soil and sediments as well as waste-water treatment models, and bioaccumulation and food chain models.

(3) Model comparison exercises to enhance reliability and credibility, especially in model documentation;

(4) Sensitivity and uncertainty analysis to provide confidence intervals to support hazard and risk-based decisions and to identify key areas for further research and model development;

(5) Establishment of a set of guidelines for good modeling practice in scientific and decision-support applications of models, with a particular attention to the model validation issues and the comparison of predicted to measured results.

Model developers have invested considerable resources to address these areas since the publication of Cowan *et al.*² in 1995. Moreover, they have expanded the scope and applicability of fate and exposure models in several other dimensions that go beyond these recommendations. Areas where there have been notable developments include:

- Development of models with a range of spatial and temporal resolutions that can be used in concert with field data to rationalize chemical concentrations and estimate the rates of emissions or key fate processes at different spatio-temporal scales;

- Inclusion of transformation products in model scenarios;
- Scenario analysis to investigate the influence of climate variability and climate change on exposure to environmental contaminants;

- Development of fate and exposure models for engineered nanoparticles and for mercury;

- Adaptation of the principles from chemical fate and exposure models to pharmacokinetic models and application to human biomonitoring data.

Here we review the progress made in these areas, discuss the mechanistic foundations of fate and exposure models, and



identify open questions and needs for strengthening future model development and application. We first provide a summary of progress in different areas and then highlight selected topics of particular interest.

2. Progress in fate and exposure model development since the mid-1990s

The areas of fate and exposure modeling where progress has been made range from chemical property data needed as model inputs to model parameterization and design, types of scenarios that can be handled by the models, model evaluation by comparison to field data, sensitivity and uncertainty analysis, and more.

Chemical properties, specific model parameters

Chemical property data are essential as model inputs. Since the publication of the property data handbooks by Mackay *et al.*,⁹ property data for many organic chemicals have been critically evaluated, missing data have been estimated with improved chemical property estimation methods, and sets of recommended best estimates have been published for several classes of environmentally important chemicals (*e.g.*, PCBs,^{9,10} HCHs,¹¹ PAHs,¹² PFASs,¹³ siloxanes,¹⁴ chlorinated paraffins¹⁵ and chlorinated dioxins and furans,¹⁶ and complex mixtures of halogenated organics¹⁷). Polyparameter linear-free energy relationships (ppLFER)¹⁸ have been established to estimate partition coefficients for a range of environmental media for which partitioning cannot be related to the octanol-water partition coefficient (K_{ow}) (*e.g.*, ice/snow,¹⁹ mineral surfaces,^{20–22} aerosols^{23–25} and polymers and biopolymers²⁶). A great deal of effort has also been invested in expanding the applicability domain of models to better assess the environmental fate and bioaccumulation of polar and ionizable organic chemicals.^{27–30} Lastly, model parameters describing environmental mass-transfer processes have been critically reviewed and updated.³¹

Emission data

Two complementary approaches have been employed to estimate the emission source strength of chemicals used in technical applications and consumer products. The first is the bottom-up approach that was pioneered by Breivik *et al.*^{32–34} to estimate the emissions of PCBs globally, and applied by Diamond and colleagues^{35–37} for the city of Toronto. Other bottom-up emission inventories have been compiled by Wang *et al.*³⁸ for PFCAs, by Glüge *et al.*³⁹ for chlorinated paraffins, Li *et al.*⁴⁰ for α -HCH, and by Zhang and Tao for 16 PAHs.⁴¹ The second approach is the back-calculation of emissions from measured concentration data by inverse modeling,^{14,42–47} which is discussed in more detail below.

Expanding the scope and applicability of the models

A key contribution in this area is the definition of a variety of metrics of exposure-related environmental and human exposure

hazard that can be calculated with fate and exposure models. These include metrics of persistence and long-range transport potential that reflect a chemical's tendency to be widely distributed, to form long-lived reservoirs in the environment, and to lead to the formation of persistent transformation products.^{5,48–58} Models have also been applied to map the remoteness of locations in the global environment from sources of chemical pollution,^{59,60} see Fig. 1. Metrics of environmental risk and human exposure potential for chemicals have been derived within the framework of fate and exposure models.^{61–65}

Multimedia models of the 1990s included bulk compartments for air, water, soil, and sediment. Several additional environmental compartments, sub-compartments and processes have been incorporated into fate and exposure models, including terrestrial and aquatic vegetation,^{66–79} DOC in terrestrial and aquatic systems,^{76,80,81} ice and snow,^{82–84} different types of aerosols,⁸⁵ mountainous regions,^{86,87} and the effect of intermittent rain.^{88–90}

The fundamental concept underlying all fate and exposure models is the integration of chemical transport, transfer and degradation processes into mass balance equations for the chemical investigated. This concept of setting up multi-media mass-balances is generally valid and goes beyond the most common type of models that have been developed and applied



Fig. 1 (a) Remoteness index calculated by von Waldow *et al.*⁵⁹ using an atmospheric transport model (chemical independent), and (b) the negative log of transfer efficiency (pTE) of a volatile chemical calculated by Goktas & MacLeod⁶⁰ using the BETR Global multimedia transport model. Higher values of remoteness index and pTE indicate locations on the Earth that are more remote from emissions of chemicals to air that occur in proportion to the intensity of night-time light observed from space. Histograms illustrate the area distribution of different values of remoteness index or pTE.



to non-ionizing, often long-lived, organic chemicals. For example, mass-balance models have been developed for nanoparticles^{91–98} and recently for microplastic.⁹⁹

A class of organic chemicals of emerging concern are the ionizable organic substances. Given that the process descriptions of most of the current multi-media environmental fate models were derived from the well-established understanding of partitioning and mass transfer of neutral organic chemicals, expanding the domain of applicability of the models to address ionizable organics represents an important development. Unit world mass balance for ionizing chemicals using activity *in lieu* of fugacity have been presented.^{100,101} The multimedia activity model for ionizable (MAMI) organic chemicals has recently been modified in the development of a multimedia chemical fate model for China (SESAME), designed using the nested structure of SimpleBox.^{102,103} The SimpleTreat model 4.0¹⁰⁴ has been updated to include improved handling of ionizable organics, thus providing a tool for estimating chemical fate and behaviour in domestic sewage and activated sludge systems for down-the-drain chemicals, such as pharmaceuticals.¹⁰⁵

Model evaluation by comparison to field data

Fate and exposure models can be evaluated by comparing the model results to field data. If a model can reproduce field data (collected under conditions that correspond to the assumptions and settings in the model), this strongly increases the credibility of the model and demonstrates that the model is suitable for the chemical and environmental system considered. Results from fate and exposure models have often been found to agree well with field data; this includes at the global level,^{63,106–111} and at the continental level^{112–115} for selected persistent organic pollutants, and also in local and regional systems, such as the cases of diuron in a small, highly dynamic tropical catchment,¹¹⁶ plant protection products in agricultural catchments at different scales,^{117–121} PBDEs in a Swiss lake,¹²² and PCBs in the Adriatic Sea.¹²³

Sensitivity and uncertainty analysis

Sensitivity and uncertainty analyses have become more and more common and are now an integral part of many fate and exposure modeling studies. MacLeod *et al.*¹²⁴ provide a practical guide to sensitivity and uncertainty analysis for fate and exposure modeling studies. In the OECD Pov and LRTP Tool the user can activate the built-in options for a sensitivity and uncertainty analysis of the results for overall persistence and long-range transport potential. Becker *et al.* (2011)¹²⁵ provide an extensive uncertainty analysis for the concentrations of endosulfan in air and seawater calculated with a global environmental fate model, and Wöhrnschimmel *et al.*¹²⁶ propagated uncertainty in chemical properties and degradation half-lives of persistent pollutants through an analysis of the effects of climate change on pollutant transport to the Arctic.

Good modeling practice

Finally, the need of incorporating good modeling practice in the development and evaluation of environmental models was proposed by Jakeman *et al.* (2006);¹²⁷ this was then specified by

Buser *et al.*,¹²⁸ who set up six principles of good modeling practice in the field of fate and exposure modeling. These principles range from a specification of the goal and scope of the assessment to specifying the model used, specifying all input and all output data, conducting a sensitivity analysis so that the most influential model parameters can be identified, and specifying the limitations of the model results and the modeling exercise.

Improved modeling of bioavailability of contaminants

Bioavailability of chemicals to terrestrial and aquatic environments and more generally the ecological realism of scenario descriptions has been pointed out as a critical issue to evaluate the exposure and therefore the toxicity of hydrophobic chemicals in the environment.^{7,129,130} Some models were recently published and have incorporated additional compartments and subcompartments (such as dissolved organic carbon, macrophytes, algae) to account for their influence on dynamically changing bioavailable concentrations,^{76,81,131,132} as well as compartment variability in scenarios.^{78,132,133}

3. Models for small spatial scales and dynamic scenarios

In the 1990s fate and exposure models had mostly been developed to describe long-lived chemicals, such as organochlorine pesticides and PCBs. Analytical chemistry techniques for such substances required large-volume samples and intensive effort in the laboratory for analysis. Thus, the temporal and spatial resolution of available measurements was low, and, due to the persistent nature of the chemicals, long time scales were needed to observe trends in concentrations. Models developed in the 1990s correspondingly described environmental conditions using long-term average conditions for temperature, rain rate, wind speed, *etc.*, and models were often applied using a steady-state assumption that represents a hypothetical conditions where emissions are balanced by removal processes.¹³⁴ In the years since the 1990s it has been increasingly recognized that environmental fate models can be more flexible if they implement more rapidly changing conditions. This is needed if the chemical considered has short degradation half-lives and/or if there are strong and rapid changes of the environmental conditions. Advances in analytical chemistry capabilities have provided more measurements at higher spatial and temporal scales to provide context for these model scenarios and to support model-measurement comparisons that enable a process-based understanding of chemical dynamics. This also made it possible to appreciate the role of temporal and spatial changes of specific compartments, such as a pond or a forest, in driving concentration changes in the main compartments *e.g.* water and air.^{76,132,133,135}

For example, Camenzuli *et al.* (2012)¹¹⁶ investigated the fate of the herbicide, diuron, in a small river catchment in Queensland, Australia. The problem in this case was that appreciable amounts of the diuron used on sugarcane and other crops in Northern Queensland were flushed into the Great



Barrier Reef lagoon by water runoff. In the lagoon, the herbicide affects, among other effects, the seaweed and thereby wildlife living on seaweed (dugongs, turtles). There is a strong seasonal change in the rain rates in Northern Queensland and the rain rates in the wet season are very high (with peaks above 200 mm per day). Camenzuli *et al.* (2012)¹¹⁶ developed a model of the Tully River catchment with six compartments (agricultural soil, non-agricultural soil, seawater, sea sediment, air, water on land that is present under flooding conditions) and ran the model with very high temporal resolution (time steps on the order of seconds). This allowed them to drive the model with the highly dynamic actual rainfall data measured at a station in the Tully River catchment (Fig. 2a).

The model results of interest were the fluxes of diuron into the seawater compartment and the diuron concentrations in that compartment. Comparison with diuron concentrations measured in the lagoon shows that the model results agree well with the measured data, see Fig. 2b. The concentrations follow the seasonal rainfall trend.

In this way, the model was established as a tool that was then used to explore the effect of a diuron restriction scenario (no application of diuron in the wettest months of the year, November to April). Such a restriction would lead to a decrease in diuron concentrations in seawater by a factor of two. Overall, this case study shows that fate and exposure models are not limited to cases with “slow” processes and average

environmental conditions, which is sometimes seen as a serious limitation of this type of model, but can also be set up in a way that they describe highly dynamic conditions with high accuracy.

Similarly to the diuron case, an integrated compartmental model (DynaPlus) was recently developed and used to predict the surface water contamination by pesticides used in an intensive orchard cultivation in a mountain region in Italy.¹²¹ Mountainous regions are characterized by rapid land response to precipitation, resulting in quick runoff chemical peaks and consequent potentially high peak exposure concentrations in aquatic ecosystems receiving such runoff. The model consisted of a dynamic water network model (built upon the Dyna model¹³⁶) and a spatially explicit terrestrial multimedia model^{81,120} parametrized using specific scenario and emission data provided by the local authorities. The model incorporated an improved algorithm to calculate water runoff in steep slopes (average 30%, up to 80%) which allowed to more accurately calculate chemical runoff in these conditions. The integrated model was run for two cultivation years and results of chemical runoff from treated orchards were compared to *ad hoc* measured water concentrations for the organophosphorus insecticide chlorpyrifos in order to benchmark the model against field data. The model simulations showed that concentration peaks of chlorpyrifos in river water (Fig. 3) spanned and oscillated between 3 and 4 orders of magnitude, in the range of 0.1 to 1000 ng L⁻¹, which is well within the range of the acute EC50 for *Daphnia* (around 100 ng L⁻¹).¹³⁷

Given that ecotoxicity data (such as those for *Daphnia*) are usually determined at constant exposure, the results of these model simulations reveal the difficulty of evaluating the effect of higher concentration peaks but shorter in time (peak exposure) in protecting aquatic ecosystems.

A dynamic model for assessing pesticide residues in fruit in comparison against EU and US maximum residue levels has recently been presented by Mendez *et al.*¹³⁸ in relation to the cultivation of bananas in Costa Rica. In addition to water, air, soil, and sediment compartments, Mendez *et al.*¹³⁸ also included a banana plant and estimated the residues of diuron, ethoprophos, and epoxiconazole. Their results demonstrate the importance of dynamic models as decision-support tool that complements ongoing efforts to assess the ecological effects of

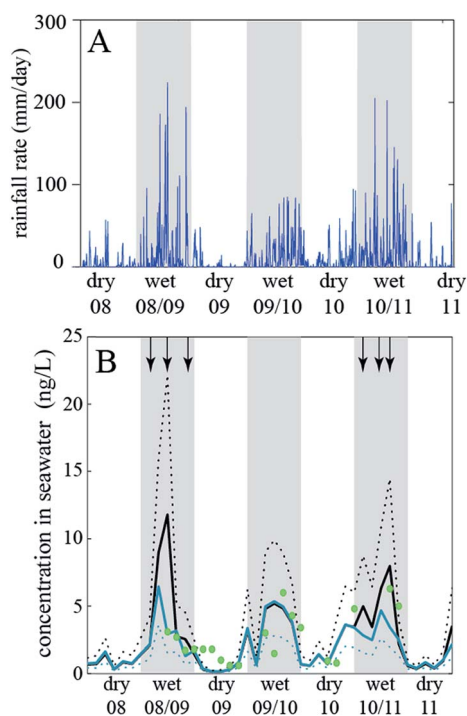


Fig. 2 (A) Rainfall data from the Tully River catchment, Queensland, Australia, and (B) diuron concentrations measured in the Great Barrier Reef lagoon (dots) and calculated with the fate and exposure model (lines) by Camenzuli *et al.* (2012)¹¹⁶. Reprinted from The Science of the Total Environment, 440, L. Camenzuli *et al.*, Describing the environmental fate of diuron in a tropical river catchment, pp. 178–185, Copyright (2012), with permission from Elsevier.

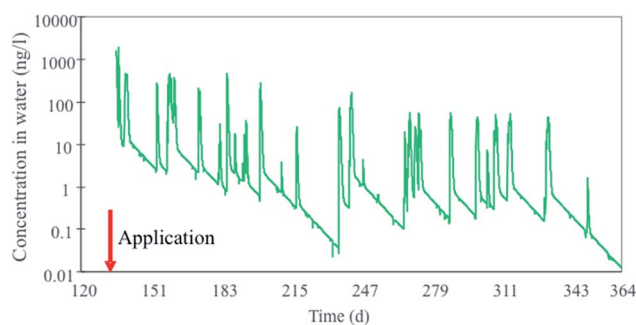


Fig. 3 Peaks of chlorpyrifos concentrations in a mountain river (Novella) in Italy in 2012 calculated with the DynaPlus model of Morselli *et al.* (2018).¹²¹



exposure to chemical mixtures and transient pulses. For instance, such models can be helpful in minimizing the occurrence of pesticide pulses, by providing a decision-making tool with respect to the timing of pesticide applications.

4. Day-night cycling of SVOCs in boundary layer air

As sampling and analytical capabilities improved for atmospheric micropollutants, measurements of persistent semi-volatile pollutants with temporal resolution of several hours became more widely available in the 2000s. In 2007, MacLeod *et al.*¹³⁹ developed a dynamic multimedia model that included variable atmospheric boundary layer height, temperature, hydroxyl radical concentrations and windspeed. They collected measurement data from six studies that reported concentrations of semi-volatile organic chemicals in air over consecutive 24 hour cycles, and demonstrated that in all cases the model could explain the drivers of day-night variability of concentrations in terms of variable process rates. Their analysis with the dynamic mass balance model identified four controlling factors that determine the day-night variability of concentrations of persistent semi-volatile chemicals in air: (1) source characteristics, (2) temperature dependent air-surface partitioning, (3) atmospheric mixing height and stability, and (4) hydroxyl radical concentration.

The insights from the 2007 modeling study informed the design of day-night measurement campaigns that were designed specifically to determine the rate of emissions of air pollutants from diffuse sources in urban areas. Several of these studies were carried out in Zurich, Switzerland to measure emission rates of PCBs,^{42,140} PBDEs,^{43,44} perfluoro alkyl substances,⁴⁷ cyclic siloxanes,¹⁴¹ and PCDD/Fs.¹⁴⁰ The recent quantification of ongoing PCB emissions in Zurich led the Swiss Federal Office for the Environment to re-open the question of PCB emission sources and to commission the set-up of a current and comprehensive PCB emission inventory for Switzerland.¹⁴²

Mass balance models applied in conjunction with day-night measurement campaign data have demonstrated the potential to infer process rates for hydroxyl radical degradation of PCBs,¹³⁹ for a more physically-based description of the air compartments in fugacity models, introducing hourly variable PBL (planetary boundary layer) compartment^{81,143,144} and for reversible air-vegetation exchange of PCBs, PBDEs and chlor-dane.^{42,145} Studies of this type provide the opportunity to evaluate the process descriptions provided by mass balance models in a relatively controlled situation, which helps to identify weaknesses in the models that can be improved, and ultimately improve model performance and reliability in applications at all spatio-temporal scales.

5. Environmental fate models as decision-support tools

Applying environmental fate models in decision-making requires that the models are understood by stakeholders,

credible and that their reliability has been assessed. For multimedia models, the three key elements are: (i) the models themselves, *i.e.* the process descriptions and their mechanistic basis, and the model parameterization; (ii) the chemical property data used as model input; and (iii) the emission data, including their temporal and spatial resolution, used as model input.

Importantly, the three elements are independent of one another, which means that each of them may introduce a certain type and degree of error into the model results, but also that errors from these different elements can be traced separately, which makes it easier to constrain the source of error. The first element, process descriptions and model parameterization, strongly relies on the general laws of nature such as the law of the conservation of mass, the law of mass action, and the laws of chemical kinetics and diffusion, as well as empirical data reflecting the environmental conditions assumed in the model. Nevertheless, in setting up a model there is always, to some extent, room for choices to be made by the model developer. The effect of this variability in model setups can be assessed by model-model comparisons. An extensive model comparison was performed for multimedia fate models used to determine the overall persistence (Pov) and long-range transport potential (LRTP) of organic chemicals.³

The other two elements, chemical property data and emission data, often introduce greater error than the choice of model or details of the model setup. Chemical property data available in data bases and compilations often show surprisingly high variability and uncertainty; they need to be selected carefully and are ideally checked for their internal consistency, *e.g.* the octanol-air partition coefficient (K_{oa}) needs to be equal to the ratio of K_{ow} and the air-water partition coefficient, K_{aw} .^{146,147} Emission data are often the most uncertain and incomplete element,¹⁴⁸ as discussed above.

Even when the property and emission data are selected carefully, there will be some remaining uncertainty that has to be accepted. For both, property and emission data, it is then advisable to determine a confidence factor or uncertainty range and to propagate this range through the model, for example by means of Monte-Carlo simulation or by applying the rules of error propagation.¹²⁴

One environmental fate model that was developed explicitly for decision making purposes is the OECD Pov and LRTP Estimation Tool.⁵ Before the actual tool was created, nine different models for Pov and LRTP calculations were evaluated and compared in much detail.³ Also a set of well-characterized reference chemicals that define the scales of Pov and LRTP was introduced.⁴ Once the validity of the underlying concepts was established and the scope and purpose of the model within a decision-making context were defined, the specific setup of the tool, *i.e.* the format of the data input and display of results, the model algorithm, options for uncertainty analysis, and the software environment, was defined.⁵ Because the tool is based on a robust and common software environment (MS Excel for both Windows and Macintosh computers), is easy to use (reliable and robust handling of incorrect input), offers all results in both a graphical and numerical format, and is available free of charge



from a trusted organization (OECD), it was quickly adopted by its users in government, research and industry. Since then, it has been used regularly for the evaluation of possible persistent organic pollutants in the context of the Stockholm Convention.

6. Outlook for improving the application of models within regulatory frameworks

This paper has summarized research conducted in the last three decades that addressed the needs identified by Cowan *et al.*² and that evolved in the various workshops that have been held since then. Improvements in characterizing and quantifying physicochemical properties and emission estimates and refinements in model formulation and parameterization have led to better comparability between model results and monitoring data, which in turn imparts greater confidence to the use of models within regulatory chemical risk assessment. Overall, there has been considerable progress in model development, model transparency and model reliability. However, in the context of regulatory risk assessment it is important to strike a balance between increasing model complexity and diversity driven by scientific progress, on the one hand, and the need for models that are practical and relatively easy to use, on the other hand. Ongoing scientific development and the presence of open scientific questions must not reduce the availability of practical tools for regulatory risk assessment out of “paralysis by analysis”. Therefore, there is a continuous need for the translation of new scientific insights into the sphere of – often simplified – modeling tools suitable for regulatory risk assessment.

This translation process is a task in itself and requires time and resources. Participants from the 2017 ECETOC workshop expressed frustration regarding the lack of advances in environmental fate and exposure models that are included within the tools used for regulatory purposes. For instance, as described above, substantial progress has been made in expanding the applicability domain of the models with respect to both chemical and environmental properties. However, the European Union System for the Evaluation of Substances (EUSES), which is used for assessing exposure of general chemicals and biocides regulated under REACH, has not been updated to reflect advances in research, with the most recent update (EUSES 2.1.1) parameterized according to algorithms and assumptions described in the 2003 EU Technical Guidance Document.¹⁴⁹ There is clearly a need to improve the pace at which advances in research are implemented within regulatory tools. However the process of evaluating new modeling approaches and adopting them into regulatory tools must be conducted in an open and transparent manner that facilitates building consensus among key stakeholders from industry, NGOs, government, and academia who are actively engaged in the development and use of environmental fate and exposure models.

The development of the OECD Tool demonstrated how bringing an expert group of modelers together can result in successful development and adoption of a regulatory modeling

tool. Another example of an expert group building consensus about the application of exposure modeling within a regulatory context is the Forum for Co-ordination of pesticide fate models and their Use (FOCUS). FOCUS was an initiative of the European Commission, with the objective to harmonize the predicted environmental concentrations (PECs) of active substances of plant protection products (PPP) in the framework of the EU Directive 91/414/EEC. It provided a platform for close co-operation of expert groups of scientists drawn from regulatory agencies, academia, and industry under the auspices of the Commission's DG SANTE.

We propose that the creation of expert groups that follow the approaches provided by FOCUS and the OECD Tool is a fundamental element for achieving consensus among stakeholders to update and improve models used in regulatory exposure assessment. Multi-stakeholder expert groups provide a forum for communication and education about developments and application of environmental fate and exposure models. When the groups are tasked with a clear objective, they can work in a focused manner to define the attributes of a fate and exposure model that is “fit for purpose” to confront a regulatory question. Tools used at lower tiers of assessment will likely address questions that differ from tools used at higher tiers of assessment. Consequently, separate expert groups may be needed to confront related questions, or a single expert group might be tasked to develop a tiered set of models that address the problem at several levels of complexity. Ideally, an active and collaborative expert group that represents all key stakeholders should be able to define the tools, assumptions, and acceptable level of uncertainty associated with the various assessment tiers that might be required in a regulatory context. The work of these groups would include model comparison exercises, and critical evaluation of assumptions and limitations of models with the ultimate goal of providing recommendations for the application of existing models, or purpose-built new software for conducting exposure assessments that reflects scientific consensus among stakeholders.

We acknowledge that creating multi-stakeholder expert groups that are tasked to agree on how to best update regulatory tools used for chemical risk assessment is not likely to be a trivial exercise. It will require commitments of time and money from the stakeholders to be successful. In the specific case of EUSES, the process could build on the foundation provided by the list of high-priority corrections, improvements, and extensions that was published by van de Meent *et al.*,¹⁵⁰ the key observations published in the 2013 EU scientific opinion,⁶ and the recommendations of the 2017 ECETOC workshop participants.¹⁵¹

A high priority for improving exposure models used in regulatory assessments is the need to expand the chemical applicability domain. The rapid development of target and non-target analytical chemistry techniques based on LC/MS over the last decades has made measurement and monitoring of environmental contaminants that are ionisable organic chemicals, including halogenated organic acids and chemicals used in pharmaceuticals and personal care products, an important area of environmental chemistry. Attention placed on these



chemicals by their detection in the environment has been a key driver for drawing regulatory attention. Particularly at lower screening and prioritization tiers of assessment, regulatory models are currently not capable of handling these chemicals in a reliable manner, and a lack of reliable property estimation methods for such chemicals further hinders screening level assessments.

Many regulatory models are also not appropriate for describing measurement data collected at high temporal resolution (e.g. hours). The 2013 Scientific Opinion⁶ expressed a need for criteria and protocols for obtaining and comparing chemical monitoring data, especially for evaluating the fate of chemical mixtures, including metabolites. Such data should be collected and assembled in databases that can be used for model development, validation and benchmarking to support developing and calibrating higher temporal resolution models that could eventually be applied with confidence within a regulatory context.

In the absence of reliable property data and regulatory models that are appropriate for interpreting monitoring data and placing the data in the context of the environmental fate, transport and exposure of chemicals, measurements documenting the occurrence of pollutants place pressure on regulatory authorities to infer potential risks without a quantitative framework.¹⁵² Recent experiences with cyclic volatile methyl siloxanes,^{153,154} and the public policy debate about regulation of microplastics in consumer products^{155,156} illustrate the confusion this situation can create. It is therefore vital that chemical property measurement and estimation methods, and environmental fate and exposure modeling, continue to advance and evolve to support rational management decisions for the 21st century's environmental contaminants of concern.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

This review article was motivated by discussions had during an ECETOC workshop, May 2017, the authors wish to acknowledge ECETOC for funding of the workshop and workshop participants. M. S. acknowledges financial support from the Czech Ministry of Education, Youth, and Sports (Grant LM2015051) and Masaryk University (CETOCOEN PLUS Project Grant CZ.02.1.01/0.0/0.0/15_003/0000469).

References

- 1 M. MacLeod, M. Scheringer, T. E. McKone and K. Hungerbühler, The State of Multimedia Mass-Balance Modeling in Environmental Science and Decision-Making, *Environ. Sci. Technol.*, 2010, **44**, 8360–8364.
- 2 C. E. Cowan, D. Mackay, T. C. J. Feijtel, D. Van de Meent, A. Di Guardo, J. Davies and N. Mackay, *The multi-media fate model: A vital tool for predicting the fate of chemicals*, SETAC Press, Pensacola, FL, 1995.

- 3 K. Fenner, M. Scheringer, M. MacLeod, M. Matthies, T. McKone, M. Stroebe, A. Beyer, M. Bonnell, A. C. Le Gall, J. Klasmeier, D. Mackay, D. van de Meent, D. Pennington, B. Scharenberg, N. Suzuki and F. Wania, Comparing Estimates of Persistence and Long-Range Transport Potential among Multimedia Models, *Environ. Sci. Technol.*, 2005, **39**, 1932–1942.
- 4 J. Klasmeier, M. Matthies, M. MacLeod, K. Fenner, M. Scheringer, M. Stroebe, A. C. Le Gall, T. McKone, D. Van De Meent and F. Wania, Application of Multimedia Models for Screening Assessment of Long-Range Transport Potential and Overall Persistence, *Environ. Sci. Technol.*, 2006, **40**, 53–60.
- 5 F. Wegmann, L. Cavin, M. MacLeod, M. Scheringer and K. Hungerbühler, The OECD software tool for screening chemicals for persistence and long-range transport potential, *Environ. Modell. Softw.*, 2009, **24**, 228–237.
- 6 European Commission, *Addressing the new challenges for risk assessment*, European Commission and Directorate General for Health & Consumers, <https://publications.europa.eu/en/publication-detail/-/publication/0132ea87-0420-4258-9ebf-ac49c9e4dcb0/language-en>, Luxembourg, 2013.
- 7 A. Di Guardo and J. L. Hermens, Challenges for exposure prediction in ecological risk assessment, *Integr. Environ. Assess. Manage.*, 2013, **9**, e4–14.
- 8 T. E. McKone and M. MacLeod, Tracking multiple pathways of human exposure to persistent multimedia pollutants: Regional, Continental, and Global-Scale Models, *Annu. Rev. Environ. Resour.*, 2003, **28**, 463–492.
- 9 *Handbook of physical-chemical properties and environmental fate for organic chemicals*, ed. D. Mackay, W. Y. Shiu and K. C. Ma, CRC/Taylor & Francis, Boca Raton, FL, 1992, vol. 1.
- 10 N. Li, F. Wania, Y. D. Lei and G. L. Daly, A Comprehensive and Critical Compilation, Evaluation, and Selection of Physical-Chemical Property Data for Selected Polychlorinated Biphenyls, *J. Phys. Chem. Ref. Data*, 2003, **32**, 1545–1590.
- 11 H. Xiao, N. Li and F. Wania, Compilation, Evaluation, and Selection of Physical-Chemical Property Data for α -, β -, and γ -Hexachlorocyclohexane, *J. Chem. Eng. Data*, 2004, **49**, 173–185.
- 12 Y.-G. Ma, Y. D. Lei, H. Xiao, F. Wania and W.-H. Wang, Critical Review and Recommended Values for the Physical-Chemical Property Data of 15 Polycyclic Aromatic Hydrocarbons at 25 °C, *J. Chem. Eng. Data*, 2010, **55**, 819–825.
- 13 Z. Wang, M. MacLeod, I. T. Cousins, M. Scheringer and K. Hungerbühler, Using COSMOtherm to predict physicochemical properties of poly- and perfluorinated alkyl substances (PFASs), *Environ. Chem.*, 2013, **8**, 389–398.
- 14 A. M. Buser, S. Schenker, M. Scheringer and K. Hungerbühler, Comparing the Performance of Computational Estimation Methods for Physicochemical Properties of Dimethylsiloxanes and Selected Siloxanols, *J. Chem. Eng. Data*, 2013, **58**, 3170–3178.
- 15 J. Glüge, C. Bogdal, M. Scheringer, A. M. Buser and K. Hungerbühler, Calculation of Physicochemical



- Properties for Short- and Medium-Chain Chlorinated Paraffins, *J. Phys. Chem. Ref. Data*, 2013, **42**, 023103.
- 16 A. Åberg, M. MacLeod and K. Wiberg, Physical-Chemical Property Data for Dibenzo-*p*-dioxin (DD), Dibenzofuran (DF), and Chlorinated DD/Fs: A Critical Review and Recommended Values, *J. Phys. Chem. Ref. Data*, 2008, **37**, 1997–2008.
 - 17 A. Gawor and F. Wania, Using quantitative structural property relationships, chemical fate models, and the chemical partitioning space to investigate the potential for long range transport and bioaccumulation of complex halogenated chemical mixtures, *Environ. Sci.: Processes Impacts*, 2013, **15**, 1671–1684.
 - 18 K.-U. Goss and R. P. Schwarzenbach, Linear Free Energy Relationships Used To Evaluate Equilibrium Partitioning of Organic Compounds, *Environ. Sci. Technol.*, 2001, **35**, 1–9.
 - 19 C. M. Roth, K.-U. Goss and R. P. Schwarzenbach, Sorption of Diverse Organic Vapors to Snow, *Environ. Sci. Technol.*, 2004, **38**, 4078–4084.
 - 20 K. U. Goss, Effects of temperature and relative humidity on the sorption of organic vapors on quartz sand, *Environ. Sci. Technol.*, 1992, **26**, 2287–2294.
 - 21 K. U. Goss, Adsorption of organic vapors on polar mineral surfaces and on a bulk water surface: development of an empirical predictive model, *Environ. Sci. Technol.*, 1994, **28**, 640–645.
 - 22 K.-U. Goss, Conceptual Model for the Adsorption of Organic Compounds from the Gas Phase to Liquid and Solid Surfaces, *Environ. Sci. Technol.*, 1997, **31**, 3600–3605.
 - 23 C. M. Roth, K.-U. Goss and R. P. Schwarzenbach, Sorption of a Diverse Set of Organic Vapors To Diesel Soot and Road Tunnel Aerosols, *Environ. Sci. Technol.*, 2005, **39**, 6632–6637.
 - 24 C. Niederer, K.-U. Goss and R. P. Schwarzenbach, Sorption Equilibrium of a Wide Spectrum of Organic Vapors in Leonardite Humic Acid: Modeling of Experimental Data, *Environ. Sci. Technol.*, 2006, **40**, 5374–5379.
 - 25 C. W. Götz, M. Scheringer, M. MacLeod, C. M. Roth and K. Hungerbühler, Alternative Approaches for Modeling Gas-Particle Partitioning of Semivolatile Organic Chemicals: Model Development and Comparison, *Environ. Sci. Technol.*, 2007, **41**, 1272–1278.
 - 26 E. Reppas-Chrysositsinos, A. Sobek and M. MacLeod, Screening-level models to estimate partition ratios of organic chemicals between polymeric materials, air and water, *Environ. Toxicol. Chem.*, 2016, **18**, 667–676.
 - 27 A. Franco and S. Trapp, Estimation of the soil-water partition coefficient normalized to organic carbon for ionizable organic chemicals, *Environ. Toxicol. Chem.*, 2008, **27**, 1995–2004.
 - 28 A. Franco, W. Fu and S. Trapp, Influence of soil pH on the sorption of ionizable chemicals: Modeling advances, *Environ. Toxicol. Chem.*, 2009, **28**, 458–464.
 - 29 A. Franco, A. Ferranti, C. Davidsen and S. Trapp, An unexpected challenge: ionizable compounds in the REACH chemical space, *Int. J. Life Cycle Assess.*, 2010, **15**, 321–325.
 - 30 W. Fu, A. Franco and S. Trapp, Methods for estimating the bioconcentration factor of ionizable organic chemicals, *Environ. Toxicol. Chem.*, 2009, **28**, 1372–1379.
 - 31 *Handbook of chemical mass transport in the environment*, ed. L. J. Thibodeaux and D. Mackay, CRC Press, Boca Raton, 2011.
 - 32 K. Breivik, A. Sweetman, J. M. Pacyna and K. C. Jones, Towards a global historical emission inventory for selected PCB congeners—a mass balance approach 3. An update, *Sci. Total Environ.*, 2007, **377**, 296–307.
 - 33 K. Breivik, A. Sweetman, J. Pacyna and K. Jones, Towards a global historical emission inventory for selected PCB congeners—a mass balance approach 1. Global production and consumption, *Sci. Total Environ.*, 2002, **290**, 181–198.
 - 34 K. Breivik, A. Sweetman, J. Pacyna and K. Jones, Towards a global historical emission inventory for selected PCB congeners—a mass balance approach 2. Emissions, *Sci. Total Environ.*, 2002, **290**, 199–224.
 - 35 M. L. Diamond, L. Melymuk, S. A. Csiszar and M. Robson, Estimation of PCB stocks, emissions, and urban fate: will our policies reduce concentrations and exposure?, *Environ. Sci. Technol.*, 2010, **44**, 2777–2783.
 - 36 S. A. Csiszar, S. M. Daggupaty, S. Verkoeyen, A. Giang and M. L. Diamond, SO-MUM: a coupled atmospheric transport and multimedia model used to predict intraurban-scale PCB and PBDE emissions and fate, *Environ. Sci. Technol.*, 2013, **47**, 436–445.
 - 37 S. A. Csiszar, M. L. Diamond and S. M. Daggupaty, The magnitude and spatial range of current-use urban PCB and PBDE emissions estimated using a coupled multimedia and air transport model, *Environ. Sci. Technol.*, 2014, **48**, 1075–1083.
 - 38 Z. Wang, I. T. Cousins, M. Scheringer, R. C. Buck and K. Hungerbühler, Global emission inventories for C4-C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, Part I: production and emissions from quantifiable sources, *Environ. Int.*, 2014, **70**, 62–75.
 - 39 J. Glüge, Z. Wang, C. Bogdal, M. Scheringer and K. Hungerbühler, Global production, use, and emission volumes of short-chain chlorinated paraffins – A minimum scenario, *Sci. Total Environ.*, 2016, **573**, 1132–1146.
 - 40 Y. F. Li, S. Venkatesh and D. Li, Modeling global emissions and residues of pesticides, *Environ. Model. Assess.*, 2005, **9**, 237–243.
 - 41 Y. Zhang and S. Tao, Global atmospheric emission inventory of polycyclic aromatic hydrocarbons (PAHs) for 2004, *Atmos. Environ.*, 2009, **43**, 812–819.
 - 42 B. Gasic, C. Moeckel, M. MacLeod, J. r. Brunner, M. Scheringer, K. C. Jones and K. Hungerbühler, Measuring and Modeling Short-Term Variability of PCBs in Air and Characterization of Urban Source Strength in Zurich, Switzerland, *Environ. Sci. Technol.*, 2009, **43**, 769–776.
 - 43 C. Moeckel, B. Gasic, M. MacLeod, M. Scheringer, K. C. Jones and K. Hungerbühler, Estimation of the source strength of polybrominated diphenyl ethers based



- on their diel variability in air in Zurich, Switzerland, *Environ. Sci. Technol.*, 2010, **44**, 4225–4231.
- 44 C. Bogdal, Z. Wang, A. M. Buser, M. Scheringer, A. C. Gerecke, P. Schmid, C. E. Muller, M. MacLeod and K. Hungerbühler, Emissions of polybrominated diphenyl ethers (PBDEs) in Zurich, Switzerland, determined by a combination of measurements and modeling, *Chemosphere*, 2014, **116**, 15–23.
 - 45 C. E. Muller, A. C. Gerecke, C. Bogdal, Z. Wang, M. Scheringer and K. Hungerbühler, Atmospheric fate of poly- and perfluorinated alkyl substances (PFASs): I. Day-night patterns of air concentrations in summer in Zurich, Switzerland, *Environ. Pollut.*, 2012, **169**, 196–203.
 - 46 A. Parajulee and F. Wania, Evaluating officially reported polycyclic aromatic hydrocarbon emissions in the Athabasca oil sands region with a multimedia fate model, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, **111**, 3344–3349.
 - 47 Z. Wang, M. Scheringer, M. MacLeod, C. Bogdal, C. E. Muller, A. C. Gerecke and K. Hungerbühler, Atmospheric fate of poly- and perfluorinated alkyl substances (PFASs): II. Emission source strength in summer in Zurich, Switzerland, *Environ. Pollut.*, 2012, **169**, 204–209.
 - 48 M. Scheringer, Persistence and Spatial Range as Endpoints of an Exposure-Based Assessment of Organic Chemicals, *Environ. Sci. Technol.*, 1996, **30**, 1652–1659.
 - 49 D. H. Bennett, T. E. McKone, M. Matthies and W. E. Kastenberg, General Formulation of Characteristic Travel Distance for Semivolatile Organic Chemicals in a Multimedia Environment, *Environ. Sci. Technol.*, 1998, **32**, 4023–4030.
 - 50 A. Beyer, D. Mackay, M. Matthies, F. Wania and E. Webster, Assessing Long-Range Transport Potential of Persistent Organic Pollutants, *Environ. Sci. Technol.*, 2000, **34**, 699–703.
 - 51 K. Fenner, M. Scheringer and K. Hungerbühler, Persistence of Parent Compounds and Transformation Products in a Level IV Multimedia Model, *Environ. Sci. Technol.*, 2000, **34**, 3809–3817.
 - 52 M. Stroebe, M. Scheringer and K. Hungerbühler, Measures of Overall Persistence and the Temporal Remote State, *Environ. Sci. Technol.*, 2004, **38**, 5665–5673.
 - 53 C. E. Cowan-Ellsberry, M. S. McLachlan, J. A. Arnot, M. MacLeod, T. E. McKone and F. Wania, Modeling Exposure to Persistent Chemicals in Hazard and Risk Assessment, *Integr. Environ. Assess. Manage.*, 2009, **5**, 662–679.
 - 54 M. Scheringer, K. C. Jones, M. Matthies, S. L. Simonich and D. Van de Meent, Multimedia Partitioning, Overall Persistence, and Long-Range Transport Potential in the Context of POPs and PBT Chemical Assessments, *Integr. Environ. Assess. Manage.*, 2009, **5**, 557–576.
 - 55 E. Reppas-Chrysositsinos, A. Sobek and M. MacLeod, Screening-level exposure-based prioritization to identify potential POPs, vPvBs and planetary boundary threats among Arctic contaminants, *Emerging Contam.*, 2017, **3**, 85–94.
 - 56 F. Wania, Assessing the Potential of Persistent Organic Chemicals for Long-Range Transport and Accumulation in Polar Regions, *Environ. Sci. Technol.*, 2003, **37**, 1344–1351.
 - 57 F. Wania, Potential of Degradable Organic Chemicals for Absolute and Relative Enrichment in the Arctic, *Environ. Sci. Technol.*, 2006, **40**, 569–577.
 - 58 M. MacLeod and D. Mackay, Modeling transport and deposition of contaminants to ecosystems of concern: a case study for the Laurentian Great Lakes, *Environ. Pollut.*, 2004, **128**, 241–250.
 - 59 H. von Waldow, M. MacLeod, M. Scheringer and K. Hungerbühler, Quantifying remoteness from emission sources of persistent organic pollutants on a global scale, *Environ. Sci. Technol.*, 2010, **44**, 2791–2796.
 - 60 R. K. Goktas and M. MacLeod, Remoteness from sources of persistent organic pollutants in the multi-media global environment, *Environ. Pollut.*, 2016, **217**, 33–41.
 - 61 J. A. Arnot, D. Mackay, E. Webster and J. M. Southwood, Screening Level Risk Assessment Model for Chemical Fate and Effects in the Environment, *Environ. Sci. Technol.*, 2006, **40**, 2316–2323.
 - 62 M. Stroebe, M. Scheringer and K. Hungerbühler, Effects of multi-media partitioning of chemicals on Junge's variability-lifetime relationship, *Sci. Total Environ.*, 2006, **367**, 888–898.
 - 63 S. Becker, C. J. Halsall, M. MacLeod, M. Scheringer, K. C. Jones and K. Hungerbühler, Empirical Investigation of the Junge Variability-Lifetime Relationship Using Long-Term Monitoring Data on Polychlorinated Biphenyl Concentrations in Air, *Environ. Sci. Technol.*, 2009, **43**, 2746–2752.
 - 64 D. H. Bennett, T. E. McKone, J. S. Evans, W. W. Nazaroff, M. D. Margni, O. Jolliet and K. R. Smith, Defining Intake Fraction, *Environ. Sci. Technol.*, 2002, **36**, 206A–211A.
 - 65 M. MacLeod and T. E. McKone, Multimedia Persistence as an Indicator of Potential for Population-Level Intake of Environmental Contaminants, *Environ. Toxicol. Chem.*, 2004, **23**, 2465–2472.
 - 66 S. Trapp, M. Matthies, I. Scheunert and E. M. Topp, Modeling the bioconcentration of organic chemicals in plants, *Environ. Sci. Technol.*, 1990, **24**, 1246–1252.
 - 67 M. S. McLachlan, K. Welsch-Pausch and J. Tolls, Field Validation of a Model of the Uptake of Gaseous SOC in *Lolium multiflorum* (Welsh Ray Grass), *Environ. Sci. Technol.*, 1995, **29**, 1998–2004.
 - 68 M. S. McLachlan and M. Horstmann, Forests as Filters of Airborne Organic Pollutants: A Model, *Environ. Sci. Technol.*, 1998, **32**, 413–420.
 - 69 F. Wania and M. S. McLachlan, Estimating the Influence of Forests on the Overall Fate of Semivolatile Organic Compounds Using a Multimedia Fate Model, *Environ. Sci. Technol.*, 2001, **35**, 582–590.
 - 70 S. Trapp and K. S. B. Miglioranza, Sorption of Lipophilic Organic Compounds to Wood and Implications for Their Environmental Fate, *Environ. Sci. Technol.*, 2001, **35**, 1561–1566.



- 71 S. Trapp, Dynamic root uptake model for neutral lipophilic organics, *Environ. Toxicol. Chem.*, 2002, **21**, 203–206.
- 72 F. Wegmann, M. Scheringer, M. Möller and K. Hungerbühler, Influence of Vegetation on the Environmental Partitioning of DDT in Two Global Multimedia Models, *Environ. Sci. Technol.*, 2004, **38**, 1505–1512.
- 73 S. Trapp, Fruit Tree model for uptake of organic compounds from soil and air, *SAR QSAR Environ. Res.*, 2007, **18**, 367–387.
- 74 P. Fantke, R. Charles, L. F. de Alencastro, R. Friedrich and O. Jolliet, Plant uptake of pesticides and human health: dynamic modeling of residues in wheat and ingestion intake, *Chemosphere*, 2011, **85**, 1639–1647.
- 75 F. A. Gobas, L. P. Burkhard, W. J. Doucette, K. G. Sappington, E. M. Verbruggen, B. K. Hope, M. A. Bonnell, J. A. Arnot and J. V. Tarazona, Review of existing terrestrial bioaccumulation models and terrestrial bioaccumulation modeling needs for organic chemicals, *Integr. Environ. Assess. Manage.*, 2016, **12**, 123–134.
- 76 M. Morselli, M. Semplice, F. De Laender, P. J. Van den Brink and A. Di Guardo, Importance of environmental and biomass dynamics in predicting chemical exposure in ecological risk assessment, *Sci. Total Environ.*, 2015, **526**, 338–345.
- 77 I. T. Cousins and D. Mackay, Strategies for including vegetation compartments in multimedia models, *Chemosphere*, 2001, **44**, 643–654.
- 78 E. Terzaghi, M. Morselli, M. Semplice, B. E. L. Cerabolini, K. C. Jones, M. Freppaz and A. Di Guardo, SoilPlusVeg: An integrated air-plant-litter-soil model to predict organic chemical fate and recycling in forests, *Sci. Total Environ.*, 2017, **595**, 169–177.
- 79 M. S. McLachlan, Bioaccumulation of Hydrophobic Chemicals in Agricultural Food Chains, *Environ. Sci. Technol.*, 1996, **30**, 252–259.
- 80 J. M. Armitage, A. Franco, S. Gomez and I. T. Cousins, Modeling the Potential Influence of Particle Deposition on the Accumulation of Organic Contaminants by Submerged Aquatic Vegetation, *Environ. Sci. Technol.*, 2008, **42**, 4052–4059.
- 81 D. Ghirardello, M. Morselli, M. Semplice and A. Di Guardo, A dynamic model of the fate of organic chemicals in a multilayered air/soil system: development and illustrative application, *Environ. Sci. Technol.*, 2010, **44**, 9010–9017.
- 82 F. Wania, D. Mackay and J. T. Hoff, The Importance of Snow Scavenging of Polychlorinated Biphenyl and Polycyclic Aromatic Hydrocarbon Vapors, *Environ. Sci. Technol.*, 1999, **33**, 195–197.
- 83 G. L. Daly and F. Wania, Simulating the Influence of Snow on the Fate of Organic Compounds, *Environ. Sci. Technol.*, 2004, **38**, 4176–4186.
- 84 J. Stocker, M. Scheringer, F. Wegmann and K. Hungerbühler, Modeling the Effect of Snow and Ice on the Global Environmental Fate and Long-Range Transport Potential of Semivolatile Organic Compounds, *Environ. Sci. Technol.*, 2007, **41**, 6192–6198.
- 85 C. W. Götz, M. Scheringer, M. MacLeod, F. Wegmann and K. Hungerbühler, Regional differences in gas-particle partitioning and deposition of semivolatile organic compounds on a global scale, *Atmos. Environ.*, 2008, **42**, 554–567.
- 86 G. L. Daly and F. Wania, Organic Contaminants in Mountains, *Environ. Sci. Technol.*, 2005, **39**, 385–398.
- 87 M. Morselli, M. Semplice, S. Villa and A. Di Guardo, Evaluating the temporal variability of concentrations of POPs in a glacier-fed stream food chain using a combined modeling approach, *Sci. Total Environ.*, 2014, **493**, 571–579.
- 88 E. G. Hertwich, Intermittent Rainfall in Dynamic Multimedia Fate Modeling, *Environ. Sci. Technol.*, 2001, **35**, 936–940.
- 89 O. Jolliet and M. Hauschild, Modeling the Influence of Intermittent Rain Events on Long-Term Fate and Transport of Organic Air Pollutants, *Environ. Sci. Technol.*, 2005, **39**, 4513–4522.
- 90 M. MacLeod, M. Scheringer, C. W. Götz and K. Hungerbuehler, in *Handbook of Chemical Mass Transport in the Environment*, ed. L. J. Thibodeaux and D. Mackay, CRC Press, Boca Raton, FL, 2011, pp. 103–136.
- 91 M. Scheringer, Environmental risks of nanomaterials, *Nat. Nanotechnol.*, 2008, **3**, 322–323.
- 92 A. Praetorius, M. Scheringer and K. Hungerbuehler, Development of environmental fate models for engineered nanoparticles—a case study of TiO₂ nanoparticles in the Rhine River, *Environ. Sci. Technol.*, 2012, **46**, 6705–6713.
- 93 J. A. Meesters, A. A. Koelmans, J. T. Quik, A. J. Hendriks and D. van de Meent, Multimedia modeling of engineered nanoparticles with SimpleBox4nano: model definition and evaluation, *Environ. Sci. Technol.*, 2014, **48**, 5726–5736.
- 94 R. Jacobs, J. A. Meesters, C. J. Ter Braak, D. van de Meent and H. van der Voet, Combining exposure and effect modeling into an integrated probabilistic environmental risk assessment for nanoparticles, *Environ. Toxicol. Chem.*, 2016, **35**, 2958–2967.
- 95 B. Nowack, Evaluation of environmental exposure models for engineered nanomaterials in a regulatory context, *NanoImpact*, 2017, **8**, 38–47.
- 96 A. L. Dale, E. A. Casman, G. V. Lowry, J. R. Lead, E. Viparelli and M. Baalousha, Modeling nanomaterial environmental fate in aquatic systems, *Environ. Sci. Technol.*, 2015, **49**, 2587–2593.
- 97 K. L. Garner, S. Suh and A. A. Keller, Assessing the Risk of Engineered Nanomaterials in the Environment: Development and Application of the nanoFate Model, *Environ. Sci. Technol.*, 2017, **51**, 5541–5551.
- 98 H. H. Liu and Y. Cohen, Multimedia environmental distribution of engineered nanomaterials, *Environ. Sci. Technol.*, 2014, **48**, 3281–3292.
- 99 E. Besseling, J. T. Quik, M. Sun and A. A. Koelmans, Fate of nano- and microplastic in freshwater systems: A modeling study, *Environ. Pollut.*, 2017, **220**, 540–548.
- 100 S. Trapp, A. Franco and D. Mackay, Activity-based concept for transport and partitioning of ionizing organics, *Environ. Sci. Technol.*, 2010, **44**, 6123–6129.



- 101 A. Franco and S. Trapp, A multimedia activity model for ionizable compounds: validation study with 2,4-dichlorophenoxyacetic acid, aniline, and trimethoprim, *Environ. Toxicol. Chem.*, 2010, **29**, 789–799.
- 102 Y. Zhu, O. R. Price, J. Kilgallon, C. Rendal, S. Tao, K. C. Jones and A. J. Sweetman, A Multimedia Fate Model to Support Chemical Management in China: A Case Study for Selected Trace Organics, *Environ. Sci. Technol.*, 2016, **50**, 7001–7009.
- 103 Y. Zhu, O. R. Price, S. Tao, K. C. Jones and A. J. Sweetman, A new multimedia contaminant fate model for China: how important are environmental parameters in influencing chemical persistence and long-range transport potential?, *Environ. Int.*, 2014, **69**, 18–27.
- 104 J. Struijs, *Application of SimpleTreat 4.0 in European substance regulations, Report 1862–4804*, On behalf of the Federal Environment Agency, Germany, Dessau-Roßlau, Germany, 2015.
- 105 L. S. Lautz, J. Struijs, T. M. Nolte, A. M. Breure, E. van der Grinten, D. van de Meent and R. van Zelm, Evaluation of SimpleTreat 4.0: Simulations of pharmaceutical removal in wastewater treatment plant facilities, *Chemosphere*, 2017, **168**, 870–876.
- 106 J. M. Armitage, M. MacLeod and I. T. Cousins, Modeling the Global Fate and Transport of Perfluorooctanoic Acid (PFOA) and Perfluorooctanoate (PFO) Emitted from Direct Sources Using a Multispecies Mass Balance Model, *Environ. Sci. Technol.*, 2009, **43**, 1134–1140.
- 107 L. Lamon, H. von Waldow, M. MacLeod, M. Scheringer, A. Marcomini and K. Hungerbühler, Modeling the Global Levels and Distribution of Polychlorinated Biphenyls in Air under a Climate Change Scenario, *Environ. Sci. Technol.*, 2009, **43**, 5818–5824.
- 108 M. MacLeod, W. J. Riley and T. E. McKone, Assessing the Influence of Climate Variability on Atmospheric Concentrations of Polychlorinated Biphenyls Using a Global-Scale Mass Balance Model (BETR-Global), *Environ. Sci. Technol.*, 2005, **39**, 6749–6756.
- 109 F. Wania and D. Mackay, A global distribution model for persistent organic chemicals, *Sci. Total Environ.*, 1995, **160/161**, 211–232.
- 110 H. Wöhrnschimmel, P. Tay, H. von Waldow, H. Hung, Y. F. Li, M. MacLeod and K. Hungerbühler, Comparative assessment of the global fate of alpha- and beta-hexachlorocyclohexane before and after phase-out, *Environ. Sci. Technol.*, 2012, **46**, 2047–2054.
- 111 F. Wania, D. Mackay, Y.-F. Li, T. Bidleman and A. Strand, Global chemical fate of α -hexachlorocyclohexane. 1. Evaluation of a global distribution model, *Environ. Toxicol. Chem.*, 1999, **18**, 1390–1399.
- 112 M. MacLeod, D. G. Woodfine, D. Mackay, T. McKone, D. Bennett and R. Maddalena, BETR North America: A regionally segmented multimedia contaminant fate model for North America, *Environ. Sci. Pollut. Res.*, 2008, **8**, 156–163.
- 113 K. Prevedouros, K. C. Jones and A. J. Sweetman, European-Scale Modeling of Concentrations and Distribution of Polybrominated Diphenyl Ethers in the Pentabromodiphenyl Ether Product, *Environ. Sci. Technol.*, 2004, **38**, 5993–6001.
- 114 M. R. Earnshaw, K. C. Jones and A. J. Sweetman, A first European scale multimedia fate modelling of BDE-209 from 1970 to 2020, *Environ. Int.*, 2015, **74**, 71–81.
- 115 F. Wania, K. Breivik, N. J. Persson and M. S. McLachlan, CoZMo-POP 2 – A fugacity-based dynamic multi-compartmental mass balance model of the fate of persistent organic pollutants, *Environ. Modell. Softw.*, 2006, **21**, 868–884.
- 116 L. Camenzuli, M. Scheringer, C. Gaus, C. A. Ng and K. Hungerbühler, Describing the environmental fate of diuron in a tropical river catchment, *Sci. Total Environ.*, 2012, **440**, 178–185.
- 117 A. Di Guardo, D. Calamari, G. Zanin, A. Consalter and D. Mackay, A fugacity model of pesticide runoff to surface water: Development and validation, *Chemosphere*, 1994, **28**, 511–531.
- 118 R. Barra, M. Vighi and A. Di Guardo, Prediction of surface water input of chloridazon and chlorpyrifos from an agricultural watershed in Chile, *Chemosphere*, 1995, **30**, 485–500.
- 119 A. Di Guardo, R. J. Williams, P. Matthiessen, D. N. Brooke and D. Calamari, Simulation of pesticide runoff at Rosemaund Farm (UK) using the SoilFug model, *Environ. Sci. Pollut. Res.*, 1994, **1**, 151–160.
- 120 D. Ghirardello, M. Morselli, S. Otto, G. Zanin and A. Di Guardo, Investigating the need for complex vs. simple scenarios to improve predictions of aquatic ecosystem exposure with the SoilPlus model, *Environ. Pollut.*, 2014, **184**, 502–510.
- 121 M. Morselli, C. M. Vitale, A. Ippolito, S. Villa, R. Giacchini, M. Vighi and A. Di Guardo, Predicting pesticide fate in small cultivated mountain watersheds using the DynAPlus model: Toward improved assessment of peak exposure, *Sci. Total Environ.*, 2018, **615**, 307–318.
- 122 C. Bogdal, M. Scheringer, P. Schmid, M. Blauenstein, M. Kohler and K. Hungerbühler, Levels, fluxes and time trends of persistent organic pollutants in Lake Thun, Switzerland: combining trace analysis and multimedia modeling, *Sci. Total Environ.*, 2010, **408**, 3654–3663.
- 123 L. Lamon, M. MacLeod, A. Marcomini and K. Hungerbühler, Modeling the influence of climate change on the mass balance of polychlorinated biphenyls in the Adriatic Sea, *Chemosphere*, 2012, **87**, 1045–1051.
- 124 M. MacLeod, A. J. Fraser and D. Mackay, Evaluating and expressing the propagation of uncertainty in chemical fate and bioaccumulation models, *Environ. Toxicol. Chem.*, 2002, **21**, 700–709.
- 125 L. Becker, M. Scheringer, U. Schenker and K. Hungerbühler, Assessment of the environmental persistence and long-range transport of endosulfan, *Environ. Pollut.*, 2011, **159**, 1737–1743.
- 126 H. Wöhrnschimmel, M. MacLeod and K. Hungerbühler, Emissions, fate and transport of persistent organic pollutants to the Arctic in a changing global climate, *Environ. Sci. Technol.*, 2013, **47**, 2323–2330.



- 127 A. J. Jakeman, R. A. Letcher and J. P. Norton, Ten iterative steps in development and evaluation of environmental models, *Environ. Modell. Softw.*, 2006, **21**, 602–614.
- 128 A. M. Buser, M. MacLeod, M. Scheringer, D. Mackay, M. Bonnell, M. H. Russell, J. V. DePinto and K. Hungerbühler, Good modeling practice guidelines for applying multimedia models in chemical assessments, *Integr. Environ. Assess. Manage.*, 2012, **8**, 703–708.
- 129 R. P. Schwarzenbach, P. M. Gschwend and D. M. Imboden, *Environmental Organic Chemistry*, John Wiley & Sons, Inc., Hoboken, New Jersey, 3rd edn, 2017.
- 130 X. Cui, P. Mayer and J. Gan, Methods to assess bioavailability of hydrophobic organic contaminants: Principles, operations, and limitations, *Environ. Pollut.*, 2013, **172**, 223–234.
- 131 F. De Laender, P. J. van den Brink, C. R. Janssen and A. Di Guardo, The ChimERA project: coupling mechanistic exposure and effect models into an integrated platform for ecological risk assessment, *Environ. Sci. Pollut. Res.*, 2014, **21**, 6263–6267.
- 132 A. Di Guardo, M. Morselli, G. Morabito, M. Semplice, P. J. Van den Brink and F. De Laender, European environmental scenarios of chemical bioavailability in freshwater systems, *Sci. Total Environ.*, 2017, **580**, 1237–1246.
- 133 E. Terzaghi, G. Zacchello, M. Scacchi, G. Raspa, K. C. Jones, B. Cerabolini and A. Di Guardo, Towards more ecologically realistic scenarios of plant uptake modelling for chemicals: PAHs in a small forest, *Sci. Total Environ.*, 2015, **505**, 329–337.
- 134 F. Wania and D. Mackay, The evolution of mass balance models of persistent organic pollutant fate in the environment, *Environ. Pollut.*, 1999, **100**, 223–240.
- 135 M. Morselli, E. Terzaghi and A. Di Guardo, Do environmental dynamics matter in fate models? Exploring scenario dynamics for a terrestrial and an aquatic system, *Environ. Sci.: Processes Impacts*, 2018, DOI: 10.1039/c7em00530j.
- 136 A. Di Guardo, C. Ferrari and A. Infantino, Development of a Dynamic Aquatic Model (DynA Model): Estimating Temporal Emissions of DDT to Lake Maggiore (N. Italy), *Environ. Sci. Pollut. Res.*, 2005, **13**, 50–58.
- 137 U. S. E. P. A. (EPA), *ECOTOX database*, <https://cfpub.epa.gov/ecotox/>, accessed October 2017.
- 138 A. Mendez, L. E. Castillo, C. Ruepert, K. Hungerbühler and C. A. Ng, Tracking pesticide fate in conventional banana cultivation in Costa Rica: A disconnect between protecting ecosystems and consumer health, *Sci. Total Environ.*, 2017, **613–614**, 1250–1262.
- 139 M. MacLeod, M. Scheringer, H. Podey, K. C. Jones and K. Hungerbühler, The Origin and Significance of Short-Term Variability of Semivolatile Contaminants in Air, *Environ. Sci. Technol.*, 2007, **41**, 3249–3253.
- 140 C. Bogdal, C. E. Muller, A. M. Buser, Z. Wang, M. Scheringer, A. C. Gerecke, P. Schmid, M. Zennegg, M. MacLeod and K. Hungerbühler, Emissions of polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans during 2010 and 2011 in Zurich, Switzerland, *Environ. Sci. Technol.*, 2014, **48**, 482–490.
- 141 A. M. Buser, A. Kierkegaard, C. Bogdal, M. MacLeod, M. Scheringer and K. Hungerbühler, Concentrations in ambient air and emissions of cyclic volatile methylsiloxanes in Zurich, Switzerland, *Environ. Sci. Technol.*, 2013, **47**, 7045–7051.
- 142 J. Glüge, C. Steinlin, S. Schalles, L. Wegmann, J. Tremp, K. Breivik, K. Hungerbühler and C. Bogdal, Import, use, and emissions of PCBs in Switzerland from 1930 to 2100, *PLoS One*, 2017, **12**, e0183768.
- 143 M. Morselli, D. Ghirardello, M. Semplice and A. Di Guardo, Modeling short-term variability of semivolatile organic chemicals in air at a local scale: an integrated modeling approach, *Environ. Pollut.*, 2011, **159**, 1406–1412.
- 144 M. Morselli, D. Ghirardello, M. Semplice, G. Raspa and A. Di Guardo, Integration of an atmospheric dispersion model with a dynamic multimedia fate model: development and illustration, *Environ. Pollut.*, 2012, **164**, 182–187.
- 145 C. Moeckel, M. MacLeod, K. Hungerbühler and K. C. Jones, Measurement and Modeling of Diel Variability of Polybrominated Diphenyl Ethers and Chlordanes in Air, *Environ. Sci. Technol.*, 2008, **42**, 3219–3225.
- 146 A. Beyer, F. Wania, T. Gouin, D. Mackay and M. Matthies, Selecting internally consistent physicochemical properties of organic compounds, *Environ. Toxicol. Chem.*, 2002, **21**, 941–953.
- 147 U. Schenker, M. MacLeod, M. Scheringer and K. Hungerbühler, Improving Data Quality for Environmental Fate Models: A Least-Squares Adjustment Procedure for Harmonizing Physicochemical Properties of Organic Compounds, *Environ. Sci. Technol.*, 2005, **39**, 8434–8441.
- 148 A. Hollander, M. Hauck, I. T. Cousins, M. A. J. Huijbregts, A. Pistocchi, A. M. J. Ragas and D. van de Meent, Assessing the Relative Importance of Spatial Variability in Emissions Versus Landscape Properties in Fate Models for Environmental Exposure Assessment of Chemicals, *Environ. Model. Assess.*, 2012, **17**, 577–587.
- 149 European Chemicals Bureau, *Technical Guidance Document on Risk Assessment*, European Commission, 2003.
- 150 D. Van de Meent, J. T. Quik and T. Traas, *Identification and preliminary analysis of update needs for EUSES, RIVM*, 2014.
- 151 ECETOC, *Advances in Exposure Modelling: Bridging the gap between research and application*, ECETOC, Brussels, 2018.
- 152 A. Cimorelli and C. Stahl, Avoiding “Proofiness”: Addressing uncertainty in environmental characterization, *Integr. Environ. Assess. Manage.*, 2014, **10**, 141–142.
- 153 D. Mackay, Risk assessment and regulation of D5 in Canada: Lessons learned, *Environ. Toxicol. Chem.*, 2015, **34**, 2687–2688.
- 154 M. S. McLachlan, Can the Stockholm Convention address the spectrum of chemicals currently under regulatory scrutiny? Advocating a more prominent role for modeling



- in POP screening assessment, *Environ. Sci.: Processes Impacts*, 2018, DOI: 10.1039/c7em00473g.
- 155 A. A. Koelmans, E. Besseling, E. Foekema, M. Kooi, S. Mintenig, B. C. Ossendorp, P. E. Redondo-Hasselerharm, A. Verschoor, A. P. van Wezel and M. Scheffer, Risks of Plastic Debris: Unravelling Fact, Opinion, Perception, and Belief, *Environ. Sci. Technol.*, 2017, **51**, 11513–11519.
- 156 G. A. Burton Jr, Stressor Exposures Determine Risk: So, Why Do Fellow Scientists Continue To Focus on Superficial Microplastics Risk?, *Environ. Sci. Technol.*, 2017, **51**, 13515–13516.

