Future Challenges to Protecting Public Health from Drinking-Water Contaminants

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Abstract
Over the past several decades, human health protection for chemical contaminants in drinking water has been accomplished by development of chemical-specific standards. This approach alone is not feasible to address current issues of the occurrence of multiple contaminants in drinking water, some of which have little health effects information, and water scarcity. In this article, we describe the current chemical-specific paradigm for regulating chemicals in drinking water and discuss some potential additional approaches currently being explored to focus more on sustaining quality water for specific purposes. Also discussed are strategies being explored by the federal government to screen more efficiently the toxicity of large numbers of chemicals to prioritize further intensive testing. Water reuse and water treatment are described as sustainable measures for managing water resources for potable uses as well as other uses such as irrigation.
INTRODUCTION

Explosive increases in human population spurring widespread development and demand for water, global climate change causing unpredictable flooding and long-lasting droughts (48), water withdrawals in coastal areas causing saltwater intrusion into drinking-water sources, and the occurrence of low levels of multiple unregulated chemical contaminants throughout the water supply necessitate that humans reassess how we consume and manage water. This review focuses on the last of these challenges and examines how novel approaches to assess quickly the toxicity of chemicals, improved analytical techniques to detect chemical contaminants, and advanced treatment to remove chemicals from water may help communities and regulators better address the issue of multiple chemical contaminants in drinking water. The article is divided into several parts related to the central theme of regulation and control of the occurrence of multiple chemical contaminants in drinking water. Featured here is a discussion about potential regulatory options for addressing the health concerns of currently unregulated drinking-water contaminants. Although the issue of microbial contaminants in drinking water represents challenges of its own, it is not discussed here because it is beyond the purview of this review. Also, we focus on the United States because the challenges faced by the developing world are quite different.

OCCURRENCE OF MULTIPLE UNREGULATED CHEMICAL CONTAMINANTS IN DRINKING WATER

Numerous nationwide investigations conducted by scientists at the U.S. Geological Survey (USGS) and elsewhere show that unregulated contaminants are present in groundwater, surface water, and finished drinking water throughout the country (6, 8, 12, 18, 19, 21–25, 28, 40, 42, 44, 49, 67–70). In fact, a suite of unregulated contaminants has been detected in virtually all water systems where such analysis has been conducted. The question to regulators is, what does the presence of these unregulated contaminants mean? Many of these chemicals are derived from domestic-use chemicals such as flame retardants, pesticides, pharmaceuticals (both prescription and over-the-counter), and personal care products. Although some chemicals are persistent in the environment and do not break down (i.e., perfluorinated chemicals), most chemicals found in water supplies can be transformed to breakdown products, which are largely uncharacterized (14) and which may be toxic alone or in the presence of other chemicals. Although toxicity testing that is required for new pharmaceuticals and pesticides provides some information about their potential health effects, no such testing is required for their environmental transformation products or for other domestic and industrial chemicals.

Given the large number of chemicals released into the environment either through discharges or through domestic/industrial/commercial use, it is not surprising that various combinations of mixtures of chemicals have been found in water samples (24, 28). Any one of these contaminants may not be of concern from a human health point of view, particularly at the low levels (1 ug/L or lower) generally found. However, uncertainty about the potential toxicity of mixtures of such contaminants requires further research, particularly for effects on wildlife. For instance, even trace levels of some of these may have deleterious reproductive effects on aquatic organisms (3, 44, 66, 70). The USGS has proposed a National Research Program to investigate potential deleterious health effects to humans and the environment owing to the presence of emerging contaminants (35), based on the numerous occurrence studies the organization has conducted over the past decade. Other scientists advocate for international strategies to address emerging contaminants in drinking water (43, 45, 47, 49, 51).
SOURCES OF MULTIPLE UNREGULATED CHEMICAL CONTAMINANTS IN DRINKING WATER

One of the primary sources of unregulated chemical contaminants in surface water used for drinking water is wastewater discharge, and this issue has been extensively studied by USGS scientists and others (9, 12, 24, 15, 36, 37, 49, 66, 69–71). Leaching from septic tanks and hazardous waste landfills as well as land application of biosolids (sludge) from wastewater treatment plants continue to be important sources of contaminants to groundwater (9, 25, 28).

The majority of the contaminants found in these studies are not part of the suite of regulated contaminants that are routinely analyzed for as part of the drinking water regulatory program. Researchers with the University of Medicine and Dentistry of the New Jersey School of Public Health (7) and the USGS (35) found that basic toxicity information is lacking for most of the contaminants found in these studies, so it is difficult to assess whether they pose a demonstrable threat to human health either on an individual basis or as contaminant mixtures.

ANALYSIS OF MULTIPLE UNREGULATED CHEMICAL CONTAMINANTS IN DRINKING WATER

The presence of multiple unregulated contaminants in our waters is not a new phenomenon. However, our ability to detect them is. Analytical methods developed by many organizations (4, 5, 55) have been used extensively by commercial and research laboratories to perform drinking-water analyses. In fact, the current regulatory approach is based, in part, on the analytical capability for detecting contaminants. Improvements in analytical instrumentation and the subsequent increase in sensitivity and selectivity over the years have led to the detection of ever lower concentrations of chemicals in environmental media. In the past 40 years, method detection limits for contaminants have improved from parts per hundred (52) to parts per trillion (54, 55), and the probable limit is a single molecule or atom in a volume of sample. It is likely that the only practical limitation will be based on the achievable purity of the blank samples (50, 55). As our ability to detect more contaminants at lower levels (nanograms or picograms per liter and lower in some cases) improves, our regulatory response must be suitable to address both the large numbers of new chemicals being detected as well as the fact that they are detected as mixtures.

Gas chromatographic (GC) measurement (24, 53, 56, 61–63) has been utilized over the years for sensitive measurement of volatile and some semivolatile contaminants. Identification is based on comparison matches to standards, and the sensitivity is generally sufficient to meet the regulatory limits. When GC was coupled with mass spectrometry (MS), the sensitivity for many compounds such as the BTEX (benzene, toluene, ethylbenzene, xylene) group (indicators of petroleum contamination) improved dramatically. MS led to identification of multiple contaminants not previously observed to occur in water, such as the gasoline additive methyl tertiary butyl ether (MTBE), polybrominated diphenyl ethers (PBDEs), and various other unregulated contaminants such as anionic, cationic, and nonionic surfactants. Instrumentation improvements created even greater sensitivity, and this sensitivity is considered when establishing maximum contaminant levels (MCLs).

As less volatile, thermally labile, and large-molecular-weight contaminants such as flame retardants and perfluorinated compounds have become targets for analysis, liquid chromatographic separation with mass spectrometry (LC/MS) has become an analytical focal point (58–59). As with many previously codified methods (57), more advanced GC/MS measurements and LC/MS analytical techniques for emerging contaminants are being developed now in advance of any regulatory limits that may be adopted in the future for these chemicals. In many ways, analytical chemistry has been the driving force behind the recent attention...
to unregulated contaminants in drinking-water supplies as more and more unregulated contaminants are discovered. Analogous advances have been made with metals measurement, but no new metals are being discovered.

CURRENT APPROACH TO REGULATING CONTAMINANTS IN U.S. DRINKING WATER

A detailed review of the history of drinking-water regulation in the United States can be found elsewhere (41). Here, we present a synopsis to put future water-quality challenges and potential solutions into perspective.

Beginning in the 1970s, the challenges facing purveyors and regulators of drinking water were addressed by a successful program of regulating toxic chemicals known at the time to occur in drinking water on a chemical-by-chemical basis. The Safe Drinking Water Act (SDWA) amendments of 1986 required the development of water-quality standards for a specific list of 83 contaminants in the first 5 years and 25 additional contaminants every 3 years subsequently. To set a contaminant-specific drinking-water standard, the maximum contaminant level (MCL), there must be adequate health effects information (from animal toxicology and/or human epidemiological studies), adequate detection capabilities to measure the contaminant (from analytical studies), some documentation of occurrence of the contaminant in the raw or finished water supply, and a suitable treatment technique to remove the contaminant from water (from engineering studies). These drinking-water standards are intended to protect consumers from adverse health effects resulting from lifetime (chronic) exposure through drinking water. Once information for these parameters is established and cost considerations are taken into account, an MCL can be established.

This process was used by the U.S. Environmental Protection Agency (USEPA) for the development of the National Interim Primary Drinking Water Regulations promulgated between 1975 and 2001 for 91 volatile organic contaminants, synthetic organic contaminants (primarily pesticides), inorganic contaminants, radionuclides, and disinfection by-products (table 1 in Reference 41). This represents the original 83 contaminants identified by the SDWA amendments plus 8 additional contaminants. Whereas the 1986 SDWA amendments call for the regulation of 25 additional contaminants every 3 years after 1991, the EPA has regulated 8 additional contaminants since then. These standards addressed many of the contaminants that were known to pose the greatest health risk on an individual basis and that were detected with some frequency at relatively elevated levels (in the parts per million range) in the nation’s drinking water. Information on these regulated contaminants can be found at the USEPA Web site (http://water.epa.gov/drink/contaminants/index.cfm#List). Some states have opted to regulate additional contaminants of local concern that have not been addressed by federal standards (16, 17) or at lower levels (e.g., arsenic in New Jersey).

Ten years later, the 1996 SDWA amendments also outline a process for identifying new chemicals for regulatory consideration. This process includes periodic development of a contaminant candidate list of unregulated chemicals for consideration based on available health risk data and potential for occurrence in drinking water and periodic unregulated contaminant monitoring rules (64) requiring nationwide monitoring of public water supplies to gather occurrence data. Since the unregulated contaminant monitoring rule process began, the USEPA has made determinations not to regulate 19 contaminants and a determination to regulate only 1 contaminant, perchlorate, a thyroid inhibitor that is present in fertilizers, rocket fuels, explosives, flares, and fireworks. A federal MCL for perchlorate has not yet been proposed or adopted.

Additional chemicals of potential concern because of their toxicity and occurrence in drinking water remain unregulated by the USEPA at this time. Many of these chemicals are included on the current EPA Contaminant Candidate List 3 and/or proposed unregulated
contaminant monitoring rule list. Examples include MTBE, a water-soluble gasoline additive found commonly in groundwater; 1,2,3-trichloropropane, a potent mutagen and carcinogen used in soil fumigants and in manufacturing processes; 1,4-dioxane, a carcinogenic solvent widely detected in groundwater; and perfluorinated chemicals (PFCs) such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), highly persistent, watersoluble, and bioaccumulative compounds formerly used in fire-fighting foams and in the manufacture of fluoropolymers used in nonstick and water-repellant products. Health effects of PFCs include carcinogenicity, developmental effects, liver toxicity, and immune-system toxicity. For other emerging contaminants of potential concern, such as nanoparticles, there are few data on occurrence and health effects.

The process of obtaining and evaluating the needed occurrence and health effects data for contaminants of concern is clearly costly and time consuming (39). Additionally, the regulatory criteria to justify development of new chemical-specific standards are very stringent. Although this chemical-specific approach will continue to be useful for addressing some important emerging contaminants, such as those mentioned above, it may not represent a sustainable approach for addressing low-level contamination with multiple chemicals that are now known to occur in many U.S. rivers, groundwater, and finished drinking water.

TOWARD A SUSTAINABLE PARADIGM FOR MANAGING DRINKING-WATER RESOURCES

The EPA defines sustainability thusly: “Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations” (http://www.epa.gov/sustainability/basicinfo.htm). Given the EPA’s definition, sustainable drinking water may be defined as consuming and managing water resources in a way that fulfills the health, social, economic, and environmental requirements of present and future generations. To be successful in creating a system of sustainable drinking water in the United States, we need to develop strategies to identify, evaluate, and manage multiple contaminants at all stages of water consumption.

The time has come to recognize that water is a finite resource. To ensure that future generations will be able to rely on the delivery of adequate water for appropriate uses, we need to look at water use and management from a sustainability point of view in addition to a risk-management point of view and regulate accordingly; that is, we need to focus on preventing contamination of water sources and reducing human and ecological exposures more as opposed to focusing on determining exact toxicities of chemicals in whole-animal studies and removing just those chemicals from drinking water. The current risk-management approach results in the regulation of too few chemicals and does not consider the effects of mixtures of chemicals.

To meet the current challenge related to unregulated chemical contaminants in drinking water, new approaches are needed to complement the present paradigm used by regulatory agencies in the United States to protect water sources from contamination and to ensure the delivery of safe potable water. The chemical-by-chemical risk-assessment approach currently used is not sufficient or sustainable by itself. We need to develop approaches to screen large numbers of chemicals rapidly for potential toxicity and to evaluate alternative or supplemental strategies for reducing exposure to drinking-water contaminants in the absence of definitive information on their potential health risks.

OPTIONS: SOURCE CONTROL AT THE MANUFACTURING STAGE

New approaches to long-term water planning and management that incorporate principles of sustainability are needed and are now being explored by national and international water experts and organizations.
One way to approach the occurrence of chemicals in drinking water (indeed, in the environment in general) is to regulate them at the manufacturing stage. In fact, this is being done to some degree in the United States (see TSCA below) and especially in Europe through a program called REACH—Registration, Evaluation, Authorisation and Restriction of Chemical substances—which came into effect in June 2007. REACH places greater responsibility on industry to control and manage risks from chemicals and to provide safety information on those substances. Manufacturers and importers are required to gather information on the characteristics of the chemicals they produce and to register the information in a central database run by the European Chemicals Agency (ECHA) in Helsinki. The Agency acts as the central point in the REACH system: It manages the databases necessary to operate the system, coordinates the in-depth evaluation of chemicals of concern, and is developing a public database in which consumers and professionals can find hazard information. REACH also calls for the progressive substitution of the most dangerous chemicals when suitable alternatives have been identified. In addition, green chemistry initiatives that utilize fewer toxic chemicals in the reaction pathway for the desired products are actively encouraged. In fact, a major goal of REACH is the phasing out of toxic chemicals in favor of suitable green alternatives.

The U.S. Toxic Substances Control Act (TSCA) of 1976 gives the USEPA the authority to require reporting, record-keeping, and testing relating to chemical substances. Some substances are generally excluded from the TSCA, including food, drugs, cosmetics, and pesticides, because other laws regulate these chemicals.

From the TSCA’s enactment in 1976 through 1994 when the General Accounting Office (GAO) issued a report on the program, five chemicals were restricted by the USEPA (PCBs, chlorofluorocarbons, dioxin, asbestos, and hexavalent chromium) from an original inventory of 60,000 chemicals. Testing was required for 200 chemicals. Since the 1994 GAO report was published 17 years ago, the inventory has increased to include 83,000 chemicals, and no additional chemicals have been restricted or banned. However, a great deal of data collection on chemicals and testing has been conducted because of the TSCA that otherwise would not have been done.

In December 2009, USEPA Administrator Lisa Jackson announced plans for a major effort to strengthen the USEPA’s chemical management program and to streamline enforcement actions. Jackson stated that “TSCA (has) fallen behind the industry it’s supposed to regulate...[T]here are troubling gaps in the available data on many widely used chemicals in commerce” (1, p. 2).

There are major differences between the European approach to addressing chemical manufacture and the U.S. approach: (a) Manufacturers are required to develop toxicity information on chemicals’ effects in the REACH program, whereas manufacturers develop this information only if USEPA rule-making requires it under TSCA; (b) the burden of proof of safety for a chemical resides with the manufacturer in REACH, whereas the burden of proof that a chemical is not safe resides with the USEPA per the TSCA; (c) regulators may, at any time, require manufacturers to supply additional toxicity information under REACH, whereas the USEPA must demonstrate that data are needed before requiring new testing and relies on existing available information for decision-making according to the TSCA.

A major limitation of the TSCA is that it does not adequately address existing chemicals. Implementation of all aspects of the TSCA for existing chemicals has been incomplete and difficult. The environmental impact of persistent chemicals such as PFCs is not included at all in the TSCA regulations, and the emerging contaminant policy is fragmented at best. To control chemicals at the manufacturing stage in the United States, more incentives to consider...
safer alternatives and more toxicity information on existing and new chemicals are needed.

OPTIONS: SOURCE CONTROL OF DISCHARGES AND LEACHING INTO FRESHWATER

A number of chemicals are reaching surface waters through the discharge of sewage treatment plants. Thinking of the rivers receiving the effluent as sustainable drinking water rather than as an infinite dilution system forces us to question the practice of discharging waste directly into water supplies. Cheap and effective technology to treat wastewater before discharge and methods to treat/dispose of sludge would help to alleviate this source of contamination.

ASSESSMENT OF RISK: TOXICITY ASSESSMENT AND RISK PRIORITIZATION

The federal government cannot develop the toxicological study data needed to establish an MCL for even a subset of the unregulated compounds detected throughout the country’s waters for several reasons: the large numbers of compounds, the fact that many compounds are breakdown products manufactured unintentionally (thus not readily available as test material), and the time and expense associated with developing the animal-based toxicological data the studies require. For example, chronic studies and the related supporting toxicity studies for one unregulated contaminant present in the drinking-water supply in Toms River, New Jersey, required more than 8 years of study effort and cost $5 million (34).

Two federal agencies are leading the way in developing new approaches that could be used to evaluate the risk of the large numbers of unregulated contaminants detected in source and finished drinking water. The USEPA is focused on developing approaches for faster and better toxicity testing of multiple chemicals, whereas the USGS has proposed a novel approach for assessing toxicity of transformation products of chemicals found in water.

The National Research Council’s (NRC) Science and Decisions: Advancing Risk Assessment (31) offers recommendations for moving the risk assessment of environmental chemicals, including drinking-water contaminants, from complex risk assessment, requiring specific types of toxicology and/or epidemiology data that are not available for many contaminants, toward a new way to consider risk management. The challenge to regulators and scientists is to find ways to assess risk appropriately in a timely and cost-effective manner. More relevant to the point of this review, NRC’s earlier publication, Toxicity Testing in the 21st Century: A Vision and a Strategy (30), recommends ways to develop new technologies that may potentially be used more quickly to evaluate chemicals for toxicity. The NRC was asked by the USEPA to evaluate alternatives to whole-animal testing to determine how toxicity testing for a large number of chemicals can be conducted more quickly and economically than it is today. Technologies under development and, to some extent, being used today include high-throughput techniques that use cellular response networks rather than whole-animal tests to study potential toxicity. Ideally, in vitro tests developed with human cells, cell lines, or components will be used to assess possible toxic responses, though finalization of these types of tests is still under development. New approaches such as these are necessary to screen the large numbers of chemicals in commercial use that are released to the environment (water, specifically) for potential human health risk. Whole-animal testing will continue to be an important component in the overall process, but this type of expensive and long-term testing will likely be reserved for priority chemicals of broad concern. These options, including high-throughput screens, functional genomics, pharmacokinetic models, and bioinformatics, are discussed by Krewski et al. (26) and on the USEPA Web sites. Brief descriptions are presented here for context.

NexGen

Advancing the Next Generation of Risk Assessment (NexGen) is a collaborative effort
among the EPA’s Computational Toxicology Program, the National Institutes of Environmental Health Sciences and National Toxicology Program, the Centers for Disease Control and Agency for Toxic Substances and Disease Registry, the National Human Genome Research Institute, and the State of California’s Environmental Protection Agency. NexGen is a program that aims to create an inexpensive and quick system for chemical risk assessment by using molecular system biology rather than traditional whole-animal toxicity testing for screening purposes.

If this effort is successful, the information generated by molecular system biology will allow regulators to construct tiered risk-assessment approaches, with each tier providing more information and becoming more complex than the one before. This approach will provide more flexibility to address contaminants of varying toxicity.

The developers of NexGen state that critical to its success is the support from key stakeholders and influencers who are already engaged on some level in the field of risk assessment and are likely already working with the EPA in some way.

**Computational Risk Assessment**

The EPA is working to complement the current approaches to chemical toxicity risk assessment through its Computational Toxicology Research Program (CompTox), which uses innovative research integrating a molecular biology, chemistry, and computer science approach to rank chemicals on the basis of potential risks. Using these methods, a large number of chemicals can be assessed in a relatively short amount of time. Using publicly available databases, toxicity testing results from more than 500,000 chemicals acquired over the past 30 years can be downloaded into computer models and used to screen chemicals for potential adverse effects to humans.

**ToxCast**

The Toxicity Forecaster (ToxCast), launched in 2007, is one of the chemical-screening tools used in CompTox. ToxCast is a tool used to prioritize chemicals by quickly screening them for toxicity. Although ToxCast is still in the development stage, we anticipate that the results will aid regulators in identifying the types of assays that are best utilized for predicting certain human end points, such as reproductive effects and liver toxicity.

ToxCast uses cellular tests rather than whole-animal tests to simulate and predict how processes in the human body may be impacted by exposure to chemicals and may determine which chemical exposures are most likely to lead to adverse health effects. ToxCast is being developed in phases. The first phase (“proof of concept”) was completed in 2009 and resulted in the development of profiles for 300 chemicals (mostly pesticides) in 500 tests (high-throughput screening assays) using human and animal cells and proteins. Toxicity-testing results were already available from conventional animal testing of chemicals screened during this phase. The purpose was to compare the results of the toxicity predicted by ToxCast with the toxicity data from the animal studies. This comparison is helping determine which ToxCast assays can accurately predict different types of toxicity and disease.

Another 700 chemicals are now being screened in ToxCast’s second phase. The chemicals being tested are found in industrial and consumer products, food additives, and drugs that never made it to the market. The failed drugs and associated human clinical trial data, donated by major pharmaceutical companies, are significant because the EPA will be able to compare ToxCast screening data with human clinical data and other toxicology studies. During phase 3, 1,000 additional chemicals will be assayed for potential toxicity.

**High-Throughput Chemical Risk Assessment**

An important potential application of ToxCast is the use of data that it generates in high-throughput chemical risk assessment (HTRA) assays. The goal of the HTRA
approach is to derive screening-level estimates of risk-based exposure levels for many chemicals quickly (20). The method uses data from rapid chemical screens to estimate exposures that would alter biological pathways in a way that may potentially lead to toxicity or disease. The overall approach combines results from ToxCast and other high-throughput screening assays with data on metabolism and pharmacokinetic modeling to estimate exposure levels reasonably expected to be without risk of chemically induced disease in human populations. It is a five-step process:

1. Identify biological pathways linked to adverse effects and disease: Identify known targets (genes, proteins) and pathways linked to disease.
2. Measure pathway-altering concentration in ToxCast high throughput screening assays.
4. Incorporate uncertainty and population variability.
5. Calculate lower limit based on 99 percentile of BPAD ($BPAD_{99}$).

Whereas conventional risk assessment relies on the dose-response model and the no-adverse-effect level, HTRA relies on establishing the biological pathway–altering dose below which there is minimal risk of the toxicity-related pathway being perturbed, the $BPAD_{99}$. It must be recognized that many complex issues related to this approach remain to be addressed. These issues relate to both the development of the methodologies needed to carry out the HTRA process and the application of HTRA results in risk assessments used for regulatory purposes.

**Virtual Tissue Modeling**

EPA scientists are using computer models to simulate how chemicals may affect organs such as the liver (v-Liver™, the Virtual Liver Project) and how they may affect the developing embryo (v-Embryo™). Traditionally, controlled tests on live animals have been used to gather information on adverse effects to target organs and developing embryos/fetuses. Although more comprehensive information is generated from these types of tests, they are too time-consuming and expensive to continue to be used on a routine basis for all chemicals of potential concern today. If successfully developed, these model tissue systems may offer an effective alternative for screening and identifying which chemicals to refer for the more intensive animals tests.

**USGS Approach**

The USGS, a nonregulatory agency, proposes two approaches for assessing environmental risks of transformation products of water contaminants: exposure-driven and effects-driven (14). In the exposure-driven approach, transformation products formed in a reaction mixture are isolated, identified, and assessed for environmental fate and toxicity. In the effects-driven approach, the disappearance of the parent compound and the toxicity of the mixture of parent compound and transformation products are monitored in bioassays over the course of the experiment. A decrease in toxicity over time is assumed to result from a transformation of the parent compound to less toxic transformation products, and further study is assumed to be unnecessary. When toxicity increases over time, identification and study of the transformation products, which are assumed to be responsible for the effects, ensue.

**APPROACHES TO ASSESS TOXICITY OF UNDEFINED COMPLEX MIXTURES OF DRINKING-WATER CONTAMINANTS**

The high-throughput approaches for toxicity testing of individual chemicals discussed above do not address the toxicity of undefined complex mixtures of drinking-water contaminants, such as those detected in the New Jersey studies (28). Concentrated extracts of environmental contaminants from sources such
as industrial effluents or hazardous waste site leachates have previously been tested broadly for mutagenicity, developmental toxicity, and other end points. Similar approaches have recently been applied to undefined complex mixtures of drinking-water contaminants containing both known and uncharacterized disinfection by-products (46). Concentrates of finished drinking water from water supplies treated with different disinfection processes were tested for mutagenicity in bacteria (10), cytotoxicity and effects on gene expression in cultured rat liver cells (11), and developmental effects in pregnant rats given the concentrates as their drinking water (29). However, even successful high-throughput and computational toxicity testing of chemicals does not fully address mixtures of chemicals at this time.

CHANGE WATER USE: INCREASE REUSE OPTIONS AND TREATMENT OF POTABLE WATER FOR CONSUMPTION

Treatment-Based Drinking-Water Standard

Even with the availability of new toxicity-screening tools, there will continue to be uncertainty regarding the health effects resulting from human exposure to mixtures of chemicals. One way to reduce human exposure to mixtures of constituents for which there is uncertainty about potential health risks is to install water treatment on drinking-water supplies that are vulnerable to contamination by unregulated synthetic organic chemicals. Such systems could be identified by modeling (such as the modeling conducted by states in response to the federal requirement for source water assessment areas, where inventories of sources of contamination near a potable water source were modeled and predictions for potential contamination were developed) or from historical monitoring data. For instance, the NJ study demonstrated that potable water sources known to be contaminated with regulated contaminants were vulnerable to contamination by unregulated contaminants as well (28). Drinking-water systems vulnerable to contamination with unregulated synthetic organics could therefore be identified as those systems that are contaminated by other, regulated organic chemicals.

In effect, this option calls for the development of a treatment-technique drinking-water standard in lieu of or in addition to chemical-specific MCLs. When there is no reliable method that is economically and technically feasible to measure a contaminant or contaminants at low concentrations of concern, a treatment technique can be set instead of an MCL. A treatment technique is an enforceable procedure or level of technological performance that water systems must follow to ensure sufficient removal of a contaminant. The EPA currently regulates the water treatment chemical epichlorohydrin using a treatment-technique requirement in lieu of an MCL because of the lack of a standardized analytical method for its measurement in water. By identifying and defining mixtures of chemicals in a similar way, a treatment-technique MCL could be developed for them.

This treatment-technique MCL approach represents action that could be taken if the considerations discussed above are followed to their logical end points. That is, the best available technology for removing many organic contaminants from drinking water, and thus preventing human exposure, is granular activated carbon, ozonation, or other readily available drinking-water treatment technologies. Most of the contaminants detected in the aforementioned studies of the occurrence of emerging contaminants in drinking water are synthetic organic compounds. A treatment-technique MCL would eliminate the need for time-consuming and expensive toxicity testing and development of chemical-specific risk assessments and regulatory standards and would address uncertainties about potential health effects of complex mixtures of multiple contaminants at low concentrations. Thus, it may represent a less expensive, as well as more public health protective, alternative to current chemical-by-chemical regulation. An
additional potential benefit is the removal of additional contaminants that may be present but may not be identified by the analytical techniques used to assess the water supply. Therefore, it may be appropriate to use contamination by regulated chemicals as a vulnerability trigger for water treatment here, unless a better trigger can be established. Other approaches include modeling the potential for nearby sources of contamination (i.e., discharges, hazardous sites) to reach a potable water intake.

To pursue such an option, additional practical information is needed about the effectiveness of various types of treatment to reduce levels of broad categories of contaminants of concern. Studies conducted in New Jersey (32, 33) evaluating the effectiveness of existing water-treatment technologies on the removal of mixtures of organic contaminants from drinking water concluded that granulated activated carbon (GAC) would be expected to work most effectively for groundwater systems, whereas a combination of treatments is best for surface-water systems.

Although GAC was identified as the most applicable technology for New Jersey groundwater systems, both air stripping and oxidation might be preferred in certain circumstances to reduce the frequency at which the carbon must be replaced, thereby reducing annual operating and maintenance costs. The Black & Veatch (33) report for surface-water systems concluded that no single treatment technique can remove all the unregulated organic compounds that were detected in New Jersey surface water. In addition, it is unlikely that all the unregulated organic compounds could be removed from a given location even using a combination of processes. Furthermore, by-products of oxidation and biological activity are likely to be generated during treatment, creating other organic chemicals while the original organic chemicals in the surface water are removed (13). At many drinking-water plants that are vulnerable to organic chemical contamination, these treatment processes may already be present to remove other currently regulated contaminants.

New Jersey is also piloting several other research projects to generate much-needed information to evaluate the feasibility of the treatment-based approach. To explore further the efficacy of using water treatment to address multiple contaminants in drinking water, the New Jersey Department of Environmental Protection funded the construction of full-scale GAC Demonstration Project units to study the removal of these mixtures of unregulated chemicals at two water systems that use groundwater sources. Past studies (28) have indicated that such groundwater systems are vulnerable to contamination by industrial and household chemicals, categories of chemicals that are generally removed by carbon treatment effectively. Both advanced and conventional chemical analyses conducted during operation of these GAC units will be used to determine optimal ways to measure compliance. Information generated by studies such as this will be invaluable toward determining whether proposal of a treatment-based MCL is a feasible and effective approach for addressing such mixtures of contaminants.

For surface water, reverse osmosis is a technique that could remove virtually all the organic contaminants of concern. However, given the expense and impracticalities of reverse osmosis, it is not a realistic approach to treat large volumes of water. Oxidation and adsorption processes appear to be the most applicable technologies because of their ability to remove a wide range of compounds. A combination of techniques at surface water systems is likely to represent the optimal approach. Furthermore, many of the large surface water systems in the United States already have multiple barriers to treat water and would need to either add a minimum of additional treatment or re-engineer the existing treatment system (33).

**Water Recycling and Reuse**

Water recycling (used synonymously with water reuse) is defined as the process of reusing wastewater for beneficial purposes such as agricultural and landscape irrigation, industrial processes, toilet flushing, and replenishing of a...
groundwater basin (referred to as groundwater recharge).

Water recycling/reuse has proven to be effective and successful in creating a new and reliable (i.e., sustainable) water supply without compromising public health (2). Nonpotable reuse is a widely accepted practice that will continue to grow, particularly in the arid southwestern part of the United States. Advances in wastewater treatment technology and health studies of indirect potable reuse have led many researchers to predict that planned indirect potable reuse will soon become more common not only in arid areas but in coastal communities where saltwater intrusion limits aquifer source water and economic considerations preclude desalination of ocean water. Recycling waste and gray water requires far less energy than treating salt water using a desalination system.

Although water recycling is a sustainable approach and can be cost-effective in the long term, the treatment of wastewater for reuse and the installation of distribution systems at centralized facilities can be initially expensive compared with such water-supply alternatives as imported water, groundwater, or the use of gray water onsite for landscaping from homes. Institutional barriers, as well as varying regulatory agency priorities and public misperception, can make it difficult to implement water-recycling projects. Finally, early in the planning process, agencies must reach out to the public to address any concerns and to keep the public informed and involved in the planning process.

Besides the initial economic costs of constructing new or retrofitted infrastructure to accommodate water reuse, public perception is the biggest obstacle (or asset) to success, although immediate lack of acceptance need not shut down a project. Likewise, to address such public misperceptions, agencies must reach out to the public early in the planning process to address any concerns and to keep the public informed and involved.

Note that “acceptance,” in general, is different from “acceptable to me.” Po et al. (38) describe studies conducted in the United States and Australia in which residents generally accepting of the theory of using recycled water reported that they could not use the water themselves. In a study of residents served by a dual system of unrecycled and recycled water, Marks et al. (27) observed that most people expected the cost of the recycled water to be lower because of its “inferior” quality. Both economic and environmental benefits are likely necessary to gain the public’s acceptance, although necessity may be an important factor as well. Therefore, it is important for regulators and water purveyors to understand the apparent contradictions and distrust and take appropriate action to address them. It is not simply a matter of education; people report not trusting the quality of recycled water despite expert testimony of its safety. More social/behavioral research on how people evaluate risk is necessary to develop strategies aimed at gaining public acceptance.

One example of a community that adopted a water reuse ordinance in 2008 is the City of Tucson, Arizona. The ordinance requires that all new single-family and duplex residential dwelling units include either a separate multiple pipe outlet or a diverter valve, and outside stub-out installation on clothes washing machine hook-ups, to allow separate discharge of gray water for direct irrigation, and they must also include a building drain for toilets, showers, and bathtubs, segregated from drains for all other plumbing fixtures and connected a minimum of three feet from the limits of the foundation, to allow for future installation of a distributed gray water system.

**CONCLUSION**

As early as 1993 (45), scientists, public health advocates, and regulators have observed, studied, and evaluated the issue of the occurrence of numerous unregulated contaminants and their breakdown products in water sources. Although the current paradigm of regulating individual chemicals provides considerable public health protection, ever-improving analytical techniques enable us to detect more chemicals at even lower concentrations. Many uncertainties exist about the potential health
risks of exposure to such mixtures of low levels of contaminants. Supplemental approaches are clearly needed to manage our water resources sustainably to ensure the delivery of safe water to future generations. Advances in toxicity testing and assessment, improvements in water reuse technologies, and the use of water treatment as a precautionary measure represent approaches that hold promise for sustaining clean and plentiful water in the decades to come.

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