

Potable Water Reuse Report

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Chemicals in Potable Reuse: Prioritizing and Controlling a Wide Universe of Compounds

Key Takeaways:

- While pathogens can cause health impacts after even short-term exposures, most chemicals of concern in potable reuse only impact public health after long-term, chronic exposures.
- Experts agree that potable reuse should focus on a *wider diversity* of chemicals than those regulated in traditional drinking water sources. One challenge is to identify which compounds should be prioritized.
- A commonly used risk-based approach prioritizes compounds that are frequently detected and at concentrations above their health thresholds. Lists of relevant compounds can be further refined through the selection of conservative indicators and surrogates.
- Multiple strategies are needed to control the ever-evolving universe of chemicals including robust and diverse treatment, source control, monitoring, and, in the case of indirect potable reuse, the environmental buffer.

Introduction

The [previous series](#) of the Potable Water Reuse Report focused on what many public health experts consider to be the primary threat in potable reuse: pathogens. Given their potential to cause infection and illness after a *single* exposure, pathogens must be consistently and effectively controlled at all times.

This Series turns the focus to chemicals. Unlike pathogens, most chemicals are *not* present at concentrations that pose an immediate public health threat (Figure 1). And yet, chemicals often get more attention from the media and hence, are more of a concern to the public. Why the disconnect between what the media and the public health experts deem to be the primary threat? Perhaps it's the awareness that there are millions of chemicals in the world and our methods for detecting them are improving every day. With analytical instruments capable of detecting many chemicals at parts per trillion concentrations (ng/L), Professor Shane Snyder said, "In most tap water in this country, it's pretty easy to find whatever you want to find." Given this ability to detect chemicals at very low concentrations, it is no surprise that studies that look for chemicals in water frequently find them. What gets lost, however, is that many of these chemicals are present at

concentrations far below levels of health concern. Of those that remain, most compounds must be present for extended periods before a health impact occurs.

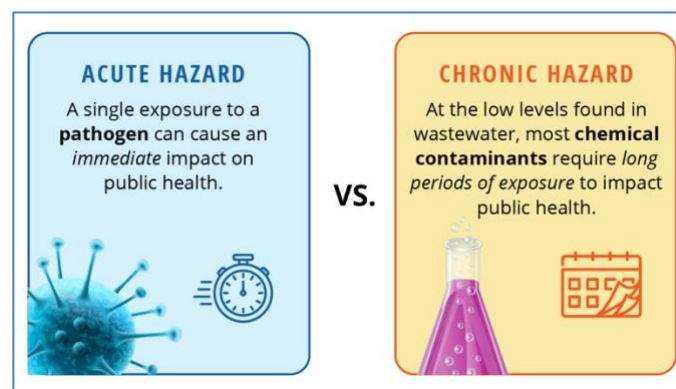


Figure 1: Chemicals are typically a chronic hazard rather than an acute hazard.

As we think about controlling exposure risk in potable reuse, two key features differentiate chemicals from pathogens: the huge **diversity** of potential compounds and the **chronic** nature of their threat. In light of this, two guiding questions for chemical control are: (1) How do we decide *which* chemicals to care about? (2) How do we

ensure our potable reuse systems control these diverse threats? For this issue, we interviewed some of the industry’s experts to gain perspective on these important questions (Table 1).

Table 1: Potable reuse experts interviewed for this Series

Interviewee	Title	Organization
Charles Bott	Chief Technology Officer	Hampton Roads Sanitation District
Eric Dickenson	Water Quality R&D Project Manager	Southern Nevada Water Authority
Jörg Drewes	Chair Professor of Urban Water Systems Engineering	Technical University of Munich
Shane Snyder	José Domingo Pérez Foundation Chair and Professor	Georgia Institute of Technology
Jessica Steigerwald	Process Systems Engineer	Southern Nevada Water Authority

1. Which Chemicals Should We Care About?

The [World Health Organization](#) estimates that there are more than 160 million known chemicals, and this universe of chemicals is constantly growing. Water reuse practitioners and regulators have the unique challenge of determining *which* of these millions of chemicals we should care about to protect public health.

Regulated Chemicals

An obvious place to start is with the chemicals that are already regulated in our drinking waters. At a minimum, water produced from potable reuse should meet existing drinking water standards. In the United States (US), all potable reuse regulations require compliance with all chemicals regulated by the Safe Drinking Water Act ([see Series 1 Issue 2](#)).

The US Environmental Protection Agency (EPA) decides which chemicals to regulate in the Safe Drinking Water Act by assessing two primary factors: a chemical’s **occurrence** in traditional source waters (i.e., surface waters and groundwaters) and its **toxicity**. If a chemical occurs frequently in public water systems at concentrations that could pose a health threat, the US EPA considers developing a regulatory standard for it. Existing Maximum Contaminant Levels cover known chemicals with both chronic and acute effects, and they consider impacts on multiple populations including exposure during sensitive periods of development.

Potable reuse represents a break from the traditional paradigm since it draws from wastewater as opposed to surface and groundwaters that benefit from regulatory structures protecting them from toxic discharges (such as

the Clean Water Act in the US). Monitoring has confirmed that wastewaters contain a higher diversity and concentration of chemicals than traditional source waters. Consequently, Snyder noted that the regulated drinking water contaminants may not be sufficient for potable reuse: “We need to be more thoughtful in the chemicals we are worried about.” In addition to concern for regulated drinking water contaminants, we are also concerned with ones that are currently unregulated. These compounds are referred to as chemicals of emerging concern (CECs). CECs may include compounds that are discharged directly into wastewater—including pharmaceuticals and personal care products, pesticides, and industrial chemicals—and compounds formed during treatment, including unregulated disinfection byproducts.

Shrinking the list of unregulated chemicals

The experts interviewed agree that it makes sense to look *beyond* just the currently regulated chemicals. But with millions of chemicals, it is not feasible to keep adding new chemicals to the monitoring list every year. Jörg Drewes put it best: “This universe of chemicals is growing every day by hundreds of new chemicals. In recycled water we will never be able to identify all of them. We need to be more tailored towards what is relevant.”

So how do we shrink this universe to focus on what is relevant? The experts describe two main approaches that can be used to tackle this question. We show in Figure 2 how these approaches are linked.

Approach 1: Identify Public Health Threats

The first approach leverages the same risk-based framework used for regulating chemicals in traditional source waters but applies it to wastewater. The distinction for potable reuse, however, is that it requires knowledge of the chemical’s occurrence in wastewater (rather than surface or groundwater), in addition to understanding the chemical’s toxicity.

One challenge is that many chemicals have never been looked for in wastewaters. As Eric Dickenson noted: “There is still a gap in our understanding of which chemicals occur in wastewater.” Consequently, monitoring campaigns are needed to determine which chemicals are present. If the campaign shows that a given chemical is never detected, it provides justification to remove it from consideration.

Yet, a compound’s occurrence in wastewaters alone is not enough to elicit concern. If the compound occurs at levels below a health threshold, then it is typically deprioritized compared to compounds present at or above their health thresholds (Figure 2).

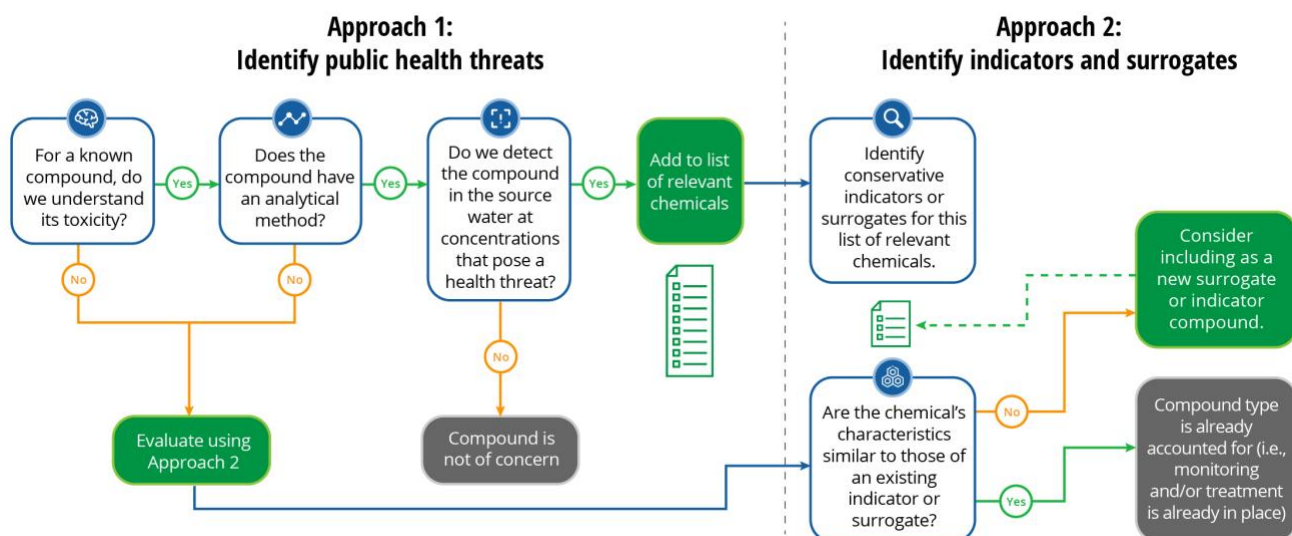


Figure 2: For the control of unregulated chemicals in potable reuse, Approach 1 is a risk-based framework to develop an initial list of chemicals that may pose a threat to public health. Approach 2 is used to refine the list to a smaller number of indicator and surrogate compounds whose control would ensure protection against the full Approach 1 list.

One challenge with Approach 1, is that some emerging chemicals are so new that they lack (1) analytical methods that are needed to detect them, and/or (2) toxicity information. In a recent research study to develop health thresholds, Jessica Steigerwald found that nearly 75% of the compounds of interest did not have sufficient toxicity information to evaluate their health risk. The reason for this is due to the complexity of developing toxicity data, which typically requires years of studies often using animal- and/or cell-based experiments. Snyder highlighted this challenge: “The regulatory paradigm with mammalian toxicology studies can’t keep up with the growing list of chemicals.”

Recently, the US EPA announced it would eliminate mammalian-based toxicity testing in lieu of “new approach methods” using non-animal testing including: (1) methods using cultured cells, tissues, or microorganisms, (2) assays testing a chemical’s reactivity with biological compounds like proteins, and (3) computer-based methods (including artificial intelligence) to predict the potential harmful effects of chemicals. Opponents worry that the information developed through the new methods alone (i.e., in the absence of animal testing) may not be as transferable to human health. Proponents argue, however, that it will provide more rapid and cost-effective information and allow more efficient evaluation of chemical toxicity.

Approach 2: Identify Indicators and Surrogates

The second approach refines the list of chemicals developed in Approach 1. The goal of Approach 2 is to

identify a set of indicators and surrogates; control of the indicators and surrogates would assure protection against the full list of chemicals in Approach 1. An **indicator** is a chemical that has greater resistance to treatment and whose removal can demonstrate the effectiveness of treatment against a wider suite of compounds. A **surrogate** is a parameter that can be measured continuously (e.g., total organic carbon or conductivity) to assess the effectiveness of treatment in real-time. The main benefit of Approach 2 is its potential to reduce the number of compounds to monitor compared to Approach 1

Using indicators for chemical control is akin to reference pathogens for pathogen control. In [Issue 2.1](#), we showed that treatment and monitoring are developed for a smaller number of reference pathogens, whose reduction ensures protection against the broader diversity of pathogens. Approach 2 applies this same logic to chemicals.

Several groups in the US have undertaken efforts to determine appropriate surrogate or indicator compounds for the universe of chemical contaminants. For example, the [California State Water Board has assembled a panel of experts](#) (including Drewes and Snyder) to develop monitoring strategies for emerging chemicals in [recycled water](#). Drewes summarized their plan: “We need to evaluate which chemicals have the properties to go through treatment. These are the key indicator groups we should use to assess treatment.” Rather than measuring an ever-expanding list of new compounds, this approach focuses on compounds that provide confidence that the treatment train protects against the diversity of chemicals potentially present in wastewater (Figure 2).

This approach is being carried into many potable reuse regulations in the US. For example, most potable reuse regulations require treatment trains that demonstrate removal of 1,4-dioxane, a low molecular weight, recalcitrant compound that can pass through many treatment barriers. In this case, 1,4-dioxane serves as an *indicator* for a wider suite of contaminants and provides confidence in the effectiveness of treatment. Many regulations also require monitoring of total organic carbon as a *surrogate* for removal of trace organics.

Approach 2 can also be used to evaluate compounds that lack occurrence and/or toxicity data. In this case, a compound's physical-chemical characteristics (e.g., chemical structure, biodegradability, polarity, molecular size, and volatility) are compared to those of existing indicators and surrogates to understand if the barriers that are already in place will also control this new compound. Dickenson said, "Regardless of a compound's toxicity, I always come back to treatment. What are the barriers that would be able to control that compound? If we have a treatment barrier in place that removes it, then I feel reassured that we can control it."

How do the approaches work together?

Using PFAS as an example: if we only use Approach 1, we may have a list of hundreds of PFAS compounds to monitor. Using Approach 2, we can refine this list by evaluating the characteristics of the PFAS compounds based on treatability and identify a smaller number of conservative indicators. Controlling for the indicators would ensure that the broader class of PFAS chemicals would also be controlled even if they are not directly monitored. In this way, Approach 1 is used to develop an initial list of relevant compounds and Approach 2 is used to refine the list to a smaller number of indicator and surrogate compounds that can be reasonably measured.

Keeping the list of chemicals up to date

The experts agree that these lists should be continually updated. Drewes emphasized, "Risk assessment is not a one-time effort. It's something you do on regular cycle." Fortunately, many institutions have implemented on-going programs to identify unregulated chemical threats for potential regulation. For example, every 5 years the EPA develops a list of unregulated contaminants that may require future regulation ([Contaminant Candidate List](#), or CCL). The EPA also implements a monitoring program to support regulatory decisions on unregulated contaminants ([Unregulated Contaminant Monitoring Rule](#), or UCMR). Steigerwald also noted the European Union's [REACH](#) program as a key reference for assessing chemical risk. Beyond the EPA, REACH, and other national inst-

itutions, Dickenson added, "We also rely on academics to identify new compounds and predict their toxicity."

Monitoring Approaches

Current monitoring approaches rely mainly on "targeted" analyses that look for specific, known compounds in water samples using techniques like mass spectrometry. But not only do we have to know the compound exists, we must have a method and standards to measure and quantify it. Targeted analyses do not address how we can control compounds that we don't know exist or aren't looking for.

Non-targeted analysis (NTA) refers to a suite of techniques that can identify the presence of chemical compounds in water samples without prior knowledge of the compounds. **High-resolution mass spectrometry** is one form of NTA that scans water samples to detect and characterize chemical structures that are present. This information can be used to identify compounds, including unexpected or previously unidentified ones.

Bioassays are another type of NTA that evaluate whether a water sample contains chemicals that impart a biological effect on living cells. Bioassays can consider not only the effect of individual chemicals but also mixtures of chemicals that may have synergistic or antagonistic effects. Snyder—a longstanding proponent of NTA—emphasized the need for a multi-pronged monitoring approach that includes NTA in combination with other targeted strategies to understand the broad world of chemical threats.

2. Controlling Chemical Threats

The approach to controlling chemicals needs to be multi-faceted to account for an ever-evolving chemical landscape that includes both knowns and unknowns. Rather than emphasize a single strategy (e.g., treatment alone), most approaches rely on multiple complementary strategies. In addition to targeted and non-targeted monitoring, these strategies include source control, multi-barrier treatment, and blending/dilution (Figure 3). Indirect potable reuse schemes also benefit from the environmental buffer. Thus, *no single* strategy is expected to be infallible, instead, a collective set of strategies is relied on to reduce chemical threats to negligible levels.

Source Control

The primary goal of source control in potable reuse settings is to minimize the concentration of chemicals discharged into the source water. In the US, the [federal pretreatment program](#) provides a solid starting point for potable reuse source control programs. Broadly, the program establishes limits for industrial discharges,

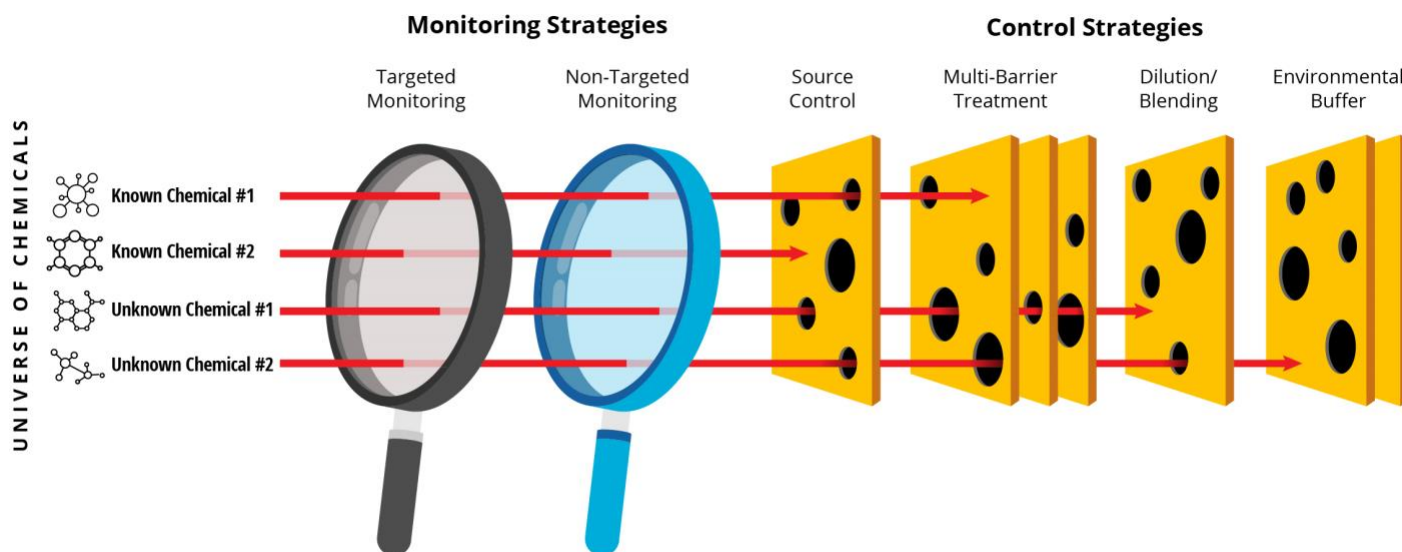


Figure 3: A collective set of strategies are needed to control the diversity of known and unknown chemicals.

requires effluent monitoring for compliance, and enforces actions when limits are exceeded. Historically, the focus of source control has been on maintaining the operation and effectiveness of wastewater treatment plants and protecting *environmental* health. While public health is also considered, the protections are limited since the treated wastewater is not intended for human consumption. With potable reuse, however, the domain of source control may need to expand to consider the wider diversity of chemicals that threaten *public* health.

By its nature, source control is a more reactive strategy. Limits for dischargers are typically established *after* a compound has been found to pass through treatment barriers or impact treatment effectiveness. Nevertheless, successful source control programs have demonstrated the ability to reduce chemicals of concern from entering the sewershed, providing an important chemical control strategy.

Charles Bott mentioned that source control has played a key role in Hampton Roads Sanitation District's strategy for controlling chemicals: "When we had a detection of acrylamide, we were able to determine the discharger in our service area and resolve the issue." He also noted how source control helped HRSD reduce concentrations of bromide, 1,4-dioxane, and PFAS precursors in their potable reuse feedwater.

Countries outside the US have implemented other strategies to protect potable reuse projects. For example, the direct potable reuse project in Windhoek, Namibia sources water exclusively from a wastewater treatment

plant that does not receive industrial wastes. Singapore's NEWater program uses extensive *monitoring* within the collection system to identify and alert operators to the presence of chemical peaks.

Multi-Barrier Treatment

Every expert we interviewed agreed on the benefits of *multi-barrier* treatment trains. For example, Dickenson emphasized the importance of using multiple *mechanisms* of control (e.g., physical removal, chemical oxidation, and biodegradation) so that a compound that passes the first barrier might still be removed by subsequent barriers. Drewes echoed this sentiment saying, "We should rely on a diverse set of technical barriers."

Multi-barrier treatment is required in many potable reuse regulations across the US, including in Colorado, California, Florida, and Arizona. To date, regulatory requirements have been built around two main treatment approaches: reverse osmosis-based treatment and so-called "carbon-based treatment," which typically uses a combination of ozone and biological activated carbon that is often followed by granular activated carbon. Regardless of the technology used, treatment *robustness* has been the key to addressing the diverse chemicals present in wastewater (see [Series 1 Issue 1](#)). By stacking treatment trains with different mechanisms of removal, we increase the likelihood that one (or more) mechanism will remove future chemicals of concern. As new chemicals are discovered, it will be important to confirm that existing treatment trains provide effective control or to evolve the trains to incorporate additional mechanisms of removal.

Dilution and Blending

In addition to treatment, dilution and blending may also be used to control chemical contaminants. For example, California's groundwater recharge regulations include strict TOC limits that can be met, in part, through blending, while the DPR regulations require sufficient mixing to dampen a one-hour peak of chemicals by a factor of ten. The practice has precedent in the Safe Drinking Water Act, which allows public water systems to blend different water sources to meet EPA standards provided the final mixture is safe and complies with regulations.

Environmental Buffer

Indirect potable reuse leverages one final tool for controlling chemicals: the environment. The benefits of environmental buffers for chemical control continue to be demonstrated in both [aquifers](#) and reservoirs, where both attenuation and dilution can provide important reductions in chemical concentrations. For this reason, Drewes noted, "If we can take advantage of the role of nature or an environmental buffer, we should, because it is very efficient treatment for chemicals that are biodegradable." Bott additionally pointed out that the environment provides valuable retention time to respond during potential failure events: "months of travel time in an aquifer offer opportunities to respond if treatment doesn't go just right."

3. Putting Chemicals in Perspective

Most chemicals in wastewater are present at sufficiently low levels that they pose a threat to public health only after

long-term (chronic) exposure. Unlike with pathogens, a brief (acute) exposure of a chemical compound above its chronic health threshold is unlikely to impact most individuals. However, continued exposure to that chemical could cause health impacts over time. It is therefore important for potable reuse systems to control against potential chemical threats in source waters.

Experts have been working to narrow down the list of chemicals of concern for decades. While there are established approaches for determining what chemicals to prioritize, the chemical universe will continue to expand. Therefore, our lists of priority chemicals must continue to evolve in parallel. Knowledge of occurrence in source waters, toxicity, and identification of indicators and surrogates can further narrow the list of chemicals of concern. Additional tools like non-targeted analysis can help identify threats from unknown chemicals or combinations of chemicals. Coupled with continued research into the next chemical threat, we can continue to refine our understanding of chemicals of concern.

When it comes to controlling chemicals, robust multi-barrier treatment is an effective approach for both the knowns and unknowns. Beyond treatment, additional strategies such as monitoring, source control, blending/dilution, and environmental buffers enhance the approach for chemical control. The next issues will take a deeper dive on the role of monitoring and source control in potable reuse projects.

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