Prioritizing Contaminants of Emerging Concern for Ecological Screening Assessments

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More than 40,000 organic chemicals have been identified as contaminants of emerging concern (CECs). Compared to population numbers and national debts, this may not initially appear to be a staggering number; yet, when considering rapid and often unbridled advances in technology, manufacturing, and agricultural practices worldwide—all of which use and then discard waste into the environment—the number takes on more meaning. Even exhaled human breath includes a few hundred volatile organic compounds. Indeed, thousands of organic chemicals are produced or imported annually into the U.S. and other industrialized nations. Furthermore, 40,000 is a conservative estimate that does not account for associated break-down products in the environment.

Many of these chemicals are characterized poorly in terms of their presence in aquatic environments and their potential effects on aquatic wildlife and humans. Certain organic chemicals have been proven harmful to fish, other animals, and perhaps also humans. It remains unclear, however, which

of these chemicals are the worst culprits. Environmental resource agencies such as the National Ocean and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), and the U.S. Environmental Protection Agency (U.S. EPA) spend millions of dollars and considerable effort to monitor concentrations of various organic chemicals that occur in trace amounts in ambient surface waters, sediments, and aquatic animals. Many agencies target what they view as CECs, recognizing that these are generally not new chemicals, yet they are chemicals creating concerns about potential risks to humans and aquatic and terrestrial ecosystems. Examples include pharmaceuticals and personal care products, which enter the environment through our households and wastewater treatment plants that do not yet filter out chemicals completely.

Within the broad category of CECs monitored, however, agencies have widely different definitions as to what a CEC actually is. For example, some researchers consider regulated chemicals such as polychlorinated biphenyls (PCBs) to be CECs, because PCBs purportedly could cause endocrine disruption, an effect for which they are not currently regulated. Others define a CEC as a chemical that is currently unregulated. Clearly, no consensus has yet been reached regarding how to define a CEC; consequently, each agency monitors its own subjective list of chemicals. The lack of a unified definition raises questions about the efficiency of the considerable efforts these agencies are expending. Furthermore, although these agencies monitor chemicals of interest to their individual agendas, attempts to implement

overarching coordination of these monitoring efforts are lacking. This leads to suboptimal estimates of the potential risks these chemicals pose to aquatic biota.

After examining the current status of CEC monitoring efforts, it is apparent that three important issues impede the ability to develop more effective, focused monitoring efforts:

1. Our ability to detect trace levels of certain organic chemicals is far outpacing our ability to understand how these measurements translate into ecological risks.
2. Different organizations work with different sets of chemicals that they identify as CECs.
3. Diagnosing the effects of CECs on aquatic populations and communities is challenging because, by definition, they occur in ecologically relevant trace amounts that are often difficult to detect using standard analytical procedures.

Given the vast number of identified chemicals, simply creating a comprehensive list of CECs suspected to be impacting the aquatic environment would result in an unwieldy list of more than 40,000 substances. Clearly, some type of system to prioritize these chemicals is needed to monitor, assess, and help focus the screening of ecological effects due to CECs.

The Challenge to Prioritize

As a step toward addressing this challenge, we developed a framework (Fig. 1) to help guide efforts to monitor CECs. We first compiled and evaluated data regarding 517 CECs that occur in surface waters in the U.S. and pose potential risks to aquatic biota. Next, we developed three alternative approaches to prioritizing these chemicals [1]. Technical input from several researchers further guided efforts throughout the process. The results of this process, along with other tools developed in the context of this research, will help water resource scientists evaluate sites where CECs may pose a risk and provide a framework to focus future monitoring efforts.

This paper focuses on CECs that currently remain unregulated and are suspected of causing, or having the potential to cause, deleterious ecological effects in aquatic systems. Such effects include decreased reproduction in fish due to endocrine disruption or reduced abundance of invertebrates due to sublethal toxicity. The primary CECs evaluated in this research, therefore, include pharmaceuticals, personal care products, natural and synthetic hormones, surfactants, current-use pesticides, flame retardants, and plasticizers (for definitions of terms, see *Coming to Terms*). Due to the diverse ways CECs can enter surface waters, we did not limit this research investigation to compounds found in wastewater effluents, but also included CECs from other potential sources driven by human activity that affect surface waters, such as concentrated animal feeding, row crop agriculture, and urban stormwater runoff.
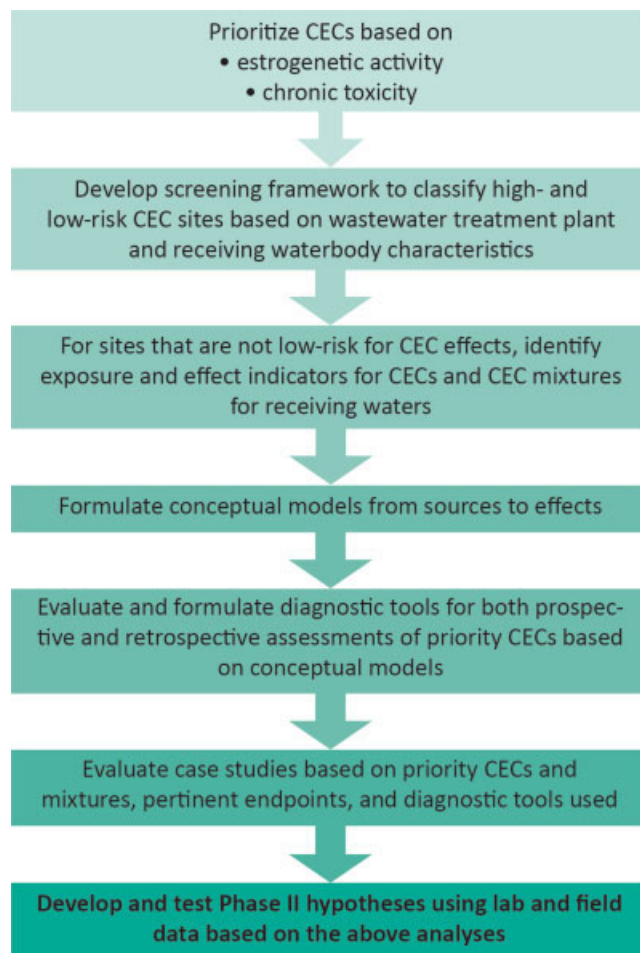

FIGURE 1: General project flowchart used in this research. Prioritizing contaminants of emerging concern (CECs) that present the most potential risk to aquatic life is a first step toward developing tools to screen and assess sites for CEC risk.

Identifying the Greatest Exposure Potential

Environmental programs in the U.S., Canada, and Europe typically focus on high production volume (HPV) chemicals, assuming that chemicals produced in high quantities and used most often are more likely to reach surface waters. Consequently, as the thinking goes, they present a greater risk than chemicals produced in smaller quantities. Many HPV chemicals, however, are unlikely to enter surface water systems, including chemicals produced, degraded, and recycled within a factory. In addition, many environmental resource programs prioritize based on the persistence, bioaccumulation, and toxicity of organic chemicals, known as the PBT approach [2]. The logic behind the PBT approach is that a chemical should be identified as high risk to the environment if it is relatively persistent, tends to bioaccumulate in the tissues of organisms, and is highly toxic at low concentrations. While this approach is appropriate for registering chemicals for production or identifying chemicals for large-scale monitoring, it may be inappropriate for local decision making or to target true risks to aquatic biota. In fact, the approach does not account for the actual detected presence of the chemical in the

environment. Numerous researchers recognize that many CECs with the greatest potency are not necessarily produced in high volume and are therefore not on the HPV list. For example, the synthetic estrogen 17α-ethinylestradiol (EE2), the most commonly prescribed estrogen and widely used in oral contraceptives, does not appear on the HPV list. The European Union (EU) has acknowledged that their chemical screening approach needs to expand beyond HPV chemicals and include low production volume chemicals, many of which might be endocrine disrupting (EDCs) ([3]; http://eceuropaeu/environment/endocrine/documents/final_report_2007pdf).

Given that organizations such as the USGS, U.S. EPA, and the International Joint Commission of the Great Lakes have engaged in fairly extensive monitoring of CECs over the past 10 to 15 years, we feel that it is more useful to base a prioritization framework on occurrence rather than modeled exposure concentrations. An occurrence-based prioritization process should yield a foundational list of CECs for many monitoring programs, particularly those monitoring CECs for the first time.

Prioritizing CECs: Developing a Framework

We reviewed more than 100 studies to find CEC monitoring data in U.S. waters with the aim of developing what we term hereafter as an occurrence database. Emphasis was placed on CEC occurrence data from freshwater systems and effluents, because monitoring data for these media are most readily available. We also sought studies that monitored primarily unregulated organic chemicals. In many cases, these studies also included more commonly monitored and regulated organic chemicals such as PCBs and legacy pesticides such as DDT and dieldrin. Although our occurrence database includes all organic chemicals monitored, the database should not be considered a comprehensive list of currently regulated chemicals.

Developing three approaches

Data in the occurrence database were assembled from an in-depth review of 70 peer-reviewed journal articles and reports that had established data-quality protocols. We checked each study's quality-control methods prior to incorporating data into the occurrence database, but did not evaluate quality-control data in each study, which was beyond the resources of this research. Moreover, we excluded studies that lacked established data-quality protocols, based on challenges in analyzing certain chemicals at low levels. Most observations in our occurrence database were measured in freshwater streams and rivers. Many geographic areas in the U.S. and some in Canada are represented, including both effluent-dominated and non-effluent surface waters. All chemicals monitored in a given study were included in our occurrence database, even if reported as undetected. Similar to the types of groupings other researchers have reported, we
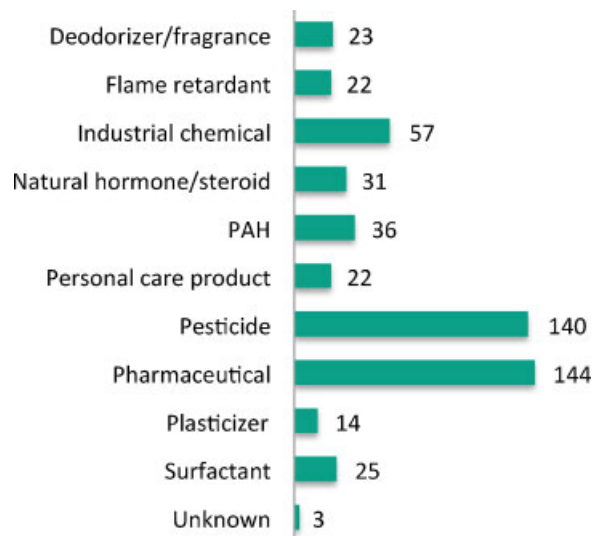

FIGURE 2: Number of different types of contaminants of emerging concern observed in the occurrence database ($n = 517$).

grouped CECs into one of 10 categories: deodorizers and fragrances, flame retardants, industrial chemicals, natural hormones and steroids, polycyclic aromatic hydrocarbons (PAHs), personal care products, current-use pesticides, pharmaceuticals, plasticizers, and surfactants. Most of the 517 CECs in our occurrence database are current-use pesticides, pharmaceuticals, and industrial chemicals (Fig. 2; see Supplemental Data, Table S1 for the list of chemicals). The chemical categorization scheme used here and by other researchers is useful but imprecise because many of the chemicals are used in multiple ways. For example, siloxanes, which are used in perfumes and soaps to make them easier to apply, are categorized as personal care chemicals. They also, however, could equally be categorized as industrial chemicals (defoaming agents).

We employed a screening approach in this research as opposed to a risk-based or probabilistic approach. We chose, therefore, to use maximum rather than median or mean observed concentrations for each CEC. In addition, the literature commonly reported maximum values and less frequently presented median or mean occurrence concentrations. Inspecting several sources of occurrence data assured us that the reported maximum value was typically within an order of magnitude of the median value when sufficient data were available for a given CEC.

Data describing the fate, toxicity, and estrogenic activity of CECs are assembled in the occurrence database from numerous sources. Estrogenic activity has become a routine consideration and a standard indication of sublethal effects because, although many chemicals are not highly toxic, they can have sublethal effects that may not be detected using standard toxicity tests. We compiled fate data (half-life in water, soil, sediment, and air; octanol-water partition coefficient [K_{OW}]; solubility in water; Henry's constant; soil adsorption coefficient; and bioconcentration factors) for CECs from the U.S. EPA's most recent Estimation Programs

Interface Suite (EpiSuite) database (U.S. EPA, http://www.epa.gov/oppt/exposure/pubs/episuitedl.htm) and Persistent, Bioaccumulative, and Toxic Profiles (PBT Profiler) (U.S. EPA, www.pbtprofiler.net).

Effects data for CECs consisted primarily of predicted chronic toxicity thresholds for fish, *Daphnia*, and algae based on quantitative structure–activity relationship (QSAR) models and an estrogenic activity value based on 17β-estradiol (E2) equivalents. We obtained predicted chronic toxicity thresholds from the U.S. EPA's Ecological Structure–Activity Relationships (ECOSAR) (U.S. EPA, http://www.epa.gov/oppt/newchems/tools/21ecosar.htm) and PBT Profiler. Whereas actual toxicity endpoints are available for a small subset of the CECs identified, we did not use them. Instead, the QSAR-based endpoints provided a comparable set of endpoints that could be used across CECs; in general, we found them similar to empirical endpoints when available.

In addition to the 517 CECs in the occurrence database, we also included fate and effects data for an additional 48 HPV compounds with relatively high potential for ecological effects [2]. Including these 48 HPV chemicals provided a way to compare this study's prioritization approach with approaches many environmental resource programs use, but one that does not depend on occurrence information.

Calculating the hazards of CECs

We calculated three hazard quotients for each CEC for which both effects and occurrence data were available. First, we calculated a hazard value (HV) based on predicting the endpoint (i.e., fish, *Daphnia*, or algae) deemed most sensitive to chronic toxicity. Calculating an HV is similar to calculating a risk assessment factor [4]. An HV greater than 1.0 indicates that the maximum observed concentration of the selected CEC exceeds the most sensitive predicted toxicity threshold.

$$\text{Hazard Value} = \frac{\text{Max Occurrence Concentration}}{\text{Lowest Chronic Toxicity Threshold}}$$

To assess the biological effects of the CECs in the occurrence database, we calculated two additional hazard quotients based on estrogenic effects. Details of the calculations can be found in the Supplemental Data. Briefly, for CECs indentified as EDCs in the EU's EDC database, we developed a predicted effect concentration (PEC) and a predicted no-effect concentration (PNEC) based on the CEC's estrogenic activity level and the PNEC and PEC thresholds for EE2 [5,6]. Observed maximum occurrence concentrations and normalized PNEC or PEC values were then used to calculate either a no-effect estrogenic activity hazard value (NEEAHV) or a probable-effect estrogenic activity hazard value (PEEAHV) for each CEC where applicable. Both values are needed to identify the likelihood of estrogenic effects given the maximum CEC concentration.

Contaminants of emerging concern with PEEAHVs of 1.0 or greater could occur at concentrations high enough to adversely affect animals' reproductive systems, such as feminization of male fish or abnormal development in mollusks. We thus considered such CECs to be high priority for risk. Likewise, CECs with PEEAHV of less than 1.0 were considered lower priority.

Three ways to prioritize

Three screening prioritization approaches were examined to address different monitoring objectives: hazard-based, hazard-based combined with persistence and bioaccumulation potential, and PBT. Table 1 summarizes each approach and its advantages and limitations. The hazard-based approach (approach 1) is based on the quotient of the maximum observed concentration for a given CEC divided by its most sensitive predicted endpoint, based on either chronic toxicity or estrogenicity effect. We considered CECs with hazard quotients of greater than 0.10 a high priority for this screening. We deliberately chose a low hazard quotient value in order to include chemicals that could conceivably present an ecological concern, but their potential effect may be underestimated. Such underestimates occur due to either challenges in accurately detecting the chemicals in surface waters or uncertainties regarding their effects based on the predicted effect values used. For example, the maximum concentration for a given CEC in our database may not actually be the true maximum that can occur in U.S. surface waters; therefore, the 0.10 threshold is used to address such instances.

Approach 1 may be useful to wastewater utilities and organizations interested in understanding the relative ecological risk of CECs based on organic chemicals that have been monitored in various national and regional studies. This approach is based in part on observed CEC measurements at many U.S. sites; as a result, it may also provide a starting point for organizations just beginning to monitor CECs based on public concerns or regulatory desires to characterize the potential effects of wastewater discharges. In addition, this approach may be useful as a screening diagnostic tool for assessing specific sites that involve a particular set of CECs (see box *The Hazard-Based Approach in Action*). Knowing the likelihood of potential effects due to CECs could help address public concerns regarding wastewater discharge and inform improvements in wastewater treatment processes.

The other two prioritization approaches relied on scores for risk or toxicity, combined with persistence and bioaccumulation (P + B). Scoring for bioaccumulation and persistence were based on approaches several other organizations have used, including the Oregon Department of Environmental Quality, Environment Canada's Domestic Substances List, and the U.S. EPA's Toxic Substance Control Act. We summed scores based on predicted chronic toxicity or estrogenic activity, bioaccumulation potential, and half-life for each CEC. A maximum score was nine, with high-priority CECs defined as having a score of at least seven. Approach 2 (hazard and P + B) provides a more inclusive list of CECs

Table 1. Advantages and limitations of the three approaches proposed for prioritizing contaminants of emerging concern (CECs)[a]

Approach	Description	Advantages	Limitations
1 Hazard-based	Maximum concentration divided by most sensitive predicted effects threshold (toxicity or estrogenicity) Quotient ≥ 0.10 considered high priority.	Simple to use and communicate. Based on actual measurements of CECs Considers CECs that are known to occur in surface waters Relatively high relevance to ecological risk	Depends on maximum concentrations observed and recorded in occurrence database Does not consider high production CECs not monitored
2 Hazard-based and fate-based (Hazard and P + B)	Sum of effect, bioaccumulation, and persistence scores Effect score based on quotient as in approach 1 Quotient $\geq 0.10 =$ score of 3 (highest priority) Log $K_{OW} \geq 5.0 =$ score of 3. Half-life in water ≥ 180 d $=$ score of 3 Total score ≥ 7 is high priority CEC	Uses effects, bioaccumulation and persistence information for each CEC—addresses fate as well as effects Based on CECs known to occur and that have been measured Relatively high relevance to ecological risk	Dependent on CECs and their maximum concentrations in the occurrence database Does not consider HPV CECs not monitored
3 Toxicity and fate-based (PBT)	Sum of toxicity, bioaccumulation, and persistence scores Toxicity score based on predicted chronic toxicity Bioaccumulation and persistence scores are the same as used in approach 2	Uses widely accepted PBT approach—consistent chemical prioritization approaches used by other agencies Considers high production volume CECs as well as other CECs Does not necessarily depend on occurrence information Capable of identifying CECs that should be evaluated or have methods developed	May include CECs that are unlikely to result in exposure to aquatic biota Based on toxicity effects, not endocrine effects Toxicity thresholds may have high uncertainty for some HPV CECs that do not have QSAR models

[a] CEC = Contaminant of emerging concern; PBT = persistence, bioaccumulation, and toxicity; HPV = high production volume chemical; QSAR = quantitative structure-activity relationship.

than obtained through approach 1, because bioaccumulation potential and persistence were added. Chemicals of emerging concern with the maximum score (nine) should be high priority, because they are known to occur at concentrations that potentially exceed toxicity or estrogenic thresholds. Furthermore, they are highly bioaccumulative and thus have the potential to affect upper trophic levels. They are also highly persistent, suggesting that they have the potential for long-term exposures. Approach 2 may be useful for organizations concerned primarily with CECs that pose a potential ecological risk based on known occurrence, yet need a more comprehensive estimate of that risk, such as fate effects and ecological risk. This approach could also be useful as a site-specific, screening diagnostic tool.

Approach 3, the PBT prioritization approach, is similar to approach 2 (hazard and P + B), except it does not rely on observed CEC concentrations or hazard quotients based on occurrence data. Instead, approach 3 is based on predicted toxicity values obtained from the ECOSAR and PBT profiler, or the inverse of the NEEAHV or the PEEAHV. This approach was used to evaluate an additional 48 HPV chemicals for which limited information regarding the likelihood of occurring in wastewater or surface waters was available. Thus, using approach 3, a CEC could be scored as high priority but may actually never occur (or cannot occur in surface waters, due to the way the chemical is used) at concentrations that would cause chronic toxicity or endocrine disruption in effluents or surface waters because of the way the chemical is used. With approach 3, a high-priority chemical is one that received a total score of at least seven. Organizations concerned primarily with the potential risk of CECs that might occur in wastewater streams or surface waters (for example, chemical manufacturing companies) may find approach 3 valuable. Approach 3 may also be useful to organizations concerned with the occurrence and risk of CECs that are not currently monitored but should be.

The Hazard-Based Approach In Action

Measuring relatively few high-risk CECs could help a wastewater treatment plant (WWTP) or regulatory agency prioritize a specific site's need for more definitive monitoring and diagnostic studies. For example, we found a WWTP in Canada that is potentially responsible for contributing to observed estrogenic effects on natural fish populations in a stream, based on measurements of a subset of priority CECs identified using the hazard-based approach. Specifically, observed concentrations of nonylphenols, estradiol, and estrone were more than double the probable effect endocrine activity hazard value (PEEAHV) based on estradiol equivalents.

At another WWTP we examined using the hazard-based approach, the effluent had very low concentrations for 26 of the 41 high-priority CECs, and total estradiol equivalents less than the no effect endocrine activity hazard value (NEEAHV). Although the remaining 15 high-priority CECs were not measured at this facility, they did measure many with the greatest potential risk. Knowing that most of the high-priority CECs were not detected suggests that this WWTP may not be a source of biological impairment due to CECs. This suggestion has been corroborated by fish population studies at this site, which thus far indicate normal sex ratios and a high measure of biotic integrity [1].

The three prioritization approaches presented here have different advantages and limitations (Table 1). The hazard-based approach (approach 1) is relatively simple to use and easy to communicate to the public; however, it is influenced by the maximum CEC concentration reported, which could change over time. Approach 2, which combines the hazard-based approach with measures of fate and bioaccumulation potential, is somewhat less influenced by the maximum concentration reported for CECs. This approach, however, may overlook certain CECs that are neither persistent nor highly bioaccumulative, but are of potential ecological concern because they continually enter surface waters from various sources (for example, nonylphenols being discharged in treated wastewater). The PBT approach (approach 3) does not depend on CEC concentrations reported in the environment and could be used to identify high-priority chemicals that have not been examined in surface waters thus far [2]. As noted, this could also be a disadvantage, because chemicals may be identified as high priority and yet may be unlikely to occur in surface waters. We do not consider one approach to be superior to the others in all cases; each has its strengths and limitations and satisfies different monitoring objectives.

Comparing Results Across the Three Approaches

As expected, the number and types of CECs identified as high priority clearly differ with the three prioritization approaches (Supplemental Data, Table S1). Approach 1 yielded the lowest number of high-priority CECs (41), whereas approach 3 yielded the most (108). All three approaches collectively identified a total of 126 unique CECs as high priority. Twenty-five CECs were consistently indicated as high priority across all three approaches (Supplemental Data,
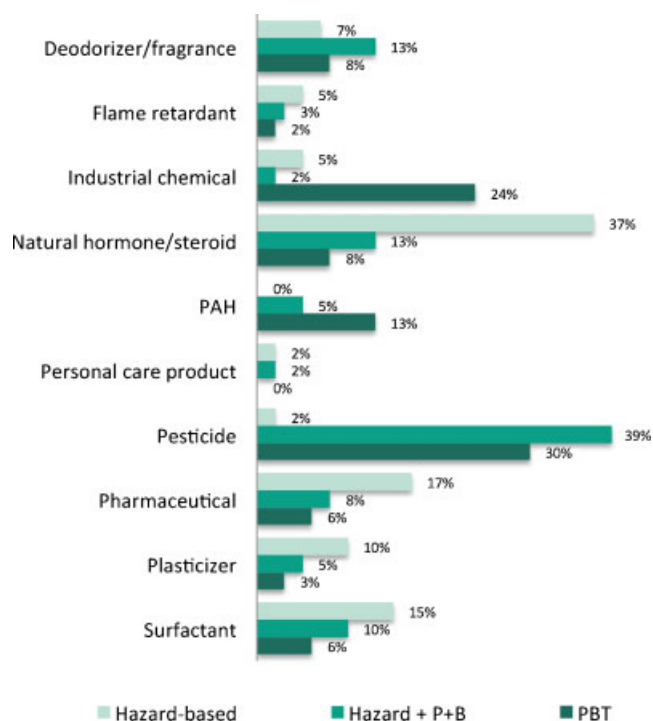

FIGURE 3: Percentage of different types of high-priority contaminants of emerging concern observed using each of the three prioritization approaches ($n = 41, 60$, and 108 for approaches 1, 2, and 3, respectively). Approach $1 =$ Hazard-based; approach $2 =$ Hazard $+ P + B$; approach $3 = $ PBT.
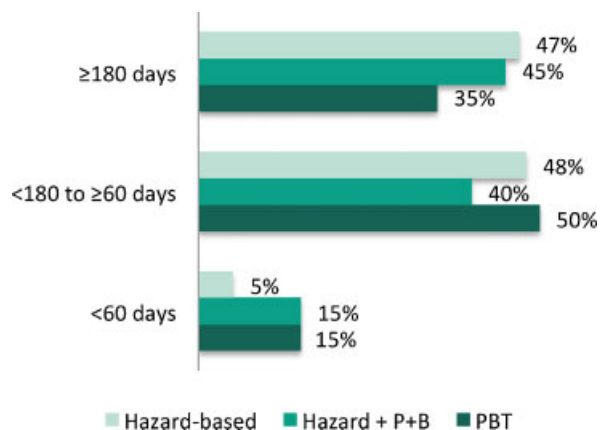
FIGURE 4: Percentage of different chemical persistence categories observed for high-priority contaminants of emerging concern identified using the three different prioritization approaches.

Differences in chemical persistence

The difference in high-priority CECs across the three approaches is exemplified by the chemical persistence observed for aquatic systems. Nearly half of the high-priority CECs using hazard-based approach 1 had relatively low persistence (half-life < 60 d), whereas approaches 2 and 3 (in which persistence was a prioritization factor) had 85% of CECs with half-lives > 60 d and 35 to 45% with half-lives > 180 d (Fig. 4). This comparison shows that chemical persistence alone may not always indicate CEC risk in aquatic systems. Many researchers note that some CECs may be frequently or continuously supplied to water bodies (through treated wastewater discharges, for example), resulting in fairly consistent exposure of organisms to chemicals, despite the fact that they are known to dissipate quickly in surface waters.

Table S1). Figure 3 shows the categories of CECs identified as high priority for each approach. High-priority CECs based on approach 1 consisted primarily of natural hormones and steroids, pharmaceuticals, and surfactants, in descending order of importance. Approach 2 was composed mostly of pesticides, natural hormones and steroids, and fragrances. Approach 3 yielded a very different list because the HPV CECs were not in the occurrence database. Pesticides comprised the majority of the high-priority CECs using approach 3, followed by industrial chemicals, and then PAHs.

Twelve high-priority CECs identified by both approaches 1 and 2 appear to be monitored infrequently based on occurrence information we compiled (Table 2). These CECs were generally not monitored by many of the larger monitoring studies, even though their potential effects may be likely at the concentrations some studies reported in surface waters. Given the high bioaccumulative potential or persistence of many of these CECs, future monitoring studies should certainly consider analyzing them. Accurately measuring these and other high-priority CECs identified in this study is critical for determining the extent to which they occur in surface

Table 2. Contaminants of emerging concern that have been rarely monitored in U.S. waterbody assessments thus far[a]

Chemical	Application	Primary use
3-Methylcholanthrene	PAH derivative	By-product of burning organic compounds such as coal; used in research to induce cancers
4-Nonylphenol diethoxycarboxylate	Surfactant	Degradation product of nonylphenol used in pesticide formulations, industrial detergents, and other products
4-Nonylphenol monoethoxycarboxylate	Surfactant	Degradation product of nonylphenol used in pesticide formulations, industrial detergents, and other products
Acetyl cedrene	Fragrance	Widely used in perfumes
Benfluralin	Pesticide	Used to control grasses and other weed species on lawns and various crops under the trade name Balan
Celestolide	Fragrance	A type of musk used as a fragrance ingredient in many personal care products such as cosmetics
Clotrimazole	Pharmaceutical	Anti-fungal drug used in many products such as Lotrimin
Di-*N*-octyl phthalate	Plasticizer	Primarily used in production of plastics to impart flexibility. Used in products such as Celluflex and Uniflex
Musk xylene	Fragrance	A type of musk used as a fragrance in perfumes and other products
Novobiocin	Pharmaceutical	An antibiotic sold under several trade names such as Albamycin and Cathomycin
Oryzalin	Pesticide	A herbicide used to control crabgrass and other weeds. Registered under the trade names Surflan, Ryzelan, and others
Octahydro-tetramethyl-naphthalenyl ethanone	Fragrance	Perfume used in cosmetics and marketed under the name Iso-E-Super

[a] These were identified as high priority based on hazard (approach 1) or hazard + persistence and bioaccumulation (approach 2).

waters and the degree to which they may be of ecological concern. As a step toward facilitating these additional monitoring studies, many research efforts are underway to provide robust, commercially available methods to reliably analyze low levels of many CECs.

Toxicity versus estrogenic effects

The biological effect values used in approaches 1 and 2 show that the most sensitive predicted chronic toxicity threshold to fish, *Daphnia*, or algae is more sensitive than the estrogenic activity-based threshold for all but 12 high-priority CECs. The CECs for which estrogenic activity thresholds are more sensitive (and therefore used instead of toxicity thresholds in the hazard quotient) included 17α-estradiol, E2, EE2, bisphenol A, estriol, estrone, equilenin, mestranol, methoxychlor, norethisterone, tamoxifen, and testosterone. These results may not be surprising, given that most CECs have purportedly weak estrogenic activity, if any. Still, they may be chronically toxic at relatively low concentrations compared to the maximum occurrence concentrations reported in the literature. It is important to recognize, however, that other potential endocrine effects exist besides estrogenic disruption (e.g., thyroid disruption effects), and these cannot be readily characterized for CECs given the current state of knowledge. Even characterizing estrogenic potential for CECs based on in vitro assays (for example, the yeast estrogen system [YES] assay), is not completely known, as many researchers [7] have noted. It is expected, therefore, that hazard quotients will be refined as new information is collected.

Identifying High-Priority Pharmaceuticals

Many of the CEC monitoring studies evaluated for this research focused entirely or partly on pharmaceuticals. Our results, however, yielded only a few pharmaceuticals of high priority using all three prioritization approaches. Based on predicted toxicity or estrogenic activity, many commonly monitored pharmaceuticals do not appear to pose a risk to aquatic biota, based on current information. This is also the case for many of the pharmaceuticals identified as high priority in Kostich and Lazorchak's landmark study [8]. Of the 50 pharmaceuticals they identified as the highest risk to aquatic life (based on predicted non-human exposure concentrations and effects on biological systems) 26 appear in our occurrence database. Only four of these compounds (EE2, 17α-estradiol, E2, and estriol), however, were identified as high priority based on the three prioritization approaches. Approach 1 identified five pharmaceuticals as high priority when accounting for actual occurrence in surface waters (norethisterone, mestranol, novobiocin, fenoprofen, and tamoxifen); notably, none of these were identified in Kostich and Lazorchak's top 50. These results illustrate that different CECs may be identified as chemicals of concern depending on whether *predicted occurrence* (approach 1) or *predicted effects* information (the current standard procedure) is used.

Additional Considerations

This research takes only the initial step toward creating a more efficient prioritization approach for ecological screening assessments based on actual measured occurrences of CECs in surface waters. Additional concerns regarding exposure duration and mixture effects when assessing CECs, however, are evident. The typical mode of action for CECs requires long-term exposures and often a chain of organism- and population-level effects before changes in the aquatic community are likely to be detected. Researchers have acknowledged that a multifaceted approach is needed to address these challenges, using a set of tools to characterize CEC exposure and effects at different biological levels: suborganism, organism, and population. This research suggests that potential or actual effects of CECs on aquatic communities can be identified using a diagnostic framework that incorporates exposure and effects at these different levels in conjunction with the hazard-based prioritization approaches we have developed here.

All three approaches are similar to the chemical-by-chemical approach used by various water resource agencies to assess the risk of commonly monitored chemicals, such as metals and legacy pesticides. Chemicals of emerging concern, however, do not generally occur in isolation in surface waters, but rather as mixtures, often in the presence of more common pollutants and other environmental stressors. Therefore, the extent to which the environment can be protected when evaluating effects based on an individual chemical approach is questionable. Many monitoring studies have shown that several CECs may occur together from a single source or at a site [9,10], and several laboratory studies have demonstrated the additive effects of certain types of CECs, such as estrogenic hormones [11]. These results indicate that although a chemical-by-chemical approach may be acceptable for developing screening hazard quotients and prioritizing CECs that pose the greatest risk to aquatic biota, actual site assessments and diagnostic tools must also consider the cumulative risk of the mixture of all CECs present.

Supplemental Data

Calculating hazard quotients to assess biological effects. (25 KB DOC).

Table S1. Contaminants of emerging concern occurrence database. (82 KB.XLS).

Coming to terms...

17α-Ethinylestradiol (EE2)—A synthetic estrogen.

17β-Estradiol (E2)—Natural estrogen hormone that occurs in mammals.

Contaminant of emerging concern (CEC)—A chemical for which there are increasing concerns regarding its potential risks to humans and ecological systems, including endocrine disruption and neurotoxicity. Within the broad category of CECs monitored, however, agencies have widely different definitions as to what a CEC actually is.

Current-use pesticides—Chemicals, including herbicides, insecticides, and fungicides, that are used to control agricultural pests and are currently approved for use in the U.S. Some pesticides are potential endocrine disruptors.

Deodorizers and fragrances—Subset of chemicals often used in personal care products that include musks and other natural or synthetic substances. Some deodorizers and fragrances demonstrate endocrine-disrupting potential to aquatic life.

Ecological Structure–Activity Relationships (ECOSAR)—Software program maintained by U.S. EPA that is used to estimate the toxicity of chemicals.

Flame retardants—Chemicals that improve the fire resistance of consumer-use products such as clothing, furniture, and electronics. Examples include polybrominated diphenyl ethers (PBDEs), which have been shown to disrupt the brain and nervous system, reproduction, and endocrine systems.

Henry's constant—A constant (k_H) that represents partial pressure of a solute divided by the concentration of the solute ($k_H = p/c$).

High production volume (HPV) chemicals—The U.S. EPA defines HPV as follows: "Under the High Production Volume (HPV) Challenge Program, companies were 'challenged' to make health and environmental effects data publicly available on chemicals produced or imported in the United States in the greatest quantities. HPV chemicals are classified as those chemicals produced or imported in the United States in quantities of 1 million pounds or more per year. As of June 2007, companies sponsored more than 2,200 HPV chemicals, with approximately 1,400 chemicals sponsored directly through the HPV Challenge Program and over 860 chemicals sponsored indirectly through international efforts" (U.S. EPA, http://www.epa.gov/hpv/).

Industrial chemicals—Substances used primarily in industrial processes to make or refine products such as solvents and stabilizers, which make other chemicals more amenable to a particular manufacturing process. Most of these chemicals are registered under the Toxic Substance Control Act (TSCA) in the U.S. and similar programs in other countries. Some of these chemicals, such as dyes, adhesives, and solvents, can be toxic to aquatic life.

Natural hormones and steroids—Chemicals that are produced naturally by plants or animals and consist of complex organic structures found in reproductive hormones such as estradiol or testosterone, as well as dietary compounds such as cholesterol. Many of these compounds have endocrine-disrupting potential for aquatic life.

Nonylphenols—Group of chemicals used as industrial surfactants, including paints, plastics, rubbers, adhesives, lubricating oils, and cleaning agents. Nonylphenols may be endocrine disruptors and persist in the environment.

Octanol–water partition coefficient (K_{OW})—Ratio of a chemical's concentration in octanol and water, often used to indicate chemical fate.

Personal care products—Chemicals designed for consumer use that are non-medicinal, such as coloring and anti-bacterial agents used in lotions and soaps.

Pharmaceuticals—Chemicals used in prescription and over-the-counter medications.

Plasticizers—Chemicals added to plastics to improve flexibility. Examples include phthalates, which have been shown to disrupt the brain and nervous system, reproduction, and endocrine systems.

Polychlorinated biphenyls (PCB)—Organic compounds used for industrial purposes including as insulating fluid in electric systems and plasticizers, until U.S. production was banned in 1979. PCBs have endocrine-disrupting and neurotoxic effects.

Polycyclic aromatic hydrocarbons (PAHs)—Chemicals produced usually as a result of combustion byproducts originating from vehicle exhaust and fossil fuel spills or atmospheric releases. Many PAHs have been shown to be toxic to aquatic life or carcinogenic to mammals.

Predicted chronic toxicity threshold—Concentration of a chemical, derived from toxicity models such as ECOSTAR, at which long-term effects on organisms are possible.

Probable effect concentration (PEC)—Concentration of a chemical at which effects on some organisms are likely.

Probable no-effect concentration (PNEC)—Concentration of a chemical below which effects on organisms are very unlikely.

Quantitative structure–activity relationship (QSAR) model—Model used to predict toxicity based on the structure of the particular chemical.

Siloxanes—Chemicals widely used in cosmetics such as deodorants and soaps, as well as other products, to help them dry more quickly and make them easier to apply.

Surfactants—Chemicals that lower the surface tension of the medium to which they are applied, or the interface between two media (air and water, water and grease, etc.). Commonly used in detergents, foaming agents, and dispersants.

Yeast estrogen screen (YES) assay—In vitro test to detect estrogens and estrogen-like chemicals in water, using yeast cells that have been genetically modified to include a human estrogen receptor. If present, estrogens or estrogen-like chemicals in the sample will bind to the receptors, and a series of chemical reactions eventually produce a detectable color change that indicates the presence of estrogenic compounds.

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