A multimedia fate model to support chemical management in China: a case study for selected trace organics

Ying Zhu[1], Oliver R. Price[2], John Kilgallon[2], Cecilie Rendal[2], Shu Tao[3], Kevin C. Jones[1], and Andrew J. Sweetman[1]*

[1]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, United Kingdom

[2]Safety and Environmental Assurance Centre, Unilever, Sharnbrook MK44 1LQ, United Kingdom

[3]Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

*Corresponding author email:

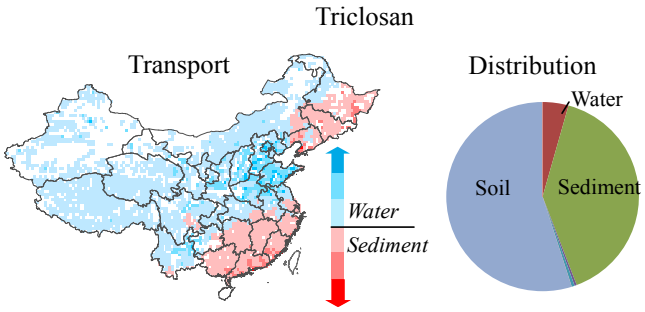
Andrew J. Sweetman, a.sweetman@lancaster.ac.uk

Abstract

SESAMe v3.3, a spatially explicit multimedia fate model for China, is a tool suggested to support quantitative risk assessment for national scale chemical management. The key advantage over the previous version SESAMe v3.0 is consideration of spatially varied environmental pH. We evaluate the model performance using estimates of emission from total industry usage of three UV filters (benzophenone-3, octocrylene and octyl methoxycinnamate) and three antimicrobials (triclosan, triclocarban and climbazole). The model generally performs well for the six case study chemicals as shown by the comparison between predictions and measurements. The importance of accounting for chemical ionisation is demonstrated with the fate and partitioning of both triclosan and climbazole sensitivity to environmental pH. The model predicts ionisable chemicals (triclosan, climbazole, benzophenone-3) to primarily partition into soils at steady state, despite hypothetically only being released to freshwaters, as a result of agricultural irrigation by freshwater. However, further model calibration is needed when more field data becomes available for soils and sediments and for larger areas of water. As an example, accounting for the effect of pH in the environmental risk assessment of triclosan, limited freshwater areas (0.03% or ca. 55 km^2) in mainland China are modelled to exceed its conservative environmental no-effect threshold. SESAMe v3.3 can be used to support the development of chemical risk assessment methodologies with the spatial aspects of the model providing a guide to the identification

regions of interest in which to focus monitoring campaigns or develop a refined risk assessment.

TOC art



Introduction

Assessment of exposure pathways, relative risk, prioritization and risk management are key for better characterising chemicals and managing potential risks to humans and the environment.[1, 2] For chemical management in China, attention is often currently focused on new chemicals (i.e. newly manufactured or imported) and trace organics that are used or can enter the environment as a common part of our daily life. Examples include active pharmaceutical ingredients, personal care product ingredients (PCPs), endocrine-disrupting chemicals, disinfection by-products and some industrial chemicals etc.[3] Several categories of trace organics can be released directly to the environment after use, or via wastewater treatment plants (WWTPs) to aquatic environments with sewage effluent as well as to soil via the application of irrigation water or sludge. Some may be ionisable, and so have different partitioning behaviour from neutral chemicals after being released.

For better chemical regulation and environmental and health protection, the European Union (EU) and the US have both introduced legal frameworks, EU REACH (2007, Registration, Evaluation, Authorisation and Restriction of Chemicals)[1] and US TSCA (1976, Toxic Substances Control Act).[4] Multimedia environmental fate models have been widely adopted by developed countries in frameworks for chemical management (e.g. EUSES, US PBT Profiler and OECD chemical screening tool etc.),[5-7] and have been demonstrated to be useful decision-support tools.[7, 8] China has so far lagged behind on many aspects of chemical management. However, as a rapidly industrialising country with a large population, the increasing use and release of trace organics has raised questions as to their potential impacts or otherwise on the environment and human health. The Ministry of Environmental Protection (MEP) of China has published the Provisions on the Environmental Administration of New Chemical Substances in China (edition 2010)[9] to require the registration of new chemicals

with relevant risk assessment information. There is therefore a research need to develop a multimedia fate model specifically for China to support the regulation[2] and there is the opportunity for China to exert leadership in the use and adoption of state-of-the-art modelling approaches.

A further development of the SESAMe model,[10, 11] SESAMe v3.3, is presented in this study to account for spatially variable surface water and soil pH values and chemical ionisation, so that ionisable chemicals can be included in model predictions for aiding chemical management for China. Three antimicrobials agents and three UV filters (i.e. triclosan (TCS), triclocarban (TCC), climbazole, benzophenone-3 (BP-3), octocrylene (OC) and octyl methoxycinnamate (OMC)), covering a range of physico-chemical properties were selected for a case study in China to: (1) predict spatially varied environmental concentrations and partitioning in environmental media, (2) demonstrate the importance of accounting for ionisation and environmental pH in chemical risk assessments and (3) illustrate the application of SESAMe v3.3 for chemical management in China. These substances represent chemicals where there are common challenges for modellers and risk assessors, to estimate use and release to the environment from diffusive everyday activities.

Methods and materials

Chemicals selection and properties

Chemical and environmental properties have been demonstrated to determine the chemical fate.[11] Figure 1 shows a chemical space plot indicating the equilibrium partitioning of chemicals in air, water and sediment dictated by logD/Kow (octanol-water partition coefficient for respectively ionisable chemicals and neutral molecules) and logKaw (Henry's Law constant for neutral molecules). Error bars show the extent of the effect of water pH on chemical partitioning between water and sediment (logD calculation see Supporting Information) on example chemicals (142 antimicrobial agents and 19 UV filters) used in commerce (chemical properties predicted mostly by Pipeline Pilot[12]). Water pH also affects the ionisable chemical partitioning between air and water, which is not discussed in this study (Supporting Information). Extreme chemicals with logD/Kow around -12 and logKaw < -20 $Pa \cdot m^3/mol$ almost entirely distribute into a single compartment; while moderate chemicals with logD/Kow between 0 and 10 or logKaw between -10 and 5 $Pa \cdot m^3/mol$ tend to distribute in multiple compartments. Other environmental parameters may also impact on this distribution (e.g. soil pH) but are not shown in Figure 1.

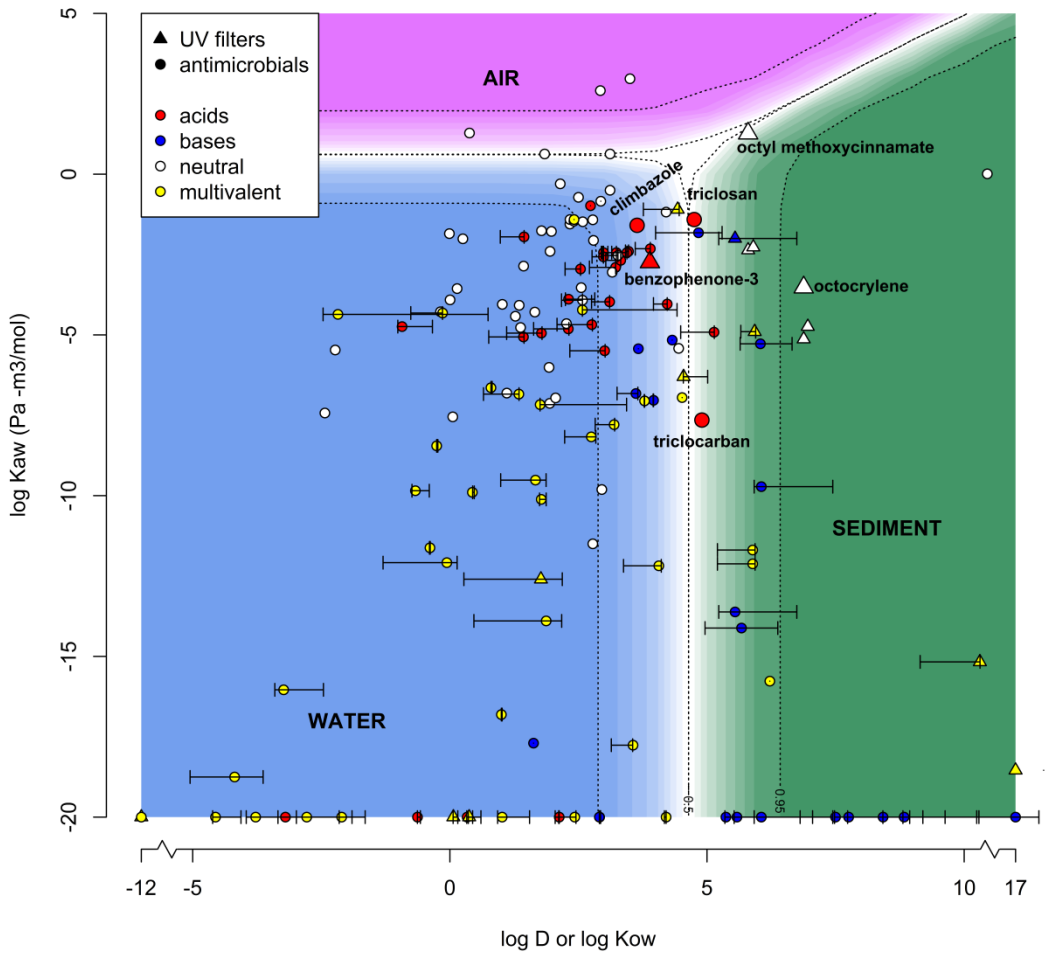


Figure 1 Chemical space plot indicating equilibrium partitioning characteristics of chemicals in air, water and sediment as dictated by logKaw (Henry's Law Constant for neutral molecules at pH = 7) and logD/Kow (octanol-water partition coefficient), which is not generated by SESAMe v3.3; the dotted lines indicate 50% and 95% partitioning into the respective compartments; circles represent antimicrobial agents and triangles are UV filters; Error bars show the range of logD for ionisable chemicals for extremes of measured environmental pH (5.7 – 10.5).

The six case study chemicals (highlighted in Figure 1) were selected from a portfolio used by the PCPs industry covering neutral and ionisable chemicals.[13, 14] Antimicrobial agents and UV filters are two commonly used groups of PCPs. They have been detected in multiple media in different regions across China.[15] UV filters are ingredients used in sunscreen products or cosmetics for protection against the adverse effect of ultraviolet radiation;[16] antimicrobial agents can be used in consumer products to protect against certain types of bacterial or fungi. The lifetime exposure of aquatic organisms to these substances can be sustained regardless of their persistence, when they are continuously discharged into the aquatic environment. Although the ecotoxicity of these chemicals has been studied and observed in acute or chronic exposure tests under high testing concentrations,[16, 17] the environmental measurements or

modelling results generally indicates concentrations below the level of concern.[18] However, these chemicals have 'intermediate' physicochemical properties (Table S1) and can partition into multiple environmental compartments, which makes them ideal case study chemicals. TCS and climbazole are acids with pKa values of 7.9 and 7.5, which are in the range of pH for freshwaters and soils in China (stated below); and BP-3 and TCC are acids with high pKa of 9.54 and 12.7. BP-3 has a lower logKow than TCC; and OC and OMC are hydrophobic neutral chemicals with relatively high logKow values (6.9 and 5.8), which are more likely to be adsorbed to sediment.

Model configuration and evaluation

So far, multimedia chemical fate models used to simulate real environments have typically focussed on neutral organic chemicals. To account for the different partitioning behaviour of ions, it requires chemical ionisation to be considered in the model and the range and variability of pH in the Chinese environment. SESAMe v3.3 (a level III spatially explicit model with a 50×50 km^2 grid) was therefore developed and updated from SESAMe 3.0[10] to incorporate spatial pH data for freshwater and sediment across China (model feature see Supporting Information). The spatial freshwater pH dataset was generated using weekly pH data from 99 gauging stations in China in 2012 (details see Supporting Information).[19] It ranged from 6.8 to 8.6 across China with a median of 7.8 (Figure S1). The pH of solid phases in sediments was assumed to be 0.6 lower than that in freshwater within the same grid cell.[20] Agricultural soil pH values ranged from 4.8 to 8.5 with a median of 6.5 (Figure S2). As with SESAMe v3.0, agricultural soil irrigation by freshwater in the same grid cell was an important process for the transport of compounds from water to soil, during which ca. 370 billion m^3 water was assumed to be uniformly distributed to agricultural soil across mainland China, as described previously by Zhu et al.[10] Other environmental parameters have been introduced previously.[10]

Emissions were assumed to be all released to freshwater. The model was used to predict the spatial concentration of chemicals in environmental media, especially aquatic systems, total mass of chemicals in each environmental compartment and net fluxes between freshwater and sediment at steady state, to show the spatial variation in transport behaviour and distribution. The neutral TCS concentration was predicted to provide a pH adjusted environmental risk assessment for China. Measured data for freshwater and sediment in China were collated from peer-reviewed literature for the six chemicals to evaluate the model (Figure S5 and Table S5). No measured data for UV filters in freshwater sediment was found, however these chemicals are highly insoluble and sorb strongly to organic material on sediment solids which will likely result in low bioavailability and toxicity in the environment.[18] Statistical

distributions of predicted and measured concentrations in freshwater and sediment for China were compared. For individual catchments, as literature on monitoring data was limited and measurements for individual sampling sites was not normally provided, average measurement were compared with average predicted concentration for grid cells covering the catchment. Model uncertainty for each chemical was explored by Monte Carlo simulation by running the model 10,000 times with parameters randomly taken from the environmental parameter and the emission databases. Sensitivity analysis was implemented by adopting a variability-based sensitivity coefficient (SCV, see Supporting Information).

Emission inventory

Emissions are principle model inputs for predicting chemical concentrations. The six chemicals are frequently used formulation ingredients, but their emissions/discharges cannot be readily acquired directly. Therefore a spatially resolved emission inventory was developed, for which chemical specific inclusion levels in products and removal ratios in WWTPs were collected or estimated.

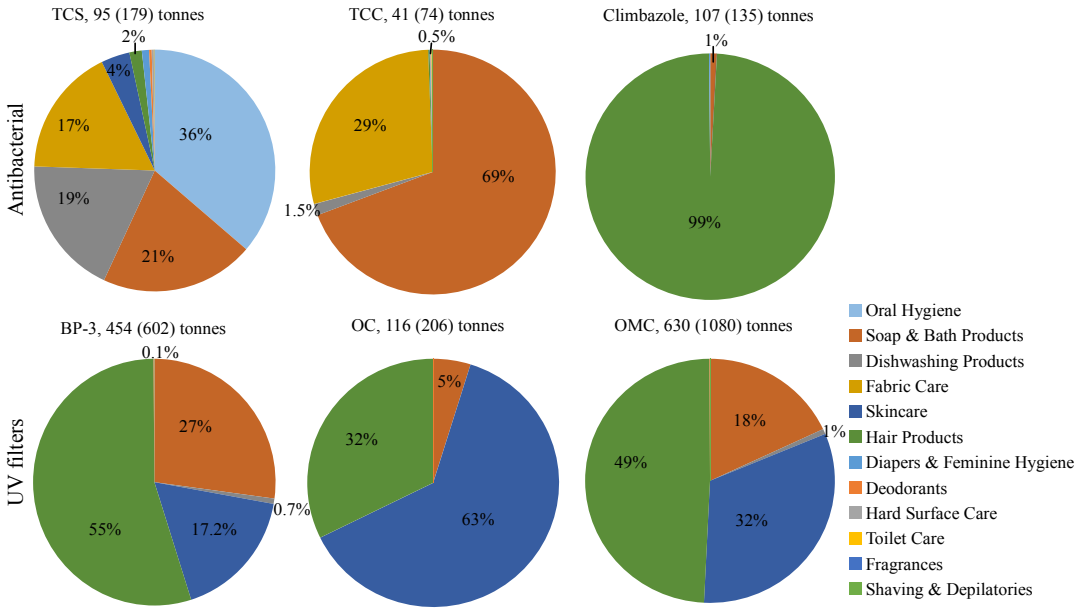


Figure 2 Estimated source composition and total emission and usage (in the brackets) of three antimicrobial agents (TCS, TCC and climbazole) and three UV filters (BP-3, OC and OMC) in China in 2012 as shown after acronym of each chemical above the pie chart

Usage. The Mintel Global New Products database[21] provided i. the (sub-)categories of personal and home care products in the Chinese market; ii. the total number of variants (products by different manufacturer with same function) released on to market under each sub-category; iii. the number of variants with each of the six chemicals under each sub-category. This provided the fraction of products containing specific chemicals. The tonnage

of products sold in the Chinese market was exported from the Euromonitor database.[22] Figure 2 shows the categories of products which contain some or all the six chemicals, which will ultimately be released to the wastewater system. Inclusion levels of chemicals for each sub-category were collected from the literature (Table S2). Combining the above information, the usage of individual chemicals in the Chinese market for 2012 was estimated. Subsequently, it was allocated to counties across China, by linking estimates of product usage at the population level (based on a population's ability to purchase individual products) with spatial distributions of GDP across China.[23]

Emissions. All products sold in the Chinese market in 2012 were assumed to be consumed and released with the domestic wastewater within the same year. Due to uneven socioeconomic development, the proportion of population connected to WWTPs for wastewater treatment varied between urban and rural areas and also between different counties. The proportion of population connections to WWTPs for urban and rural areas were estimated based on the per capita daily domestic water use, the domestic wastewater discharge and the rural and urban population data at the province level (details see Table S3 and Supporting Information). Owing to a lack of data, urban and rural per capita water use was assumed to be equal and the estimated proportion of population connection to WWTPs was assumed to be the percentage of wastewater processed by WWTPs and assigned to each county.

The measured removal ratios of the six chemicals in WWTPs taken from the peer reviewed literature ranged from 55->97% for TCS,[24, 25] 96-98% for TCC,[26] 18-67% for climbazole,[27, 28] 10-99% for BP-3,[29-31] 40-99% for OMC [30-32] and 36-99% for OC.[31-33] The variation of values for each chemical is due to different sampling seasons and methods or WWTP technologies in different studies. To aid the selection of a representative value for a secondary activated sludge plant (which is the typical wastewater technology in China), the SimpleTreat 3.2 model,[34] which can model ionisable chemicals, was used. The predicted values were typically within the removal ratio ranges from the literature and were considered reasonable and thus used in the SESAMe model. The predicted removal ratios were 95% for TCS, 96% for TCC, 89% for OMC, 91% for OC and 49% for BP-3. For climbazole, the predicted value was 12% and beyond the measured range (reasons see Supporting Information), so a measured value of 40% from a study in Beijing[27] was assumed.

The emissions of the six chemicals by county were calculated combining the usage, chemical removal ratio in WWTPs and the fraction of domestic wastewater treated by WWTPs. This estimation method is not limited to the six chemicals but can be used for most PCP chemicals.

The emissions by county were allocated by population to the 50×50 km^2 grid using ArcGIS 10.2.2.

Correcting for pH dependent toxicity

For ionisable chemicals, toxicity has been demonstrated to be pH dependent.[35, 36] However, current toxicity data or standard guidelines on such chemicals are suggested without pH correction or pH conditions, which may cause high uncertainty for environmental risk assessments. For example, 100 ng/L of total TCS was the recommended standard by the UK Technical Advisory Group on the Water Framework Directive for long-term exposure in freshwater but without suggesting the applicable environmental pH;[37] the PNEC (predicted no effect concentration) of TCS was reported to range from 26.2 to 1550 ng/L as total TCS concentration,[35, 38-40] probably due to uncertainties and variability in pH during toxicity studies, which typically increased (7.5/7.7 to 8.65/10.2) in the growth media during the algal test due to photosynthesis.[35, 41] This range of values may also have resulted from other factors such as the measurement system used or analytical measurement errors, etc. It was demonstrated that where strictly controlled pH conditions were used, the effective component for toxicity (i.e. neutral TCS) should have relatively constant concentration in toxicity test with daphnia[35] and algae[42] (Table S4).

Therefore, a pH-corrected indicator of $PEC_n/PNEC_n$ (PEC, predicted environmental concentration; the subscript 'n' indicates the neutral concentration) was developed for ionisable chemicals to better account for toxicity in the environment and ultimately a more realistic environmental risk assessment. TCS was selected as an example, as it is well studied with a large toxicity dataset.[41] $PNEC_n$ in freshwater can be derived by the same method for PNEC - $NOEC_n/EC_{n,X}$ (x, 5-20%) of a most sensitive aquatic species to TCS (i.e. certain algae)[16, 17] divided by the assessment factor (AF).[43] $NOEC_n$ was calculated using NOEC at different pH levels reported by Roberts et al.,[42] as the pH in exposure growth media was well controlled in this study (Table S4). The lowest $NOEC_n$ (1.5 μg/L) was used to calculate the $PNEC_n$ for freshwater as a conservative estimation for environmental quality, by which a $PNEC_n$ of 150 ng/L was estimated with an AF of 10. PEC_n across mainland China was predicted using SESAMe v3.3. It should be noted that such an indicator is only suggested for weak monovalent acids and bases that are mostly present in neutral forms; and the toxicity of multivalent acids or bases in water are more complex which are not considered here.

Results and discussion

Emission inventory

Figure 2 shows the total emissions and usage (in brackets) (the units are tonnes) estimated to be 95 (179) for TCS, 41 (74) for TCS, 107 (135) for climbazole, 454 (602) for BP-3, 116 (206) for OC and 630 (1080) for OMC in mainland China for 2012. Oral hygiene (36%), soap & bath products (21%), dishwashing (19%) and fabric care products (17%) comprise the main sources of TCS; soap & bath products (69%) are the main sources of TCC; climbazole is mainly used in hair products (99%) as an anti-dandruff agent. OC is mostly used in skincare products (63%) including daily face care (usage 47 tonnes) and sun care products (usage 80 tonnes), as it is more photo-stable than the other UV filters and can stabilize the other UV filters in the formula;[44] in contrast, hair products are the dominant category for BP-3 (55%) and OMC (49%); soap & bath products are an important source for BP-3 (27%) and fragrances are an important source for OMC (32%).

The emission and usage in this study for 2012 are respectively ca. 1.5 and 1.8 times higher for TCS[45] but less than half for climbazole[46] of those estimated for 2011 by Zhang et al. Although product consumption will probably increase every year in China along with the economic growth, it is still unlikely that the usage/emission of TCS could increase significantly over a year. As an important category of products consumed in the Chinese market, the consumption of fabric care products (power/liquid detergents) is probably greatly underestimated (431 t/year)[45] by Zhang et al. For climbazole, the fraction of variants for shampoo that contain this chemical in our study (1.15%) is estimated to be lower than that by Zhang et al. Uncertainty may exist in usage and emission estimation for these chemicals, because (1) it remains challenging to obtain total industry usage and estimate a more accurate wastewater connectivity to WWTPs in China; (2) the lack of information, the inclusion level is assumed to be constant for all variants under the same category and the removal ratio is assumed to be identical in all WWTPs across the country for individual chemical, which are probably not a reflection of reality.

Figure S3 shows total emissions by county across China (exclusive of Taiwan) in 2012 for the six selected chemicals. The ranges (5^{th}-95^{th} percentiles) plus median are 0.001-0.11 (median, 0.02) tonnes TCS, 0.0004-0.05 (0.01) TCC, 0.002-0.12 (0.03) climbazole, 0.007-0.5 (0.1) BP-3, 0.001-0.14 (0.02) OC and 0.01-0.75 (0.14) OMC. Generally, emissions of all six chemicals are relatively high in highly populated regions in Liao River basin in Liaoning, North China Plain (NCP), Jiangsu, Shanghai, north Zhejiang, eastern Sichuan, coastal regions in Fujian and Guangdong. Several regions in Guangdong province (e.g. Dongguan, Guangzhou, Shenzhen and Foshan etc.) and Shanghai have the highest emission of all six chemicals, followed by Beijing. The lowest usage and emission for six chemicals is in Cuoqin in Tibet. Figure S4 shows the emissions allocated to 50 × 50 km^2 grid.

Model evaluation and spatial distribution of the six chemicals

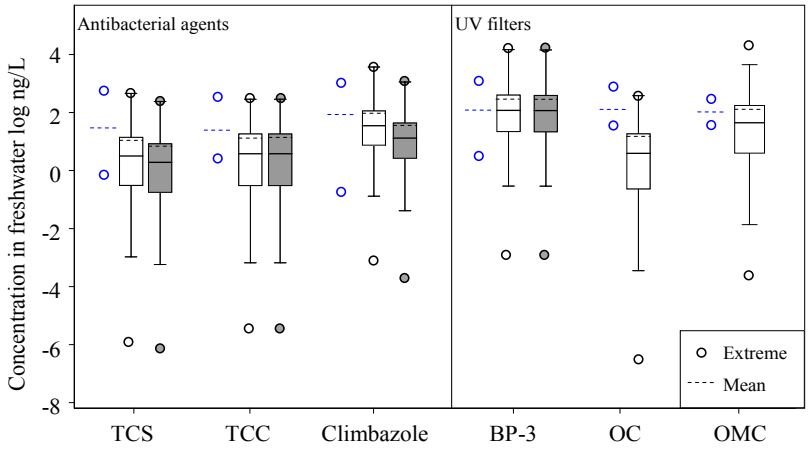


Figure 3 Boxplot (SPSS 18) of predicted total and neutral chemical concentrations (predictions for all grid cells), and measurements in freshwater (blue). White-box group indicates predicted total chemical concentrations (neutral plus ionic molecules); grey-box group indicates predicted neutral concentrations; the horizontal solid line in the box is the median; top and bottom of the box are respectively the 75th and 25th percentiles; the top and bottom of the whisker are respectively the highest and lowest case within 1.5 times the interquartile range. Extreme circles are max/min values.

The model generally performs well for the six chemicals as shown by the comparison between predictions and measurements (Figure 3, S6-S9). Predictions cover a broader range of concentrations than measurements, especially for lower concentrations, as measured data are only available for several major catchments with higher emissions in more densely populated regions (Figure S5). In addition, in the Chinese aquatic environment, the four ionisable chemicals mostly exist in neutral form, although concentrations of neutral molecules are significantly less than total concentrations for TCS and climbazole with lower pKa values. The statistical distributions of measurements and predictions of grid cells covering sampling sites match well for both water and sediment, although the model cannot capture certain hotspots (Figure S7-S8); a catchment based comparison between measurements and predictions, with differences within 2 orders of magnitude, also reflects a reasonable agreement for such types of model predictions for the purpose of preliminary risk assessment (Figure S9).[47] The differences are probably a reflection of the model calculating the average concentration of the individual 50×50 km^2 grid cell in contrast to measurements representing an instant on-site level. Therefore, larger number of sampling sites relative to the catchment area which cover both mainstream and tributaries would probably ensure a better match with model predictions, e.g. TCS and TCC (Table S5). For climbazole in the Yangtze River, as the sample size (n=27) was relatively low compared to the large area of the river basin, a greater

299 difference is shown between measurements and predictions. Therefore, the model is capable
300 for preliminary risk assessment and assessing of the probability of exceedance for different
301 regions; however it may have higher uncertainty on risk assessment for a grid cell which has
302 two unconnected streams with significantly different emissions in a region with high use of
303 the chemicals. Results of the sensitivity analysis are shown in Table S6. The distribution of
304 chemical concentrations in freshwater and sediment using Monte Carlo simulation is
305 lognormal and is shown in Figure S10, along with the interquartile range. Further model
306 calibration is needed when more field data becomes available for soils, sediments or for larger
307 areas of water.

308 A range of concentrations (5^{th} - 95^{th}, plus median in brackets) are predicted in freshwater and
309 sediment as follows (Figure S11-S12): freshwater, 2.3×10^{-4} - 71 (3) ng/L for TCS, 4.0×10^{-4} -
310 57 (4) ng/L for TCC, 0.03 - 334 (35) ng/L for climbazole, 0.05 - 1209 (118) ng/L for BP-3,
311 7×10^{-5}-74 (4) ng/L for OC and 0.004 - 634 (44) ng/L for OMC; freshwater sediment, 8×10^{-5} -
312 25 (1.2) ng/g for TCS, 1.5×10^{-3} – 183 (13) ng/g for TCC, 6×10^{-4} - 13 (1.3) ng/g for
313 climbazole, 2×10^{-3} - 56 (6) ng/g for BP-3, 4×10^{-4} - 250 (14) ng/g for OC and 4×10^{-3} - 386 (29)
314 ng/g for OMC. The chemicals present in sediment are mostly predicted to be adsorbed on
315 solids rather than in pore water especially for high logKow chemicals. As a result of the
316 freshwater irrigation in agricultural production, predictions show the range of concentrations
317 (5^{th} - 95^{th}, plus median in brackets) in agricultural soil across mainland China as 3×10^{-9} – 0.2
318 (0.008) ng/g for TCS, 3×10^{-11} – 0.1 (0.01) ng/g for TCC, 5×10^{-10} – 0.7 (0.1) ng/g for
319 climbazole, 2×10^{-10} – 1.7 (0.2) ng/g for BP-3, 3×10^{-8} – 0.04 (0.003) ng/g for OC and 1.5×10^{-8}
320 – 0.4 (0.03) ng/g for OMC. The difference with estimated emissions for TCS and climbazole
321 between this study and those by Zhang et al.[45, 46] is in the same order of magnitude. However,
322 this study predicts much broader concentration ranges for the two chemicals in both
323 freshwater and sediment than those by Zhang et al. (Table S7), probably as the finer
324 resolution of SESAMe v3.3 can identify extreme values better. Model predictions also
325 indicate a chemical input to coastal seawater system (predicted concentrations see
326 Supplement Information).

327 Generally, the spatial distribution patterns of concentrations for the six chemicals are similar
328 and also match those of estimated emissions at the national scale. For all chemicals, regions in
329 the NCP, Liao River basin in Liaoning, Jiangsu and coastal area in Zhejiang, Fujian and
330 Guangdong have higher concentrations than other regions, which also have higher emissions
331 due to high population density. Also the high concentration in NCP is probably related to the
332 low river discharge there. Regional contrasts exist between emissions and concentrations
333 mainly due to the discharge flow, e.g. regions that have the highest emissions in Guangdong
334 and Shanghai do not have the highest concentrations in freshwater and sediment as a result of

the dilution by large discharge flows; whilst western and northern Guizhou do not have very high emissions but have relatively high concentrations due to low discharge flow.

Chemical fate and partitioning among environmental media

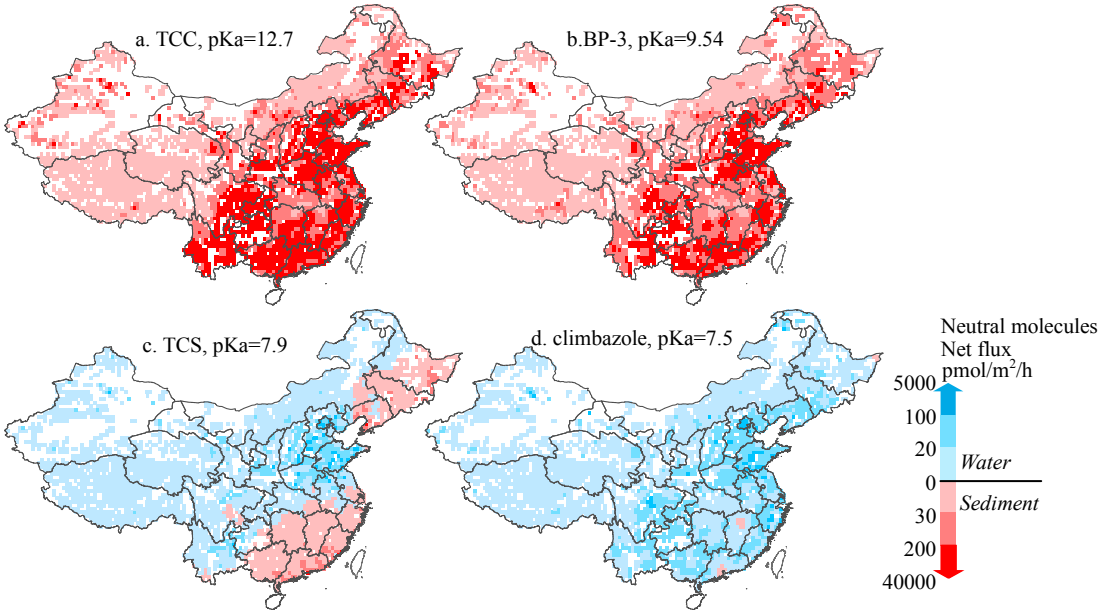


Figure 4 the net flux of neutral molecules of ionisable chemicals between freshwater and sediment compartments in the scenario that chemical is all released to water; blue indicates the net flux from sediment to freshwater and red is from water to sediment

As a result of constant emission to freshwater, the total molecules (neutral plus ionic forms) of all six chemicals and ionic molecules of the four ionisable chemicals are predicted to be transported from freshwater to sediment across China at steady state (Figure S15). However, the regionally varied main transport direction of neutral molecules (the main toxic form) of TCS and climbazole (Figure 4) demonstrates that the fate of ionisable chemicals is sensitive to small changes in environmental pH if their pKa values are within the range of ambient pH. The neutral molecules of TCS and climbazole are mainly transported from freshwater to sediment in red areas but from sediment to freshwater in blue areas. In red areas (lower water pH), chemicals are mostly present in the neutral form in freshwater after being released and so are transported mainly from water to sediment. In blue areas (higher water pH), a higher proportion of molecules are in the ionic form in freshwater but become neutral after partitioning to sediment (pH 0.6 lower than that in water), so neutral molecules partition back to freshwater. The water pH ranges of red areas are 6.8-7.8 for TCS and 6.8-7.2 for climbazole (Figure 4c-d). However, the sediment pH assumption is only one scenario, so there might be regional uncertainty due to the possibly different sediment pH values in the actual Chinese environment. Sediment can therefore act as either a receiving compartment or

a source for neutral/toxic molecules of ionisable chemicals. BP-3 and TCC are mainly present in their neutral form in the Chinese environment, unless the region is polluted resulting in an abnormally high pH, so neutral molecules are mainly transported from freshwater to sediment across China.

Not all of these 'down-the-drain' chemicals emitted to water primarily remain or degrade in the aquatic environment. At the national scale, agricultural soil is also predicted to be an important compartment at steady state for ionisable chemicals with relatively low pKa and logKow values. However, the origin of the chemical loading is assumed to originate from water irrigation as land application of sewage sludge or wastewater released directly to soil is currently not considered. For example, TCS (54% in soil and 41% in freshwater sediment, respectively), climbazole (63% in soil, 13% in freshwater sediment and 18% in freshwater) and BP-3 (54% in soil, 21% in freshwater sediment and 19% in freshwater) are all predicted to be transported to soil via irrigation (Figure S13, Table S8 and details see Supporting information). These chemicals have either relatively low logKow (BP-3) or low pKa (TCS) or both (climbazole), so a higher proportion will be present in freshwaters rather than in sediments when continuously released compared to chemicals with high logKow and pKa (Figure 1). They can subsequently be transported to agricultural soil by freshwater irrigation and converted to neutral forms (BP-3 is already neutral) in most regions in China with ca. 85% regions of soil pH < 7.5. The neutral molecules tend to adhere to soils. Climbazole has both lower pKa and logKow, so it is modelled to have the highest proportion in soils among the three. However, it should be noted that despite representing an important environmental compartment that chemicals tend to distribute in, soil concentrations of these chemicals are low as stated above, and are far below the terrestrial toxicity threshold;[48, 49] Irrigation will probably not be the main source of such chemicals to soil regionally if sludge amendment[50] or direct re-use of wastewater to soil is routinely used.

The other three neutral (TCC is almost neutral) hydrophobic chemicals are modelled to partition more to sediment after release, so only a limited proportion of chemicals will be transported to soil by freshwater irrigation, i.e. TCC (85% in freshwater sediment, 8% in agricultural soil and 1.7% in freshwater), OC (91% in freshwater sediment, 3% in soil, 1.7% in freshwater) and OMC (77% in freshwater sediment, 12% in agricultural soil, 7% in freshwater) (Figure S13). The chemical distribution in different media can vary regionally, as shown in Figure S14. Regional uncertainty should be noted owing to the assumptions on agricultural irrigation with constant amount of freshwater per area in this model. In reality, agricultural production may vary in different regions, e.g. rice and wheat, which will require significantly different amounts of irrigation water per area; and the source of irrigation water may not only come from the local surface water in some regions but from other regions/grid

cells. However, no monitoring data is available to explore the validity of this prediction. More discussions on vegetation can be found in Supporting Information.

This is a first study accounting for environmental fate of ionisable chemicals at the national scale for China. The findings that TCS and climbazole mainly distribute in soil at steady state (Figure S13) contrast with conclusions by Zhang et al. that the greatest amount of chemical is predicted to be in sediment for climbazole (83.7%)[46] and TCS (96.7%)[45]. It is believed that conclusions on environmental fate of these chemicals are more refined in this study, because in Zhang's study (1) only sewage irrigation was considered (no freshwater used), which provides insufficient water supply for agricultural irrigation requirements, so the chemical transfer to soil is likely to be underestimated; and (2) the two chemicals were modelled in their neutral form only, which would probably overestimate the ratio of chemicals in sediment to those in water, especially for TCS with a higher logKow than climbazole.,If modelling TCS as a neutral chemical by SESAMe v3.3, it appears that the predicted nationally averaged concentration in sediment is approximately twice as high as that predicetd by modelling it as an acid, So in this study, although sewage irrigation hasn't been considered, freshwater irrigation, albeit with diluted chemical concentrations compared to wastewater, is predicted to be an important source of the two chemicals to soil. This conclusion is probably applicable to many other down-the-drain chemicals with low pKa or logKow values.

Accounting for ionisable chemicals in environmental risk assessment

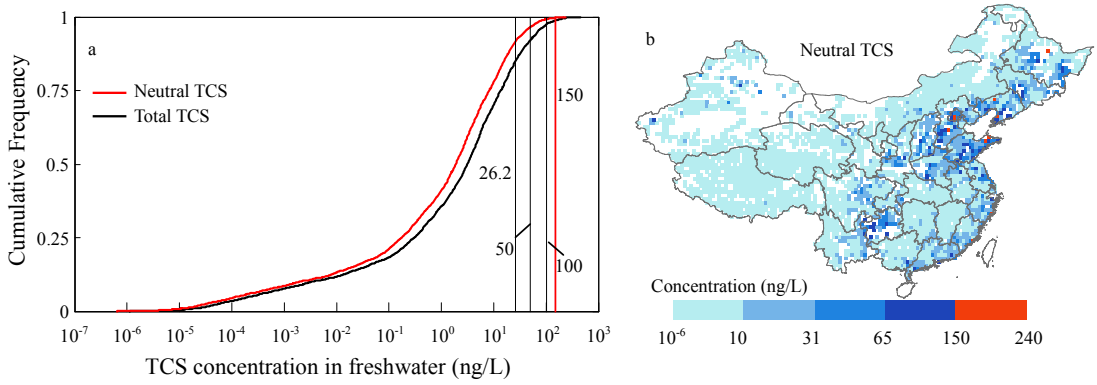


Figure 5 a, cumulative frequency of total and neutral TCS concentration in freshwater and the comparison with PNEC or other guideline values reported for water shown as vertical lines (the red vertical line representing 150 is $PNEC_n$); b, concentration of neutral TCS in freshwater across China.

An illustrative pH dependent environmental risk assessment has been conducted on TCS by comparing its $PNEC_n$ (150 ng/L) with both the PEC and the PEC_n produced by SESAMe v3.3 (Figure 5a). It was estimated that limited freshwater areas (0.03%, 55 km^2) in mainland China have PEC_n values exceeding 150 ng/L. These areas are mainly in NCP, Liaodong Peninsula

and Shandong Peninsula, as shown in red in Figure 5b, which requires further investigation by researchers to ascertain actual environmental risks posed by TCS and its relative contribution versus other wastewater constituents (e.g. pharmaceuticals, substances released with industrial wastewater and pesticides etc.). The blue areas in Figure 5b are probably of lower risk than the red areas on average (more discussions see Supporting Information). However, the different vertical lines in Figure 5a indicate the significant deviation of environmental risk assessment if a distinct threshold is chosen; and if comparing PEC with the threshold, the areas at risk will probably be overestimated.. The same method can be applied to sediments and soils for other ionisable chemicals.

Potential application of SESAMe v3.3 in chemical management in China

The use of these case study chemicals is illustrative and a previous model version has also been successfully applied on benzo[a]pyrene, with a greater focus on atmospheric emissions.[10] The illustrations show that SESAMe v3.3 can be a potential tool linking emissions, exposure concentrations in the environment with toxicity data. This can provide chemical prioritization and screening level assessment with spatial information, which could potentially resolve the issues stated at the beginning in the introduction and provide a guide to identify relatively high risk regions for monitoring campaigns and a refined risk assessment, which can support chemical management in China.

Why SESAMe v3.3 Firstly, as a multimedia fate model, the outputs can be easily interpreted by decision makers, which has been previously argued to be an advantage compared to more sophisticated models such as chemical transport models.[51] Secondly, SESAMe v3.3 can predict concentrations in multiple media for a broad range of chemicals including ionisables, which is competitive for developing an effective chemical management strategy with consideration of different exposure pathway to the environment or humans. It surpasses models which only predict concentrations within a single environmental compartment (e.g. atmospheric models and water quality models etc.). Besides, for chemicals mainly released to water, water quality models (such as GREAT-ER[52] etc.) currently cannot model at the national scale owing to the high requirements for hydrological parameters, but reversely SESAMe v3.3 can be used. Very few national scale studies using multimedia models for China have been implemented or published to date. As discussed above, the river basin based multimedia models by Zhang et al. for national modelling of pharmaceuticals and PCPs for China[45, 46, 53, 54] are fugacity models, which will probably result in higher uncertainty in concentration and fate estimations for ionisable chemicals.

Role in national water quality management Wu et al. (2010) has indicated that China should make its own national water quality criteria (WQC) system, rather than take the WQC

from developed countries directly, as China has different eco-environmental systems/structures and priority pollutants as compared with other countries[55]. Besides, the priority pollutants probably vary regionally within the country, due to the diverse environmental conditions[11] and unbalanced economic development across the country. Currently approaches to water quality management in China are usually adopted at the river basin or provincial level by different institutions, which may result in incompatible approaches between regions. National estimates of chemicals in aquatic systems by SESAMe v3.3 could provide an overall perspective for a national strategy with a unified method. Before this, BasinBox has been an example of multimedia fate models being developed for evaluating chemical risks in river basins for EU.[56]

Role in new chemical registration management Because quantitative risk assessment is required for new chemicals registration in China,[9] SESAMe v3.3 could also be used for preliminary risk estimation before a chemical is allowed to enter the Chinese market. For registration purposes and definitive risk assessments, data on the mass or volume of chemicals to be introduced to the market are required which can be used for the estimation of emissions, otherwise, OECD emission scenario documents[57] can be utilized to explore chemical emissions for a screening level assessment. A national strategy for estimating chemical usage in the country is important and needs be established. Care should be taken when using predictive tools to estimate physico-chemical properties and toxicity data for all chemical registrations. In particular, the use of mathematical estimations by models such as EPI Suite[58] should be carefully interpreted for ionisable chemicals[59] but has been widely used by researchers, which may cause higher uncertainties. In particular, the pH conditions for toxicity data should be reported for ionisable chemicals to properly interpret study results for use in risk assessment.

Supporting information

Additional information on description of model features, methods, input parameters, the literature for measured data and output figures are in the Supporting Information. The Supporting Information is available free of charge on the ACS Publications website at http://pubs.acs.org/.

Acknowledgements

We thank the Safety and Environmental Assurance Centre, Unilever, for funding the research. We also thank two pre-reviewers, Antonio Franco and Stuart Marshall in Unilever, for providing valuable comments.

Reference

(1) European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). European Commission 2007. http://ec.europa.eu/growth/sectors/chemicals/reach/

(2) Boxall, A. B. A.; Rudd, M. A.; Brooks, B. W.; Caldwell, D. J.; Choi, K.; Hickmann, S.; Innes, E.; Ostapyk, K.; Staveley, J. P.; Verslycke, T.; Ankley, G. T.; Beazley, K. F.; Belanger, S. E.; Berninger, J. P.; Carriquiriborde, P.; Coors, A.; DeLeo, P. C.; Dyer, S. D.; Ericson, J. F.; Gagne, F.; Giesy, J. P.; Gouin, T.; Hallstrom, L.; Karlsson, M. V.; Larsson, D. G. J.; Lazorchak, J. M.; Mastrocco, F.; McLaughlin, A.; McMaster, M. E.; Meyerhoff, R. D.; Moore, R.; Parrott, J. L.; Snape, J. R.; Murray-Smith, R.; Servos, M. R.; Sibley, P. K.; Straub, J. O.; Szabo, N. D.; Topp, E.; Tetreault, G. R.; Trudeau, V. L.; Van Der Kraak, G. Pharmaceuticals and personal care products in the environment: What are the big questions? *Environ. Health Perspect.* 2012, *120*, (9), 1221-1229.

(3) Monsalvo, V. M.; McDonald, J. A.; Khan, S. J.; Le-Clech, P. Removal of trace organics by anaerobic membrane bioreactors. *Water Res.* 2014**,** *49*, 103-112.

(4) Toxic Substances Control Act of 1976, Public Law 94-469. United States. http://www.epa.gov/agriculture/lsca.html

(5) Vermeire, T. G.; Jager, D. T.; Bussian, B.; Devillers, J.; denHaan, K.; Hansen, B.; Lundberg, I.; Niessen, H.; Robertson, S.; Tyle, H.; vanderZandt, P. T. J. European Union System for the Evaluation of Substances (EUSES). Principles and structure. *Chemosphere* 1997, *34*, (8), 1823-1836.

(6) US EPA, PBT Profiler. http://www.pbtprofiler.net/

(7) Webster, E.; Mackay, D.; Wania, F.; Arnot, J.; Gobas, F.; Gouin, T.; Hubbarde, J.; Bonnell, M. *Development and application of models of chemical fate in Canada. Modelling Guidance Document. Report to Environment Canada.* CEMN Report No. 200501. Canadian Environmental Modelling Network, Trent University, Peterborough, Ontario K9J 7B8, Canada: 2005.

(8) *Initial Risk-Based Prioritization of High Production Volume (HPV) Chemicals. Triclocarban (CASRN 101-20-2)*; U.S. Environmental Protection Agency: 2009.

(9) Provisions on the Environmental Administration of New Chemical Substances in China. Ministry of Environmental Protection, China. http://www.mep.gov.cn/gkml/hbb/bl/201002/t20100201_185231.htm

(10) Zhu, Y.; Tao, S.; Price, O.; Shen, H.; Jones, K.; Sweetman, A. Environmental distributions of benzo[a]pyrene in China: Current and future emission reduction scenarios explored using a spatially explicit multimedia fate model. *Environ. Sci. Technol.* 2015, *49*, (23), 13868-13877.

(11) Zhu, Y.; Price, O. R.; Tao, S.; Jones, K. C.; Sweetman, A. J. 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.

(12) BIOVIA Pipeline Pilot Website. http://accelrys.com/products/collaborative-science/biovia-pipeline-pilot/

(13) European Commission. Growth - Internal market, industry, entrepreneurship and SMEs. http://ec.europa.eu/growth/tools-databases/cosing/index.cfm?fuseaction=ref_data.annexes_v2

(14) European Chemicals Agency. List of active substances and suppliers. http://echa.europa.eu/information-on-chemicals/active-substance-suppliers

(15) Loftsson, T.; Ossurardottir, I. B.; Thorsteinsson, T.; Duan, M.; Masson, M. Cyclodextrin solubilization of the antibacterial agents triclosan and triclocarban: Effect of ionization and polymers. *J. Incl. Phenom. Macro.* 2005, *52*, (1-2), 109-117.

(16) Brausch, J. M.; Rand, G. M. A review of personal care products in the aquatic environment: Environmental concentrations and toxicity. *Chemosphere* 2011**,** *82*, (11), 1518-1532.

(17) Capdevielle, M.; Van Egmond, R.; Whelan, M.; Versteeg, D.; Hofmann-Kamensky, M.; Inauen, J.; Cunningham, V.; Woltering, D. Consideration of exposure and species sensitivity of Triclosan in the freshwater environment. *Integr. Enviro. Assess. Manage.* 2008, *4*, (1), 15-23.

(18) Kaiser, D.; Sieratowicz, A.; Zielke, H.; Oetken, M.; Hollert, H.; Oehlmann, J. Ecotoxicological effect characterisation of widely used organic UV filters. *Environ. Pollut.* 2012, *163*, 84-90.

(19) The weekly report of national key section water quality automatic monitoring for main river basin, China. http://datacenter.mep.gov.cn/

(20) Franco, A.; Trapp, S. A multimedia activity model for ionizable compounds: Validation study with 2,4-dichlorophenoxyacetic acid, aniline, and trimethoprim. *Environ. Toxicol. Chem.* 2010, *29*, (4), 789-799.

(21) Mintel Global New Products Database Website; http://www.gnpd.com

(22) Euromonitor Website; www.euromonitor.com

(23) Hodges, J. E. N.; Vamshi, R.; Holmes, C.; Rowson, M.; Miah, T.; Price, O. R. Combining high-resolution gross domestic product data with home and personal care product market research data to generate a subnational emission inventory for Asia. *Integr. Enviro. Assess. Manage.* 2014, *10*, (2), 237.

(24) Bendz, D.; Paxeus, N. A.; Ginn, T. R.; Loge, F. J. Occurrence and fate of pharmaceutically active compounds in the environment, a case study: Hoje River in Sweden. *J. Hazard Mater.* 2005, *122*, (3), 195-204.

(25) Lozano, N.; Rice, C. P.; Ramirez, M.; Torrents, A. Fate of Triclocarban, Triclosan and Methyltriclosan during wastewater and biosolids treatment processes. *Water Res.* 2013, *47*, (13), 4519-4527.

(26) Heidler, J.; Sapkota, A.; Halden, R. U. Partitioning, persistence, and accumulation in digested sludge of the topical antiseptic triclocarban during wastewater treatment. *Environ. Sci. Technol.* 2006, *40*, (11), 3634-3639.

(27) Qi, W.; Singer, H.; Berg, M.; Mueller, B.; Pernet-Coudrier, B.; Liu, H.; Qu, J. Elimination of polar micropollutants and anthropogenic markers by wastewater treatment in Beijing, China. *Chemosphere* 2015, *119*, 1054-1061.

(28) Wick, A.; Fink, G.; Ternes, T. A. Comparison of electrospray ionization and atmospheric pressure chemical ionization for multi-residue analysis of biocides, UV-filters and benzothiazoles in aqueous matrices and activated sludge by liquid chromatography–tandem mass spectrometry. *J. Chromatogr. A* 2010, *1217*, (14), 2088-2103.

(29) Golovko, O.; Kumar, V.; Fedorova, G.; Randak, T.; Grabic, R. Removal and seasonal variability of selected analgesics/anti-inflammatory, anti-hypertensive/cardiovascular pharmaceuticals and UV filters in wastewater treatment plant. *Environ. Sci. Pollut. Res.* 2014, *21*, (12), 7578-7585.

(30) Liu, Y. S.; Ying, G. G.; Shareef, A.; Kookana, R. S. Occurrence and removal of benzotriazoles and ultraviolet filters in a municipal wastewater treatment plant. *Environ. Pollut.* 2012, *165*, 225-232.

(31) Balmer, M. E.; Buser, H. R.; Muller, M. D.; Poiger, T. Occurrence of some organic UV filters in wastewater, in surface waters, and in fish from Swiss lakes. *Environ. Sci. Technol.* 2005, *39*, (4), 953-962.

(32) Li, W. H.; Ma, Y. M.; Guo, C. S.; Hu, W.; Liu, K. M.; Wang, Y. Q.; Zhu, T. Occurrence and behavior of four of the most used sunscreen UV filters in a wastewater reclamation plant. *Water Res.* 2007, *41*, (15), 3506-3512.

(33) Bueno, M. J. M.; Gomez, M. J.; Herrera, S.; Hernando, M. D.; Agüera, A.; Fernández-Alba, A. R. Occurrence and persistence of organic emerging contaminants and priority pollutants in five sewage treatment plants of Spain: Two years pilot survey monitoring. *Environ. Pollut.* 2012, *164*, 267-273.

(34) Franco, A.; Struijs, J.; Gouin, T.; Price, O. R. Evolution of the sewage treatment plant model simpletreat: Use of realistic biodegradability tests in probabilistic model simulations. *Integr. Enviro. Assess. Manage.* 2013, *9*, (4), 569-579..

(35) Orvos, D. R.; Versteeg, D. J.; Inauen, J.; Capdevielle, M.; Rothenstein, A.; Cunningham, V. Aquatic toxicity of triclosan. *Environ. Toxicol. Chem.* 2002, *21*, (7), 1338-1349.

(36) Rendal, C.; Kusk, K. O.; Trapp, S. Optimal choice of pH for toxicity and bioaccumulation studies of ionizing organic chemicals. *Environ. Toxicol. Chem.* 2011, *30*, (11), 2395-2406.

(37) *Updated recommendations on environmental standards, river basin management (2015-21), Final Report.*; UK Technical Advisory Group on the Water Framework Directive.

(38) Reiss, R.; Mackay, N.; Habig, C.; Griffin, J. An ecological risk assessment for triclosan in lotic systems following discharge from wastewater treatment plants in the United States. *Environ. Toxicol. Chem.* 2002, *21*, (11), 2483-2492.

(39) Capdevielle, M.; Van Egmond, R.; Whelan, M.; Versteeg, D.; Hofmann-Kamensky, M.; Inauen, J.; Cunningham, V.; Woltering, D. Consideration of exposure and species sensitivity of Triclosan in the freshwater environment. *Integr. Enviro. Assess. Manage.* 2008, *4*, (1), 15-23.

(40) Chen, Z. F.; Ying, G. G.; Liu, Y. S.; Zhang, Q. Q.; Zhao, J. L.; Liu, S. S.; Chen, J.; Peng, F. J.; Lai, H. J.; Pan, C. G. Triclosan as a surrogate for household biocides: An investigation into biocides in aquatic environments of a highly urbanized region. *Water Res.* 2014, *58*, 269-279.

(41) Yang, L. H.; Ying, G. G.; Su, H. C.; Stauber, J. L.; Adams, M. S.; Binet, M. T. Growth-inhibiting effects of 12 antibacterial agents and their mixtures on the freshwater microalga Pseudokirchneriella subcapitata. *Environ. Toxicol. Chem.* 2008, *27*, (5), 1201-1208.

(42) Roberts, J.; Price, O. R.; Bettles, N.; Rendal, C.; van Egmond, R. Accounting for dissociation and photolysis: A review of the algal toxicity of triclosan. *Environ. Toxicol. Chem.* 2014, *33*, (11), 2551-2559.

(43) *Technical Guidance Document on Risk Assessment in support of Commission Directive 93/67/EEC on Risk Assessment for new notified substances and Commission Regulation (EC) No 1488/94 on Risk Assessment for existing substances and Directive 98/8/EC of the European Parliament and of the Council concerning the placing of biocidal products on the market*; European Commission Joint Research Centre, 2003.

(44) Manova, E.; von Goetz, N.; Hungerbuehler, K. Ultraviolet filter contact and photocontact allergy: consumer exposure and risk assessment for octocrylene from personal care products and sunscreens. *Brit. J. Dermatol.* 2014, *171*, (6), 1368-1374.

(45) Zhang, Q. Q.; Ying, G. G.; Chen, Z. F.; Zhao, J. L.; Liu, Y. S. Basin-scale emission and multimedia fate of triclosan in whole China. *Environ. Sci. Pollut. Res.* 2015, 1-14.

(46) Zhang, Q. Q.; Ying, G. G.; Chen, Z. F.; Liu, Y. S.; Liu, W. R.; Zhao, J. L. Multimedia fate modeling and risk assessment of a commonly used azole fungicide climbazole at the river basin scale in China. *Sci. Total Environ.* 2015, *520*, 39-48.

(47) Armitage, J. M.; Cousins, I. T.; Hauck, M.; Harbers, J. V.; Huijbregts, M. A. Empirical evaluation of spatial and non-spatial European-scale multimedia fate models: results and implications for chemical risk assessment. *J. Environ. Monit*. 2007, *9*, (6), 572-81.

(48) Wang, X.; Zhang, C.; Liu, Z.; Wang, W.; Chen, L. Development of predicted no effect concentration (PNEC) for TCS to terrestrial species. *Chemosphere* 2015, *139*, 428-33.

(49) Richter, E.; Wick, A.; Ternes, T. A.; Coors, A. Ecotoxicity of climbazole, a fungicide contained in antidandruff shampoo. *Environ. Toxicol. Chem.* 2013, *32*, (12), 2816-25.

(50) Polesel, F.; Plósz, B. G.; Trapp, S. From consumption to harvest: Environmental fate prediction of excreted ionizable trace organic chemicals. *Water Res.* 2015, *84*, 85-98.

(51) MacLeod, M.; Scheringer, M.; McKone, T. E.; Hungerbuhler, K. The state of multimedia mass-balance modeling in environmental science and decision-making. *Environ. Sci. Technol.* 2010, *44*, (22), 8360-8364.

(52) Feijtel, T.; Boeije, G.; Matthies, M.; Young, A.; Morris, G.; Gandolfi, C.; Hansen, B.; Fox, K.; Holt, M.; Koch, V.; Schroder, R.; Cassani, G.; Schowanek, D.; Rosenblom, J.; Niessen, H. Development of a geography-referenced regional exposure assessment tool for European rivers - GREAT-ER contribution to GREAT-ER #1. *Chemosphere* 1997, *34*, (11), 2351-2373.

(53) Zhang, Q. Q.; Ying, G. G.; Pan, C. G.; Liu, Y. S.; Zhao, J. L. Comprehensive evaluation of antibiotics emission and fate in the river basins of china: Source analysis,

multimedia modeling, and linkage to bacterial resistance. *Environ. Sci. Technol.* 2015, *49*, (11), 6722.

(54) Zhang, Q. Q.; Zhao, J. L.; Ying, G. G.; Liu, Y. S.; Pan, C. G. Emission estimation and multimedia fate modeling of seven steroids at the river basin scale in China. *Environ. Sci. Technol.* 2014, *48*, (14), 7982-7992.

(55) Wu, F.; Meng, W.; Zhao, X.; Li, H.; Zhang, R.; Cao, Y.; Liao, H. China embarking on development of its own national water quality criteria system. *Environ. Sci. Technol.* 2010, *44*, (21), 7992-7993.

(56) Hollander, A.; Huijbregts, M.; Ragas, A.; Van de Meent, D. BasinBox: a generic multimedia fate model for predicting the fate of chemicals in river catchments. *Living Rivers: Trends and Challenges in Science and Management*, Springer: 2006; pp 21-38.

(57) OECD emission scenario documents. http://www.oecd.org/chemicalsafety/risk-assessment/emissionscenariodocuments.htm

(58) Estimation Programs Interface Suite™ for Microsoft® Windows, v 4.1. Environmental Protection Agency, Washington, DC, USA. 2012.

(59) Snyder, E. H.; Connor, G. A.; McAvoy, D. C. Measured physicochemical characteristics and biosolids-borne concentrations of the antimicrobial Triclocarban (TCC). *Sci. Total Environ.* 2010, *408*, (13), 2667-2673