Using REACH registration data to rank the environmental emission potential of persistent and mobile organic chemicals

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Abstract

Organic chemicals that are persistent and mobile in the aquatic environment exhibit a hazard to contaminate drinking water resources. In this study an emission score model was developed to rank the potential of REACH registered substances to be emitted into the environment. It was applied to a list of 2167 substances registered under the REACH legislation that were previously identified to be persistent and mobile organic chemicals (PMOCs) in groundwater or to be hydrolyzed to form transformation products fulfilling the PMOC criteria. The emission score model is based on the tonnage placed on the European market and on seven emission-related use characteristics (high release to environment, wide dispersive use, intermediate use, closed system use, professional use, consumer use, and substance in article), reported in the companies' registrations under REACH. Applying the model resulted in a list of 1110 substances (936 PMOCs and 174 precursors to PMOCs) that are estimated to be released into the environment, while 1054 substances were estimated not to be emitted and 3 substances could not be evaluated due to severe data gaps. The 936 PMOCs and the 174 precursors were ranked in two lists with regard to their emission potential. The model was shown to be fit for purpose in terms of suggesting and prioritizing substances for scientific investigations with a focus on environmental water quality. Though targeted for PMOCs, the presented scoring system is illustrative of how REACH registration data can be used to assess the emission potential of various substances.

Keywords: Prioritization, Environmental emissions, Transformation products, Drinking water, Polar contaminants, Water quality

1 Introduction

The number of chemicals produced and used in industrial or in consumer applications worldwide is continuously increasing.[1] Within the ambit of the European chemicals regulation REACH,[2] more than 16,500 substances are currently registered (as of October 2017) with a manufactured or imported volume in the European Union (EU) exceeding one ton per year. Many more substances will be registered by the final registration deadline May 31st, 2018 (according to Article 23(3) of the European Parliament Regulation (EC) 1907/2006[2]). According to Article 10 of the REACH legislation, manufacturers, importers and downstream users of substances in the EU are obliged to collect information on substance properties and uses and to report them in a registration dossier to the European Chemicals Agency (ECHA). The extent of information to be provided depends on the volumes of the substances manufactured in or imported into the EU (including import of substances within products according to Article 7 of the REACH legislation), which have to be reported as well. Besides information on the identity of the registered substance, the dossiers can contain information on toxicity, and exposure within different environmental compartments, depending on the legal requirements. In case a substance is exclusively used for synthesis of another substance under the conditions defined in articles 17 and 18 of REACH, the legislation offers the possibility to register such a substance as an 'isolated intermediate' with reduced requirements regarding the information to be provided for the registration.

Trace-analytical methods to determine contaminants in environmental samples are expensive and time-consuming in their development and application. They are further limited in the number of substances that can be analyzed in a single run. Thus, chemical analytical methods are often restricted to groups of substances with similar physical-chemical properties. Given the vast number of substances in use, it is thus evident that only a tiny fraction can be monitored by chemical analysis. It is therefore of utmost importance and relevance to

prioritize substances of highest concern for environmental monitoring programs. Prioritization by modeling has proven to be a powerful tool.[3,4] Most prioritization studies reported in literature so far have ranked substances with regard to their human exposure potential, as a prerequisite for risk assessment.[5-12] Other modeling studies attempted to identify emerging contaminants based on substance properties such as persistence in the environment or the potential to bioaccumulate.[13-16] Collectively, such studies model the hazard of the substances, and only few studies so far have explicitly attempted to model the potential of a large set of organic chemicals to be released into the environment, i.e. emissions, which is a key component of assessing risk.[5,12,16-19] Arnot and co-workers[5] ranked about 12,000 organic substances for human exposures (intake rates and internal human concentrations) using quantitative estimates of chemical emissions. The same study included an uncertainty analysis highlighting the greatest source of uncertainty in the model calculations were the estimates of chemical emissions. Bitsch et al.[12] used tonnage bands and Environmental Release Categories (ERC) registered under REACH as well as biodegradation and potential bioaccumulation to identify which chemicals are of potential health concern and are likely to occur in the food chain. McLachlan et al.[16] ranked substances for both estimates of actual human exposures and concentrations in the environment. Also this study used quantitative estimates for emissions and the rankings were revised with expert judgement. The rankings were further used to prioritize chemicals for target analysis as an evaluation of the results of the model-based screening.[16] Fischer and co-workers[19] developed an 'Emission Index' model that was later evaluated by Undeman et al.[20] for its ability to rank contaminants found in sewage treatment plants. The model was found to be of limited use in its current form, based on only weak correlations between the Emission Indices and the observed levels of the chemicals in the sewage treatment plants. The approach by Breivik et al.[17] was met with difficulties in application, as access to consistent input data was claimed to be "fragmented or even

impossible". The input parameters considered intuitive by Breivik et al. for inclusion in any approach to screen substances for emissions are a) total quantities in commerce, b) chemical function, and c) physical-chemical properties. The same study also demonstrated the importance of having up-to-date and accurate information on quantities for developing reliable emission scenarios.[17]

The environmental hazard potential is generally associated with substances exhibiting persistence, bioaccumulation and toxicity in the environment, so called PBT substances, and having long-range transport potential (LRTP) to reach remote locations. Most modelling studies in the literature have focused on such considerations.[5,11-16] Little attention has been given to highly polar substances that are mobile in the aquatic environment. If such mobile substances are also persistent, they could widely distribute in surface and groundwater (including raw waters used for drinking water production) and therewith present a hazard through threatening the quality of our drinking water resources, as well as pristine freshwater ecosystems. We denote such substances persistent and mobile organic chemicals (PMOCs).[21] PMOCs that are additionally toxic are referred to as PMT (persistent, mobile, and toxic) substances.[22] PMT substances have recently gained the interest of authorities, and there are activities attempting to identify them for potential regulatory measures.[23-25]

In this study we combine two goals. The first is to develop a qualitative emission scoring and ranking system using REACH registration data exclusively, which may serve as a semi-consistent basis for comparing chemicals, and thereby partially addressing the aforementioned concern by Breivik et al.[17] of fragmented input data. The second goal is to apply this system to substances registered under REACH that are PMOCs or PMOC precursors. The purpose of combining these goals is that there is a need to identify PMOCs that may be in the aquatic environment, but are not being monitored. Currently, the research community knows little about the presence of PMOCs from monitoring studies, due to their intrinsic property to be

115 extremely mobile in water, which causes them to be very challenging to analyze.[21] Only very
116 recently chemical analytical methods specifically targeting at PMOCs were developed[26,27] and
117 a modeling study that identified PMOCs among the REACH registered substances was
118 developed.[28] This modeling study by Arp et al.[28] resulted in a list of more than 2000
119 substances on the EU market that are suspected to be PMOCs or to hydrolyze to form PMOCs
120 and thus have the potential to be ubiquitous environmental water contaminants. However, in
121 order for a PMOC to be environmentally relevant, it also needs to be released.[23] To address
122 this, the present study expands off of this previous modeling study by Arp et al.,[28] by
123 developing an emission scoring system (E-score) based on information retrieved from
124 dossiers of the substances registered under REACH.

125 Our approach is distinctively different from published studies[5,12,16-19] in several respects: i)
126 We did not attempt to quantify emissions nor to predict environmental concentrations, but to
127 prioritize (rank) the target substances relatively to each other with respect to their emission
128 potential; ii) we started from a list of substances that were modeled to be PMOCs in
129 groundwater (or PMOC precursors); iii) we included environmental transformation in our
130 study by also estimating the emission potential of substances that were modeled to hydrolyze
131 to PMOCs; iv) we had access to the confidential dossiers from the REACH registration
132 process, giving us accurate figures of marketed volumes.

133

134 **2 Material and methods**

135 *2.1 PMOC target substances*

136 As the starting list of substances to be evaluated with respect to their environmental emission
137 potential we used the list of suspected PMOCs and PMOC precursors derived from the
138 substances registered under REACH (https://echa.europa.eu/information-on-

chemicals/registered-substances; as of December 2014) and presented by Arp et al.[28] This list consists of a total of 2167 unique substance identities (including organic and pseudo-organic substances), whereof 1811 have been modeled to be persistent and mobile in the aquatic environment (PMOC score of 4 to 5 in Arp et al.[28]) and 356 have been modeled to be PMOC precursors (i.e. to have the potential to be hydrolyzed to PMOCs with a PMOC score of 4 to 5). These substances typically had a high persistency (>40 days half-life in groundwater, considering biodegradation and hydrolysis), low log K_{oc} (mostly <3; for neutral chemicals), low log D_{oc} (mostly <3; for ionizable and ionic chemicals over a pH range of 4 to 10) and high water solubility (mostly >50 mg/L over a pH range of 4 to 10). EC inventory numbers and CAS numbers were used as identifiers for the unique substances.

2.2 Environmental emission score (E-score)

The environmental emission score (E-score) of a substance, i.e. the likelihood of the substance to be emitted into the environment, was calculated for PMOCs and PMOC precursors using the equation

$$\text{E-score} = \log(\text{tonnage} + 1.1) \times \Sigma\text{UCs} \qquad \text{eq. 1}$$

where 'tonnage' is the annual tonnage of the substance placed on the EU market (in t/yr, but for the calculation is considered unitless; see subsection 2.3 below) and ΣUCs is the sum of scores given to the substance for the 7 individual use characteristics (UCs; see subsection 2.4 below). The E-score is thus a unitless figure that allows ranking the qualitative emission potential of the substances relatively to each other, but does not yield quantitative data on the magnitude of estimated emissions.

2.3 Tonnage

The information on total tonnage was taken from one of the three databases from ECHA described in Table 1. These data bases were, in order of priority, database A – an aggregated

query in early 2015 for all REACH registrations; database B – a similar (but registration-specific) query from May 2014, and database C – the publically available REACH information (as of December 2014). A more detailed description of the databases is given in the Supplementary Material. Exact figures of tonnages placed on the EU market from database A were preferentially used. These figures are expected to reflect potential emissions much better than production volumes or tonnage bands from public databases (e.g. database C). However, the E-score does not take into account the specific tonnage for an individual use, nor any technical or organizational measures to prevent or reduce releases to the environment. Such specific information could not be retrieved automatically from the databases and was thus not feasible to include in a study on thousands of substances. In case no information about tonnage was available from databases A or B, or if the tonnage was given as 0 t, then the upper end of the tonnage band given in database C was used as a worst-case scenario. The logarithm of the tonnage was chosen in the E-score calculation in order to leverage the tonnage data relative to the scoring system used for the ΣUCs, with the range in 'log (tonnage + 1.1)' being from approx. 0.05 to 8.5. A factor of 1.1 was added to the tonnage before calculating the logarithm to avoid negative results for substances with a marketed tonnage <1 t/yr.

Table 1. Databases used with availability of data relevant for the present study.

	Database A[a]	**Database B**[a]	**Database C**[b]
Type and source of database	Database query from early 2015 by ECHA for all registrations (aggregated)	Database query from May 2014 by ECHA for all registrations (registration-specific)	Public REACH database on ECHA's website accessed in December 2014
Substance name	+[c]	+	+
EC number	+	+	+
CAS number	-[c]	+	+
Tonnage placed on the EU market	Exact tonnage	Estimation of maximum tonnage	Tonnage band

Use characteristics			
High release to environment	+	-	+
Wide dispersive use	+	-	+
Intermediate use	+	-	+
Closed system use	+	-	+
Professional use	+	-	+
Consumer use	+	-	+
Substance in article	+	-	+

[a] Databases A and B were compiled by ECHA from confidential business information in the REACH registration dossiers. The databases are available to Member State Competent Authorities for specific regulatory purposes. Access to the databases and the registration dossiers was available through cooperation with the German Federal Environment Agency (UBA). In the context of the present project the data in databases A and B were accessed at UBA's premises and provided by UBA for the 2167 suspected PMOCs and PMOC precursors.

[b] https://echa.europa.eu/de/information-on-chemicals/registered-substances

[c] A '+' means that data was available in the respective database, a '–' means that no data was available

2.4 Use characteristics

The seven UCs considered in the present study are listed in Table 1. They outline specific information on operational conditions during uses of the substances related to the likelihood of emissions on a generic level. Each characteristic was individually evaluated for each substance in order to come to the decision if the substance possesses this characteristic (TRUE) or not (FALSE). This was done according to modified criteria (see subsections 2.4.1-2.4.7 below) initially defined by ECHA. The initial criteria by ECHA for the TRUE/FALSE decisions are defined in database B and are based on the generic use descriptors in the REACH registrations. The aggregated information in database A regarding these generic use descriptors was used in the TRUE/FALSE decisions for the UCs (if not stated otherwise below). The scores given to the substances for each of the UCs are summarized in Table 2. The scores (numbers) were given based on the authors' judgement of how strongly a certain UC is expected to correlate with the potential for emissions, due to the absence of consistent, actual, empirical emission rates reported in REACH (or elsewhere). The UC 'high release to environment' was given the highest priority (highest numerical score), as this amounts

directly to environmental emissions. Further, also the UCs 'wide dispersive use', 'intermediate use', and 'closed system use' are directly related to emissions (or the presumed absence of emissions in the latter two cases) and were given second priority, while the remaining characteristics only imply that environmental emissions could (but not necessarily will) occur and were thus given the lowest scores. If a UC outcome of either TRUE or FALSE could not exclude emissions, a score greater than zero was assigned to both cases. E.g., a FALSE classification for 'high release to environment' does not mean complete absence of releases according to the ECHA criteria. In any case, the model is quite insensitive towards changes in the magnitude of these scores, since they are all equally used in a simple summation (ΣUCs). It is emphasized that the model output is not quantitative, but is only a relative ranking of the substances with respect to their emission potential as characterized by the selected UCs. The sum of the scores of all seven UCs can range from 6 to 21. The criteria for evaluation of each UC are described below and two examples of scoring and ranking are given in the Supplementary Material.

Table 2. Scores given based on the TRUE/FALSE decision for each of the use characteristics.

Use characteristic	Score for TRUE	Score for FALSE
High release to environment	7	3
Wide dispersive use	4	1
Intermediate use	0	3
Closed system use	1	3
Professional use	1.5	0.5
Consumer use	2	0.5
Substance in article	0.5	0

2.4.1 High release to environment. Following the criteria defined by ECHA a high release is expected if ≥10% of the initial amount of a substance in a process or use is emitted to at least one environmental compartment (air, water, soil). This endpoint was thus evaluated as TRUE if at least one of the Environmental Release Categories (ERC) 2, 5, 8a, 8c, 8d, 8f, 10b, 11b, or 12b, as defined in REACH, was assigned to an individual registration dossier of the substance in the chapter for use description. See table R.16-7 in the respective guidance document[30] for a detailed description of release rates for these ERC. Otherwise the evaluated decision was FALSE.

2.4.2 Wide dispersive use. This characteristic was evaluated as TRUE if at least one of the following criteria applied: 'Number of consumer uses (upper bound) >0', 'number of professional uses (upper bound) >0', at least one of the ERC 8-11 was assigned to the substance in an individual registration dossier, or at least one of the process categories (PROC) 10, 11, 13, 15, 17, 18, or 19 was assigned to the substance in an individual registration dossier. See table R.12-11 in the respective guidance document[29] for a detailed description of the PROC. If none of the above criteria applied, then the evaluated decision was FALSE.

2.4.3 Intermediate use. The information for a decision on intermediate use (intermediate means a substance that is manufactured for and consumed in or used for chemical processing in order to be transformed into another substance[2]) was taken from database C. It was evaluated as TRUE if there were exclusively registrations of the type 'intermediate' recorded; otherwise it was evaluated as FALSE.

2.4.4. Closed system use. The information for a decision on closed system use was taken from database C. It was evaluated as TRUE if 'all identified uses take place in closed system' was answered with 'yes'; otherwise it was evaluated as FALSE.

2.4.5 Professional use. This characteristic was evaluated as TRUE, if 'number of professional uses (upper bound) >0' or if this information was ambiguous or lacking. Professional use was thus only evaluated as FALSE if 'number of professional uses (upper bound) = 0'.

2.4.6 Consumer use. This characteristic was evaluated as TRUE, if 'number of consumer uses (upper bound) >0' or if this information was ambiguous or lacking. Consumer use was thus only evaluated as FALSE if 'number of consumer uses (upper bound) = 0'.

2.4.7 Substance in article. This characteristic was evaluated as TRUE, if 'number of article categories >0' or if this information was ambiguous or lacking. Substance in article was thus only evaluated as FALSE if there was no article category given.

2.5 Significant data gaps or ambiguous data

For some of the PMOCs and PMOC precursors the data that were needed to evaluate the UCs were incomplete, or the information on tonnage and/or UCs was ambiguous. For small data gaps or ambiguity, the worst-case scenario was assumed for the respective UC. However, in some cases significant data gaps or contradictory data existed, which hampered a sound calculation of the E-score. This was the case for the following combinations of data gaps and/or ambiguous data:

a) Tonnage = 0 t and 'intermediate use' FALSE (contradictory data).

b) Tonnage = 0 t, 'intermediate use' not specified, 'closed system use' not specified, and 'substance in article' not specified.

c) Tonnage given, 'high release to environment' not specified, 'intermediate use' not specified, 'closed system use' not specified, and 'substance in article' not specified.

Substances with significant data gaps as specified in a)-c) were not given a numerical E-score based on the information from databases A-C. Tonnages and UCs for these substances were instead evaluated case by case using the information available on ECHA's public website

http://echa.europa.eu/de/information-on-chemicals/registered-substances (accessed between July 2015 and December 2016).

2.6 Evaluation of the E-score model and sensitivity analysis

The E-score model was evaluated using several approaches, as described in subsection 3.3 below. Correlation analyses based on the Pearson product-moment was conducted between log(tonnage + 1.1) vs. E-score ranking, ΣUCs vs. E-score ranking, and log(tonnage + 1.1) vs. ΣUCs, using Origin Pro 2016. Tonnage proved to be the most influential parameter in the model (see section 3.3); therefore a sensitivity analysis was performed, investigating how the results would change if only tonnage was considered in the E-score, but not UCs. Furthermore, it was also tested how the results would change if only the maximum single UC score was used in eq. 1 instead of ΣUCs. Another evaluation approach was based on a literature search using the Web of Science search engine (www.webofknowledge.com/). For this purpose, the substances with estimated emissions (1110 in total, see section 3.1 'class 2 substances') were grouped in 11 E-score groups with 101 substances in each group. Group I contained the 101 substances with the highest calculated E-score and group XI with the lowest. Roughly every 9^{th} substance in each group was randomly picked (11 per group, resulting in a total of 121 substances) and searched for using the following keywords in the search category 'topic': 'substance name' AND (*environment* OR *water* OR *soil* OR *effluent*). The same search was also done for 30 (from a total of 1054) randomly selected substances with no predicted emissions (group XII, see section 3.1 'class 3 substances'). The median of the number of 'hits' was calculated for the 11 substances per group (30 substances for group XII) and correlated with the E-score ranking of the groups (i.e. the Roman numeral group numbering). The grouping and calculation of medians were done to smoothen the results of the correlation. The assumption in this evaluation was that the more of a substance is emitted into (and consequently for persistent substances occurring in) the environment, the

more reports exist in the scientific literature containing the name of the substance together with any of the searched keywords, i.e. the more ‘hits’ one would get when performing such a search.

3 Results and discussion

3.1 Prioritized substances

Applying our E-score calculation approach (eq. 1) to the 2167 modeled PMOCs (1811 substances) and PMOC precursors (356 substances) resulted in three classes of substances based on emission potential, as follows:

Class 1 - substances for which an E-score could not be calculated due to incomplete information. Initially, this class of substances with significant data gaps or ambiguous data comprised a total of 29 substances. After case by case evaluation using the information available on ECHA’s public website, 14 and 12 of these substances could be classified into class 2 and class 3, respectively. The 3 substances remaining in class 1 were all REACH registered PMOCs (not precursors).

Class 2 - substances with indicators of environmental emissions: A total of 1110 substances (including the 14 cases from class 1) had tonnage and UCs indicating emissions (i.e. not fulfilling both a tonnage of 0 t and ‘intermediate use’ TRUE). The calculated E-score for class 2 substances is assumed to be positively correlated with the likelihood of the substance being emitted into the environment.

Class 3 - substances with indicators of negligible environmental emissions: A total of 1054 substances (including the 12 cases from class 1) had indicators of no (or minor) environmental emissions (i.e. a tonnage class of 0 t and an ‘intermediate use’ TRUE). Class 3 substances were not considered further in the present study.

The final distribution of PMOCs and PMOC precursors between the three classes is shown in Figure 1.

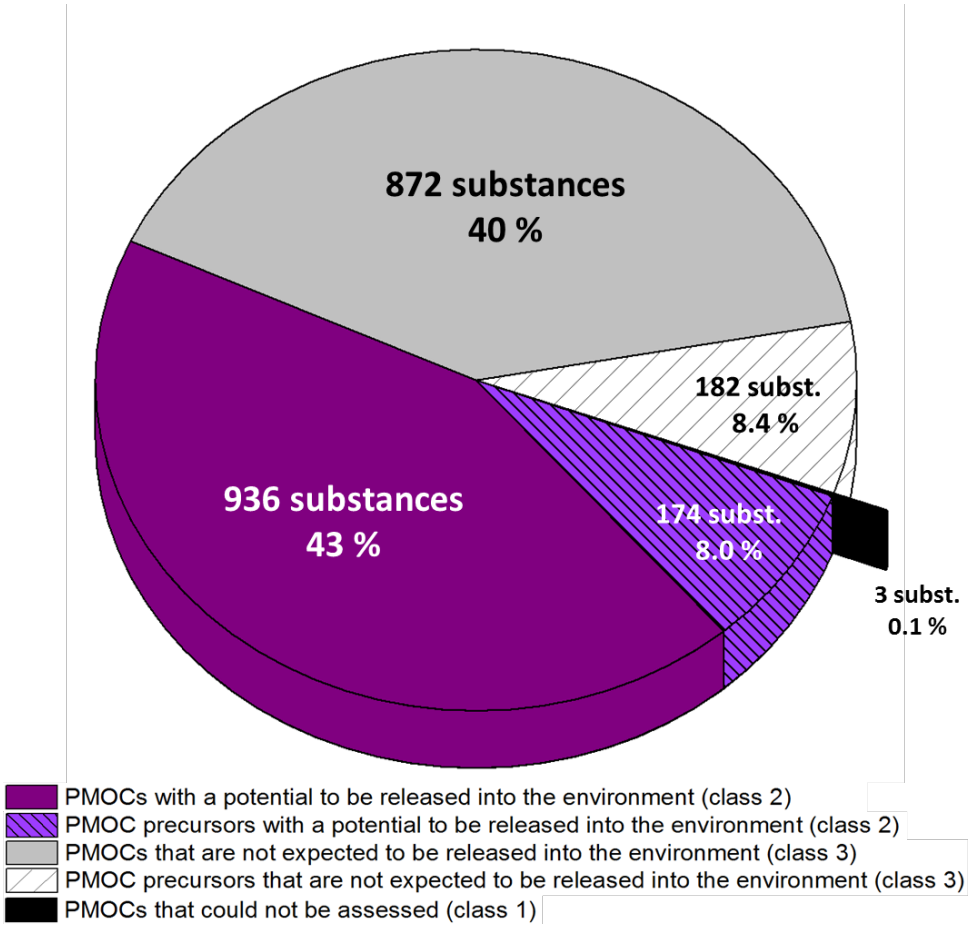

Figure 1. Distribution of PMOCs and PMOC precursors between the E-score classes.

3.1.1 PMOCs registered under REACH. Of the 1110 class 2 substances 936 were REACH registered substances predicted to be PMOCs (Figure 1). These 936 substances are ranked in Table S1 in the Supplementary Material in order of their calculated E-score, with rank 1 (carbonate/carbonic acid) representing the highest E-score. The values of the E-scores themselves cannot be disclosed, as they might allow back-calculation of confidential data from the REACH registration dossiers (especially tonnages) used as input data. The 3

remaining PMOCs from class 1 (no E-score calculable, see Figure 1) are listed at the end of Table S1. Some individual cases of substances are discussed in section 3.4.

3.1.2 Precursors of PMOC hydrolysis products. The remaining 174 of the 1110 class 2 substances are REACH registered substances that were predicted to hydrolyze under environmental conditions to form PMOCs[28] (Figure 1). These 174 precursors are listed in Table S2 in the Supplementary Material in order of their calculated E-score (rank 1 represents the highest E-score). The predicted hydrolysis products that were modeled to be PMOCs are shown in Table S2 with their Simplified Molecular Input Line Entry Specification (SMILES) codes. As can be seen from Table S2, one precursor substance can hydrolyze to form several PMOC hydrolysis products. Vice versa, one PMOC hydrolysis product can also be formed from different precursor substances. Some of the PMOC hydrolysis products are also the same structure as other REACH registered substances, including some of the PMOCs already considered. This has the implication that a subset of the REACH registered PMOC substances can be released directly, or as transformation products of other substances.[28] Selected highly ranked precursors are briefly discussed in subsection 3.4.

3.2 Uncertainties in the prioritization

The aim of the study was to prioritize PMOCs with regard to their environmental emission potential. The list of suspected PMOCs and PMOC precursors published by Arp et al.[28] was used as a starting point. As discussed in detail by Arp and co-workers, the persistency and mobility modeling as well as the modeling of hydrolysis under environmental conditions are associated with uncertainties, which are thus transferred into our study. The E-score model itself also contains uncertainties. As mentioned in subsection 2.3 above, specific tonnages for individual uses or ‘end-of-pipe’ measures to reduce emissions to the environment from the individual use processes were not taken into account in the E-score calculation. The applied UCs do not contain sufficient empirical information to predict actual substance emissions.

The TRUE/FALSE decisions with regard to the different UCs were further based on data submitted by registrants within the REACH registration process, and these data were not independently checked. A recent compliance check by order of the UBA demonstrated that only 4 to 45% of the investigated dossiers were compliant with the requests from the REACH regulation (information requirements referred to in article 10; Annexes VI-XI) with respect to information provided for five different environmental endpoints. A large number of dossiers (43 to 82%) were generally classified as 'complex', i.e. a classification in 'compliant' or 'non-compliant' was not possible due to poor documentation.[31] Taken together, all these uncertainties will undoubtedly lead to both false negatives as well as false positives in our estimation of the likelihood of a substance to be emitted in significant amounts. Thus, some of the highly ranked substances in Table S1 may not necessarily be present in environmental water samples; whereas, REACH registered substances missing from Table S1 may be currently contaminating water resources. The prioritization should be seen as qualitative hypotheses of substances that could potentially threaten raw water bodies, but this has to be confirmed (or disproved) case by case. On the other hand, the tonnage information from the confidential sections of the registration dossiers we used as input data for our E-score model is certainly more accurate than publically available tonnage band data. Therefore, we expect our E-score estimation model to perform at least as well as or better than models earlier published in literature.[5,16-19] Assuming that reporting in REACH will become more accurate and more comprehensive in future also with respect to UCs, it would be of interest to repeat this E-scoring at a later time.

3.3 Evaluation of the E-score model and sensitivity analysis

The relative sensitivity of the model output (the E-score ranking) towards the two factors in the model equation (eq. 1) was tested by correlating the E-score ranking with both factors individually. A strong positive correlation ($r = 0.92$) was found between log(tonnage +1.1)

and ranking and a weaker positive correlation (r = 0.55) between ΣUCs and ranking. This shows that in our model both factors significantly contributed to the output, whereby the marketed tonnage had the strongest influence on the final rank of a substance. However, using only tonnage as ranking criterion would result in 21% of the substances changing their position in Table S1 or S2 with more than 100 ranks. This demonstrates that ΣUCs is also an important parameter in the model. ΣUCs and log(tonnage +1.1) correlated only very weakly with each other (r = 0.28), confirming that the TRUE/FALSE decision criteria for the UCs were not (markedly) influenced by the tonnage of the substance, i.e. that the two factors in the E-score calculation were not strongly co-dependent of each other. If only the maximum single UC score was used in the E-score calculation instead of ΣUCs, less than 10% of the substances would change their ranking position with more than 100 ranks. This further corroborates that the model is relatively insensitive towards the values of the scores for the different UCs.

The results of the E-scoring were further evaluated using the Web of Science search approach described in subsection 2.6. The obtained histogram between the ranges of E-score ranks and the Web of Science ‘hits’ is shown in Figure 2. The very strong positive relationship in Figure 2 between increasing E-score range and ‘hits’ suggests that our model in general identifies substances of interest to the environmental and chemical community, and is fit for the purpose of qualitatively ranking emissions. This is further confirmed by a glance at the top ranked PMOCs in Table S1. Many of these are common salts or solvents; though these may not be the most interesting substances for an environmental chemist looking for emerging contaminants, they are expected to qualify as PMOCs with a high emission potential.

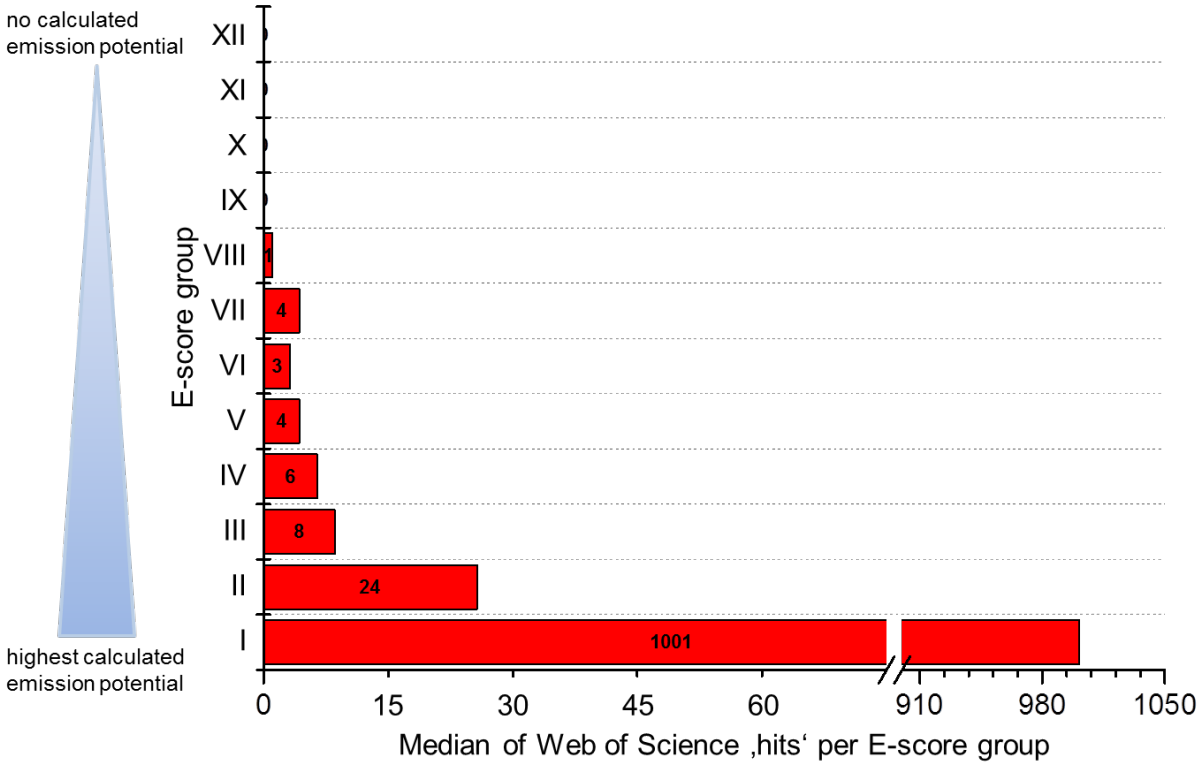

Figure 2. Evaluation of the E-score results using a Web of Science literature search. The x-axis shows the median of the 'hits' of the 11 investigated substances per group (30 for group XII). The y-axis shows the groups consisting of 101 substances per group (1054 for group XII). Group I is the group of substances with the highest E-scores and group XI with the lowest E-scores (class 2). Group XII are the class 3 substances without predicted emissions.

3.4 Identifying PMOCs of concern

Amongst the highly ranked PMOCs (Table S1) there are organic water contaminants known from the literature, such as melamine (rank 8, reported in river water, groundwater, and tap water[32-34]), bisphenol S (rank 132, reported in river water[35]), sulphanilic acid (rank 159, reported in groundwater[36,37]), acesulfame (rank 277, reported in wastewater, surface water, groundwater, and tap water[38]), dapsone (rank 324[39,40]), and saccharine (rank 498, reported in wastewater, surface water, and groundwater[38,41]). It is likely that many less well-known or hitherto unreported PMOCs that are problematic to raw water are also within these highly ranked substances. To this end, Table S1 has already been used successfully by Montes and co-workers[27] in a first chemical analytical approach to screen environmental water samples

421 for novel and emerging PMOCs. PMOCs detected in this screening study included toluene-4-
422 sulfonic acid (rank 50), 1,3-di-*o*-tolylguanidine (rank 427), and trifluoromethane sulfonic acid
423 (rank 429), which has recently been detected in raw water and drinking water sources for the
424 first time.[26,27] This result, as well as future observations of other PMOCs in this prioritized list
425 in raw water sources, represent the ultimate evaluation of our modelling approach, and its
426 utility. The list of prioritized PMOCs presented in Table S1 can thus serve as a starting point
427 for suspect screening of further, yet unknown raw water contaminants. This is particularly the
428 case for the highly ranked substances that did not occur commonly in the literature evaluation
429 exercise, as the reason for this gap in the literature may be a general lack of available
430 analytical techniques for these substances, and therefore a lack of screening and monitoring
431 data.[21] Further considerations for prioritization of the highly ranked PMOCs presented here
432 would be information on toxicity[24,25] and more detailed information on specific usages, such
433 as in household products, which would increase the risk of wide-spread emissions and water
434 contamination.

435 The top-ranking precursors that were predicted to hydrolyze into PMOCs (Table S2) include
436 several aromatic isocyanates (rank 1-3), the brominated flame retardant
437 hexabromocyclododecane (rank 4), as well as large molecules that resulted in a multitude of
438 potential PMOC hydrolysis products (such as propoxylated trimethylolpropane, rank 7).
439 However, it needs to be acknowledged that the yields and accuracy of the predicted hydrolysis
440 are uncertain, as these were all based on QSARs;[28] therefore, the likelihood of detecting these
441 transformation products in the environment is less than for PMOCs from Table S1. The high
442 ranking of hexabromocyclododecane hydrolysis products is indicative of this uncertainty, as
443 this compound is not known to readily hydrolyze under environmentally relevant conditions.
444 Nevertheless, this list can be used as a starting point to prioritize which substances should be
445 investigated for their ability to hydrolyze or transform into potentially problematic PMOCs.

Acknowledgments

We gratefully acknowledge the European Union Joint Programming Initiative 'Water Challenges for a Changing World' (Water JPI) with financial support by the 'Bundesministerium für Bildung und Forschung' (Germany, project no. 02WU1347A) and 'Forskningsrådet' (Norway, project no. 241358/E50).

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