Science of the Total Environment 848 (2022) 157124

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

European scale assessment of the potential of ozonation and activated carbon treatment to reduce micropollutant emissions with wastewater

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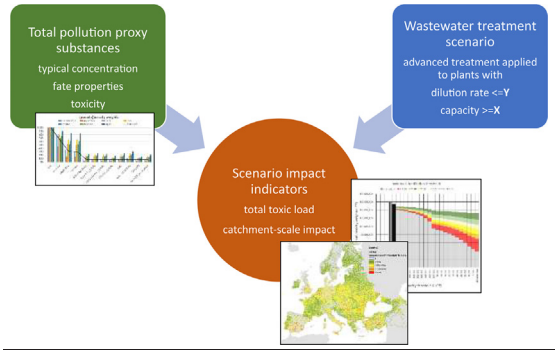
HIGHLIGHTS

- We build indicators of cumulative micropollutant toxicity of wastewater in the EU.
- Toxicity evaluated from 1337 proxy substances and estimated treatment removal.
- Current toxicity equivalent to untreated sewage discharge of 160 million people.
- Advanced treatment at large wastewater treatment plants reduces this to 95 million.
- Advanced treatment also at smaller plants approximately halves current pollution.

GRAPHICAL ABSTRACT

Flow diagram of the comparative risk assessment.



ARTICLE INFO

Editor: Damià Barceló

Keywords:
Advanced wastewater treatment
toxicity indicators
total pollution proxy substances
ozonation, activated carbon

ABSTRACT

Micropollutants (MPs) in wastewater pose a growing concern for their potential adverse effects on the receiving aquatic environment, and some countries have started requiring that wastewater treatment plants remove them to a certain extent. Broad spectrum advanced treatment processes, such as ozonation, activated carbon or their combination, are expected to yield a significant reduction in the toxicity of effluents. Here we quantify the reduction of effluent toxicity potentially achieved by implementing these advanced treatment solutions in a selection of European wastewater treatment plants. To this end, we refer to a list of "total pollution proxy substances" (TPPS) composed of 1337 chemicals commonly found in wastewater effluents according to a compilation of datasets of measured concentrations.

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http://dx.doi.org/10.1016/j.scitotenv.2022.157124
Received 7 March 2022; Received in revised form 27 June 2022; Accepted 28 June 2022
Available online 2 July 2022

We consider these substances as an approximation of the "chemical universe" impinging on the European wastewater system. We evaluate the fate of the TPPS in conventional and advanced treatment plants using a compilation of experimental physicochemical properties that describe their sorption, volatilization and biodegradation during activated sludge treatment, as well as known removal efficiency in ozonation and activated carbon treatment, while filling the gaps through *in silico* prediction models.

We estimate that the discharge of micropollutants with wastewater effluents in the European Union has a cumulative MP toxicity to the environment equal to the discharge of untreated wastewater of ca. 160 million population equivalents (PE), i.e. about 30 % of the generated wastewater in the EU. If all plants above a capacity of 100,000 PE were equipped with advanced treatment, we show that this load would be reduced to about 95 million PE. In addition, implementing advanced treatment in wastewater plants above 10,000 PE discharging to water bodies with an average dilution ratio smaller than 10 would yield a widespread improvement in terms of exposure of freshwater ecosystems to micropollutants, almost halving the part of the stream network exposed to the highest toxic risks.

Our analysis provides background for a cost-effectiveness appraisal of advanced treatment "at the end of the pipe", which could lead to optimized interventions. This should not be regarded as a stand-alone solution, but as a complement to policies for the control of emissions at the source for the most problematic MPs.

1. Introduction

It is estimated that about 235,000 single chemical substances are registered for use around the world (Wang et al., 2020). Many of these chemicals end up in the aquatic environment through discharges of urban wastewater (e.g. Alygizakis et al., 2019; Finckh et al., 2022). Several individual compounds have been identified as a potential source of risk and, in some cases, have undergone restrictions or ban. Many substances show concentrations that may exceed risk thresholds for aquatic ecosystems. Also when concentrations are relatively low for individual substances, our understanding of their cumulative adverse effects is still limited (see Supporting Information (SI), Note 1).

With a societal expectation to bring pollution to as low a level as possible, in line with the precautionary principle, pollution can be controlled by avoidance or reduction of chemical use and/or emissions at the point of manufacturing, the point of use, water treatment at the "end of the pipe", or a combination of all three (Kümmerer et al., 2018, 2019). While each strategy has a solid rationale, it is unlikely that we can avoid treatment of chemicals prior to discharge even if accompanied by actions to limit emissions (see SI, Note 2).

Yet, the removal of chemicals present in small concentrations, or micropollutants (MPs), by wastewater treatment plants (WWTPs) entails additional costs that may be difficult to justify, considering that some of these facilities are already struggling to comply with requirements on conventional pollutants. Therefore, assessing the cost-effectiveness of policies in this field is essential. In this contribution we focus on the effectiveness of MP removal at the regional scale in the European Union (EU), while costs and their optimization are the subject of a companion paper (Pistocchi et al., 2022). Our aim is to scope the level of effort required to address MP and identify plausible scenarios. This means estimation of the change in toxicity corresponding to different levels of wastewater treatment.

The removal of MPs may entail highly specialized processes depending on the target substances (e.g. ion exchange or high-pressure membranes for short-chain perfluoroalkyl substances: Li et al., 2020). However in reality, the most used treatment processes are limited to oxidation with ozone (O_3), adsorption onto activated carbon (AC) and membrane filtration, alone or in various combinations possibly including nature-based solutions for polishing (e.g. Brunsch et al., 2018). When performing to their technical specifications, any of these treatment processes can remove a broad spectrum of substances (Wang et al., 2018, Baresel et al., 2019, Schollée et al., 2021, Pesqueira et al., 2020, Gutiérrez et al., 2021, Rizzo et al., 2019, Gardner et al., 2013), although no process is able to remove all MPs. In this work, we refer to the two advanced treatment solutions most commonly adopted in Europe, O_3 and AC, (Rizzo et al., 2019).

Several studies have addressed the possibilities and limitations of conventional and advanced wastewater treatment to remove a number of contaminants of emerging concern. A few studies have assessed the effect of advanced treatment on the concentrations of representative contaminants in the receiving water bodies. However, to the best of our knowledge no previous research has assessed the effects of implementing advanced urban wastewater treatment on the cumulative toxicity in the receiving water bodies at a European scale. In this contribution, we analyse the implications of different scenarios of advanced treatment at selected European WWTPs. To this end, we calculate the cumulative toxicity of a list of "total pollution proxy" substances detected in wastewater. We propose to estimate the toxicity of the effluents from various levels of treatment, relative to the toxicity of influent (untreated) wastewater, as if it were a single virtual contaminant, or "meta-chemical", subject to removal and dilution. In this way, we can appraise how the requirement of advanced treatment on selected WWTPs can reduce, in relative terms, the cumulative toxic discharges to the environment and the cumulative toxicity of the receiving water bodies at regional scale.

In the following sections, we first illustrate our approach to building indicators of the cumulative toxicity of raw wastewater and to assessing the changes in cumulative toxicity under different scenarios of wastewater treatment. The results suggest the potential and limitations of end-of-pipe MP removal in controlling cumulative toxicity at the EU scale.

2. Materials and methods

In this exercise, we refer to toxicity for ecosystems. Extending our concept to human toxicity is conceptually straightforward, but requires specific considerations beyond the scope of this work.

The toxicity of an individual compound is typically quantified by the compound's concentration divided by a threshold concentration at which a toxic effect is observed, known as the "toxic units" (TU) of the compound. In order to describe the overall toxicity of a mixture of MPs, we assume an additive behavior (Cedergreen, 2014). In principle, we may use a linear additive model (the sum of concentrations normalized by a "reference level of concern") to characterize the toxicity of a mixture, if we know all its compounds. Although simplistic and subject to limitations (e.g. Schuwirth, 2020), this way to describe the toxicity of a mixture of substances usually correlates well with toxicity bioassays, as shown for example for photosynthesis inhibition in algae (Kienle et al., 2019), but also with community effects (Liess et al., 2021).

When the concentration of a compound is divided by a regulatory standard, such as a predicted no-effect concentration (PNEC: ECHA, 2008) referred to the most sensitive organism, rather than an experimentally measured toxic concentration, the ratio is known as "risk quotient" (RQ). A PNEC reflects the precautionary principle as it uses the lowest effect concentration for any organism, and the uncertainty of data through appropriate safety factors: compounds for which we have limited data might have a lower PNEC through a higher safety factor, while highly toxic pesticides with good data might have a higher PNEC. An additive model based on RQ quantifies a "worst case" assuming that all organisms are as sensitive as the most sensitive one. This more protective model is potentially biased and is not expected to necessarily correlate to measurable toxic effects of a

mixture on organisms (for instance, a herbicide is very toxic to algae but may exhibit low toxicity to animals). However, it reflects the deviation of concentrations from a regulatory standard, which we can regard as a "pseudo-toxicity".

Ideally, for the estimation of toxicity with an additive linear model we would need to consider all substances present in untreated wastewater (WWTP influent). As this is effectively impossible, we worked with a list of chemicals representing a "proxy" of the universe of substances of concern.

Our analysis includes the following steps, illustrated below in more detail:

1) Identification of a list of "total pollution proxy" substances (TPPS) that approximate the universe of MPs relevant to wastewater treatment.
2) Assumption of a typical influent (raw) wastewater concentration for each TPPS
3) Estimation of typical TPPS removal from wastewater through conventional treatment
4) Attribution of an expected additional removal due to advanced treatment, for each TPPS
5) Definition of advanced wastewater treatment scenarios and calculation of cumulative toxicity indicators for each scenario.

2.1. "Total pollution proxy" substances (TPPS) and their properties

Unfortunately, there is no straightforward criterion to decide whether a given list of substances is sufficiently representative of all chemicals of concern. We are only aware of the substances that we measure, and any of the many other chemicals present in the technosphere represent "unknown unknowns" of possible future concern (Muir et al., 2019; Menger et al., 2021; Schulze et al., 2019; Alygizakis et al., 2018). We could not identify a "consensus" reference dataset of monitored substances in wastewater, therefore we compiled a list of chemical substances (details in the SI) included in representative monitoring campaigns: the European-wide study by Finckh et al., 2022 and the Dutch WATSON database (http://www.emissieregistratie.nl/erpubliek/erpub/wsn/default.aspx). The list was complemented by additional substances identified on the basis of expert judgment by the authors of this work (e.g. Ternes et al., 2017) or identified as persistent, mobile and toxic (PMT) by the German Environment Agency (Berger et al., 2018), or otherwise regulated by EU water-related legislation (e.g. Van Dijk et al., 2021) if not included already. This led to a list of 1337 substances (or groups of substances), whose details are provided as SI. The list includes several pharmaceuticals and personal care products, substances used in households, metabolites and transformation products, and inorganic substances including metals.

The properties of substances used to describe their fate in WWTPs include the partition coefficient between water and solids, **Kd**, or solids' organic carbon, **Koc** (L/kg); the non-dimensional Henry's law constant, **Kaw** (–); and a biodegradation rate in conventional biological treatment plants, **Kdeg** (h^{-1}).

We compiled measured values of the above properties from the literature for as many substances as possible (see SI). When measured properties were not available, we filled the gaps by *in silico* predictions. For partitioning, we used the ACD-Percepta (https://www.acdlabs.com/products/percepta/) and OPERA (Mansouri et al., 2018) models. When both models provide an estimate, we consider the geometric mean of the two. For substances dissociating as acids or bases, we estimate the acid dissociation constant (Ka) using the geometric mean of the values from both models. We then apply the equations by Franco et al., 2013, as in the SimpleTreat 4.0 model (Struijs, 2014) to estimate Koc from the octanol-water partition coefficient (Kow) for the neutral form of the molecule. The Kow is also estimated with the ACD-Percepta and OPERA models. The non-dimensional Henry's law constant is estimated with the OPERA model alone. For biodegradation, we used the Biowin model included in USEPA's EPISuite (USEPA, 2012). A conventional value of the biodegradation rate was attributed on the basis of the Biowin model results as explained in the SI. The attribution of properties to a relatively long list of substances as considered here entails a significant uncertainty, as further examined in the SI. In principle, we could reduce the uncertainty by referring to a smaller number of better-known molecules. However, in this way we would miss to include many substances of potential concern. There is apparently a trade-off between uncertainty and comprehensiveness in the analysis of mixtures. To avoid missing potentially important substances, we accept a higher uncertainty of which we discuss the implications for policy support.

2.2. TPPS concentration in raw wastewater

MP concentrations in raw wastewater may vary significantly across the EU depending on chemical use patterns, the contribution of industrial emissions to wastewater, the combination of stormwater with wastewater, and several other factors. Despite this, we assume for each substance a representative, uniform concentration in the raw sewage entering the WWTP because this makes a comparison of wastewater treatment scenarios independent of the specific composition of wastewater at each plant. We conventionally attribute a concentration to each substance based on available data including:

- a measurement campaign in the context of the 4th Joint Danube Survey (JDS4, http://www.danubesurvey.org/jds4/about),
- the abovementioned Dutch WATSON database,
- the measurements of the campaign by Finckh et al., 2022,
- concentrations derived from emission estimates available in the European Environmental Footprint 3.0 exercise (Saouter et al., 2020).

Details are provided in the SI. Importantly, the uncertainty affecting the concentration of substances in wastewater may be even larger than the attribution of physicochemical properties (see SI).

2.3. Representation of cumulative toxicity

In this work, we use the following threshold concentrations to estimate mixture toxicity using TUs:

1) The concentration at which a toxic effect is observed for 50 % of the organisms in a test population (EC50) for fish, crustaceans, Daphnia Magna and algae, calculated with the Chemprop model (UFZ Department of Ecological Chemistry, 2021)
2) The hazardous concentration for 50 % of the species (HC50) according to the species sensitivity distributions (SSD) provided in Posthuma et al., 2019a, 2019b, for acute toxicity;
3) The HC50 according to the SSD of Posthuma et al., 2019a, 2019b, for chronic toxicity.

The various EC50 reflect the toxicity of the mixture for specific, although representative, organisms. The HC50 reflects an ecosystem-scale effect. Conceptually, a chronic HC50 would be the most representative indicator to describe long-term effects of MP discharged on a quasi-continuous basis in the environment, while reference to acute toxicity thresholds is expected underestimate the actual risks, because MPs are usually present at concentrations not causing an acute effect.

We also use the minimum predicted no-effect concentration (PNEC) among all known endpoints, according to the NORMAN Database System (https://www.norman-network.com/nds/ecotox; Dulio et al., 2020) to estimate mixture pseudo-toxicity using RQs.

The above (pseudo-)toxicity criteria yield each a different estimation of the mixture toxicity, and of the contribution of individual substances. The variability of estimates is arguably a first approximation of the uncertainty in defining water quality criteria for MPs.

2.4. TPPS concentration in treated wastewater

In order to estimate the concentration of our TPPS in effluents of mechanical and biological treatment, we use the equations of the SimpleTreat

model v. 4.0 (Struijs, 2014). We use **Kd** (or **Koc**), **Kaw** and **Kdeg** as input to compute the fraction of each substance expected to remain in the effluents after mechanical treatment, biological treatment for carbon removal, and biological treatment for nitrogen removal. A WWTP is represented as a combination of a primary settler, a conventional activated sludge (AS) bioreactor and a secondary settler with sludge recirculation, with a sludge retention time (SRT) equal to 3 days for carbon removal, and 14 days for nitrogen removal. The fraction of raw wastewater concentration for the i-th substance that remains after each type of treatment is computed as:

$$\begin{aligned}\eta_{i,I} &= S_I(Koc_i, Kaw_i)\\ \eta_{i,II} &= S_{II}(Koc_i, Kaw_i, Kdeg_i)\\ \eta_{i,III} &= S_{III}(Koc_i, Kaw_i, Kdeg_i)\end{aligned} \quad (1)$$

where S_I is the % of influent concentration found in the primary settler effluent, S_{II} is the % of influent concentration found in the final effluent of an AS plant with SRT = 3 days (sufficient for carbon removal), and S_{III} is the % of influent concentration found in the final effluent of an AS plant with SRT = 14 days (sufficient for nitrification). All the above are computed using SimpleTreat (see Struijs, 2014, for calculation details). While SimpleTreat has been shown to predict MP removal in WWTPs with sufficient accuracy when fed with accurate values of the partitioning and degradation properties (Comber et al., 2019), our calculation is limited by the accuracy of our input data. A comparison with the available data on the removal of the substances in our list showed limited capacity to reproduce individual observed removal rates and removal efficiencies. At the same time, the variability of observed removal for many substances hinders the definition of a representative value on an experimental basis for the purposes of this exercise. Although largely conventional, our calculation is designed to be homogeneous across all substances.

2.5. Additional TPPS removal due to advanced treatment

In principle, the concentration in effluents of advanced treatment can be estimated in a similar way. However, modelling the removal of MP in advanced treatment processes requires the specification of process design and operating conditions at least in general terms, and the estimation of specific kinetic parameters, usually to be determined experimentally (although models for their indirect estimation are being increasingly developed: Lee and Von Gunten, 2016). Here we make use of observed removal efficiencies in advanced treatment. We have compiled this information for as many of the TPPS as we could (see SI), under a set of representative configurations of advanced treatment processes, namely:

(1) ozonation at dosages of less than 0.4, between 0.4 and 0.6 and above 0.6 g O_3 /g DOC, in any case followed by sand (or any other appropriate biologically active) filtration;

(2) Granular activated carbon (GAC), either fresh or after more than 10,000 bed volumes (BV);

(3) ozonation combined with GAC using fresh or preloaded GAC.

For the majority of TPPS this information could not be retrieved, hence we referred to the average of known removal efficiencies (see SI). This is a largely simplified working assumption: in reality, the removal of a substance from wastewater depends on several aspects, including a plant's operational conditions (Fischer et al., 2019). We further assume that biological nitrogen removal is always implemented at a WWTP before advanced treatment. In this way, we estimate the fraction of raw wastewater concentration for the i-th substance that remains after each of the above configurations of advanced treatment as $\eta_{i,\,IV} = \eta_{i,\,III}(1 - \varepsilon_i)$ where ε_i is the corresponding advanced treatment removal efficiency.

2.6. Risk indicators under the different scenarios

Having assumed a uniform concentration in wastewater over the EU for all TPPS and the same removal efficiency for all WWTPs with a given level of treatment, the (pseudo-)toxicity of wastewater depends only on the level of treatment and can be represented by the following "weights":

$$\begin{aligned}w_0 &= \sum_{i=1}^{n}\frac{C_i}{T_i}\\ w_I &= \sum_{i=1}^{n}\frac{C_i}{T_i}\eta_{i,I}\\ w_{II} &= \sum_{i=1}^{n}\frac{C_i}{T_i}\eta_{i,II}\\ w_{III} &= \sum_{i=1}^{n}\frac{C_i}{T_i}\eta_{i,III}\\ w_{IV} &= \sum_{i=1}^{n}\frac{C_i}{T_i}\eta_{i,IV}\end{aligned} \quad (2)$$

In (Eq. (2)):

- w_0, w_I, w_{II}, w_{III}, w_{IV} are the (pseudo-)toxicity of raw sewage and wastewater after mechanical treatment, biological treatment for carbon removal and for both carbon and nitrogen removal, respectively;
- n is the number of TPPS considered. Due to data gaps, n is each time the number of substances for which a concentration and a toxicity threshold are simultaneously available (n < =1337),
- C_i represents the concentration assumed for each substance in raw wastewater,
- T_i the assumed concentration threshold
- the terms $\eta_{i,\,I}$, $\eta_{i,\,II}$ and $\eta_{i,\,III}$ were defined in (Eq. (1)) and $\eta_{i,\,IV} = \eta_{i,\,III}(1 - \varepsilon_i)$.

We can compute a set of weights for each of the 7 concentration thresholds (EC50 for fish, crustaceans, *Daphnia magna*, algae, HC50 for chronic and acute exposure, or PNEC).

Using the (pseudo-)toxicity metrics of (Eq. (2)), we build two indicators, representing (1) cumulative toxic discharge and (2) cumulative toxicity at the catchment scale. In the SI, we present and discuss also an additional indicator of cumulative toxicity at the discharge points of WWTPs.

The indicator of cumulative toxic discharge is computed as the weighted sum of population equivalents (PE) subject to various levels of treatment. In the EU, Member States are supposed to report the population of all urban agglomerations above 2000 PE subject to the various levels of treatment, and the population served by all WWTPs (EC, 2020b).

We account for the PE of agglomerations that are not treated or treated with individual appropriate systems (IAS), such as septic tanks, assumed equivalent to primary level, while we assume the rest of the PE of agglomerations are transferred to a WWTP. We compute the indicator of cumulative toxic discharge with reference to a set of m WWTPs and l agglomerations in Europe (m = 26,681 and l = 27,076 according to EC, 2020b), as:

$$\begin{aligned}L = \sum_{k=1}^{l}(w_I\delta_{I,k} + w_0\delta_{0,k})P_k + w_I\sum_{j=1}^{m}P_j\delta_{I,j} + w_{II}\sum_{j=1}^{m}P_j\delta_{II,j} + w_{III}\sum_{j=1}^{m}P_j\delta_{III,j}\\ + w_{IV}\sum_{j=1}^{m}P_j\delta_{IV,j}\end{aligned} \quad (3)$$

where:

- P_k is the wastewater load, expressed in PE, from the k-th agglomeration;
- P_j the wastewater load in PE, treated by the j-th WWTP;
- $\delta_{0,\,k}$ and $\delta_{I,\,k}$ the fractions of P_k that are untreated or subject to primary treatment, respectively;
- $\delta_{I,\,j}$, $\delta_{II,\,j}$, $\delta_{III,\,j}$ and $\delta_{IV,\,j}$ are Boolean variables equal to 1 if the j-the WWTP provides mechanical, biological carbon removal, biological carbon and nitrogen removal, or advanced treatment, respectively, and 0 otherwise.

The indicator of cumulative toxicity at the catchment scale is a map CT (x,y), accounting for the accumulation of all toxic loads from their point of release along the stream network.

$$CT(x,y) = w_0 \frac{\int_{A(x,y)} P_{0(\xi,\zeta)} d\xi d\eta}{Q_{(x,y)}} + w_I \frac{\int_{A(x,y)} P_{I(\xi,\zeta)} d\xi d\eta}{Q_{(x,y)}} + w_{II} \frac{\int_{A(x,y)} P_{II(\xi,\zeta)} d\xi d\eta}{Q_{(x,y)}} + w_{III} \frac{\int_{A(x,y)} P_{III(\xi,\zeta)} d\xi d\eta}{Q_{(x,y)}} + w_{IV} \frac{\int_{A(x,y)} P_{IV(\xi,\zeta)} d\xi d\eta}{Q_{(x,y)}} \quad (4)$$

where $P_{0(x,y)}$, $P_{I(x,y)}$, $P_{II(x,y)}$, $P_{III(x,y)}$, $P_{IV(x,y)}$ are the wastewater discharges at location (x,y) (expressed in PE) subject to no treatment, mechanical, biological treatment for carbon removal, for nitrogen removal and advanced treatment, respectively, $Q_{(x,y)}$ is the diluting discharge at (x,y), A(x,y) is the drainage area at point (x,y). We account not only for wastewater discharges from WWTPs and from IAS and untreated wastewater in agglomerations based on the data reported at EU scale (EC, 2020b), but also from other European countries not reported under the UWWTD, as well as smaller agglomerations outside the scope of the UWWTD, using the estimates presented in Vigiak et al. (2020). As diluting discharge we consider the estimated annual average flow estimated as in Pistocchi et al., 2019 (see SI). The indicator of (Eq. (4)) is computed at the cells (x,y) of a regular grid of 5 km resolution over Europe in a GIS using standard map-algebraic operations with flow accumulation operators as described in detail in Pistocchi, 2014. The indicator CT(x,y) reflects a steady state, plug-flow model of conservative chemical transport in the stream network. In the SI, we discuss a variant of the indicator reflecting the same model, but adding chemical dissipation along the stream network. Such model can describe also the transport of a specific substance, in which case we can compare results with observations (see SI).

We use the indicators of the cumulative toxicity of TPPS to compare different scenarios of MP removal.

For each urban WWTP in the EU, we consider the present level of treatment (baseline scenario), the level of treatment required by the existing legislation in place (scenario of full compliance with the current Directive 91/271/EEC) and additional scenarios of advanced treatment.

The baseline scenario reflects the level of treatment as reported by the EU Member States based on the data on WWTPs reported by the EU Member States in 2018 (EC, 2020b), referred to the year 2016.

Under a full compliance scenario, WWTPs are supposed to have at least biological treatment, so $\delta_{I,\,j} = 0 \;\forall\, j$. Moreover, all agglomerations are expected to have no untreated discharge, and all individual systems performing up to the standards of a biological WWTP, so $\delta_{0,\,k} = \delta_{I,\,k} = 0 \;\forall\, k$. Under full compliance, all plants discharging in sensitive areas are required to implement nitrogen removal. To this end, we refer to the available maps of sensitive areas (https://www.eea.europa.eu/data-and-maps/data/wise-wfd-protected-areas-1/data-download/wise-wfd-protected-area-under).

The additional scenarios of advanced treatment considered assume that, at the point of discharge in the receiving water body, all WWTPs with a capacity of $P_j \geq X$ and dilution ratio $Q_j \leq Y$ are upgraded with an advanced treatment process. The dilution ratio is the ratio of concentration in the effluents to concentration in the receiving water body, and is conventionally estimated assuming the water body has a background concentration equal to 0. The dilution ratio depends on the water flow (in the case of a freshwater stream) or the hydrodynamic conditions at the outfall (for discharge in coastal waters), and is computed as explained in detail in the SI. We regard the dilution ratio as an indicator of impact in the receiving water bodies (Pistocchi et al., 2018; Büttner et al., 2022).

We explore scenarios corresponding to X between 2000 PE and 1,000,000 PE, and Y between 2 and 100 as well as Y $\rightarrow \infty$ (i.e., no upper limit above which dilution is assumed to be sufficient). Table 1 summarizes the definition of scenarios and how the above assumptions are implemented in the calculation of the toxicity indicators.

3. Results

3.1. Relative toxicity of wastewater after a given level of treatment and corresponding toxicity drivers

Out of the list of 1337 TPPS, about 90 % are covered in terms of physicochemical properties, although usually estimated indirectly (Table 2). However, we could attribute an influent concentration only for 688 of them (51.5 %, Table 2). Substances for which we have both an influent concentration and a (pseudo-)toxicity threshold range from 419 (31.3 %) for chronic HC50 to 602 (45.0 %) for PNEC (Table 2). The 7 (pseudo-)toxicity thresholds considered here seem reasonably consistent with each other, although clearly different in scope and value for a given substance (as further discussed in the SI). We compute the overall (pseudo-)toxicity weights of raw and treated wastewater according to (Eq. (2)) by limiting the summations to those substances for which we have all necessary inputs.

In principle, the weights (Eq. (2)) represent the TU or sum of RQ in wastewater and could be presented in absolute terms: the higher their value, the higher the (pseudo-)toxicity of wastewater. However, for a comparative risk assessment among scenarios, we present the summations normalized through a division by w_0 (Eq. (2)). In this way, the normalized (pseudo-)toxicity of wastewater subject to a given treatment is the percentage of the (pseudo-)toxicity of raw wastewater. Fig. 1 shows the cumulative (pseudo-)toxicity of wastewater after various levels of treatment as a percentage of that of raw wastewater, based on the 7 (pseudo-)toxicity thresholds (chronic or acute HC50, EC50 for fish, algae, *Daphnia magna* and crustaceans, and PNEC) considered here. These change significantly depending on the threshold chosen. In general, weights with EC50 for fish,

Table 1
definition of the scenarios. For symbols, see text except: $\delta_{SA,\,j}$ is the Boolean variable indicating whether the j-th WWTP discharges in a sensitive area requiring nitrogen removal; $\delta_{Nrem,\,j}$ is the Boolean variable indicating whether the j-th WWTP is reported to perform nitrogen removal (irrespective of legal requirements).

Scenario	cumulative toxic discharge indicator, L (Eq. (3))	Catchment scale toxicity indicator, CT (Eq. (4))	Interpretation
Baseline	$\delta_{0,k}$, $\delta_{I,k}$, $\delta_{I,j}$, $\delta_{II,j}$, $\delta_{III,j}$ as reported by EU Member states (EC, 2020b); $\delta_{IV,j} = 0 \;\forall\, j$	$P_{0(x,y)}$, $P_{I(x,y)}$, $P_{II(x,y)}$, $P_{III(x,y)}$ reflect the reported wastewater discharges (EC, 2020b). For agglomerations below 2000 PE, estimates according to (Vigiak et al., 2020). $P_{IV(x,y)} = 0$.	This scenario represents the current conditions
Full compliance	$\delta_{0,k} = \delta_{I,k} = 0 \;\forall k$; $\delta_{I,j} = 0 \;\forall\, j$; $\delta_{III,j} = \max\,[(P_j \geq 10{,}000\ PE) * \delta_{SA,\,j}, \delta_{Nrem,j}]$; $\delta_{II,j} = 1 - \delta_{III,j}$; $\delta_{IV,j} = 0 \;\forall\, j$.	$P_{II(x,y)}$, $P_{III(x,y)}$ reflect wastewater discharges generated outside or inside sensitive areas requiring nitrogen removal, or anyway the presence of nitrogen removal (EC, 2020b). For agglomerations below 2000 PE, estimates according to (EC, 2020b). $P_{0(x,y)} = P_{I(x,y)} = P_{IV(x,y)} = 0$.	In comparison with the baseline, this scenario represents the improvements on toxicity deriving from wastewater treatment, excluding discharges that are untreated or only mechanically treated and implementing nitrogen removal where required.
Advanced treatment	$\delta_{0,k} = \delta_{I,k} = 0 \;\forall k$; $\delta_{I,j} = 0 \;\forall\, j$; $\delta_{III,j} = (1 - \delta_{IV,j}) * \max\,[(P_j \geq 10{,}000\ PE) * \delta_{SA,j}, \delta_{Nrem,j}]$; $\delta_{II,j} = (1 - \delta_{IV,j}) * (1 - \delta_{III,j})$; $\delta_{IV,j} = (P_j \geq X) * (Q_j \leq Y)$.	$P_{0(x,y)}$, $P_{I(x,y)}$, $P_{II(x,y)}$, $P_{III(x,y)}$ as above, after subtracting $P_{IV(x,y)}$. $P_{IV(x,y)}$ is the sum of discharges from plants with $(P_j \geq X) * (Q_j \leq Y) = 1$ within each grid cell.	These scenarios show the change in toxicity that may be expected from different combinations of the X and Y thresholds, in addition to full compliance.

Table 2
Summary of available data.

Calculation inputs	Available	Coverage
# substances considered	1337	100 %
Influent concentration	688	51.5 %
SSD - chronic HC50	419	31.3 %
SSD - acute HC50	542	40.5 %
PNEC	602	45.0 %
EC50 for fish	554	41.4 %
EC50 for crustaceans	554	41.4 %
EC50 for Daphnia m.	554	41.4 %
EC50 for Algae	554	41.4 %
Degradation reported	56	4.2 %
Koc reported	112	8.4 %
Degradation (EPISuite Biowin)	1120	83.8 %
Henry's const.	1179	88.2 %
Koc computed	1179	88.2 %
Reported biological removal	36	2.7 %
Reported removal, 4th stageO3 < 0.4 g/gDOC	52	3.9 %
Reported removal, 4th stageO3 0.4 to 0.6 g/gDOC	141	10.5 %
Reported removal, 4th stageO3 > 0.6 g/gDOC	96	7.2 %
Reported removal, 4th stageGAC fresh	151	11.3 %
Reported removal, 4th stageGAC > 10,000 BV	29	2.2 %
Reported removal, 4th stageGAC + O3	128	9.6 %
Reported removal, 4th stageGAC + O3 (preloaded)	126	9.4 %

Daphnia magna, crustaceans and algae tend to be higher than weights with chronic and acute HC50 for a given level of treatment (Fig. 1). Those with algae EC50 are the highest in all cases. Weights with PNEC are closer to those with the EC50 than with the HC50, and usually match those using a crustacean EC50. The weights drop by around 30 % with mechanical treatment (except with acute HC50 where they drop by 60 %), and by around 70 % with biological treatment. Our modelled removal efficiencies of biological treatment suggest only a small improvement when moving from carbon removal to nitrogen removal. Additional advanced treatment brings wastewater (pseudo-)toxicity further down to less than 10 % of that of raw wastewater, with little variability among treatment processes.

In spite of the variability of the cumulative (pseudo-)toxicity of the effluents with the threshold chosen, the (pseudo-)toxicity of advanced treatment effluents is remarkably constant, always between 0.27 and 0.3 times that of tertiary treatment effluents, irrespective of the threshold (see Fig. 1). This is a consequence of the fact that, for most substances, the removal efficiency of advanced treatment was assumed to be the average of the removal efficiency of the few substances for which observation were available (only 2.2-11 % of substances, Table 1). This is of most practical interest when appraising the benefits of advanced treatment: as all 7 (pseudo-)toxicity thresholds chosen for T_i in (Eq. (2)) tend to yield a similar result, we can simply refer to an "average" set of weights. In order to confirm this statement, we conducted a sensitivity analysis (presented in detail in the SI). The latter indicated that the weights are indeed quite robust with respect to the assumed concentrations and (pseudo-)toxicity thresholds of the TPPS. Based on this evidence, for the calculation of our toxicity indicators, we adopt as weights the average of the medians resulting from the sensitivity analysis (plotted as a continuous line in Fig. 1) for chronic and acute HC50 and PNEC. The assumed weights stipulate that the (pseudo-)toxicity of primary, secondary tertiary and advanced treatment effluents is 65.95 %, 31.48 %, 29.55 % and 7.83 % of that of raw (untreated) wastewater, respectively (see SI for further details).

While the (pseudo-)toxicity of wastewater is reduced roughly in the same way irrespective of the threshold adopted, the substances driving (pseudo-)toxicity change significantly with the threshold. On average, only 20 to 30 % of the substances among the top 20 contributors to (pseudo-)toxicity using one threshold are at the same time among the top 20 contributors using another threshold (Fig. 2). Meanwhile, for a given threshold chosen, the majority of top 20 substances contributing to (pseudo-)toxicity of raw wastewater are also among the top 20 contributors for tertiary and advanced treatment effluents (Table 3), as expected from the assumption on advanced treatment removal efficiencies.

Fig. 3 illustrates these aspects in more detail by showing the list of 97 unique substances (out of the 1337 investigated) appearing among the top 20 contributors to cumulative (pseudo-)toxicity according to the 7 threshold criteria. For each substance, we show the corresponding fractional contribution to cumulative (pseudo-)toxicity based on each threshold, for raw wastewater, biological and advanced treatment effluents. While some substances appear to be relevant under more than one criterion, and their contribution varies only moderately depending on the threshold criteria, most substances appear among the top 20 contributors only for one or two thresholds. When a substance appears among the top contributors only for the PNEC criterion (e.g. Telmisartan), it is possible that the threshold is excessively conservative and should be reconsidered. In any case, changes on a few single substances do not affect the results significantly, as shown by the sensitivity analysis (see SI).

Micropollutants expected to contribute the most to the cumulative toxicity of wastewater include pharmaceuticals and other household chemicals, but also halogenated compounds, metals or inorganic compounds, and polycyclic aromatic hydrocarbons (PAHs). The latter may be an example of substances wrongly identified because of the bias caused

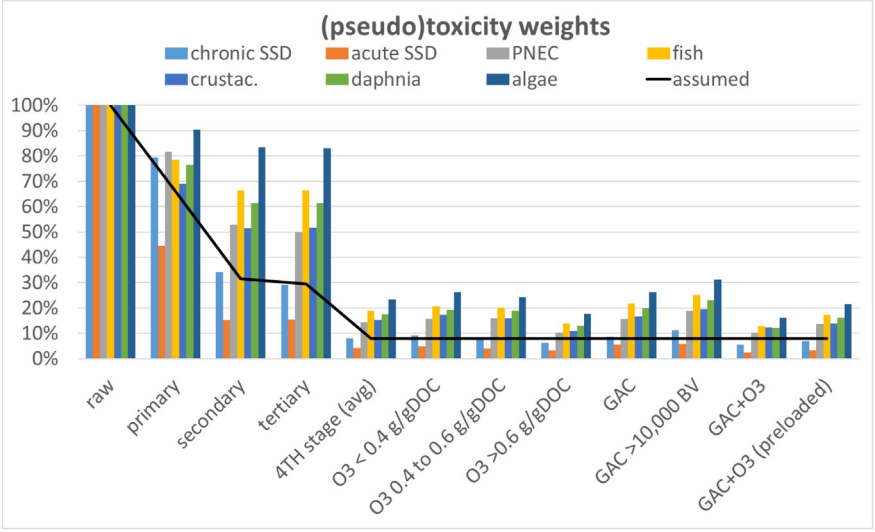

Fig. 1. Toxicity weights of raw and treated wastewater. Chronic = based on EC50 of chronic SSD; Acute = based on EC50 of acute SSD; PNEC = based on the lowest known PNEC; primary = wastewater after mechanical treatment; secondary = after biological treatment for carbon removal; tertiary = after biological nitrogen removal; 4th stage (avg) = average across all different advanced treatment combinations.

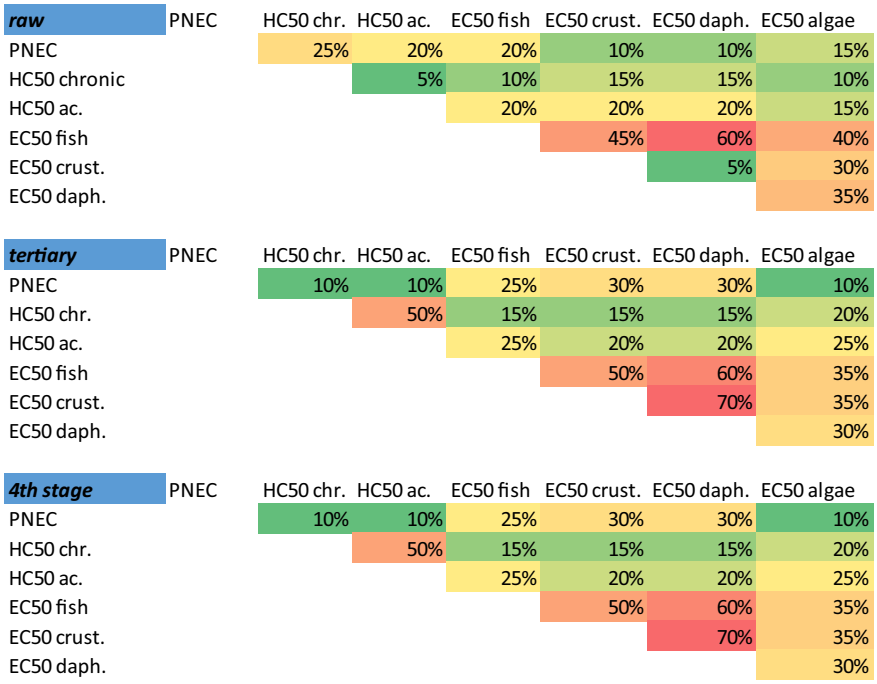

Fig. 2. For a toxicity threshold criterion in a table column and another criterion in a table row, the table displays the % of top 20 substances contributing to cumulative (pseudo-)toxicity of raw wastewater, tertiary effluents and advanced (4th stage) treatment effluents that are the same under the two criteria (chr. = chronic; ac. = acute crust. = crustaceans; daph. = Daphnia magna).

by lack of specific data on removal efficiency, as they are well known to undergo substantial removal e.g. with GAC.

3.2. Risk indicators

Assuming the weights shown in Fig. 1, we estimate the component of the cumulative toxic discharge indicator L (Eq. (3)) due to WWTPs only, under current (baseline) conditions in the EU. This amounts to about 160 million PE. Put another way, the wastewater treatment currently in place discharges the same amount of MPs that would come with the raw (untreated) wastewater of about 160 million PE. Compared to the 517.2 million PE served by WWTPs in the EU (EC, 2020b), this represents about 30 % of the generated pollution.

The cumulative toxic discharge from individual appropriate systems (IAS, term $w_I \Sigma_{k=1}^{l} P_k \delta_{I,k}$ in (Eq. (3))) and untreated wastewater in the agglomerations (term $w_0 \Sigma_{k=1}^{l} P_k \delta_{0,k}$ in (Eq. (3))), is presented separately from the cumulative toxic discharge from WWTPs in Fig. 4. These components correspond to 7.2 and 6 million PE, respectively.

In order to appreciate the contribution of combined sewer overflows (CSO), we assume these discharge 5 % of the annual dry weather flow of all WWTPs as untreated wastewater. This is a largely conservative estimate (see Pistocchi et al., 2019), and gives an upper bound to the contribution of CSO equal to 25.8 million PE (Fig. 4). In reality, the contribution of CSO to the overall cumulative toxic discharge is significant but limited to a few million PE, considering that only a part of the sewer networks is combined, and proper CSO management can reduce the discharges to less than 2 % of the annual dry weather flow (Pistocchi et al., 2019; Quaranta et al., 2022).

Applying (Eq. (3)) to different scenarios, we calculate the change in discharges from WWTPs alone (results shown in Fig. 4). Under a scenario of full compliance with the UWWTD, the cumulative toxic discharge would be reduced only slightly, as a consequence of improving the performance of the non-compliant WWTPs only.

In contrast to the relatively minor reduction of cumulative toxic discharge from baseline to full compliance scenarios, we can obtain significant improvements by setting different WWTP capacity and dilution thresholds in the receiving waters.

Improvements become more apparent when the WWTP capacity threshold is set to X = 100,000 PE or less, and less apparent for a given capacity threshold as we decrease the dilution ratio threshold. For example, if we required advanced treatment for all plants above 100,000 PE, irrespective of dilution, we would reduce the cumulative toxic discharge from about 150 million PE at full compliance to less than 100 million PE. For the same capacity threshold X = 100,000 PE but dilution rate threshold Y = 10, the cumulative toxic discharge would remain above 120 million PE. At the most extreme end, implementing advanced treatment at all plants irrespective of capacity and dilution would reduce the cumulative toxic discharge below 40 million PE. On the contrary, with as low a dilution ratio threshold as Y = 2, we would not achieve a reduction of cumulative toxic discharge below 130 million PE even if we implemented advanced treatment at plants of all sizes. For any plant size X, a dilution threshold Y = 10 represents a situation that is usually mid-way between Y = 2 and requiring treatment at all plants (irrespective of dilution), see Fig. 4.

The maps of indicator CT (Eq. (4)) represent the spatial distribution of (pseudo-)toxicity-weighted concentrations of effluents in freshwater, resulting from the spatial distribution of WWTPs and agglomerations. The rather abstract units of the indicator, (pseudo-)toxicity-weighted PE m^{-3} s, can be interpreted in a more informative way if we assume a certain emission rate per PE. For the sake of illustration, we refer to the example of

Table 3
% of the top 20 substances contributing to cumulative (pseudo-)toxicity that are the same between raw wastewater, tertiary effluents and advanced (4th stage) treatment effluents, for different threshold criteria (chr. = chronic; ac. = acute crust. = crustaceans; daph. = Daphnia magna). Additional details on the substances are provided in the SI.

Comparison	PNEC	HC50 chr.	HC50 ac.	EC50 fish	EC50 crust.	EC50 daph.	EC50 algae
Raw to tertiary	65 %	75 %	70 %	85 %	75 %	85 %	90 %
Raw to 4th stage	70 %	75 %	70 %	85 %	75 %	85 %	85 %
Tertiary to 4th stage	90 %	100 %	100 %	100 %	100 %	100 %	95 %

	raw							tertiary							4th stage						
substance	***PNEC***	***HC50 chr.***	***HC50 ac.***	***EC50 fish***	***EC50 crust.***	***EC50 daph.***	***EC50 algae***	***PNEC***	***HC50 chr.***	***HC50 ac.***	***EC50 fish***	***EC50 crust.***	***EC50 daph.***	***EC50 algae***	***PNEC***	***HC50 chr.***	***HC50 ac.***	***EC50 fish***	***EC50 crust.***	***EC50 daph.***	***EC50 algae***
17-alpha-ethinylestradiol	3.10%							1.22%							1.28%						
17b-Estradiol	1.27%																				
2,2',3,4,4',5',6-heptaBromodifenylether				0.44%	0.14%	0.27%	0.21%														
2,4-D (Dichlorophenoxyacetic acid)	0.75%														0.49%						
2,4-Dichlorophenol					3.89%			0.86%			0.05%	7.24%			0.90%			0.05%	6.98%		
3,5,6-Trichloro-2-pyridinol					0.35%	0.97%						0.61%	1.41%						0.58%	1.40%	
4,4'-Methylene-bis(2-methyl aniline)		0.05%							0.16%							0.18%					
Acetaminophen		0.10%			0.12%	0.65%															
Acetochlor	0.72%						1.58%	1.66%						1.37%	1.74%						1.38%
Al			0.11%																		
Allethrin											0.04%							0.04%			
Ametryn							0.14%							0.10%							0.10%
Amitriptyline		45.52%							85.18%							84.74%					
Anthracene				0.40%			0.12%			0.14%	0.32%			0.07%			0.14%	0.32%			0.07%
Atrazine							0.25%							0.27%							0.47%
Atrazine-desethyl									0.03%							0.06%					
Azinphos methyl				0.06%	0.43%						0.06%	0.48%						0.06%	0.47%		
BDE-209		42.43%	55.79%						4.05%	8.70%						4.48%	9.16%				
Benzidine		0.55%							2.19%							2.42%					
benzo(b)fluoranthene				0.09%		0.06%					0.07%		0.04%					0.07%		0.04%	
Benzo(k)fluoranthene				0.10%		0.06%					0.08%		0.05%					0.08%		0.05%	
Benzo[a]pyrene	0.64%			0.08%				1.92%			0.12%		0.08%		2.02%			0.12%		0.07%	
Benzo[ghi]perylene			0.13%	0.79%	0.25%	0.49%	0.38%		0.12%	1.00%	1.18%	0.48%	0.77%	0.43%		0.13%	1.06%	1.18%	0.46%	0.77%	0.43%
Benzyldimethyldodecylammonium				0.17%		0.11%					0.21%	0.09%	0.14%	0.08%				0.21%	0.08%	0.14%	0.08%
Benzyldimethyltetradecylammonium				0.23%		0.14%	0.11%				0.25%	0.10%	0.16%	0.09%				0.25%	0.10%	0.16%	0.09%
beta-sitosterol			35.57%							62.17%							65.50%				
Bromate		1.25%							0.17%							0.19%					
Caffeine	0.43%	0.28%							0.20%							0.22%					
Candersartan	2.60%							6.99%							7.54%						
Carbendazim				0.07%							0.10%							0.07%			
Chlorfenvinphos												0.09%							0.09%		
Chlorotoluron							0.20%							0.22%							0.36%
Chlorpyrifos			0.14%	2.77%	22.01%	34.69%				0.37%	1.43%	14.25%	18.69%				0.39%	1.43%	13.73%	18.58%	
chrysene											0.05%		0.03%					0.05%		0.03%	
Clarithromycin							0.40%							0.06%							
Cu		0.27%	1.74%																		
Cybutryn (Irgarol)							0.16%							0.18%							0.14%
Diazinon					8.40%	0.61%						7.05%	0.43%						10.11%	0.63%	
Dichlorvos					0.24%	0.68%		0.87%				0.44%	1.06%		0.90%				0.42%	1.05%	
Diclofenac					0.14%																
Didecyldimethylammonium				0.42%	0.14%	0.26%	0.20%														
Difenoconazole						1.14%							0.70%							0.75%	
Diflubenzuron													0.06%							0.06%	
dipyridamol	4.93%							11.40%							11.96%						
Diuron							0.23%							0.24%							0.16%
Dodecyl sulfate				43.11%	24.48%	47.17%	86.72%				60.00%	42.69%	68.46%	90.74%				60.09%	41.15%	68.08%	91.07%
Endosulfan										0.10%							0.10%				
Ethyl azinphos	0.40%			1.59%				0.61%			1.20%				0.57%			1.08%			
Fe			0.04%																		
fenantrene				0.06%							0.03%							0.03%			
Fenthion					2.66%	0.51%		0.65%				4.19%	0.67%		0.68%				4.04%	0.66%	
Fipronil												0.18%							0.20%		
Fluoranthene	13.50%	0.03%	0.35%	46.82%	16.22%	6.63%	1.17%	19.23%	0.07%	1.30%	33.29%	14.45%	4.92%	0.63%	20.18%	0.07%	1.37%	33.33%	13.93%	4.89%	0.63%
Furosemide			0.05%						0.04%	0.37%						0.03%	0.22%				
Galaxolide					0.13%																
Genistein									0.03%							0.04%					
heptachlor	21.82%							11.81%							12.40%						
hexaBromodifenylether				0.07%																	
hexadecaneic acid	1.33%	5.14%	1.20%						1.44%	0.55%						1.59%	0.57%				
Hg			0.09%																		
Imidacloprid					0.31%	0.49%		0.57%				0.57%	0.75%		0.86%				0.79%	1.06%	
Indeno[1,2,3-cd]pyrene				0.48%	0.16%	0.30%	0.23%				0.73%	0.30%	0.48%	0.26%				0.73%	0.29%	0.47%	0.26%
Isoproturon		0.04%					2.10%		0.21%	0.23%				2.34%		0.18%	0.19%				1.83%
Ketoconazole								0.53%													
Metazachlor															0.49%						
Methylchloroisothiazolinone		0.05%	0.25%						0.23%	1.95%						0.33%	2.73%				
Metribuzin																					0.06%
mineral oil										0.10%							0.11%				
Mn										0.11%							0.12%				
Mycophenolic acid		2.95%							2.89%							2.01%					
N,N-Dimethyldodecylamine	0.52%		0.22%				0.50%		0.03%	0.48%				0.16%		0.04%	0.51%				0.16%
N,N-Dimethyldodecylamine N-oxide		0.11%																			
N-Acetyl-4-aminoantipyrine			1.01%							6.45%							4.90%				
Naphthalene				0.49%							0.20%							0.20%			
N-Formyl-4-aminoantipyrine			1.86%							12.27%							9.21%				
Ni			0.05%																		
Nicosulfuron								0.68%							0.71%						
nonylfenol		0.48%	0.06%						2.32%	0.47%						2.56%	0.50%				
oleanolic acid	2.16%	0.09%																			
Pendimethalin							0.35%							0.09%							0.09%
pentachlorobenzene	1.09%							0.78%							0.82%						
perfluorooctane sulfonate (PFOS)	1.00%							2.98%							3.13%						
Permethrin	9.24%	0.04%	0.09%	1.12%	17.15%	2.22%		4.59%	0.03%	0.11%	0.28%	5.33%	0.57%		4.82%	0.03%	0.12%	0.28%	5.13%	0.57%	
Phenazone			0.17%							1.17%							1.01%				
Picoxystrobin		0.06%							0.03%							0.04%					
Piperine		0.05%							0.20%							0.22%					
Pirimiphos-methyl					0.57%							0.43%							0.42%		
Propachlor								0.50%													
Pyrazophos	1.28%							1.77%							1.86%						
Salycilic acid					1.00%	1.92%						0.14%	0.22%						0.13%	0.22%	
Secobarbital										0.13%							0.14%				
Telmisartan	23.09%							19.13%							14.82%						
Terbutryn														0.08%							0.07%
Terbutylazine							0.33%					0.10%		0.21%					0.13%		0.28%
tetradecaneic acid	0.97%																				
Triclosan							3.29%							1.69%							1.62%
Zn		0.16%	0.41%																		

Fig. 3. Contribution, according to different criteria, to cumulative (pseudo-)toxicity of the top contributing substances in raw wastewater, effluents of tertiary treatment and advanced (4th stage) treatment. Colours from yellow to red indicate increasing contribution to toxicity of the mixture (grouped by columns), while green indicates negligible contribution.

diclofenac, a drug commonly considered of concern for which we can assume an environmental quality standard (EQS) of 100 ng/L (Ort et al., 2009; EC, 2012). If we assume an emission rate (ER) of diclofenac equal to 240 ug/day per PE to wastewater (Ort et al., 2009), then values of 1000 or 10,000 or 50,000 PE m^{-3} s correspond to a concentration of about 3 ng/L, 30 ng/L or 150 ng/L, respectively. These concentrations occur with a discharge in the stream network equal to the annual average, and may be higher during low flow, or lower during high flow conditions. Therefore these thresholds may be regarded as discriminating situations where concentrations are:

- low (always safely below EQS: CT <1000 PE m^{-3} s),
- medium-low (below EQS, albeit with lower margins of safety: 1000-10,000 PE m^{-3} s),
- medium-high (usually below EQS but at risk of exceedance in case of low flows: 10,000-50,000 PE m^{-3} s),
- high (usually above EQS: >50,000 PE m^{-3} s).

This categorization is based on diclofenac, and would be valid for any other micropollutant having a similar ratio between ER and EQS. For micropollutants with higher ER/EQS, a lower amount of PE could be conveyed per $m^3\ s^{-1}$ of streamflow before exceeding the EQS, and the other way around for micropollutants with lower ER/EQS.

Fig. 5 shows indicator CT for the two extreme cases of the baseline scenario and the scenario of a dilution threshold Y = 100 and a capacity threshold X = 5000 PE, representing an upper end of the uptake of advanced treatment. While the general patterns do not change in a dramatic way, some differences emerge quite clearly in terms of a reduction of the

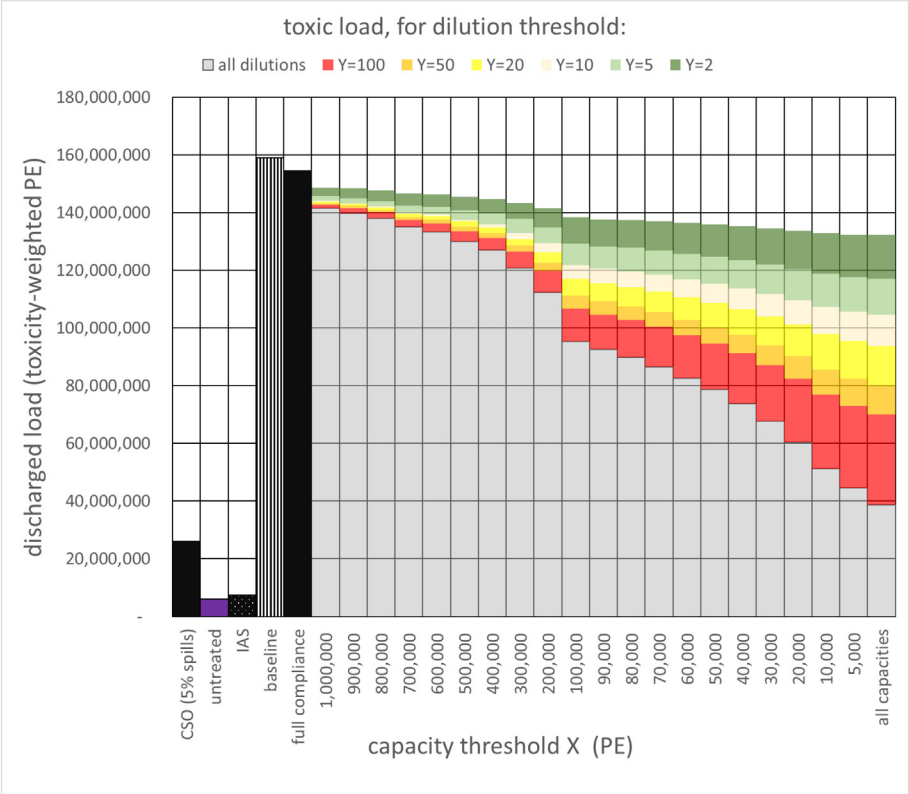

Fig. 4. Impact indicator L (Eq. (3)) under baseline, full compliance and various advanced treatment scenarios.

higher concentrations. Regions with concentrations close to or above EQS, common throughout Europe where population density is high, tend to shift towards low concentrations. This can be more clearly appreciated if we consider the frequency of exceedance of low, medium and high concentrations (Fig. 6): moving from baseline to full compliance and advanced treatment scenarios we can see a systematic reduction of the exceedance of the high (>50,000 toxicity-weighted PE m^{-3} s) and medium-high (10,000-50,000 toxicity-weighted PE m^{-3} s) concentrations. In most cases, these are reduced to medium-low (below 10,000 toxicity-weighted PE m^{-3} s) or even low (<1000 toxicity-weighted PE m^{-3} s) concentrations, with improvements becoming more pronounced with increasing dilution threshold and decreasing population threshold. When advanced treatment is more widespread, medium-low concentrations also tend to shift towards low concentrations.

It is useful to consider an additional "compromise" scenario where we assume that all plants above a capacity X = 100,000 PE undergo advanced treatment irrespective of dilution, while all plants of capacity X between 100,000 PE and 10,000 PE undergo advanced treatment only when dilution is below a threshold Y = 10. This scenario may represent a practical compromise between the need of a widespread implementation of advanced treatment in order to improve the conditions of the receiving water bodies, and the need to limit the burden for smaller plants usually having more limited management capabilities. Fig. 6 shows how this "compromise" scenario performs in a way comparable to the most stringent scenarios in terms of reducing the extent of the stream network with high concentrations, while potentially entailing lower costs. At the same time, the "compromise" scenario is clearly less satisfactory than the most stringent scenarios when it comes to maximizing the extent of the network with low concentrations.

4. Discussion

We have presented indicators of wastewater toxicity at the European scale. The appraisal of wastewater toxicity for the aquatic environment requires an evaluation in absolute terms, e.g. using bioassays (Malaj et al., 2014; Prasse et al., 2015; Altenburger et al., 2015; Brack et al., 2019). The sum of toxic units of a mixture of chemicals is an acceptable proxy for the absolute toxicity and may help identify the chemicals responsible for the observed toxicity. Effluents of biological WWTPs, representing a typical configuration compliant with the UWWTD in the EU, do not undergo monitoring of MPs on a routine basis. The extensive campaign of Finckh et al., 2022 highlights that the sum of toxic units of a list of 499 MPs measured in the in effluents of 53 European WWTPs may exceed risk thresholds (indicating a toxic effect on biological endpoints) in many cases. When present, advanced treatment was found to reduce the sum of toxic units of biological treatment effluents by a factor of 10 or more. In order to quantify the expected effects of advanced treatment on the toxicity of wastewater effluents, here we have computed the toxic units (or risk quotients) for a list of substances that we regarded as a proxy for the total pollution conveyed by wastewater, based on seven toxicity thresholds. We have shown that the sum of toxic units is sensitive to the chosen thresholds. However, the relative toxicity of effluents from different levels of treatment changes only weakly with the threshold chosen. This allows us to define, for each level (mechanical, biological or advanced) of treatment, a "toxicity weight" representing the effluents' toxicity as a percentage of the toxicity of untreated wastewater. From the available information, we have derived a weight of about 0.7 for mechanical treatment effluents, about 0.3 for biological treatment effluents, and less than 0.1 for advanced treatment effluents. In this way, we define a single "meta-chemical" representing the wastewater chemical mixture rather than individual pollutants. We have used the weights to compute the overall toxic discharge and the distribution of toxicity across the whole European stream network for the meta-chemical. We simulate changes in the toxic discharge and the distribution of toxicity under scenarios of advanced treatment, in this way generalizing the findings of Finckh et al., 2022.

The cumulative toxic discharges from WWTPs in the European Union, assuming full compliance with the current legislation, are equivalent to untreated wastewater of about 150 million PE. Under an extreme scenario, this amount could be reduced to less than 40 million PE if all WWTPs have

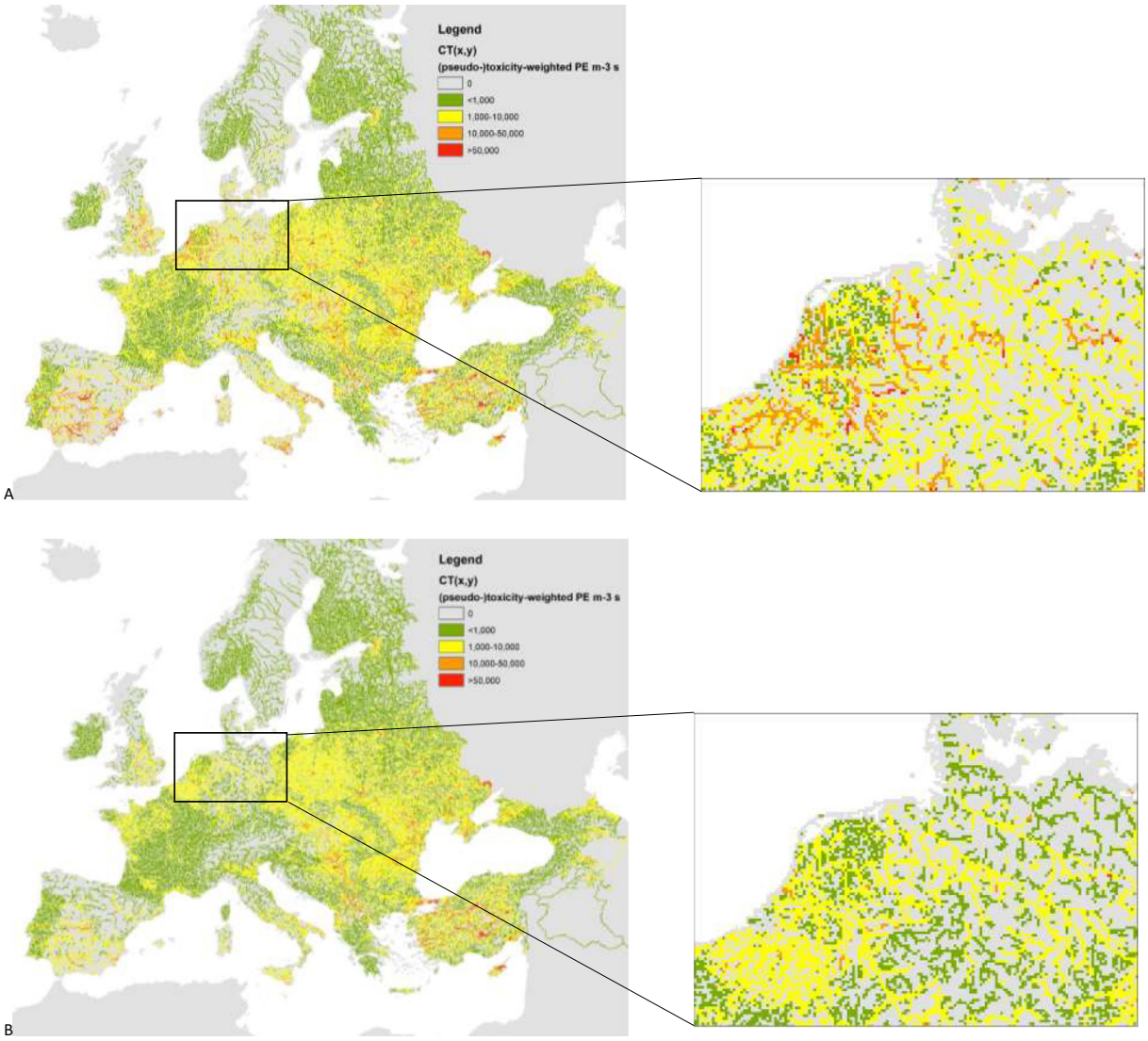

Fig. 5. Example maps CT(x,y): (A) Baseline, (B) scenario of advanced treatment at all plants with any dilution.

an advanced treatment in place for MPs. Under a more moderate scenario, implementing advanced treatment at all WWTPs with a capacity above 100,000 PE would reduce the cumulative toxic discharge to about 95 million PE. Other scenarios, requiring advanced treatment for plants above a given capacity threshold and discharging in a water body below a dilution ratio threshold, may enable similar reductions while targeting situations where toxic impacts are highest. Overall, our analysis shows that a requirement of advanced treatment should be applied at least to plants of 100,000 PE capacity, given the sharp drop in total toxic cumulative toxic discharge when targeting plants with this capacity, while the reduction that can be achieved when targeting only larger plants seems rather limited.

Our "toxicity weights" indicate a higher toxicity of advanced treatment effluents compared to what emerges from the measurements of Finckh et al., 2022, and may owe to the fact that we estimate effluent concentrations based on an assumed removal efficiency of advanced treatment. This is assumed constant for the majority of the substances, due to lack of specific information, and is likely to underestimate the removal of substances that drive the toxicity in the cases considered in Finckh et al., 2022. Weights reflecting more closely the toxic units of Finckh et al., 2022 would magnify the toxicity reduction deployed by advanced treatment compared to our estimate, and would only strengthen the conclusions of our analysis. However, the pattern found here would not change substantially.

The reductions in the overall cumulative toxic discharge are comparable with those identified in studies referred to specific MPs. For instance, Ort et al., 2009, present an assessment for Switzerland targeting two pharmaceuticals (carbamazepine and diclofenac) with defined environmental quality standards (EQS). They find predicted environmental concentrations to exceed the EQS in many cases, but usually not by more than one order of magnitude. They select optimal combinations of measures at specific WWTPs, enabling the non-exceedance of the EQS through a reduction of discharges of the two pharmaceuticals between 30 and 80 %.

Compared to the reduction of cumulative toxic discharge achieved by targeting WWTPs above a threshold, cumulative toxic discharges associated with the population in agglomerations above 2000 PE which are untreated or served by individual appropriate systems (IAS) appear quite small (Fig. 4). In contrast, combined sewer overflows (CSO) may be a significant source of cumulative toxic discharge when not properly managed. Overall, even a complete elimination of these sources of pollution would not achieve a reduction of cumulative toxic discharge comparable to that enabled by implementing advanced treatment on all WWTPs with a capacity of 100,000 PE or more.

Advanced treatment could also bring a sizable and widespread improvement in terms of toxicity at the catchment scale. This is more evident when advanced treatment is required for at least all WWTPs with a capacity of

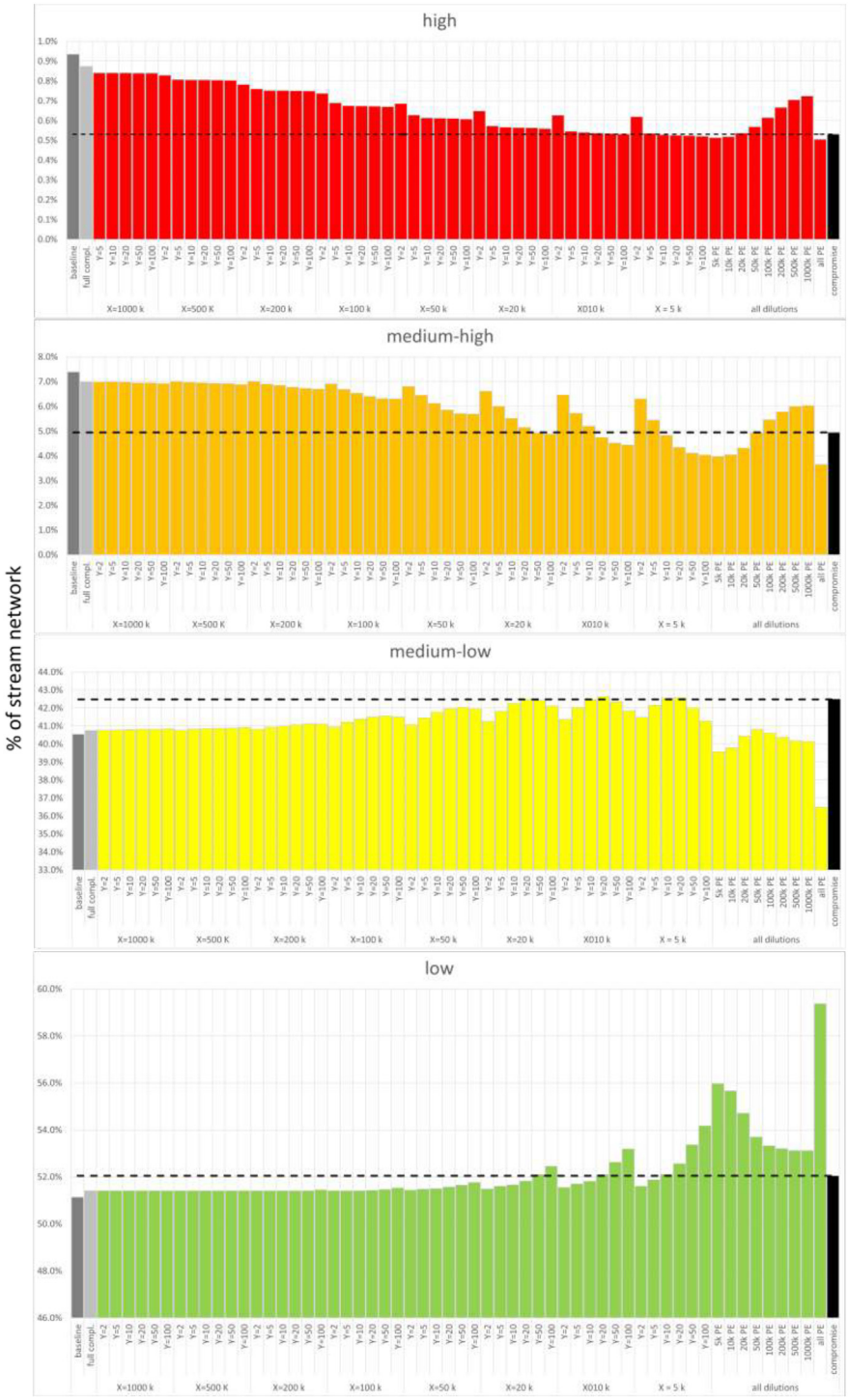

Fig. 6. Frequency distribution of the 4 classes of Indicator CT (high, medium-high, medium-low and low: see text for details) under various scenarios: baseline, full compliance and other scenarios are defined by a capacity threshold X and a dilution threshold Y. Scenarios with advanced treatment for plants above various capacities irrespective of dilution ("all dilutions") and the "compromise" scenario are also plotted for comparison. The scenario with "all dilutions" and "all PE" represents the minimum pollution technically achievable.

100,000 PE or more, and all plants below 100,000 PE but above 10,000 PE discharging with a dilution ratio of 10 or less (Fig. 6).

Our indicators reflect various assumptions that must be regarded critically. First, we compute the relative toxicity of wastewater based on the level of treatment, while we know the effectiveness of treatment may vary to a significant extent depending on the specific operating conditions of a WWTP.

Second, we assume that the universe of pollutants present in wastewater can be approximated by a list of TPPS. Their choice is to some extent arbitrary. We aimed to include virtually all substances that have been flagged as of potential concern for wastewater to date, but we expect that several substances may have been overlooked - because they were not included in the lists reviewed, because they represent "unknown unknowns", or because they are substances not yet identified as a concern.

Third, we assume a uniform and constant concentration of TPPS in raw wastewater, while the substances present in wastewater may vary considerably in space and time, reflecting the specific local use of chemicals. The assumption of a uniform and constant concentration for the TPPSs simply ignores this variability. The concentration that we assume in raw wastewater comes from available measurements, and may not be always representative of the actual concentrations. In addition, we do not account for the potential formation of toxic by-products from the degradation of parent compounds. While the variability of MP concentrations in raw wastewater can be high, the absence of systematic monitoring for most MPs hinders any assessment of a "representative" concentration.

Other practical limitations may have an influence on our results. A (pseudo-)toxicity threshold is not available for all TPPS, hence we ignore a number of potentially relevant substances just because of data gaps. Our estimation of the removal of TPPS depends on a simplified WWTP scheme and assumed values of sorption and biodegradation parameters. For both, an experimental determination is essential and indirect estimates may not be satisfactory. Removal with advanced treatment (oxidation or sorption) requires an even more specific characterization of the substances and is very difficult to predict based on models. We have collected data on the removal efficiency of advanced treatment only for a small percentage of the TPPSs, and therefore our assessment reflects a *de facto* almost constant removal efficiency. This may in principle under- or overestimate the effect of advanced treatment. Evidence from Finckh et al., 2022, suggests that the reduction of effluent toxicity achieved through advanced treatment may be higher than we assume here. The indicator of toxicity at catchment scale (Eq. (4)) neglects the decay of substances in the stream network, in principle causing an overestimation of the impacts. The extent of the overestimation is difficult to assess, because we do not include the variability of influent and effluent concentrations nor other sources of contaminants (such as industrial discharges or urban runoff). Unfortunately, there are few, if any, possibilities to overcome these limitations. For all input data, we have tapped into the most extensive datasets that we could find and, to the best of our knowledge, there is no other readily accessible data source to improve our indicators.

The uncertainties and limitations discussed above are anyway unlikely to significantly affect the conclusions of this study. The toxicity weights of (Eq. (2)) accounting for the relative toxicity of raw wastewater and effluents of mechanical, biological and advanced treatment have proven robust in a sensitivity analysis (see SI), even if the parameters of some single substances are not correct. The toxicity indicators would change significantly only if the toxicity of advanced treatment effluents, relative to that of secondary or tertiary effluents, were much higher than we assume. This would be contrary to the expectations based on Finckh et al., 2022. The indicators provide a way to appraise how more or less stringent requirements for the advanced treatment of wastewater reflect in a reduction of the scale and intensity of the impacts, in a way similar to other holistic and comparative assessments of alternatives, such as life cycle analyses. They aim at an EU scale overview, and arguably hide a nuanced picture with significant variability among European countries and regions. In principle, the development of more systematic monitoring of MPs at WWTPs, and a better understanding of the fate of individual substances in conventional and advanced treatment processes, may lead to more accurate and less uncertain results in future applications of the framework that we propose here.

5. Conclusions

We use indicators of cumulative toxic discharge and toxicity distribution in the stream network to show how the implementation of advanced treatment may yield an appreciable reduction of impacts. The extent of the reduction depends on which plants are subject to advanced treatment, which implies different costs and difficulties. Based on our calculations, advanced treatment at all plants with a capacity of 100,000 PE or more enables a reduction of the overall cumulative toxic discharge of about 40 % with the assumed (pseudo-)toxicity weights. Advanced treatment at all plants with a capacity of 10,000 PE or more, when the dilution in the receiving waters is 10 or less, enables almost a halving of the length of the stream network exposed to high toxicity. A "compromise" scenario taking advantage of the two configurations above may be identified through appropriate optimization methods (e.g. Coppens et al., 2015).

The proposed indicators embed simple concepts of total discharge, dilution and accumulation of toxicity along the stream network, and represent the equivalent of simple mass balances, while reflecting the cumulative effect of a relatively large set of contaminants under the assumption of a linear additive model of toxicity. The relative toxicity of wastewater subject to different levels of treatment shows only a weak dependence on the assumed toxicity thresholds. As such, the indicators may support a cost/effectiveness analysis to define general policy targets of advanced urban wastewater treatment in Europe. This is the subject of a companion paper (Pistocchi et al., 2022) to which the reader is referred for further details.

CRediT authorship contribution statement

Alberto Pistocchi: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing - original draft; Writing - review & editing.

Nikiforos A. Alygizakis: Data curation.

Werner Brack: Conceptualization, Data curation, Validation; Writing - review & editing.

Alistair Boxall: Conceptualization, Data curation, Validation; Writing - review & editing.

Ian T. Cousins: Conceptualization, Data curation, Validation; Writing - review & editing.

Jörg E. Drewes: Conceptualization, Data curation, Validation; Writing - review & editing.

Saskia Finckh: Data curation.

Tom Gallé: Conceptualization, Data curation, Validation; Writing - review & editing.

Marie Launay: Conceptualization, Data curation, Validation; Writing - review & editing.

Michael S. McLachlan: Conceptualization, Data curation, Validation; Writing - review & editing.

Mira Petrovic: Conceptualization, Data curation, Validation; Writing - review & editing.

Tobias Schulze: Data curation.

Jaroslav Slobodnik: Conceptualization, Data curation, Validation; Writing - review & editing.

Thomas Ternes: Conceptualization, Data curation, Validation; Writing - review & editing.

Annemarie Van Wezel: Conceptualization, Data curation, Validation; Writing - review & editing.

Paola Verlicchi: Conceptualization, Data curation, Validation; Writing - review & editing.

Caroline Whalley: Conceptualization, Data curation, Validation; Writing - review & editing.

Declaration of competing interest

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

Acknowledgements

This work was developed in the context of the Blue2 project through an administrative arrangement between the Joint Research Centre and DG Environment of the European Commission.

Appendix A. Supplementary data

Additional information and data are available with this contribution, as supplementary electronic material. Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.scitotenv.2022.157124.

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