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The Challenge of Micropollutants in Aquatic Systems

René P. Schwarzenbach *et al.*

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that address water challenges (*35*) and to make sure that scientists understand what kinds of knowledge are required by policy-makers and by society at large.

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REVIEW

The Challenge of Micropollutants in Aquatic Systems

René P. Schwarzenbach,* Beate I. Escher, Kathrin Fenner, Thomas B. Hofstetter, C. Annette Johnson, Urs von Gunten, Bernhard Wehrli

The increasing worldwide contamination of freshwater systems with thousands of industrial and natural chemical compounds is one of the key environmental problems facing humanity. Although most of these compounds are present at low concentrations, many of them raise considerable toxicological concerns, particularly when present as components of complex mixtures. Here we review three scientific challenges in addressing water-quality problems caused by such micropollutants. First, tools to assess the impact of these pollutants on aquatic life and human health must be further developed and refined. Second, cost-effective and appropriate remediation and water-treatment technologies must be explored and implemented. Third, usage and disposal strategies, coupled with the search for environmentally more benign products and processes, should aim to minimize introduction of critical pollutants into the aquatic environment.

About one-fifth of the world's population does not have access to safe water, and two-fifths suffer the consequences of unacceptable sanitary conditions (*1*). Pathogens in water cause more than 2 million deaths annually; most are children under the age of 5. The increasing chemical pollution of surface and groundwaters, with largely unknown long-term effects on aquatic life and on human health, could easily lead to a problem of similar or even greater magnitude. More than one-third of the Earth's accessible renewable freshwater is used for agricultural, industrial, and domestic purposes, and most of these activities lead to water contamination with numerous synthetic and geogenic compounds (Table 1). It therefore comes as no surprise that chemical pollution of natural waters has already become a major public concern in almost all parts of the world.

Industry and municipalities use about 10% of the globally accessible runoff and generate a stream of wastewater, which flows or seeps into rivers, lakes, groundwater, or the coastal seas (*1*). These wastewaters contain numerous chemical compounds in varying concentrations. About 300 million tons of synthetic compounds annually used in industrial and consumer products partially find their way into natural waters (Table 1). Additional pollution comes from diffuse sources from agriculture, where 140 million tons of fertilizers and several million tons of pesticides are applied each year (*2*). In the European Union, for instance, there are more than 100,000 registered chemicals, of which 30,000 to 70,000 are in daily use (EINECS, European Inventory of Existing Chemical Substances). The input of 0.4 million tons of oil and gasoline components through accidental spills represents yet another important source of water pollution. Other notable sources of contamination are the intrusion of salty water into groundwater due to overexploitation of aquifers; the human-driven mobilization of naturally occurring geogenic toxic chemicals, including heavy metals and metalloids (Table 1); and the biological production of toxins and malodorous compounds.

To date, an effective and sustainable global strategy against this insidious and mostly unseen contamination of aquatic environments barely exists. Source controls and technical systems, such as wastewater treatment plants, function as partial barriers, particularly in highly industrialized countries, but major challenges remain. The source, behavior, and treatment of the relatively small number of macropollutants (*3*) such as acids, salts, nutrients, and natural organic matter, occurring at μg/liter to mg/liter concentrations, are relatively well understood: High nutrient loads can lead to increased primary production,

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oxygen depletion, and toxic algal blooms. In such cases, the challenges are to predict ecosystem responses, to optimize treatment technologies, and to develop integrated policies at the scale of river basins (*4*).

It is far more difficult to assess the effect on the aquatic environment of the thousands of synthetic and natural trace contaminants that may be present in water at low to very low concentrations (pg/liter to ng/liter) (*5*, *6*). Table 2 illustrates a range of micropollutants of possible toxicological concern. These chemicals have been found ubiquitously in natural waters in the past 25 years, not only in industrialized areas but also in more remote environments. Some chemicals are not degraded at all (e.g., heavy metals) or only very slowly (e.g., persistent organic pollutants such as DDT, lindane, or polychlorinated biphenyls). They can therefore be transported via water or air to locations hundreds or even thousands of miles away from their source (*7*, *8*). Those compounds that are less persistent and not prone to long-range transport may still be of concern if they are continuously emitted or form problematic (bio)transformation products (*9*, *10*). Examples of this category include hormones and drugs, or persistent degradation products of surfactants such as nonylphenol.

Assessing the impact of micropollutants in aquatic systems is a formidable task requiring improved analytical and modeling tools to probe the distribution, bioavailability, and biological effects of single compounds and of chemical mixtures. Methods to classify existing and new chemicals on the basis of their potential to harm humans and the environment must also be refined. Mitigation technologies to reduce the impact of micropollutants, as well as strategies to minimize their introduction into the environment, require further development. A complementary approach is the advancement of "green" chemistry, which entails design of more environmentally friendly industrial processes and more benign products.

Here we review the scientific challenges in addressing these issues. We frame the concerns primarily from an environmental-protection perspective with a focus on aquatic ecosystems, but without neglecting the human health issues. Protecting natural waters against chemical pollution safeguards aquatic life and thus, directly

Table 1. Dimensions of water problems: water use and macro- and micropollutant fluxes.

Human appropriation of freshwater supply (km^3/year) (**4**)	
Total global runoff	40,700
Accessible global runoff	12,500
Water withdrawals (total)	4,430
Agriculture	2,880
Industry	975
Municipalities	300
Reservoir losses	275
Fluxes of macropollutants with world rivers (10^6 tons/year) (46)	
Total inorganic nitrogen (~75% anthropogenic)	21
Total phosphorus (60% anthropogenic)	5.6
Anthropogenic inputs of heavy metals to aquatic systems (10^6 tons/year) (47)	
Zn, Cr, Ni, Pb, Cu, Cd, Hg	0.3–1
Anthropogenic fluxes affecting water quality (10^6 tons/year) (2, 48)	
Global fertilizer production (2000)	140
Global pesticide production	5
Synthetic organic chemicals production	300
Oil spills (average 1980–2000)	0.4

Table 2. Examples of ubiquitous water pollutants.

Origin/usage	Class	Selected examples	Related problems	References
Industrial chemicals	Solvents	Tetrachloromethane	Drinking-water contamination	(*49*)
	Intermediates	Methyl-*t*-butylether		
	Petrochemicals	BTEX (benzene, toluene, xylene)		
Industrial products	Additives	Phthalates		(*7*)
	Lubricants	PCBs (polychlorinated biphenyls)	Biomagnification, long-range transport	
	Flame retardants	Polybrominated diphenylethers		(*50*)
Consumer products	Detergents	Nonylphenol ethoxylates	Endocrine active transformation product (nonylphenol)	(*51*)
	Pharmaceuticals	Antibiotics	Bacterial resistance, nontarget effects	(*52*)
	Hormones	Ethinyl estradiol	Feminization of fish	(*12*)
	Personal-care products	Ultraviolet filters	Multitude of (partially unknown) effects	(*53*)
Biocides	Pesticides	DDT	Toxic effects and persistent metabolites	(*11*, *54*)
		Atrazine	Effects on primary producers	(*55*)
	Nonagricultural biocides	Tributyltin	Endocrine effects	(*56*)
		Triclosan	Nontarget effects, persistent degradation product (methyl-triclosan)	(*57*)
Geogenic/ natural chemicals	Heavy metals	Lead, cadmium, mercury		(*47*)
	Inorganics	Arsenic, selenium, fluoride, uranium	Risks for human health	(*37*)
	Taste and odor	Geosmin, methylisoborneol	Drinking-water–quality problems	
	Cyanotoxines	Microcystins		(*58*)
	Human hormones	Estradiol	Feminization of fish	(*59*)
Disinfection/oxidation	Disinfection by-products	Trihalomethanes, haloacetic acids, bromate	Drinking-water–quality, human health problems	(*60*)
Transformation products	Metabolites from all above	Metabolites of perfluorinated compounds	Bioaccumulation despite low hydrophobicity	(*61*)
		Chloroacetanilide herbicide metabolites	Drinking-water–quality problems	(*62*)

or indirectly, human health. Production of drinking water from highly polluted raw water may be technically feasible and even necessary in regions of extreme water scarcity. In general, however, purification is much easier and much more cost-effective if the raw water already meets high quality standards. Additional exposure routes to waterborne pollutants may cause health risks, e.g., direct skin contact or contamination of aquatic food sources (e.g., fish) and agricultural products. Hence, any measures taken to prevent the chemical pollution of surface and groundwater resources will not only improve ecosystem health, but will also benefit both the production of clean water and safe food for human consumption.

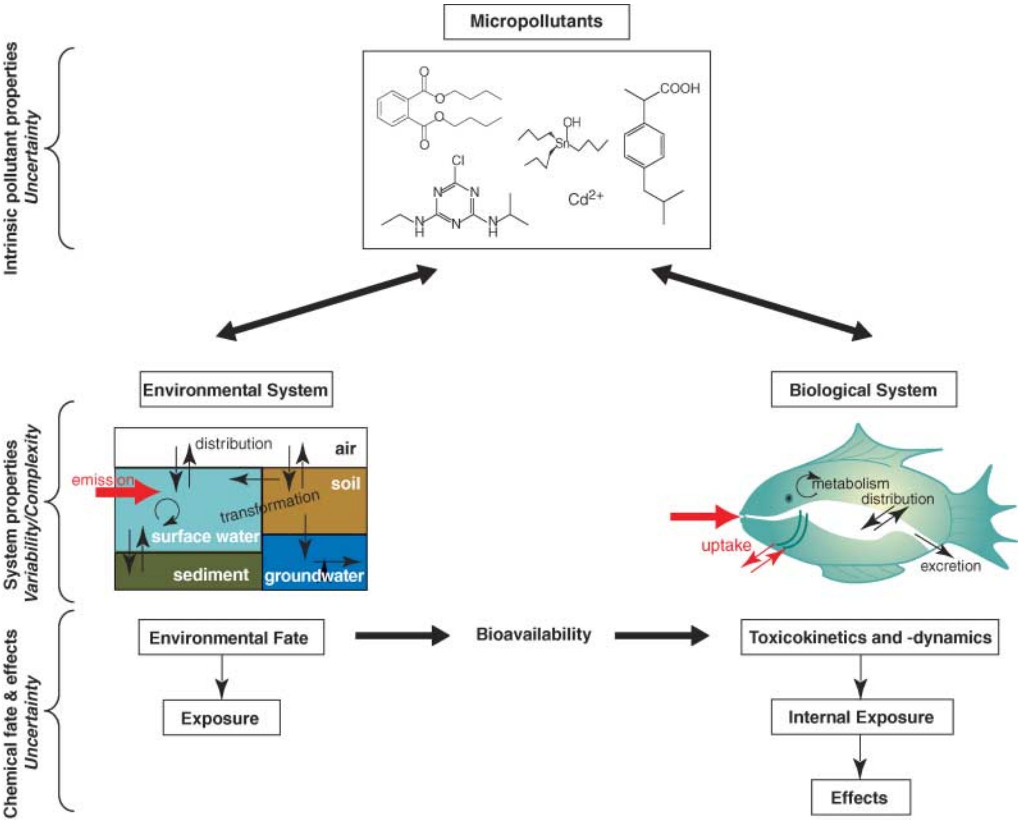

Fig. 1. Consistent exposure and effect assessment is possible if processes in the environmental system and in the organisms (biological system) are treated with the same modeling structure and tools. Within this concept, pollutants interact with environmental and biological systems according to their intrinsic physicochemical properties and reactivities, yielding a characteristic pattern of environmental and internal exposure concentrations for each pollutant. Final exposure and effect assessment according to this concept will always be subject to uncertainty due to inherent variability and complexity of both environmental and biological systems. Quantification and explicit communication of irreducible uncertainties therefore need to be an integral part of exposure and effect assessment.

Assessment of Micropollutants in Aquatic Systems

The assessment of whether or not a particular compound is a pollutant is based upon an understanding of its exposure, i.e., its input, distribution and fate in a defined system, and of the effect(s) that the compound has on organisms, including humans, due to its presence in the system. Figure 1 illustrates the key features and commonalities between exposure and effect assessment. Quantification of the pertinent processes that determine a compound's transport, fate, and effect in aquatic systems is a prerequisite for modeling the risks of new and existing chemicals, for designing mitigation strategies, and for adapting manufacturing practices accordingly.

To date, it has been common practice, in particular in European legislation, to divide the risk assessment of chemicals rather strictly into exposure and effect assessment, even though, particularly on a molecular level, there is considerable overlap. Therefore, a lot of synergy can be realized as research groups specialized in exposure assessment increase their cooperation with colleagues in the field of effect evaluation. Given the enormous complexity of ecosystems, it is not possible to capture in detail every process related to the behavior of micropollutants. Relevant processes must be described at an appropriate level of complexity to provide appropriate answers to the questions asked. The level of complexity may vary from case to case, but the goal is to make a model as simple as possible and as comprehensive as necessary for the problem in hand.

Exposure assessment in the (aquatic) environment has hinged primarily on analytical measurements of single chemical compounds or of bulk parameters (e.g., total organic halogens) in samples from various environmental compartments—water, sediments, soils, air (*11*)—as well as from organisms of different trophic levels within a food chain (*12*). Such measurements provide important information on the temporal and spatial extent of pollution by known chemicals and can also uncover unexpected contamination (see examples and references in Table 2). However, such phenomenological inventories are of limited value, because they usually do not allow one to draw any generalizable conclusions on the compound's behavior in the environment. Pertinent compound- and system-specific properties and reactivities such as adsorption to solid phases, partitioning between solid and aqueous phases, or the formation of complexes in solution, as well as of abiotic and biological transformations, need to be understood and quantified. Such molecular insights are a prerequisite for reliable exposure assessments of chemical compounds in complex macroscopic systems.

In recent years, much progress has been made in the description of complexation and phase-transfer processes of inorganic and organic micropollutants at the molecular level (*13*, *14*). These new approaches place the great variability of compound and system properties in a much more unified and thus generalizable context. However, there are still many gaps to fill, for example, regarding the compound properties of polar as well as ionizable organic chemicals and of those with a high number of functional groups. Previous research focused mainly on apolar and monopolar compounds like PCBs (polychlorinated biphenyls), PAHs (polycyclic aromatic hydrocarbons), chlorinated solvents, or chlorinated pesticides like DDT or lindane. The modern polyfunctional and often ionizable pesticides, biocides, drugs, and personal-care products, to which attention has more recently turned, require more sophisticated models that additionally account for specific complexation or ionic interactions with other reactants. In addition, the physical form of pollutant (dissolved, colloidal, or particulate) will influence fate and effect. Manufactured nanomaterials are well-known chemicals in a new dress, i.e., in a physical state that completely changes their fate and behavior. They were initially only considered to be relevant air pollutants, but more recently their potential hazard in aquatic systems has resulted in manifold research initiatives (*15*).

The current primary challenge in assessing and predicting transformation of micropollutants is presented by the biologically mediated class of reactions. In part, this situation stems from the intrinsic difficulty of classifying and quantifying biological activity in complex macroscopic systems. Moreover, in contrast to the models for describing homogeneous chemical and photochemical processes in aquatic systems (*13*), the treatment of enzymatic and surface-mediated reactions is still in its infancy. Hence, future research should be directed more intensively toward developing tools for assessing (bio)transformation processes in environmental settings and toward improving predictive models for biodegradability on the basis of structural information (*16*).

With respect to effect assessment, there is an even greater need for more fundamental approaches that are based on explanatory principles, obtained by investigating the underlying responsible molecular mechanisms instead of comparing empirical data from descriptive studies (*17*). Traditionally, the (eco)toxicity of a given pollutant is determined by standardized tests, with the use of selected model organisms and toxicity endpoints, such as acute toxicity or lethality in algae, daphnia, and fish (*18*). In such standard tests, the effect is related to exposure concentrations in the surrounding medium (water, sediment, or food) and bioavailability. The uptake and the internal concentrations in the organism are often not known, although the concentration at the target site corresponds to the biologically effective dose. The toxicokinetic processes of uptake, internal distribution, metabolism, and excretion (Fig. 1) relate the concentrations at the target site to external exposure. Often it is too tedious or not possible to quantify this cascade of processes. Total internal concentrations can be used in many cases as a surrogate parameter to better assess the observed effects (*19*, *20*).

There are three main modes of toxic action: baseline toxicity, receptor-mediated, and reactive mechanisms (*21*). Baseline toxicity is caused by a nonspecific disturbance of the structure and functioning of biological membranes. Internal effective membrane concentrations of baseline toxicants are constant and independent of the biological species and the type of molecule (*19*, *20*). Thus, much of the apparent biological variability can be resolved if toxicity studies are approached on a mechanistic level. Even for receptor-mediated and reactive mechanisms, a differentiation between the internal concentrations and the intrinsic potency at the target site can help to derive general principles and understand differences in species sensitivity (*21*).

In the environment, organisms (including humans) are exposed not only to isolated micropollutants but to complex chemical mixtures, the individual components of which might be present at concentrations too low to raise concern. However, additive or even synergistic effects can render such mixtures dangerously potent. For example, a recent study has shown that when five estrogenic compounds are mixed in concentrations all below levels at which their individual effects can be detected, their cumulative impact on fish was detrimental (*22*). It was long assumed that only compounds with the same mode of toxic action are concentration-additive in mixtures, but recent research has shown that even mixtures of compounds with different modes of action may cause nonnegligible effects (*23*). These and related findings have shifted the research focus from searches for synergistic effects, which are spectacular but less common, to systematic investigations of mixture effects of noninteracting compounds. Various mixture toxicity concepts have evolved for mixtures of compounds with the same mode of toxic action and for those that act at different target sites (*21*, *23*). These mixture concepts are increasingly being applied in risk assessment of chemical mixtures. For example, Switzerland is currently developing water-quality criteria that include additive effects for mixtures of pesticides in surface waters (*24*).

The mutual interaction of thousands of chemicals in the environment with millions of biological species will ultimately determine whether a given pollutant (mixture) leads to marginal or catastrophic ecological consequences. Nonchemical stressors, such as temperature or ultraviolet light, may further modulate observed ecotoxicological effects (*25*). Clearly, classification rules are necessary to reduce such complexity. Categorizing pollutants according to their primary interactions with biomolecules provides a basis for assigning primary mechanisms of toxicity and resulting modes of toxic action (*21*). The mechanistic bases for toxicity are also steadily emerging from genomics, proteomics, and metabonomics studies (*26*). The genome of a number of classical ecotoxicological model organisms has been sequenced, and some gene chips are already commercially available, facilitating the application of the genomic techniques in environmental applications (*27*). Changes in gene expression profiles, modified protein levels, and alterations in the metabolome upon the exposure to a micropollutant yield valuable information on the mode(s) of toxic action. The challenge is to interpret the wealth of data obtained with the omics techniques and to link the molecular and biochemical effects to in vivo effects and exposure conditions. At present, there is belief that these techniques are a great tool for research and for prioritizing further testing but that they cannot be applied as stand-alone tools in environmental risk assessment. Further limits are that they cannot describe complex interactions in ecosystems, a field that is addressed by stress ecology (*28*).

Mitigation of Aqueous Micropollutants

There is an increasing need for more powerful strategies to mitigate water contamination because industrial chemical use and demand for clean water is steadily rising. On the one hand, these strategies have to aim at reducing the use of critical chemicals and thus their introduction into the environment. On the other hand, they have to focus on the treatment of existing contamination by more efficient and cost-effective methods. The latter case includes both the containment and the remediation of contaminated sites, as well as the treatment of wastewaters and raw waters for human consumption.

Most contaminated sites are rather complex, heterogeneous systems. Consequently, often too little system knowledge is available to apply any remediation technique in an optimal way. It therefore comes as no surprise that more than two decades of research and application of remediation approaches have not shown the expected success. Traditional approaches such as pump-and-treat have turned out to be rather inefficient in that they require active treatment times of several years. Thus, they are economically unfeasible, particularly when considering the vast number of sites with a potential to cause substantial water contamination. Hence, strategies focusing on microbial or abiotic degradation in situ, or natural attenuation, have to be considered as long-term treatment options. This means that processes determining the transport and the transformation behavior of a given micropollutant and of its transformation products must be understood and quantified in detail. Such knowledge forms the basis for sound decisions on whether to leave a contaminated site without any measures or whether additional engineering actions are necessary. Such actions include, for example, enhancing microbial activity by adding appropriate electron donors or acceptors to the system (*29*), or introducing abiotic reactants into contaminated groundwaters such as zero-valent metals in permeable reactive barriers (*30*).

Mitigation of organic micropollutants should be based on knowledge of the mineralization pathways to stable and nontoxic products and their reaction rates. For inorganic micropollutants such as heavy metals, processes that lead to immobilization as insoluble or matrix-bound species need to be identified and quantified. Many of these processes have been studied extensively in laboratory model systems mimicking natural attenuation, and information on rates and products of degradation pathways is available. However, the major challenge is to transfer this knowledge for the assessment of long-term treatment options to contaminated soils or groundwaters. Because degradation of persistent micropollutants requires the presence of relevant microbial communities and the expression of appropriate enzymes, prediction of in situ rates of microbial attenuation pathways is extremely difficult. To this end, new strategies for monitoring, manipulating, and predicting microbial processes are being developed on the basis of molecular biological methods to identify active microbial communities (*31*) or with stable-isotope techniques, which can be applied to identify and quantify in situ micropollutant transformations (*32*).

In contrast to remediation of contaminated sites, end-of-pipe pollutant mitigation by wastewater and drinking-water treatment has to occur at much shorter time scales of minutes to days. Furthermore, micropollutants are commonly present in much lower concentrations. Therefore, highly selective and rapid reactions have been designed to remove micropollutants in the presence of organic and inorganic matrices that are a thousand- to a million-fold more abundant than the target chemicals. To date, there are a number of fairly standardized unit processes (e.g., chemical and biological oxidation, adsorption, sedimentation, filtration) available to mitigate micropollutants in water treatment by transformation or removal by physical methods, including adsorption and filtration. To allow treatment of large quantities of water per unit time (thousands of m^3/hour), these processes use very reactive oxidants including ozone, OH radicals, chlorine, chlorine dioxide, or permanganate (*33*); high-capacity adsorbents such as activated carbon; or efficient filters such as synthetic membranes.

A major future challenge in wastewater and drinking-water treatment is to improve existing unit processes and to design new ones to remove a large number of chemically very different micropollutants in a broad range of water matrices. For wastewater treatment, this implies optimization of conventional processes for removal of compounds like pharmaceuticals through adsorption and biodegradation in activated sludge treatment (*34*) or using ozone to eliminate, for example, estrogenic compounds (*35*).

For drinking-water treatment, complete mineralization is often not feasible. Therefore, the assessment of reaction products and oxidation by-products, which result from the oxidation of matrix components, e.g., bromate from bromide (*33*), is an important additional challenge. The kinetics and mechanisms of by-product formation need to be investigated in more detail because their toxicity, biological activity, and degradability relative to their precursor are usually not known. Persistent micropollutants can be removed by membrane filtration (nanofiltration and reverse osmosis) or activated carbon (*36*). However, depending on operation time, the adsorption or retention capacity of both approaches decreases due to interference with natural organic matter; in addition, biofouling can lead to clogging of filters. For their successful application, both approaches need improved regeneration strategies, which avoid decreasing their performance and redischarging micropollutants into the environment.

A fundamentally different problem is encountered when there is a widespread occurrence of micropollutants of geogenic origin—for example, selenium, arsenic, or fluoride—in groundwater aquifers of rural areas of developing countries. In this situation, small-scale, household-based removal techniques are often the only possible mitigation strategy due to the lack of a centralized infrastructure. Geogenic micropollutants are found in increased concentrations because their content in some geological formations is elevated and because they are negatively charged and therefore bind weakly to aquifer material under neutral and slightly alkaline pH conditions. In the case of arsenic, it is the anoxic conditions that release reduced arsenic species into groundwaters (*31*). More than 100 million people worldwide drink water with fluoride concentrations exceeding the World Health Organization (WHO) guideline value of 1.5 mg/liter, above which dental or crippling skeletal fluorosis (*37*) can occur; a similar number of people in Southeast Asia (notably Bangladesh) and Southern and Central America drink water with arsenic concentrations above the WHO limit (10 μg/liter), putting them at risk of dermal lesions, cardiovascular damage, or skin cancer (*38*). Meeting the WHO guideline of 10 μg of arsenic per liter is a major drinking-water challenge worldwide for both geochemists and process engineers (*39*). Photochemical oxidation (*40*) or co-oxidation with either Fe(II) or zerovalent-iron (*41*) and subsequent coprecipitation with Fe oxides (or hydroxides) removes arsenic. To date, however, neither approach is reliable, inexpensive, or simple to use. Therefore, none is yet suited for use in developing countries. Currently, the only solution is the monitoring of water resources to identify safe sources of drinking water. In this situation, the challenge is to develop reliable, affordable, and simple field equipment that local inhabitants with little training could use for monitoring. Because many countries are not in the position to monitor their water, it is imperative that scientists further their understanding of the geochemical, geological, climatologic, and land-use factors underlying geogenic contamination of groundwater. Progress will likely come from combining process knowledge with geographic information from remote sensing and other sources to provide better spatial predictions of areas at risk.

Preventive Management of Water Quality

Despite advances in water treatment, a precautionary approach toward water and chemical management—one that reduces introduction of problematic chemicals into the environment in the first place—should be given a high priority for reducing risks to human health and ecosystem integrity.

For this purpose, the tools of "green" or sustainable chemistry are essential. Efficiency engineering of chemical production processes aim to reduce material flows and replace hazardous auxiliary materials (*42*). Prospective chemical risk assessment is mostly used in the context of market authorization, but it also allows for proactive approaches in designing new, more environmentally benign chemical compounds (*43*). The assessment must typically rely on limited, basic information about a compound such as its molecular structure and a few physicochemical properties. The development of sound, mechanistically based quantitative structure-activity relationships is therefore an important task, albeit a challenging one given the multitude of chemical structures. One elegant approach is to design new compounds that contain only natural building blocks, connected by linkages known to be readily cleaved enzymatically. This "benign by design" strategy has, for example, been realized by industry to replace persistent textile auxiliaries used as dispersing agents (*43*).

Once a chemical is in use, contamination of water resources should be avoided to the largest extent possible. Intensive agriculture in the developed world, for instance, is a major cause of diffuse water pollution leading to eutrophication and contamination of surface and groundwater resources with pesticides and veterinary medicines. Field studies have shown that various, spatially highly heterogeneous factors such as soil type, presence or absence of drainage systems, and local topography strongly influence the tendency of a given agricultural area to release pesticides into surface waters through fast-flow processes such as runoff or drainage (*44*). Knowledge of these governing factors is a prerequisite for optimizing management practices at a field or regional level; the next scientific challenge lies in developing the capacity to identify problematic areas by using available geo-referenced information, and in using this information to adapt agrochemical use.

In developing countries, in contrast, the nature of pesticide use and the mitigation options for related problems are quite different. Surveys carried out in Central America, Brazil, and Nigeria reveal acute dangers of direct pesticide poisoning of humans, due to mishandling of equipment and overuse of pesticides through ignorance of the relevant hazards (*45*). Consequently, pesticide concentrations in surface and groundwaters are estimated to be high, but virtually no monitoring data are available. Beyond implementing training and information programs for the farmers, alleviation of this problem also requires identification of those pesticides least likely to be problematic under local conditions. Scientifically, this task requires defining environmental risk-assessment protocols appropriate for the specific social and ecological conditions encountered in tropical regions (e.g., history and conditions of tropical soils influencing chemical reactivity and partitioning behavior). There is also a need on the part of regulatory authorities to enforce substance bans more strictly. Currently, large quantities of the pesticides used in such poorer regions may not even be authorized for use but can be bought on the black market (*45*).

Outlook

Scientific progress in aquatic micropollutant management clearly depends on interdisciplinary collaboration. Chemists and biologists must work together to harness the potential of new screening techniques for assessing the environmental impact of micropollutants; environmental chemists and engineers must strive to develop synergies between pathogen removal and the oxidation of micropollutants in water-treatment technologies. Furthermore, given the importance of chemicals in modern societies, sustainable solutions can only be found through active involvement of all stakeholders, including consumers, chemical manufacturers, politicians, and public authorities. This cooperation requires that pertinent topics in environmental chemistry, toxicology, and engineering be accorded a more prominent status in future curricula in chemistry, engineering, and the life sciences. With this article we hope to increase awareness of the urgency and global scale of the water-quality problems arising from micropollutants.

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PERSPECTIVE

Waterborne Infectious Diseases—Could They Be Consigned to History?

Alan Fenwick

The development of water resources, particularly in Africa, has changed the face of the continent, opening up land for agriculture, providing electric power, encouraging settlements adjacent to water bodies, and bringing prosperity to poor people. Unfortunately, the created or altered water bodies provide ideal conditions for the transmission of waterborne diseases and a favorable habitat for intermediate hosts of tropical parasitic infections that cause disease and suffering. The recent progress in control of these waterborne and vector-borne diseases, such as guinea worm, schistosomiasis, lymphatic filariasis, and onchocerciasis, suggests that many of them could be controlled effectively by 2015, which is the target for reaching the Millennium Development Goals. Donations of safe and effective drugs by several pharmaceutical companies, funds for delivering these donated drugs from foundations and bilateral donors, and effective global health partnerships should make these diseases history.

About 15% of the world's population lives in areas of water stress. Many people struggle to obtain access to enough water to drink, keep clean, and meet their other needs to live. Two and a half billion people (more than a third of the world's population) have no access to improved sanitation, and more than 1.5 million children die each year from diarrheal disease (*1*). In rural areas, particularly in Africa, the same water that is