The Evolution and Future of Environmental Fugacity Models

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Abstract In this chapter we first review the concept of fugacity as a thermodynamic equilibrium criterion applied to chemical fate in environmental systems. We then discuss the evolution of fugacity-based models applied to the multimedia environmental distribution of chemicals and more specifically to bioaccumulation and food web models. It is shown that the combination of multimedia and bioaccumulation models can provide a comprehensive assessment of chemical fate, transport, and exposure to both humans and wildlife. A logical next step is to incorporate toxicity information to assess the likelihood of risk in the expectation that most regulatory effort will be focused on those chemicals that pose the highest risk. This capability already exists for many well-studied chemicals but we argue that there is a compelling incentive to extend this capability to other more challenging chemicals and environmental situations and indeed to all chemicals of commerce. Finally, we argue that deriving the full benefits of these applications of the fugacity concept to chemical fate and risk assessment requires continued effort to develop quantitative structure–activity relationships (QSARs) that can predict relevant chemical properties and programs to validate these models by reconciliation between modeled and monitoring data.

Keywords Mass balance modeling · Fugacity · QSARs · Chemical hazard assessment · Chemical risk assessment

1 Introduction: The Fugacity Concept

For the purposes of monitoring, modeling, and regulation, the obvious expression of the quantity of chemical present in compartments or phases such as in air, water, or fish is concentration with units such as ng/m^3, mg/L, $\mu g/g$, or mol/L. These concentrations do not directly convey any information about the relative equilibrium

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status between phases. To obtain this information requires additional information in the form of equilibrium partition coefficients. Alternatively, by expressing the quantity present in terms of fugacity the equilibrium status between phases becomes immediately obvious since when phases reach equilibrium the thermodynamic criteria of fugacity, activity, or partial pressure are equal. When interpreting the results of multimedia mass balance models the use of fugacity conveys directly how close the system is to equilibrium and the direction of the diverse diffusive transfer processes. The use of partition coefficients in the various flux equations is thus avoided. It also transpires that the formulation of the mass balance equations in either algebraic or differential forms is much easier when using the fugacity formalism, and the results are more readily interpreted.

Mathematically, if two-phase concentrations are C_1 and C_2 and the partition coefficient is K_{12} then the relative equilibrium status is $C_1 : C_2K_{12}$ or $C_1/K_{12} : \mathrm{C}_2$. In the fugacity formalism K_{12} is split into two phase-specific capacity terms such that K_{12} is Z_1/Z_2. The concentration C_1 is then Z_1f_1 and C_2 is Z_2f_2 where f_1 and f_2 are the fugacities that directly express the relative equilibrium status. The driving force for interphase diffusion is then $(f_1 - f_2)$ and at equilibrium f_1 and f_2 are equal. Fugacity is expressed in units of partial pressure, Pascals (Pa), and Z values (fugacity capacities) have units of $\mathrm{mol/(m^3\ Pa)}$. Z values express the capacity or affinity of the phase for the chemical and depend on the phase composition, temperature, and physicochemical properties of the substance.

In the fugacity formalism mass transfer and reaction rate parameters or D values are defined such that the rates of transport or reaction are the product Df with units of mol/h. These D values can be regarded as fugacity rate coefficients.

Full details of methods of estimating Z and D values and fugacities are provided in the text by Mackay [1]. Our focus here is on how fugacity models have evolved over recent decades and on likely future developments.

2 Evolution of Multimedia Fugacity Models

The earliest or Level I models simulate the simple situation in which a chemical achieves equilibrium between a number of phases of different composition and volume. The prevailing fugacity is simply $M/\Sigma V_\mathrm{i}Z_\mathrm{i}$ where M is the total quantity of chemical (mol), V_i is volume ($\mathrm{m^3}$), and Z_i is the corresponding phase Z value, $[\mathrm{mol/(Pa\ m^3)}]$. Although very elementary and naive, this simulation is useful as a first indication of where a chemical is likely to partition. It is widely used as a first step in chemical fate assessments.

More realistic Level II models introduce the rate of chemical reaction or degradation and advection, but interphase equilibrium is still assumed. Level III models introduce intercompartmental transfer rates, thus equilibrium no longer applies. For Level III models it is then necessary to specify the chemical's mode-of-entry to the environment, that is, to air, water, or soil, or some combination of these media. Valuable insights obtained from these models include those of overall chemical persistence or residence time and potential for long-range transport (LRT) in air or water. Level IV models, which involve the solution of differential mass balance equations, can be used to describe the time-dependent or dynamic behavior of chemicals.

Figures 1–3 illustrate the results of Level I, II, and III models for pyrene using the chemical properties listed in Table 1. For the Level III model emission is 50% each to air and to water. A key feature of these models is that they identify the critical partitioning and degradation rate properties that control chemical fate.

From Fig. 1 it can be seen that most of the pyrene partitions to soil in the Level I modeled system. This reflects the high K_{OW} of pyrene and the much larger volume of soil than of sediment (by a factor of 36) in the standard equilibrium criterion (EQC) environment [2]. The Level II simulation shown in Fig. 2 gives a first estimate of chemical persistence, and since equilibrium is assumed in this case also, partitioning is still predominantly to soil. The model shows that less than half of the loss from the system is degradation in the soil; 24.2% is removed by advection in the air. Three chemical residence times are given: the total time, the reaction time, and the advection time. The total residence time is the "two-thirds" time for clearance of the chemical from the system. The reaction time is the "two-thirds" time for chemical removal by degradation alone and is generally considered to be the chemical persistence. The advection time considers only chemical removal by transport to a neighboring region. Thus, the persistence estimated by the Level II model for pyrene in a standard EQC environment is about 2 years. This estimate of persistence is refined using the Level III model. Figure 3 shows a persistence estimate for pyrene

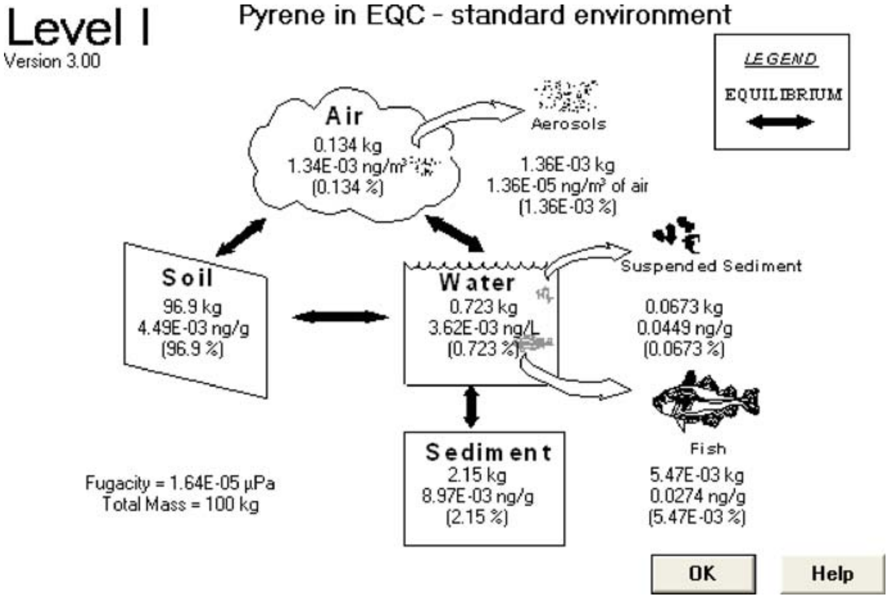
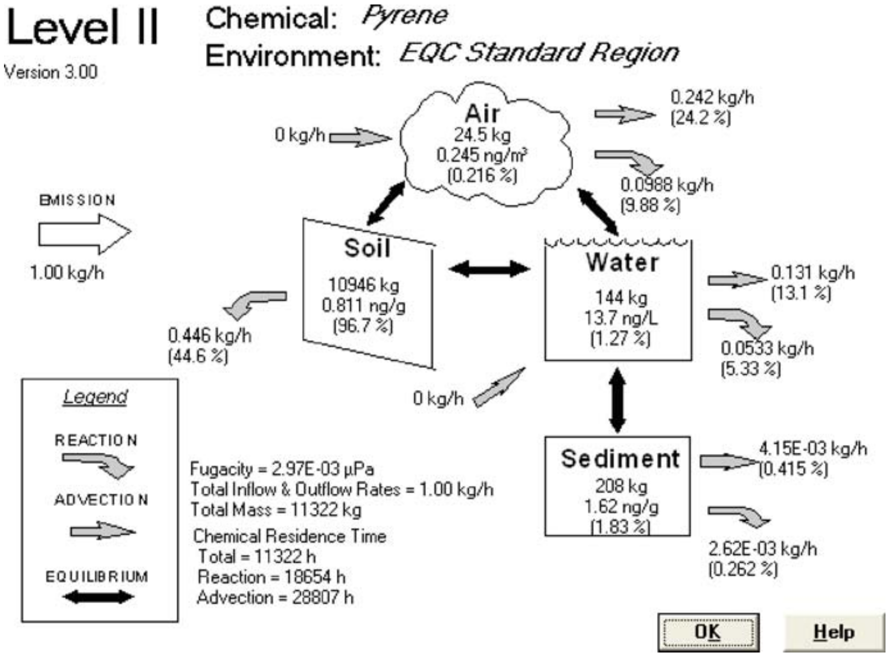
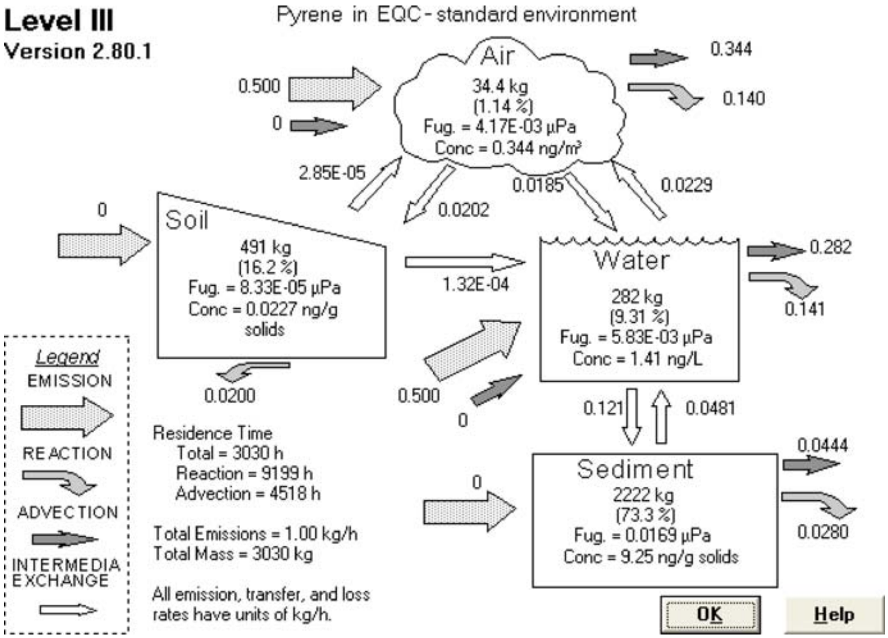


Fig. 1 Level I diagram for pyrene in the EQC environment



Fugacity = 2.97E-03 µPa
Total Inflow & Outflow Rates = 1.00 kg/h
Total Mass = 11322 kg
Chemical Residence Time
Total = 11322 h
Reaction = 18654 h
Advection = 28807 h

Fig. 2 Level II diagram for pyrene in the EQC environment



Residence Time
Total = 3030 h
Reaction = 9199 h
Advection = 4518 h

Total Emissions = 1.00 kg/h
Total Mass = 3030 kg

All emission, transfer, and loss rates have units of kg/h.

Fig. 3 Level III diagram for pyrene in the EQC environment with 50% of the emissions to each of air and water

Table 1 Properties of pyrene [32]

	Pyrene
CAS	129-00-0
Formula	$C_{16}H_{10}$
Molar mass (g/mol)	202.25
Melting point (°C)	150.62
Vapor pressure (Pa)	0.0006
Solubility (g/m^3)	0.132
Log K_{OW}	5.18
Half-lives (h)	
Air	170
Water	1,700
Soil	17,000
Sediment	55,000
Fish	50
Birds/mammals	17

of about 1 year, assuming equal emissions to air and water. Level III calculations do not assume that the chemical has achieved equilibrium between the different bulk compartments of the environment (air, water, soil, and sediment). This can be seen in Fig. 3 by examining the relative transfer rates between media. The majority of the pyrene in the system is now located in the sediment. This can be attributed to the emission to water and the relatively fast water-to-sediment transfer rate. Approximately 70% of the pyrene emitted to the air blows out of the modeled system and into the adjoining region while over half of the pyrene discharged to the water flows out of the system. The loss rates in air and water as a result of degradation processes are approximately equal and are about half the loss rate by water outflow (advection).

Table 2 lists a selection of fugacity models that have been applied to evaluative (hypothetical) and real environments. These and other fugacity models are available from the Centre for Environmental Modelling and Chemistry (formerly the Canadian Environmental Modelling Centre) website (http://www.trentu.ca/cemc).

3 Fugacity Models of Long-Range Transport

As Figs. 2 and 3 show, a useful feature of Level II and III models is that they can demonstrate the extent to which a chemical is lost from a region by atmospheric or water transport, that is, advective loss, as distinct from loss by degradation. It is possible to calculate the contribution of each loss mechanism to the overall persistence or residence time. When the advective residence time is short, that is, advection is rapid, the implication is that much of the chemical discharged into the region will flow to neighboring downwind or downstream regions. Whereas a local contamination problem is alleviated, the problem is merely transported to other regions where

Table 2 Fugacity models applied to evaluative and real environments

	Latest version/release date	Description	Publications describing/ using this model
Models for evaluative environments			
EQC	2.02/May 2003	The equilibrium criterion model uses chemical-physical properties to quantify chemical behavior in an evaluative environment. The environment is fixed to facilitate chemical-to-chemical comparison.	[2, 33, 34]
Level I	3.00/Sept. 2004	A model of the equilibrium distribution of a fixed quantity of conserved chemical, in a closed environment.	[1, 35]
Level II	3.00/Sept. 2005	A model of the equilibrium distribution of a nonconserved chemical discharged at a constant rate into an open environment at steady state.	[1, 35]
Level III	2.80/May 2004	A model of the steady-state distribution of a nonconserved chemical discharged at a constant rate into an open environment.	[1, 35]
RAIDAR	2.00/January 2010	The risk assessment identification and ranking model is a screening-level exposure and risk assessment model that brings together information on chemical partitioning, reactivity, environmental fate and transport, bioaccumulation, exposure, effect levels, and emission rates in a holistic framework.	[21, 22]
TaPL3	3.00/Sept. 2003	The transport and persistence Level III model is intended as an evaluative tool for the detailed assessment of chemicals for persistence and potential for long-range transport in either air, or water in a steady-state environment.	[10]
Models for real environments			
ChemCAN	6.00/Sept. 2003	A Level III model containing a database of 24 regions of Canada. By the addition of regional properties, it is easily applicable to other regions.	[36–38]
CalTOX	2.3/March 1997	A regional scale multimedia exposure model designed to assess the fate and human health impacts of contaminants. Human doses are derived as products of chemical concentrations in contact media and exposure factors for each media.	[39]

Most of these models and models listed in later tables are available from the Web site http://www.trentu.ca/cemc the resulting contamination can be of concern, especially because there may be no direct control of sources. This general issue, which has ethical and international aspects, was first addressed in connection with SO_2 atmospheric transport from the United Kingdom and continental Europe to Scandinavia. It has become a major issue of concern as a result of the realization that levels of organic contaminants such as PCBs in the arctic environment and especially in arctic wildlife are remarkably high. Human exposure to these contaminants can be substantial because the resident population often consumes terrestrial and marine wildlife such as caribou and whale meat.

The Stockholm Convention has addressed this issue by regulating 12 substances or groups of substances that have been demonstrated to undergo LRT [3]. Scientific and modeling aspects of LRT have been addressed in a number of reports and books. Two general modeling approaches have emerged; multi-box Eulerian models and characteristic travel distance (CTD) Lagrangian models, both of which can employ the fugacity concept.

The most compelling evidence that significant LRT has occurred is provided by monitoring data in remote regions, for example, as summarized in Arctic Monitoring and Assessment Programme reports [4]. Multibox modeling can play a complementary role by demonstrating that monitoring data are consistent with our present understanding of LRT processes. Models can be used to identify and prioritize chemicals for persistence and LRT potential and provide estimates of the fraction of the mass of chemical released in one location that may reach a distant region as well as the rate of transport. Examples of this approach are Wania's arctic contamination potential (ACP) [5, 6], MacLeod's transfer efficiency [7], and the distant residence time (DRT) concept [8].

The CTD models are typically used to rank chemicals because of their simplicity and ease of interpretation. To calculate the CTD of a chemical, a one-region environment is simulated and then an expected "distance" that a chemical may be transported in a mobile phase (air or water) that is moving at a defined speed is calculated. The distance travelled by the chemical is related to several factors including the fugacity of the chemical in the transporting phase as well as the expected time that the chemical will exist in that phase (persistence) [9, 10].

Table 3 lists studies of LRT, many of which employ the fugacity concept.

4 Evolution of Bioaccumulation Fugacity Models

Bioaccumulation is the net result of competing rates of chemical uptake and elimination in an organism and can result in concentrations in organisms that are orders of magnitude greater than those in the air or water environment [11, 12]. Bioaccumulation includes uptake by respiration (bioconcentration) of chemical from the environment surrounding the organism (air or water) and dietary exposures. Dietary exposures can result in biomagnification, an increase in concentration

Table 3 Models and studies of long-range transport

	Latest model version/ release date	Description	Publications describing/ using this model
TaPL3	3.00/Sept. 2003	See Table 2.	[10, 40]
BETR-North America		A regionally segmented multicompartment, continental-scale, mass balance chemical fate model for North America.	[41]
BETR-World	409/2003 500/	A regionally segmented multicompartment, global-scale, mass balance chemical fate model.	[8, 42]
BETR-Global		A global-scale multimedia contaminant fate model that represents the global environment as a connected set of 288 multimedia regions on a 15° grid.	[43]
GloboPOP	1.10/2003	A zonally averaged multimedia model describing the global fate of persistent organic chemicals on the time scale of decades.	[5, 44]

from food to the consuming organism. Biotransfer factors are also used to express the food-to-organism increases in concentration, especially in an agricultural setting [13].

The fugacity concept proves to be particularly useful when simulating the uptake of chemical by organisms such as fish from their environment (e.g., water) and their food. The bioconcentration phenomenon is essentially a result of the chemical seeking equi-fugacity between the respiring organism and its environment. The concentration ratio or bioconcentration factor (BCF) is essentially $Z_\mathrm{O}/Z_\mathrm{E}$ where Z_O applies to the organism and Z_E to the environment. Hydrophobic, bioaccumulative substances such as DDT and PCBs tend to have low values of Z_E and high values of Z_O and thus high BCFs.

Two general approaches have been used to assess and predict bioaccumulation: relatively simple regression models or QSARs and more complex mechanistic models that simulate all uptake and loss processes [11, 12].

Regressions for BCF–octanol water partition coefficient (BCF–K_OW) for fish and biotransfer factor–K_OW (BTF–K_OW) for agricultural species in the human food chain are still widely used for bioaccumulation and human exposure assessments. The use of simple regression equations implies that all chemicals with the same K_OW have the same BCF in fish or BTF in agricultural food webs. Biomagnification and biotransformation processes can, however, result in orders of magnitude difference in exposures, particularly for more hydrophobic chemicals, and these processes are not explicitly accounted for using simple regression equations. Laboratory-derived BCF data do not include dietary exposure, which is an important route of exposure for hydrophobic chemicals in the environment. Air-breathing organisms exchange chemical with the air for which the octanol–air partition coefficient (K_{OA}) is an important property and is not explicitly included in K_{OW}-based regressions for BTFs.

In response to these problems, bioconcentration models have been extended to address bioaccumulation by including food uptake and losses by metabolic conversion, respiration, fecal egestion, and growth dilution. It is relatively straightforward to apply these models to multiple organisms comprising food webs. Most effort has been devoted to aquatic organisms but recently there has been increasing attention to air-breathing organisms [14–17]. The major challenge has been to describe dietary rates and feeding preferences, especially during different seasons and life stages. Differences in species' physiology (body size, feeding rates) and characteristics (herbivores, carnivores, bioenergetics, feeding preferences) play a role in bioaccumulation processes and can be included in fugacity bioaccumulation models, resulting in more accurate simulations and predictions. Important considerations for using mechanistic bioaccumulation models include the principle of parsimony (Occam's Razor), parameterization, and reliable physical chemical property information (e.g., K_{OW}, K_{OA}, biotransformation rates). Sensitivity and uncertainty analyses can help direct priorities for accurate input data requirements.

These models have shown that uptake by edible vegetation from air and soil is fundamental to compiling reliable models of bioaccumulation in wildlife and humans. The uptake losses and translocation of chemicals in vegetation have proved to be challenging but fugacity models can provide insights into the important process of plant bioaccumulation.

As more information becomes available on the processes of uptake, release, and internal disposition of chemicals in fish and wildlife, the logical next step is to compile a more detailed model of chemical fate within the organism. The simple models discussed earlier generally treat the organism as a single compartment or "box." The more detailed models exploit the considerable experience in physiologically based pharmacokinetic (PBPK) models developed for medical and pharmaceutical purposes. These PBPK models can provide more information for accumulation in specific organs within the body and the rates of transport and transformation within the body and excretion processes. Most PBPK models are based on conventional concentration/rate constant/partition coefficient expressions [18, 19], but they can be rewritten in fugacity format [20]. Again, the fugacity formalism is advantageous because differences in the equilibrium status of chemical levels between blood and various organs and tissues are immediately apparent.

Table 4 lists a number of bioaccumulation models and studies.

Table 4 Bioaccumulation and PBPK models and studies

	Latest version/ release date	Description	Publications describing/ using this model
Fish	2.00/November 2004	A single organism bioaccumulation model treating the steady-state uptake and loss of an organic contaminant by a fish.	[1,35]
FoodWeb	2.00/March 2006	A mass balance model of contaminant flux through an aquatic food web.	[45]
Mysid	1.00/August 2007	A single organism bioaccumulation model treating the dynamic uptake and loss of an organic contaminant by the opossum shrimp (*Mysis relicta*).	[46]
AquaWeb	1.2/March 2007	A steady-state aquatic food web bioaccumulation model for estimating of chemical concentrations in organisms from chemical concentrations in the water and the sediment.	[47–51]
BAF-QSAR	1.5/May 2008	A model to estimate bioaccumulation factors for fish species in lower, middle, and upper trophic levels of aquatic food webs.	[52,53]
ACC-HUMAN		A nonsteady-state bioaccumulation model predicting human tissue levels from concentrations in air, soil, and water.	[54]
PBPK	1.0/January 2003	A physiologically based pharmacokinetic model describing the disposition of contaminants in an adult male human. It treats a parent chemical and, if desired, two metabolites that may be formed reversibly or irreversibly. Tissue concentrations for the chemical and any metabolites can be simulated for acute, occupational, and environmental exposure regimes.	[55]
PBPK/PBTK models		Some publications available outlining physiologically based pharmaco-/toxico-kinetic models for various species.	[18–20,56–58]
Terrestrial-based bioaccumulation models		Some publications available outlining terrestrial-based food web bioaccumulation models for various species.	[14,54,59–61]

5 Fugacity Models of Specific Compartments and Processes

The results of multimedia mass balance models often show the need to focus more attention on specific compartments such as soils to which a pesticide is applied or to water bodies that receive chemical discharges from direct discharges or from sewage treatment plants. Several such models have been developed, especially for sewage treatment plants, lakes, and rivers. For those evaluating chemical fate it is useful to have the capability of addressing in detail the likely chemical fate in these more local and site-specific conditions. The models may be used to explore remedial options and likely remediation times. As is discussed later such models are best regarded as individual "tools" available from a "tool box" of models.

Table 5 lists a number of these models.

Table 5 Fugacity models of specific compartments and processes

	Latest version/ release date	Description	Publications describing/using this model
AirWater	2.00/Nov. 2004	A model to calculate air–water exchange characteristics, including unsteady-state conditions, based on the physical chemical properties of the chemical and total air and water concentrations.	[1, 35]
BASL4	1.00/Apr. 2007	The biosolids-amended soil: Level IV model calculates the fate of chemicals introduced to soil in association with contaminated biosolids amendment.	[62, 63]
QWASI	3.10/Feb. 2007	The quantitative water air sediment interaction model assists in understanding chemical fate in lakes.	[64–69]
Sediment	2.00/Nov. 2004	A model to calculate the water–sediment exchange characteristics of a chemical based on its physical chemical properties and total water and sediment concentrations.	[1, 35]
Soil	3.00/Aug. 2005	A model for the simple assessment of the relative potential for reaction, degradation, and leaching of a pesticide applied to surface soil.	[1, 35]
STP	2.11/Mar. 2006	The sewage treatment plant model estimates the fate of a chemical present in the influent to a conventional activated sludge plant as it becomes subject to evaporation, biodegradation, sorption to sludges, and to loss in the final effluent.	[70, 71]

6 Evolution of More Comprehensive Multimedia and Bioaccumulation Fugacity Models

A logical step in modeling chemical fate, exposure, and even effects is to combine models that describe the fate of the chemical in the largely abiotic environment with bioaccumulation and food web models resulting in a more complete simulation of chemical behavior and exposure to humans and wildlife. Table 6 lists a selection of fugacity and non-fugacity models that combine fate, exposure, and effects and can be used for regulatory purposes. These models can be used to screen list of chemicals to identify those substances that are of greatest potential risk to humans and the environment for more comprehensive assessments using monitoring data. For example, the risk assessment, identification, and ranking (RAIDAR) model combines information on chemical partitioning, reactivity, environmental fate and transport, food web bioaccumulation, exposure, effect endpoint, and emission rate in a coherent mass balance evaluative framework [21, 22]. RAIDAR fate calculations are similar to those in the EQC model [2]; however, food web models representative of aquatic and terrestrial species such as vegetation, fish, wildlife, agricultural products, and humans are also included. RAIDAR is distinct from other models listed in Table 6 because the food web models assessing exposure to humans and ecological receptors include mechanistic expressions for chemical uptake and elimination. Thus, biomagnification and biotransformation processes in the food web can be included for the exposure assessment. An illustration of the RAIDAR model for chemical assessments is given in Sect. 6.1.

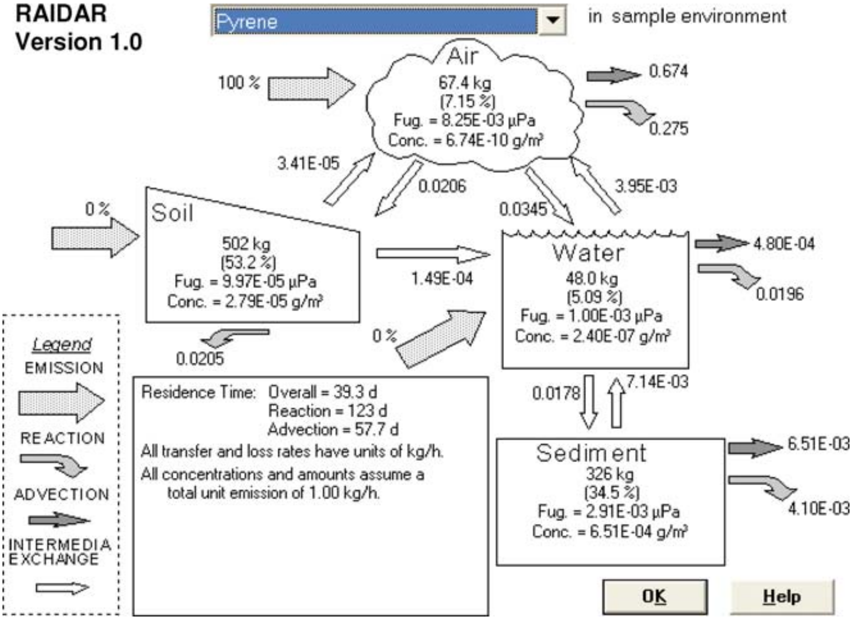
Table 6 Comprehensive models of chemical fate and bioaccumulation

	Latest version/ release date	Description	Publications describing/using this model
CalTOX	2.3/March 1997	See Table 2.	[39]
EUSES	2.0/2004	The European Union System for the Evaluation of Substances brings together exposure and effect assessments and risk characterization for environmental populations and humans, including occupational and consumer scenarios at local, regional, and continental scales.	[72, 73]
IMPACT 2002		The IMPACT 2002 model provides characterization factors for the midpoint categories: human toxicity, aquatic ecotoxicity, and terrestrial ecotoxicity for life-cycle impact assessments.	[74]
RAIDAR	2.00/January 2010	See Table 2.	[21, 22]

Combining the key elements of chemical exposure and effect at a screening level allows for a holistic approach for evaluating chemicals and may prove to be a valuable educational tool for regulators, scientists, and students. Combined model predictions can guide environmental monitoring programs by identifying the media in the environment (physical and biological) in which chemical concentrations and fugacities are expected to be the greatest. A holistic approach for chemical risk assessment (emissions, exposure, and effect) also provides the opportunity to identify the key processes and chemical properties that contribute the most uncertainty to the underlying risk calculation. Uncertainty and sensitivity analyses can be used to prioritize data gaps that often occur for the large numbers of chemicals requiring chemical assessment.

6.1 An Illustrative Case Study for Chemical Exposure and Risk Assessment

Figure 4 illustrates the output of RAIDAR fate calculations for pyrene using an arbitrary unit emission rate of 1 kg/h to air. This is a hypothetical rate of emission and the model user can choose either Level II or Level III fate calculations. As discussed earlier for Level II calculations, equilibrium between the environmental compartments of air, water, soil, and sediment is assumed; therefore, there is no need to



Residence Time: Overall = 39.3 d
Reaction = 123 d
Advection = 57.7 d

All transfer and loss rates have units of kg/h.

All concentrations and amounts assume a total unit emission of 1.00 kg/h.

Fig. 4 Level III fate calculations for pyrene in the RAIDAR environment assuming 100% emissions to air select a mode-of-entry for chemical release to the environment. For Level III calculations the predicted distribution of a substance in the physical compartments of the environment is determined from the specified mode-of-entry information. In this illustration it is assumed that 100% of the chemical is released to air.

The overall residence time in the evaluative regional environment (100,000 km^2) is 39.3 days. This overall residence time includes chemical transfers out of the region (advection) and chemical degradation (reaction) within the region. Approximately 67% of the pyrene that is released to air in the region is removed from the region by advection in air and the advection residence time is 57.7 days. The reaction residence time, or persistence, is 123 days. Thus, overall persistence in the system based solely on reaction is quite different from the overall residence time. This highlights the need to clearly determine the specific assessment objectives and the influence of model assumptions when comparing chemical persistence.

Based on predicted chemical concentrations and fugacities in the bulk physical compartments of air, water, soil, and sediment, chemical concentrations and fugacities are then calculated in the representative species in RAIDAR using mass balance food web models. Figure 5 displays fugacities for pyrene in the biological species in the model food webs. These fugacities are based on the assumed unit emission rate and include estimated biotransformation rates [23]. For certain persistent chemicals the fugacities are observed to increase in higher trophic level organisms (biomagnification). In this example, the fugacities decrease in higher trophic level organisms, a phenomenon known as trophic dilution. For example, the biomagnification factor (BMF) from the terrestrial herbivore to the terrestrial carnivore is 0.19 (BMF $<$ 1). This is largely due to biotransformation within the predator organisms. Lack of biotransformation as slow growth usually leads to biomagnification.

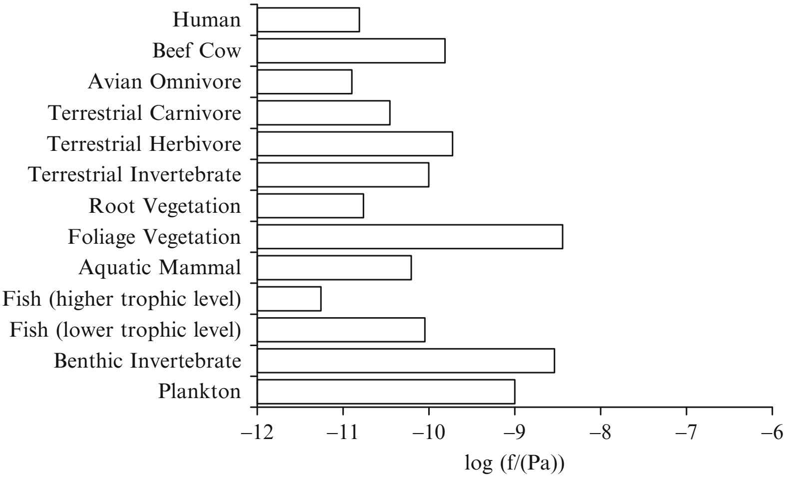


Fig. 5 Illustration of fugacities (f) for pyrene in some of the biological compartments in the RAIDAR evaluative environment

The next step is to include toxicity in the chemical assessment by selecting an effect level or concentration. In this illustration an acute narcotic toxic effect endpoint of 5 mmol/kg wet weight is selected [24]. The hazard assessment factor (HAF) is an intensive hazard property being a combined function of persistence, bioaccumulation, and the selected toxicity endpoint [22]. The HAF is the dimensionless ratio of the calculated unit concentration in an organism (C_U) to the toxic effect endpoint (C_T) assuming a hypothetical "unit" emission of 1 kg/h. The HAF provides a single value for comparing all chemicals of interest for the combined properties of persistence, bioaccumulation, and the selected toxicity endpoint. As illustrated previously the fugacities and unit concentrations (C_U) can be calculated for all representative RAIDAR species based on the assumed unit emission rate. In the present example for pyrene, "benthic invertebrates" are identified as the representative species with the greatest hazard quotient ($C_\mathrm{U}/C_\mathrm{T} = 3.0 \times 10^{-5}/5$) and thus the HAF is 6.0×10^{-6}. If biotransformation estimates were not included in the assessment for pyrene biomagnification in the food webs would occur resulting in the identification of "terrestrial carnivores" as the most vulnerable species and the HAF would be 4.5×10^{-3} (about 1,000 times larger).

The previously described calculations are independent of the actual quantity of chemical released to the environment, being based on assumed unit emission rates, and are therefore only hazard metrics. A screening level RAIDAR risk assessment factor (RAF) can be simply calculated from the HAF by multiplying by an estimate of the actual chemical emission rate [22]. For example, an estimated emission rate in Canada for pyrene is 10.7 kg/h [25], and the resulting RAF is 6.4×10^{-5}. The implication is that prevailing levels are well below levels at which pyrene is expected to cause toxic effects. This case study illustrates the need to consider all elements of a chemical's properties (persistence, P, bioaccumulation, B, and toxicity, T) and quantity discharged (Q) when evaluating chemicals for their potential risks to humans and the environment [22].

7 The Issue of Fidelity and Complexity

These models can become very complex by attempting to include numerous organisms and vegetation types. Further, there may be a need to include municipal and industrial waste treatment processes. It is also apparent that urban regions often experience higher levels of emissions than rural regions, thus urban regions often experience higher levels of contamination than rural regions and urban residents and wildlife may experience greater exposure. This can be addressed by replacing the single soil environment with urban, rural, or agricultural and pristine soils. Pesticides may be preferentially applied in an agricultural setting. It is increasingly apparent that for some chemicals used domestically and in consumer products, for purposes such as plasticizers or for reducing flammability, indoor exposure can greatly exceed outdoor exposure. The implication is that detailed simulation of environmental fate is largely irrelevant for humans who experience their greatest exposure indoors.

A tension thus develops between the need to increase model complexity to address all possible routes of exposure and the need to ensure that the model is robust, transparent, understandable, and is free from gross errors. The optimal answer may be to develop a suite of modeling "tools" that address a variety of aspects of chemical fate. This *tool box* can contain models of the types described earlier, as well as models addressing specific situations such as waste water treatment, indoor exposure, pesticide dissipation in an agricultural setting, and even less common conditions such as aquaculture. If this is to be accomplished the model-to-model transition should be as simple and as user-friendly as possible. The use of fugacity in this context offers the advantage that a common system of units applies, thus the fugacity output from one model becomes the input to the next model. The nature of the process in changing fugacity also becomes immediately apparent. For example, an effective waste water treatment plant may typically achieve a reduction in fugacity of a contaminant by a factor of 10, that is, essentially 90% removal. A bird such as an owl consuming a contaminated rodent should experience a fugacity increase as a result of biomagnification by a factor such as 30 if the contaminant is not biotransformed, but only by a factor of 3 or less if the bird has the metabolic capability to degrade the substance. In short, viewing the environmental fate of chemicals through the lens of fugacity can provide valuable insights into the many varied and complex processes that chemicals undergo in the environment.

8 The Future: A Speculation

Society through its many national and international regulatory agencies has become increasingly intolerant of inadvertent exposure to chemical substances. There are increasing demands for improved assessment of the risks of adverse effects to humans and wildlife and for more vigorous and effective measures to identify the chemicals of greatest concern and restrict their use accordingly. This is a demanding task, especially because there are believed to be some 100,000 chemicals requiring assessment. Fugacity modeling can, we believe, contribute to this process but many challenges remain. In this final section we speculate on some needs and directions.

8.1 Chemical Properties

Models of chemical fate, fugacity, or otherwise require information of sufficient accuracy on chemical properties such as vapor pressure, partition coefficients, and reactivity in a variety of media ranging from the atmosphere to the human liver. The availability of such data is very limited, especially for the less-studied substances and for mixtures [26]. There is thus an obvious incentive to develop and improve QSARs or QSPRs that can estimate these properties from chemical structure. Considerable progress has been made, but much remains to be done, especially for more complex molecules containing oxygen, nitrogen, sulfur, phosphorus, silicon, fluorine, and metal moieties. Present models do not always satisfactorily address ionizing and surface active substances or those of high molar mass such as dyes and pigments. A coordinated program of laboratory-based property determination and QSAR development is needed.

8.2 Ground-Truthing Models

There is concern that model-based predictions of chemical fate may be subject to systematic error because some important processes are omitted or poorly described. An example is the role of snow in scavenging the atmosphere and accumulating chemical seasonally in snowpacks or ice. Modeling is relatively inexpensive and easy compared with monitoring, and there has thus been a tendency for predictions to outstrip observations. What is clearly needed is a continuing program of "ground-truthing" models by comparison of modeling and monitoring data, especially including exposure. An example is the recent study by McKone et al. [27] of the fate and exposure of organo-phosphorus pesticides by agricultural workers in which the model predictions extended from application conditions, to environmental concentrations, to exposure, and to levels of metabolites in urine. Another is the assessment of fate and exposure to phthalate esters by both environmental routes and from consumer products [28]. Unless there is a continuing effort to ground truth models, there is a danger that exposure may be underestimated, with implications for adverse effects on human or ecosystem health. Conversely overestimation may result in unnecessary restrictions and economic penalties to industry and to society at large.

8.3 Fugacity and Toxicity

Some 70 years ago Ferguson showed that for nonselective or narcotic chemicals toxic effects were elicited at a relatively constant chemical activity in the organisms' "circum environment" of air or water [29]. The corresponding concentrations varied over many orders of magnitude. This concept is inherent in the concepts of critical body residue or body burden corresponding to toxic endpoints. Fugacities, like concentrations, vary greatly but both can be readily converted into activities and to body burdens providing a direct link from fugacities in the environment as predicted from multimedia models and activity levels in the exposed organism. Of course, many chemicals exert selective toxicity as a result of specific biochemical interactions, but if toxic potency can be estimated for specific modes of toxic action in the form of multiples of narcotic levels, this could provide a predictive capability for nonnarcotics. The potential of this approach has been suggested by Verharr et al. [30], McCarty et al. [24], and others [31].

If a robust link can be established between toxic levels of chemicals and their external and internal fugacities this has the potential to provide a coherent mechanism by which the proximity of environmental levels to those of concern from the viewpoint of toxic effects could be quantified and evaluated. Fugacity can then play an increasingly valuable role in assisting society to manage the multitude of chemicals of commerce on which our present standard of living depends, with assurance that levels of risk of adverse effects are acceptably low.

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