

PFAS Experts Symposium: Statements on regulatory policy, chemistry and analytics, toxicology, transport/fate, and remediation for per- and polyfluoroalkyl substances (PFAS) contamination issues

John A. Simon¹ | Stew Abrams² | Tim Bradburne³ | Dan Bryant⁴ | Matthew Burns⁵ | Daniel Cassidy⁶ | John Cherry⁷ | Sheau-Yun (Dora) Chiang⁸ | Douglas Cox⁹ | Michelle Crimi¹⁰ | Elizabeth Denly¹¹ | Bill DiGuseppi¹² | Jim Fenstermacher¹³ | Stephanie Fiorenza¹⁴ | Joseph Guarnaccia¹⁵ | Nathan Hagelin¹⁶ | Linda Hall¹⁷ | John Hesemann¹⁸ | Erika Houtz¹⁹ | Stephen S. Koenigsberg²⁰ | Francois Lauzon²¹ | Jeffrey Longworth²² | Tom Maher²³ | Angus McGrath²⁴ | Ravi Naidu²⁵ | Charles J. Newell²⁶ | Beth L. Parker²⁷ | Tadbir Singh²⁸ | Paul Tomiczek²⁹ | Rick Wice³⁰

¹Nathan Associates Inc, Arlington, VA

²Langan

³BBJ Group

⁴Woodard & Curran

⁵WSP

⁶Western Michigan University

⁷University of Guelph

⁸CDM Smith

⁹GHD

¹⁰Clarkson University

¹¹TRC

¹²Jacobs

¹³Ramboll

¹⁴BP

¹⁵BASF

¹⁶Wood

¹⁷GSI

¹⁸Burns & McDonnell

¹⁹Arcadis

²⁰EN Rx

²¹Stantec

²²Barnes & Thornburg

²³Civil & Environmental Consultants

²⁴Stantec

²⁵CRC Care

²⁶GSI

Abstract

Sixty leading members of the scientific, engineering, regulatory, and legal communities assembled for the PFAS Experts Symposium in Arlington, Virginia on May 20 and 21, 2019 to discuss issues related to per- and polyfluoroalkyl substances (PFAS) based on the quickly evolving developments of PFAS regulations, chemistry and analytics, transport and fate concepts, toxicology, and remediation technologies. The Symposium created a venue for experts with various specialized skills to provide opinions and trade perspectives on existing and new approaches to PFAS assessment and remediation in light of lessons learned managing other contaminants encountered over the past four decades. The following summarizes several consensus points developed as an outcome of the Symposium:

- Regulatory and policy issues: The response by many states and the US Environmental Protection Agency (USEPA) to media exposure and public pressure related to PFAS contamination is to relatively quickly initiate programs to regulate PFAS sites. This includes the USEPA establishing relatively low lifetime health advisory levels for PFAS in drinking water and even more stringent guidance and standards in several states. In addition, if PFAS are designated as hazardous substances at the federal level, as proposed by several Congressional bills, there could be wide-reaching effects including listing of new Superfund sites solely for PFAS, application of stringent state standards, additional characterization and remediation at existing sites, reopening of closed sites, and cost renegotiation among PRPs.

²⁷University of Guelph

²⁸ECOS

²⁹Civil & Environmental Consultants

³⁰Battelle

Correspondence

John A. Simon, Nathan Associates Inc., 1777

N. Kent Street, Arlington, VA 22209.

Email: jsimon@nathaninc.com

- Chemistry and analytics: PFAS analysis is confounded by the lack of regulatory-approved methods for most PFAS in water and all PFAS in solid media and air, interference with current water-based analytical methods if samples contain high levels of suspended solids, and sample collection and analytical interference due to the presence of PFAS in common consumer products, sampling equipment, and laboratory materials.
- Toxicology and risk: Uncertainties remain related to human health and ecological effects for most PFAS; however, regulatory standards and guidance are being established incorporating safety factors that result in part per trillion (ppt) cleanup objectives. Given the thousands of PFAS that may be present in the environment, a more appropriate paradigm may be to develop toxicity criteria for groups of PFAS rather than individual PFAS.
- Transport and fate: The recalcitrance of many perfluoroalkyl compounds and the capability of some fluorotelomers to transform into perfluoroalkyl compounds complicate conceptual site models at many PFAS sites, particularly those involving complex mixtures, such as firefighting foams. Research is warranted to better understand the physicochemical properties and corresponding transport and fate of most PFAS, of branched and linear isomers of the same compounds, and of the interactions of PFAS with other co-contaminants such as nonaqueous phase liquids. Many PFAS exhibit complex transport mechanisms, particularly at the air/water interface, and it is uncertain whether traditional transport principles apply to the ppt levels important to PFAS projects. Existing analytical methods are sufficient when combined with the many advances in site characterization techniques to move rapidly forward at selected sites to develop and test process-based conceptual site models.
- Existing remediation technologies and research: Current technologies largely focus on separation (sorption, ion exchange, or sequestration). Due to diversity in PFAS properties, effective treatment will likely require treatment trains. Monitored natural attenuation will not likely involve destructive reactions, but be driven by processes such as matrix diffusion, sorption, dispersion, and dilution.

The consensus message from the Symposium participants is that PFAS present far more complex challenges to the environmental community than prior contaminants. This is because, in contrast to chlorinated solvents, PFAS are severely complicated by their mobility, persistence, toxicological uncertainties, and technical obstacles to remediation—all under the backdrop of stringent regulatory and policy developments that vary by state and will be further driven by USEPA. Concern was expressed about the time, expense, and complexity required to remediate PFAS sites and whether the challenges of PFAS warrant alternative approaches to site cleanups, including the notion that adaptive management and technical impracticability waivers may be warranted at sites with expansive PFAS plumes. A paradigm shift towards receptor protection rather than broad scale groundwater/aquifer remediation may be appropriate.

1 | INTRODUCTION

The *Remediation Journal* published an issue dedicated to per- and polyfluoroalkyl substances (PFAS) in Spring 2018. The articles in that issue have been widely viewed and cited, and the Journal's

management realized that a PFAS-dedicated symposium would be an excellent follow-on to the special journal issue. Subsequently, on May 20 and 21, 2019, 60 leading members of the scientific, engineering, regulatory, and legal communities assembled for the PFAS Experts Symposium in Arlington, Virginia.

This invitation-only event provided a platform for discussing perspectives on PFAS issues based on the quickly evolving developments of PFAS regulations, chemistry and analytics, transport and fate concepts, toxicology, and remediation technologies. The event was organized and moderated by industry leaders from environmental consulting, industry, regulatory (including the US Environmental Protection Agency [USEPA]), nonprofit technical and research, and legal fields.

The Symposium created a venue for experts with various specialized skills to provide opinions and trade viewpoints on existing and new approaches to PFAS assessment and remediation in light of lessons learned managing other contaminants encountered over the past four decades.

The organizers structured the Symposium as an interactive event with sessions comprised of a mix of panel discussions, focused platform presentations, and breakout groups for in-depth discussion. The emphasis on open forum interaction provided an opportunity for discussion and debate. A standard conference “stand-and-deliver” format was greatly minimized so as to optimize a consensus-driven environment. The focused presentations fed into group discussions whereby the industry leaders were able to grapple with the multifaceted and interconnected problems engendered by PFAS.

The Symposium covered the following six topics:

- policy and regulatory developments;
- chemistry and analytics;
- toxicology;
- transport and fate;
- existing remediation technologies; and
- remediation research

The meeting participants agreed that PFAS possess chemical properties that make them uniquely suited for a wide variety of industrial and commercial applications, which also incidentally endows them with extraordinary stability in the environment. As more PFAS-contaminated sites are identified across the United States, the need for characterization, remediation, and management strategies for PFAS-contaminated media will grow. The number of individual PFAS that have been identified are already in the thousands with new compounds still being discovered. In turn, the toxicity of most of these compounds may never be well understood. But even if PFAS end up being less toxic than currently perceived, their solubility, mobility, and persistence in the subsurface will yield contaminated footprints and plume volumes that dwarf those caused by more common contaminants (e.g., petroleum constituents, chlorinated solvents, etc.).

The consensus takeaway message from the Symposium participants is that PFAS, as compared to prior contaminants like chlorinated solvents, present a unique (“diabolical” as characterized by the esteemed hydrogeologist John Cherry [University of Guelph]) challenge. This is because, in contrast to chlorinated solvents, PFAS are severely complicated by their mobility, persistence, toxicological uncertainties, and technical obstacles to remediation—all under the backdrop of stringent regulatory and policy developments that vary by state and will be further driven by USEPA. Concern was expressed

about the time, expense, and complexity required to remediate PFAS sites and whether the challenges of PFAS warrant a regulatory paradigm shift.

At the outset of the Symposium, another stated goal was for the meeting participants to collaborate on an article capturing the participants’ most important insights to share with remediation practitioners and other experts who were unable to attend the event. Subgroups comprised of subject matter experts provided statements within the six topic areas covered during the Symposium. This article provides a compilation of these statements as topics for the remediation community to consider as we collectively attempt to tackle challenges posed by the ever escalating PFAS contamination issues.

2 | REGULATORY AND POLICY ISSUES

In general, environmental legislation and their associated regulations are driven by a growing awareness, often perpetuated by the media and political pressure, that action is needed to protect human health and the environment. Well-known historic examples include legislation and regulations to manage asbestos, lead-based paint, and chlorinated solvent issues. Perceived risks to human health related to PFAS, primarily through drinking water ingestion, are receiving considerable media and political attention due to events such as:

- Data collected under the USEPA’s Unregulated Chemicals Monitoring Rule 3 (UCMR 3) revealed that over six million people were consuming water in 2015 above the USEPA’s Lifetime Health Advisory Levels for perfluorooctanoic acid (PFOA)/perfluorooctane sulfonate (PFOS; Hu et al., 2016).
- The UCMR 3 data showed that water suppliers serving 16.5 million people in the United States had detectable PFAS in their water (Hu et al., 2016).
- Numerous community-wide drinking water ingestion issues resulting from PFAS contamination at manufacturing and aqueous film-forming foam (AFFF) application sites (e.g., Bennington, Vermont; Parchment, Michigan; Decatur, Alabama; and the Ohio River Valley in the vicinity of Parkersburg, West Virginia).
- Many high profile lawsuits, including an \$850 million settlement by 3M in 2018 and a \$670 million settlement by DuPont in 2017, and more than 75 cases related to AFFF contamination of drinking water.

The response by many states to this media exposure and public pressure is to relatively quickly establish programs to regulate PFAS sites—be it by identifying exposures through statewide sampling programs or requiring investigations and cleanups. This includes the USEPA establishing relatively low Lifetime Health Advisory Levels for drinking water and even more stringent guidance and standards by several states. The compounding trifecta of (a) low PFAS standards, (b) increased regulatory scrutiny, and (c) the mobility and persistence of PFAS are resulting in a quickly expanding number of sites with PFAS-contaminated groundwater and, in many cases, impacted drinking water supplies deemed to warrant investigation and remediation.

There are far too many regulatory and policy developments to possibly capture in this summary article; however, the following discussion summarizes the topics that arose most frequently and spurred the most lively conversations during the PFAS Experts Symposium.

2.1 | Under CERCLA, if PFAS become “hazardous substances,” what could potentially result from a regulatory and policy perspective?

On January 8, 2019, three members of Congress introduced the *PFAS Action Act of 2019* in the US House of Representatives. Similarly, a group of 14 Senators introduced an identical bill in the Senate on March 1st. Both bills have bipartisan support. If passed, the proposed legislation requires USEPA to designate “all PFAS” as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The proposed legislation clearly refers to the entire class of PFAS, not a select few compounds or PFAS included in a specific list. The passage of this legislation could have the following wide reaching effects:

- New Superfund sites could be included on the National Priority List based solely on PFAS in soils, groundwater, surface water, and, theoretically, releases into air. Furthermore, USEPA could unilaterally order removal actions for imminent and substantial endangerment to public health or the environment from PFAS contamination.
- If a 24-hour spill quantity is established, which is likely under CERCLA, releases of the types of PFAS that remain in commerce (generally shorter chain perfluoroalkyl substances) could become reportable.
- Existing CERCLA removal and remedial action and Resource Conservation and Recovery Act (RCRA) correction action sites with cleanups underway for non-PFAS contaminants of concern could require additional remedial investigation and response activities to address PFAS; USEPA is already routinely adding PFAS sampling to 5-year reviews of Superfund site remedies.
- The stringent PFAS standards that many states are introducing (discussed below) will likely become more relevant since these stringent standards will be the applicable or relevant and appropriate requirements (ARARs) for establishing PFAS remedial action objectives at Superfund sites.
- The PFAS legislation could lead to potential reopening/renegotiation of financial allocation between responsible parties and arguments of divisibility based on the likelihood that wastes allegedly contributed to a site contained PFAS. In a cost causation allocation model, PFAS could become more of a cost driver than other contaminants because of the toxicity, mobility, recalcitrance, and increased treatment expense (e.g., compare PFAS to chlorinated solvents from a remedy cost driver perspective at sites where the two classes of contaminants are commingled). The cost associated with PFAS response actions could alter allocation shares among responsible parties at Superfund and other allocated sites.
- USEPA and states could bring cost-recovery (Section 107) claims for environmental response actions related to PFAS investigation

and remediation. In addition, the legislation could lead the way to private party cost-recovery (Section 107) and contribution (Section 113(f)) claims for response action costs related to PFAS investigation and remediation. On a related note, previously implemented remedies may be ineffective for PFAS, which could open the door to arguments that costs incurred were not “necessary” costs of response.

- Natural resources damages have been claimed by several states and more could be filed by additional federal/state/tribal trustees for injuries arising from PFAS impacts to fish, wildlife, and other protected natural resources.

If passed, the bills could have legal challenges that could delay or cause enforceability to come into question (particularly if the bills regulate PFAS as a class) and further potential legal challenges if the USEPA applies the CERCLA listing to environmental media other than drinking water, which, until recently, was the only media for which USEPA had an analytical method. Furthermore, questions about excluding from liability current/past uses of PFAS that were required by law, such as AFFF at airports, will likely arise.

The effects of the *PFAS Action Act* whether it is narrowed in scope to only apply to listed PFAS or applicable to all PFAS would have far-reaching impacts within the realm of CERCLA.

Even if this bill is not enacted as legislation, the USEPA’s *PFAS Action Plan*, issued on February 14, 2019, includes provisions for the Agency to consider other regulatory mechanisms to regulate PFOA and PFOS as hazardous substances (USEPA, 2019a). Therefore, many of the above issues may become reality with or without the bill becoming law.

2.2 | What is the USEPA’s response to the PFAS contamination issues?

Two USEPA representatives provided presentations at the PFAS Experts Symposium: Hannah Holsinger, the drinking water program’s PFAS lead for the Office of Ground Water and Drinking Water, and Laurence Libelo, Chief of the Science Policy Branch, Office of Superfund Remediation and Technology Innovation. Ms. Holsinger outlined USEPA’s *PFAS Action Plan*, which consists of the following elements (in addition to regulating PFOA and PFOS as hazardous substances):

- The USEPA is committed to following the maximum contaminant level (MCL) rulemaking process as established under the Safe Drinking Water Act (SDWA) and, as a next step, is planning a proposed regulatory determination for PFOA and PFOS under the SDWA by the end of 2019.
- The Agency is gathering and evaluating information to determine if regulation is appropriate for other chemicals in the PFAS class.
- The USEPA will propose nationwide drinking water monitoring for PFAS under the next UCMR monitoring cycle.
- The USEPA is rapidly expanding the scientific foundation for understanding and managing risks from PFAS organized around

understanding toxicity, understanding exposure, assessing risks, and identifying effective treatment and remedial actions.

- USEPA is considering including PFAS as part of the toxics release inventory and initiating a proposal to prohibit the uses of certain PFAS through the Toxic Substances Control Act new chemicals program.
- The USEPA will work collaboratively to develop a risk communication toolbox that includes multimedia materials and messaging for federal, state, tribal, and local partners to use with the public.

From a technical/policy perspective, Dr. Libelo outlined the Agency's research program, including but not limited to assembling human health and ecotoxicity data, which the Agency has completed but is continuing to supplement. In addition, USEPA in concert with the National Institute of Environmental Health Sciences is conducting its own human health studies using a high throughput approach to test 150 individual PFAS. The testing will generate toxicity, toxicokinetic, and other types of data to help inform decisions about the potential health effects of PFAS. From an ecotoxicological perspective, the Agency is developing a research plan including identification of sensitive taxa, bioaccumulation, benchmarks, and thresholds and is collaborating with the US Department of Defense (DOD) to develop ecological screening level benchmarks. Finally, to improve analytical laboratory methods for PFAS, the Agency is working to expand the universe of PFAS with approved drinking water methods; developing new methods for analyzing PFAS in surface water, groundwater, soils, sediments, biosolids, and air; and researching analytical methods for improving the ability to identify new PFAS. These developments will improve the ability to assess PFAS sites from both a contaminant distribution and toxicological perspective.

2.3 | The high degree of variability in federal and state PFAS cleanup criteria presents a unique challenge for consultants and the regulated community

Due in part to uncertainty in PFAS toxicity, several states have issued or proposed low part per trillion (ppt) drinking water standards or groundwater cleanup goals while neighboring states do not have any defined criteria. Furthermore, as Ms. Holsinger reported, USEPA is planning a regulatory determination for PFOA and PFOS under the SDWA that could ultimately lead to MCLs. USEPA published *Draft Interim Recommendations to Address Groundwater Contaminated with PFOA and PFOS* for public comment on April 25, 2019 with federal preliminary remediation goals (PRGs) for PFOA and PFOS, including a PRG of 70 ppt for PFOA and PFOS combined for groundwater that is a current or potential source of drinking water (USEPA, 2019b). The 70 ppt combined PFOA and PFOS concentration is consistent with the Agency's Lifetime Health Advisories for PFOA and PFOS published on May 15, 2016 (USEPA, 2016a).

Many states have adopted USEPA's 70 ppt combined PFOA and PFOS Lifetime Health Advisories as reiterated by the Agency in the

PFAS Action Plan and Draft Interim Recommendations to Address Groundwater Contaminated with PFOA and PFOS. Several states have taken actions to propose and implement their own PFAS remediation criteria, for example:

- California—proposed interim notification levels for drinking water at 14 ppt for PFOA and 13 ppt for PFOS.
- Minnesota—established drinking water advisory levels of 35 ppt for PFOA, 15 ppt for PFOS, and 47 ppt for perfluorohexane sulfonate (PFHxS).
- New Jersey—established an MCL of 13 ppt for perfluorononanoic acid (PFNA) and proposed MCLs of 13 ppt for PFOA and 14 ppt for PFOS.
- New York's Drinking Water Quality Council recommended that the Department of Health adopt an MCL of 10 ppt for PFOA and 10 ppt for PFOS.
- Vermont issued emergency PFAS drinking water limits of 20 ppt for PFOA, PFOS, PFHxS, perfluoroheptanoic acid (PFHpA), and PFNA. Vermont's Investigation and Remediation of Contaminated Properties Rule is being amended to list these PFAS as hazardous materials and the Groundwater Protection Rule and Strategy is being amended to adopt an enforcement standard of 20 ppt for these five PFAS. Like the USEPA's Lifetime Health Advisories for PFOA and PFOS, the 20 ppt enforcement standard applies both individually and to the sum of the five listed PFAS.
- New Hampshire's Department of Environmental Services initiated rulemaking to establish MCLs and Ambient Groundwater Quality Standards for four PFAS: PFOA (12 ppt), PFOS (15 ppt), PFNA (11 ppt), and PFHxS (18 ppt).

Approximately 20 states have adopted a wait-and-see approach to regulating PFAS, with no established or proposed PFAS standards.

The DOD, in an April 10, 2019 letter to Senator Jeanne Shaheen (New Hampshire), states that "Using the EPA risk assessment process, the unacceptable risk to human health for cleanup of groundwater with PFOS and PFOA is approximately 380 parts per trillion (ppt)." This statement illustrates the divergence of opinions on acceptable PFAS standards between DOD and the states/USEPA.

For responsible parties and consultants considering the wide range of criteria, it is challenging to determine what, if any, remedial response actions should be taken for detections of PFAS in soil or groundwater at a given site. The state-specific remediation goals will play a large role in establishing the need for remediation. Meanwhile, companies that are trying to establish appropriate environmental reserves for addressing PFAS contamination at various facilities across multiple states are having difficulty in estimating the expected remediation costs for sites, with some sites with remedial objectives at 13 ppt for PFOA, others to 70 ppt, and some having no state-specific criterion. Remedial measures may be required for sites located in California, New Jersey, or Vermont but not for the same type of PFAS contamination problem for facilities located in Georgia, Montana, or West Virginia.

2.4 | USEPA's technical impracticability guidance could play an important role in addressing PFAS sites with groundwater contamination

A primary objective of Superfund and RCRA corrective action is groundwater restoration to drinking water standards. When this is not technically feasible, the USEPA will consider making a technical impracticability (TI) determination (USEPA, 1993). From 1988 to 2014, the Agency granted 105 TI waivers at Superfund sites. These decisions are typically based on an inability to treat, remove, or contain contaminants and long timeframes to reach cleanup goals. The absence of remedial technologies capable of meeting remedial action objectives in complex geologic and hydrogeologic settings and sites with nonaqueous phase liquids (NAPLs) have often been contributing factors for non-PFAS TI waivers to date (USEPA, 2015). Information regarding determination of TI findings for RCRA sites is not readily available.

Volatile organic compounds (VOCs) were the most common class of contamination addressed by Superfund TI waivers (67%) between 1988 and 2011. Geology (64%) and the occurrence of NAPL (55%) accounted for the top two reasons a TI waiver was justified (USEPA, 2012). However, the physical and chemical properties which control the transport and fate of PFAS are creating remediation challenges far more technically unique and complicated than groundwater problems in the 1980s caused by chlorinated VOCs. There will likely be more areas where groundwater is broadly affected by PFAS, perhaps not unlike a region in Italy with a spatially expansive plume encompassing dozens of municipalities (World Health Organization, 2017). Since contaminated drinking water is one of the most well documented PFAS human exposure pathways (Lindstrom, Strynar, & Libelo, 2011) and considering the technical difficulties framing the issue and remediating groundwater to PFAS standards in the 10–70 ppt range, TI determinations could become an important part of Superfund site and RCRA facility remedy decisions. These evaluations could limit active soil and groundwater remediation but are likely going to be predicated on either treating drinking water or providing an alternative water supply to ensure protectiveness.

3 | CHEMISTRY AND ANALYTICS

The chemical properties of PFAS combined with the need to achieve low detection limits complicate PFAS analytical techniques. A long time ago the remediation community became accustomed to standard, validated analytical methods for contaminants in most common environmental media. In fact, most remediation practitioners take for granted the ability of laboratories to provide valid data. However, this is not necessarily the case for analysis of PFAS, which only has standard USEPA methods for drinking water (a method that includes groundwater, surface water, and wastewater should be finalized in the near future). All other environmental

media, and PFAS beyond the methods' lists, are analyzed using method modifications that vary from laboratory to laboratory.

3.1 | Analysis of PFAS samples requires planning and specialized knowledge

It is well understood that PFAS analyses are being performed using liquid chromatography/dual mass spectrometry (LC/MS/MS). As of the date of the Symposium, there were only two USEPA methods for PFAS using LC/MS/MS, USEPA Method 537 Version 1.1 and Method 537.1, both only applicable to drinking water. The primary difference in the two methods is that the first applies to 14 compounds and the second adds in four "replacement" compounds (hexafluoropropylene oxide dimer acid [GenX], 4,8-dioxa-3H-perfluorononanoic acid (ADONA), 9-chlorohexadecafluoro-3-oxanonane-1-sulfonate [F53B major], and 11-chlororeicosafuoro-3-oxaundecane-1-sulfonic acid [F53B minor]). Both methods are intended for water with low total suspended and dissolved solids. However, groundwater samples often are turbid and/or have high total dissolved solids that can interfere with the accuracy and precision of the methods. The drinking water methods are modified not only for use with other matrices but also in sample preparation and extraction and the method of quantification. A common modification to Method 537.1 is the use of isotope dilution for quantitation, which is superior to the internal standard method that is prescribed, because it accounts for matrix effects, allows lower reporting limits, and provides greater accuracy.

On June 12, 2019 (after the PFAS Experts Symposium), USEPA published proposed Method 8327 for the analysis of 24 PFAS in groundwater, surface water, and wastewater samples using LC/MS/MS. USEPA has validated this method but, as of August 2019, has not yet formally included it in the USEPA's SW-846 compendium of test methods. However, this method uses direct injection and an external standard quantitation method. It is not sufficient for low-level detection or rigorous reporting quality. Also, there remain gaps for environmental media other than water and for analyzing PFAS outside of the 24 compounds in Method 8327.

USEPA is currently (as of August 2019) developing a method for complex matrices, including soils and biosolids, that should be available later in 2019 (Method 8328). This method will include the same 24 compounds as Method 8327, plus GenX, and will utilize isotope dilution for quantification. The Agency is also developing a new method (Method 533) for drinking water targeting shorter chain PFAS because the 537 methods discussed above perform poorly for some compounds with four carbons (i.e., C₄ compounds). USEPA is also developing a method for analysis of air samples, the total oxidizable precursor (TOP) assay, and a total organic fluorine (TOF) method.

The DOD has developed an accreditation standard, called the Quality Systems Manual (QSM) for Environmental Laboratories (Version 5.2), that is accredited through the Environmental Laboratory Accreditation Program. QSM 5.2 provides a checklist of elements and quality acceptance criteria for media and analytes

without USEPA published methods. The QSM 5.2 accreditation is the preferred approach for projects not covered by a USEPA Method.

3.2 | Planning and laboratory oversight are important for generating valid PFAS data

The key to a successful PFAS analytical program lies in the planning process. Instead of simply inquiring if a laboratory can perform an analysis for media or analytes, an experienced analytical chemist should discuss the laboratory's methodology to ensure that valid data can be generated for the media sampled and desired compounds. There is limited consistency in the laboratory community with respect to what modifications are implemented, how the samples are prepared, the quantification approach for target PFAS, quality control procedures, and whether or not sample cleanups are performed. As data users, remediation practitioners need to understand the modifications laboratories are implementing or not implementing and how these modifications may be affecting the data. Interpreting PFAS data can be challenging due to the many variations in analytical protocols amongst laboratories. Some of the more significant sources of variability are discussed below.

- Solid Phase Extraction: Most laboratories that are using the modified EPA 537 method are performing a solid phase extraction (SPE) preparation method before the analysis of samples.
 - PFAS can partition in the sample bottle similar to the way they partition in the environment, to the surface. It is important that laboratories utilize the entire sample volume in the extraction procedure. If subsampling from the bottle, there is a potential low bias for the longer chain perfluoroalkyl sulfonates (PFASs) > C8 and perfluoroalkyl carboxylates (PFCAs) > C10.
 - It is also important that the laboratories are rinsing the sample bottles with a water-miscible solvent such as methanol after adding the sample to the SPE cartridge and then adding that methanol rinse to the SPE cartridge because the long-chain perfluoroalkyl acids (PFAAs) can still adhere to the HDPE bottles; this will ensure a complete quantitative transfer.
 - Because there is a wide range of solubilities from C4 to C14 PFAS, this can make SPE challenging. For example, styrene divinylbenzene cartridges have shown poor recoveries of perfluorobutanoic acid and perfluoropentanoic acid. If the pH of the sample is too low (5–6), some PFAS can be lost on the SPE cartridge, depending on the sorbent used. It is important to evaluate which SPE cartridge the laboratory is using and potential limitations, if any.
- Analysis:
 - The sample extract is injected onto the liquid chromatograph column. Again, just like the sample bottle, PFAS can partition to the surface of the extract vial. Before analysis, it is important for the laboratory to vortex the final extract to ensure it is homogenous before analysis and in case partitioning has occurred. If this step is not implemented, the PFAS results may not be representative of the sample.

- The ratios of the transition ions (also called parent/daughter ions) are monitored and evaluated by each laboratory differently. Some laboratories do not even calculate the ion ratios. Some laboratories calculate the ion ratio and do nothing with the information. Some laboratories have generated their own in-house limits for the ion ratios and flag the ion ratios that are outside of these limits in the raw data but, in some cases, this does not get transposed to the final result. Some laboratories use the DOD QSM requirements of 50–150%.
- Linear and branched isomer integration must be performed manually so it is important to:
 - confirm that the laboratory is integrating the linear and branched isomers properly, as there will be some uncertainties in this from laboratory to laboratory;
 - have analytical calibration standards available for the branched isomers so the laboratory is not quantifying the branched isomers using calibration standards for the linear form (this may affect the accuracy of the final result); and
 - understand that interpretation of branched isomers may vary between laboratories and it may even vary between analysts; there may be several peaks that are less defined for branched isomers relative to the single pronounced peak for the linear isomer.
- Laboratories may be using one of three methods of quantitation: external standard, internal standard, and isotope dilution. Isotope dilution is the gold standard for quantitation and the only method that corrects results for potential matrix effects.
- Quantitation using isotope dilution may have some differences depending on the laboratory.
 - It is important to consider at what point in the analytical process the laboratory adds the isotopes to the samples. Is the laboratory adding the isotopes into the sample bottle or are they adding the isotopes to the SPE cartridge after the sample has been added? The preference is to add isotopes to the sample bottle so the isotopes are present in the sample throughout the entire analytical procedure.
 - Laboratories also report the percent recoveries of these isotope standards. There are limits to how low or high these recoveries can be. These limits vary depending on the laboratory or, possibly, the regulatory authority. Isotope recovery limits can also vary considerably which may affect corrective actions taken by each laboratory.

3.2.1 | How will practitioners know what procedures the laboratory is implementing?

The steps outlined above are important and practitioners will not necessarily know what procedures the laboratory followed by simply reviewing the laboratory data package. Practitioners should correspond with the laboratory, audit the laboratory, and review the laboratory's standard operating procedures. If the laboratory is not performing certain steps or evaluating data differently, it may generate data which are not representative of the entire sample.

3.3 | Selecting the appropriate PFAS analyte list

One of the challenges in PFAS investigations is deciding which analytes to measure. When selecting PFAS analytes, there are undeniable disadvantages to measuring more analytes than are regulated or required, as a number of states mandate analysis for many PFASs for which there are not standards.

First, without toxicological data to assist in determining a safe level of any particular PFAS, it can be confusing to interpret what positive detections mean, particularly in the context of drinking water. Often a regulatory body sets the target analyte list, which will include analytes for which there are no established regulatory standards. Second, one result that may arise from generating data for a long list of analytes is that they will later be de facto regulated together as a weighted or unweighted summation. UCMR 3 required the measurement of six PFAS, four of which—PFNA, PFOS, PFOA, and perfluorobutane sulfonic acid (PFBS)—have been researched to the extent to which at least some regulatory entities have set individual standards for these compounds. The other two, PFHxS and PFHpA, have less toxicological data. The consequence of this data collection effort seems to be that a number of states have set a combined regulatory limit for the longer fluorinated carbon species (two or more of PFNA, PFOS, PFOA, PFHxS, and PFHpA). Finally, because PFAS detection limits are especially low and often lower than background levels in some types of media, the chances of a low-level detection above reporting limits are high.

In contrast, there are also strong arguments in favor of generating data for a longer list of analytes, when required or not. Most of the cost incurred in collecting and analyzing samples for PFAS occurs in the organizational and sampling mobilization phases. Although PFAS is an expensive analysis relative to many analytes, the additional cost of going from six analytes to 24 is marginal. By analyzing for a long list of analytes, the need to resample in the future along with the associated costs may be avoided.

Additionally, a longer list of analytes can provide information useful to the conceptual site model (CSM) development and PFAS forensics. Appreciably different PFAS signatures, as determined by relative amounts of PFAS measured, can point to discrete sources, variable in situ transport, and influence remedial design. Additionally, short-chain PFAS data collection, including compounds like 6:2 fluorotelomer sulfonate, can provide information on potential PFAA precursor transformation.

3.4 | TOP assay and TOF methods can provide unique insight for PFAS remedy design

Another challenge in PFAS analysis is knowing when to apply a supplemental analysis, such as the TOP assay or TOF methods. Deploying tools like the TOP assay and TOF methods is useful in several key contexts. First, these techniques can each be used in assessing whether PFAS content may be present in consumer or industrial products. This may be desirable when an entity is trying to future proof products, especially if fluorochemical ingredients are

determined to be unnecessary for product features or performance. Second, these methods can be used to assess the total scope of PFAS contamination, which can influence remedial design. This may be of particular interest for AFFF sites where there are numerous PFAS present that are not typically reported with other PFAS analytical methods, or it may be useful when evaluating the efficacy of a remediation technology. Like non-PFAS cocontaminants, the presence of additional PFAS (e.g., polyfluorinated compounds) that are unmeasured may influence the breakthrough time of target PFAS in granular activated carbon (GAC) or other media. In addition, the TOP assay can detect whether there are polyfluorinated compounds present that may transform upon application of chemical treatment for other contaminants in groundwater.

The TOP assay and TOF methods have undergone considerably less standardization than routine PFAS methods, which have guidelines in the form of standard USEPA methods (at least for water samples) and the DOD QSM. Thus, performance among laboratories may vary more widely than is desirable. The TOP assay provides information about PFAA chain length, but it is not predictive of terminal end products. The TOF method should be used with caution on samples that may contain organofluorine in the form of non-PFAS molecules, such as fluorinated pharmaceuticals, as the TOF concentration will be overestimated relative to PFAS.

3.5 | Collecting samples for PFAS analysis presents its own set of challenges

Collecting samples of groundwater, soil, and other matrices for PFAS analysis is typically performed using conventional sampling techniques with a few modifications. As we know, PFAS are ubiquitous and potentially present in many consumer products. PFAS have been used to manufacture clothing, sunscreens, and other items that could be used personally by field personnel and also in items used in environmental site investigations. Modifications to conventional sampling methods are generally employed to prevent potential cross-contamination of the samples. Some familiar rules of PFAS sampling include avoiding polytetrafluoroethylene, low-density polyethylene, glass materials, adhesive notes, water-proof field books, Tyvek, certain sunscreens, aluminum foil, and so forth (Interstate Technology & Regulatory Council [ITRC], 2018a). It should be noted that little data exist confirming the presence of PFAS in these materials, some of which could be considered victims of “urban legend” regarding potential interferences. Additionally, industry-standard sampling practices should avoid most potential interferences.

Field quality control (QC) samples are very important when sampling for PFAS, probably more critical for this group of contaminants than others, and are needed to evaluate the usability of any data set. There are different regulatory programs that require the collection of trip blanks, field blanks, and equipment blanks. The following discussion evaluates the relative importance of these various types of QC samples.

Trip blanks are used to check for the potential for cross-contamination of PFAS samples during shipment. PFAS are generally not volatile and the possibility of cross-contamination within the cooler from sample to sample is highly unlikely. In most instances, trip blanks collected to date have shown nondetect results for PFAS. Field blanks are used to check for PFAS contamination from ambient conditions and again, in most instances, field blanks collected to date have shown nondetect results. Equipment blanks are a bit more critical. Equipment blanks can help determine the likelihood of PFAS leaching from the equipment used for sampling and are important because the equipment actually comes into contact with samples. Depending on the project objectives, it may even be prudent to collect a preinvestigation equipment blank by sending a section or piece of the equipment (if practical) to the laboratory for a more vigorous leachate analysis. Ultimately, equipment blanks are a strong demonstration that the decontamination process is effective and the equipment is not contributing PFAS to the sample.

The use of financial resources for collecting and analyzing trip blanks and field blanks may not be worthwhile. In the realm of QC, the costs of equipment blanks provide the most meaningful and value-added control to evaluating PFAS results.

4 | TOXICOLOGY AND RISKS

Understanding the toxicity and human health risks of PFAS has proven to be a unique and complex challenge for risk assessors and toxicologists. Several toxicologists who participated in the PFAS Experts Symposium opined on the significant amount of research that is necessary for developing solid science-based toxicity criteria and the fact that adequate toxicity data are not available for the vast majority of PFAS in current commercial use. For some of the more commonly encountered PFAS, this lack of comprehensive toxicity data has led to the application of additional uncertainty factors when regulators established health-based standards and guidelines (“standards”) for PFAS. These standards have far-reaching implications in that they affect remediation strategies, metrics, and costs, while also affecting public perception.

For example, a person who ingests water containing PFAS above a standard tends to be more concerned than someone who ingests water below the concentration—even if the exceedance is minor or if the standard is conservative. Furthermore, despite their health-protective basis, the standards developed for PFAS have garnered backlash from the public, who often expect that zero detectable contamination should be the goal.

The enormous resources necessary to develop toxicity data sufficient to support the regulation of thousands of individual PFAS has led to calls to regulate PFAS as a class. Ironically, the lack of toxicity data that is driving these demands precludes the development of a scientifically-based class regulatory scheme at present. Nonetheless, public and social pressures to regulate PFAS make a class-based regulatory paradigm a distinct possibility for these compounds.

The following overview statements highlight four areas of uncertainty for toxicology and risk that were a focus at the PFAS Experts Symposium.

4.1 | Do PFAS replacement compounds pose concerns for human health?

Concerns over adverse health and environmental effects of “long-chain” PFCAs ($C_nF_{2n+1}COOH$, $n > 7$) and PFSAs ($C_nF_{2n+1}SO_3H$, $n > 6$) have led manufacturers to replace long-chain PFCAs and PFSAs with alternate chemicals. These PFAS “replacement compounds” include short-chain PFAAs like PFHxA and PFBS and fluorinated ether carboxylates such as GenX and ADONA. These replacement PFAS cannot be transformed to long-chain PFAS, are cleared much more rapidly in rodents than the long-chain PFAAs, and are thought to be less toxic and less persistent to humans as a result. Currently-available information suggests that most short-chain PFAS do not accumulate; however, the long half-life of PFHxS in humans (estimated to range from 5.3 to >30 years [Li et al., 2018]) indicates it can bioaccumulate with continued exposure, and that fluorinated carbon chain length alone does not determine the bioaccumulation potential.

Available toxicity data suggest that while there are some shared toxicological effects with the long-chain PFAAs, the replacement compounds studied to date are less toxic and less biologically persistent than the PFAAs. The adequacy of the overall database for replacement PFAS has been questioned, however, as comprehensive peer-reviewed data are not uniformly available for replacement PFAS. Key uncertainties include information on human health effects, the human half-life of these compounds, the magnitude of species differences in clearance, whether their toxicologic mode of action is the same in rodents and humans, and whether optimal dosing periods have been used when studying adverse effects. Because commercial use of some of these chemicals has resulted in human exposure, resolution of these uncertainties is essential to understanding the level of exposure that represents a concern for human health.

4.2 | New considerations for toxicokinetic modeling

Human toxicity values for PFAS are primarily based on animal studies and, currently, rely on toxicokinetic modeling to account for differences in PFAS half-lives between animals and humans. This modeling is a key source of uncertainty in PFAS toxicity assessments, and there is no consensus on the most appropriate method or model to use for interspecies toxicokinetic extrapolation. A recent publication (Convertino et al., 2018) estimated the human half-life of PFOA based on direct serum measurements in cancer patients given known doses of PFOA as a potential therapeutic agent. The study is unique in that it evaluated a single PFAS under controlled conditions where the applied dose and urinary elimination were closely tracked. The results contradict all

previous measurements of PFOA half-life in exposed human populations by suggesting much faster elimination rates and a shorter half-life than previously measured, and raise important questions about the basis of the differing estimates. For example, we do not know how cancer affects the distribution and elimination of PFOA, nor do we know whether the clinical doses used may have saturated normal human clearance mechanisms. Given the significance of human half-life data and their impact on interspecies extrapolation, investigating the basis for the reported difference in PFOA elimination is an important avenue for further investigation.

The observed differences in biologic half-life and elimination kinetics between animals and humans for PFOA and other PFAS are an area of significant uncertainty; further study is needed to reduce this uncertainty and better define the human toxicokinetics of PFAS. In addition, the human toxicokinetics of the short-chain replacement compounds have not been well studied and require further attention.

4.3 | Do we need a new paradigm for developing PFAS toxicity criteria?

Presently, regulatory agencies adhere to a chemical-by-chemical approach for developing toxicity criteria for most environmental contaminants, including individual PFAS. This is a time-consuming approach that is failing to meet regulatory and societal needs for the toxicological data required to support PFAS human health risk assessments. Currently, the USEPA has health effects support documents only for PFOA (USEPA, 2016b) and PFOS (USEPA, 2016c), and has drafted toxicity support documents for two other PFAS: PFBS and related compound potassium perfluorobutane sulfonate (USEPA, 2018a) and hexafluoropropylene oxide dimer acid and its ammonium salt (USEPA, 2018b). Given the many hundreds or thousands of PFAS that may be present in the environment—often as complex and site-specific mixtures—it is imperative that a more efficient toxicity and risk assessment paradigm for PFAS be considered.

An important area of research is how to develop scientifically defensible toxicity criteria that can be applied to different groups of PFAS (e.g., based on fluorinated carbon chain length, functional group, or extent of fluorination). Modern toxicological methods like high throughput testing can both assess PFAS by structural class and evaluate the risks for subsets of the PFAS mixtures found in the environment. USEPA has developed similar strategies for dioxin and dioxin-like compounds (“Toxicity Equivalency Factors”), polycyclic aromatic hydrocarbons (“Relative Potency Factors”), and a congener specific approach for polychlorinated biphenyls. The Dutch National Institute for Public Health and the Environment recently published a technical report describing the development of relative potency factors for some PFAS (Zeilmaker, Fragki, Verbruggen, Bokkers, & Lijzen, 2018). These approaches should be considered and developed further to advance PFAS risk assessment methodology.

4.4 | Use of uncertainty factors in developing drinking water standards

When developing safe drinking water standards for PFAS, regulatory agencies employ uncertainty factors to account for gaps in scientific knowledge in several areas (e.g., extrapolating animal toxicity results to humans, inter-human variability, and extrapolation of lowest observed adverse effect levels [LOAELs] to no observed adverse effect levels [NOAELs]). Accounting for interspecies toxicokinetic differences, choice of critical adverse health effects and confidence in the toxicity database may all lead regulatory agencies to include additional uncertainty factors with the resulting human “no effect” level typically two to three orders of magnitude below the corresponding animal NOAEL. Some states (e.g., Massachusetts) are proposing to include an additional database uncertainty factor. In addition, many regulatory agencies apply a “Relative Source Contribution” term which assumes that 80–90% of PFAS exposure comes from non-drinking water sources, such as consumer products.

As a result of applying these uncertainty and source contribution factors, state and federal drinking water standards and guidance for PFOA and PFOS are several orders of magnitude below the NOAELs or LOAELs observed in animals. Although these uncertainty factors were applied to yield health-protective regulatory criteria, inadequate consideration has been given as to whether they are overly conservative. To some degree, they are an artifact of a risk analysis system developed decades ago. Alternate approaches, such as using better biologically- and mechanistically-based data could reduce the magnitude of these uncertainty factors while simultaneously increasing confidence in the values.

5 | TRANSPORT AND FATE OF PFAS

Although much is not yet known about most PFAS to predict their behaviors in the subsurface, there is an adequate base level of knowledge to examine PFAS site conditions to begin developing CSMs. For example, the state of analytical methods for PFAS is sufficient to begin answering many of the most important questions about the nature and extent of these contaminants in the subsurface, but not strong enough for all questions or all contaminant-hydrogeological conditions to be determined over the long term. We can reliably quantify 24 key PFAS in low turbidity water samples, which is likely sufficient to initiate best practices for groundwater contamination studies within distinct PFAS source zone and flow system conditions. Perhaps this is sufficient to undertake most aspects of site characterization and monitoring to establish foundational relationships and baseline conditions for future comparisons. However, due to the range and complexity of the PFAS class of chemicals and range of hydrogeologic system and source zone conditions, there are substantial information and data gaps regarding the processes influencing their transport and fate to inform risk assessments or best practices for characterization and monitoring, let alone containment and/or remediation. Sufficient knowledge

exists from the past 30–40 years of contaminant hydrogeology practice advanced with a range of other contaminant types, especially the challenges posed by chlorinated and brominated hydrocarbons, to provide a strong basis to begin the fundamental investigation work required for PFAS sites.

5.1 | Rigorous site characterization is particularly important for PFAS investigations

Over the past 30–40 years, the remediation industry developed sophisticated and cost-effective tools for subsurface site characterization for a wide range of hydrogeological conditions. The existing analytical methods (described previously in the Chemistry and Analytics section) and advanced subsurface characterization methods that were developed over the past four decades are sufficient to advance our understanding of the subsurface nature, extent, and transport behavior of key PFAS contaminants in a wide variety of field situations. This was not the case when the dense nonaqueous phase liquid (DNAPL) crisis was recognized in the 1980s, which resulted in much confusion, ineffectiveness, and delays with cost-effective decision-making where chlorinated solvents were concerned. Learning from this past experience, rigorous site characterization should be performed before committing to a dedicated monitoring network or remediation program to ensure understanding of the groundwater flow system (e.g., groundwater flow paths from source to discharge areas) as well as the distribution and composition of the contaminant mass within the hydrogeological heterogeneity. Remediation practitioners have learned the hard way that it is critical to characterize in detail the groundwater flow systems affecting contaminant migration pathways and subsurface processes influencing contaminant distributions, including storage and re-release from low permeability zones and rates of change, to develop robust, process-informed CSMs leading to effective soil and groundwater monitoring and remediation strategies.

Implementing high spatial resolution characterization methods is required before designing appropriately placed monitoring wells to inform our understanding of PFAS transport and fate efficiently and effectively over time. Multiple measurement types over a range of spatial and temporal scales can inform specific processes (e.g., migration along interfaces, diffusion, partitioning to solids, and/or biochemical reactions) and their combined effects within the system (e.g., within the plume, at the plume front versus internal to the source zone).

5.2 | PFAS-specific sampling and analytical methods

As described in Section 3, the PFAS analytical methods for drinking water and other relatively low solids matrices are advancing well (including excellent QA/QC performance), so we are arriving at a good place to begin understanding the nature and extent of groundwater concentration distributions of this short list of PFAS contaminants in the mobile zones. These data sets will enable practitioners to assess plume dimensions, internal architecture and fluxes across multiple transects along the length of the plume, and natural attenuation with distance along flow paths to properly assess

impacts to receptors such as water supply wells or discharge to surface water. Methods for appropriate scales of sampling are sufficiently advanced for these efforts now that the analytical methods for water samples are established for a select number of analytes. However, analytical methods are not sufficiently advanced to understand the total PFAS mass concentrations in sediment cores to distinguish mass attached to solids due to various sorption mechanisms. Total mass extraction of chlorinated solvents from soil and rock core samples for reliable mass concentration distributions in the vadose zones and low permeability sediments proved difficult as well (e.g., Dincutoiu, Górecki, & Parker, 2003, 2006; Górecki & Parker, 2005). Understanding the transport of PFAS constituents in the subsurface will require improved soil/rock/sediment extraction and analytical methods to quantify contaminant mass distribution and fluxes through the vadose and groundwater zones along plume flowpaths with varying hydraulic conductivities. Sampling and analysis of cores will complement groundwater samples that preferentially sample the higher permeability zones and not what is stored in the lower permeability zones or adsorbed onto aquifer sediments. Depth-discrete sampling for PFAS along cross-sections transverse to groundwater flow directions can improve placement of groundwater monitoring intervals for better CSMs for PFAS plumes.

5.3 | The potential for cross-contamination between aquifers is a key consideration for PFAS investigations

Well fields and previous and current remedial actions need to be considered in the context of potential PFAS impacts from a transport perspective. For example, the potential for cross-contamination from drilling boreholes and from existing wells with long well screens pose a risk for cross-contamination between water-bearing zones/aquifers. At sites that have already been investigated for other contaminants, a key concern is whether those investigations have unknowingly resulted in redistributing PFAS through naturally less-vulnerable aquifers due to the breaching of natural aquitards. Historically, this risk was only a viewed as a major concern when considering investigating source zones with the presence of DNAPLs or high dissolved contaminant concentrations (e.g., Britt, 2005; Lacombe, Sudicky, Frape, & Unger, 1995; Sterling et al., 2005). The fact that trace ppt PFAS concentrations can exceed regulatory standards and guidance levels accentuates the concern for cross-contamination at PFAS sites relative to other common groundwater contaminants. Note: cross-contamination should always be considered a concern for any contaminant; however, it is accentuated for PFAS due to ppt thresholds.

5.4 | The focus has been on PFOA and PFOS, but other PFAS must be considered when evaluating transport and fate at PFAS sites

There is limited information on the transport, fate, and short- and long-term toxicity of most PFAS. The transport and fate for PFAS sites are often complicated by the large number of PFAS that can be

present at many sites, particularly those with complex AFFF formulations, and by the differences between linear and branched isomers of some PFAS. The list of PFAS is currently estimated at 5,000 and continually increasing. The physical–chemical properties of each of these compounds or their biogeochemical interactions are not well understood, and it is expected that simultaneous presence of these varying compounds is also likely to strongly influence the transport and fate behavior of PFAS, so PFAS composition and how this evolves with transport distance or contaminant age will possibly be important factors. As seen with other contaminant mixtures, even from the same class of chemicals, the different propensities of individual PFAS to partition onto aquifer sediments cause separation of individual compounds in dissolved plumes (e.g., Freyberg, 1986; Mackay, Freyberg, Roberts, & Cherry, 1986). For example, linear chain compounds within the PFAS class have a higher K_{oc} than their branched-chain isomers and, thus, have a higher adsorption affinity (Kärrman, Elgh-Dalgren, Lafossas, & Møskeland, 2011). Furthermore, due to the number of individual PFAS present at AFFF sites, transport at these sites may be more complicated due to competition between PFAS for adsorption sites than at other PFAS sites with fewer PFAS. Along the same lines, PFAS adsorption can be complicated by the presence of non-PFAS cocontaminants in soil and groundwater. However, such critical information for most PFAS is significantly lacking in the literature. In addition, much of the research conducted to date used freshly spiked soils, which does not reflect long-term field contaminated sites. Hence, the early establishment of well-characterized field sites as observatories could provide the opportunity to study these contaminants and their actual behavior, and complement more controlled laboratory and modeling studies. A greatly improved understanding of the underlying physicochemical processes that control the overall transport behaviors in the subsurface, including source zone depletion, is critical for the formulation of CSMs and for risk assessment modeling.

Key information gaps for the fundamental mechanisms controlling PFAS transport and fate include:

- 1) the release of major PFAS from source zones and the separation of individual fractions;
- 2) influence of physical processes and parameters for PFAS contaminants (dispersion, diffusion, interfacial flow, etc.);
- 3) the effect of cocontaminants on transport;
- 4) differences in adsorption between various isomers;
- 5) transport behavior of PFAS other than PFOA, PFOS, and, perhaps, a few other compounds studied to date such as PFNA and PFBS;
- 6) whether transport mechanisms are different than generally accepted adsorption isotherm theories at low, e.g., ppt, concentrations; and
- 7) the transport and potential abiotic reactions (e.g., fluorotelomers) and possible long-term biological reactions in groundwater plumes.

Understanding these and other data and information gaps will assist in developing new process-based contaminant transport model

frameworks for simulating PFAS migration as a function of critical aquifer properties and hydrogeochemical conditions.

5.5 | Potential applications of existing mathematical flow and transport models

Many mathematical models exist that represent the physical, chemical, and biological processes affecting the transport and fate of various contaminant types in groundwater, hence there is potential to use these models to simulate the various scenarios for PFAS transport, once the conceptual models for these contaminants are developed. Although little is known about PFAS parameters for many of the important processes, conservative assumptions can be made to represent many relevant scenarios. These CSMs may be viewed as hypotheses at first and then through laboratory and field testing may be viewed as more robust with parameters for the range of PFAS contaminants, their source conditions, and the hydrogeologic environments within which they reside and are transported. However, PFAS have their own set of unique properties requiring new thinking about the relative magnitude effects these properties play in their transport and attenuation in subsurface environments. This is where numerical models and simulation experiments can be used effectively to assess the multiple process interactions on the overall plume behavior.

5.6 | A better understanding of the unique mechanisms controlling the transport and fate of PFAS in aquifer systems is needed to assess risk and support remediation efforts

The physicochemical properties of PFAS result in unique mechanisms that significantly affect the transport and fate of these compounds. For example, because most PFAS occur in groundwater in ionic form, they are subject to electrostatic forces that result in enhanced adsorption effects. Most PFAS also behave as surfactants, meaning they are attracted to air–water interfaces. These mechanisms will require contaminant hydrogeologists to develop customized approaches and tools to evaluating the transport and fate of these compounds and ensure representative sampling methodologies to assess concentrations, mobility, and fate, and how these affect remediation technology effectiveness. Design tools such as groundwater flow and contaminant transport and fate models must be tailored to account for these mechanisms, and remediation technologies must be employed in a manner that overcomes or leverages these effects.

Additional research is needed to develop representative PFAS porous media diffusion coefficients and associated physicochemical effects for use in numerical modeling. For example, technologies are already being developed to exploit PFAS air–water interface attraction effects (e.g., foam fractionation). However, the effect of diffusion transport on PFAS plume behavior is much more complex and requires understanding the style of the heterogeneity (e.g., interfaces between the lower and higher K zones) to determine the

surface area for the diffusive fluxes to occur so that the concentration gradients that drive this diffusion transport can be estimated. Furthermore, adsorption theories developed to date are based on part per million (ppm) or part per billion (ppb) groundwater concentrations, not ppt as is the case for PFAS. It is not clear that these adsorption theories will apply to PFAS at these ultra-low concentrations, particularly given the surfactant properties of PFAS. Therefore, additional research on PFAS adsorption at the low concentrations often experienced at PFAS sites is also needed to adequately model how these compounds migrate in soil and groundwater systems.

The combination of these factors controls the extent to which diffusion and adsorption affects plume front migration and attenuation of PFAS concentrations affecting plume velocities and mass discharge to receptors, or mass removal effectiveness during remediation.

The importance of geology and process-based CSMs has been increasingly recognized within the soil and groundwater remediation industry, and the emergence of PFAS as contaminants of significant concern underscores the need for improved characterization of complex sites, re-assessment of empirical based models for the ppt contaminant levels, and numerical performance of mathematical models at sites with PFAS contamination. Site geology and flow system hydraulics represent the fundamental controls on contaminant transport, particularly for mobile contaminants such as PFAS. In addition, aquifer properties that profoundly impact contaminant flux and attenuation processes, particularly for PFAS, are strongly informed by geologic conditions. These properties include organic carbon content, which affects PFAS mass distribution and transport, and mineralogy, which affects electrostatic and ionic reactions between aquifer materials and PFAS behavior. Sound CSMs that appropriately characterize these unique combinations of properties and mechanisms critical to PFAS plume behavior are needed for assessing risks and evaluating remedies, and accurately predicting outcomes. Hence, one of the most urgent tasks for addressing the uncertainties with PFAS sites is to identify, from the suite of established site characterization methods, which combination of data sets and scales of measurements will be most effective for identifying and quantifying the key processes relevant to PFAS migration at sites and deploy those methods with sufficient intensity at a representative number of sites. These field observatories will provide foundational insights for robust general conceptual models for the relevant combinations of PFAS source zone and hydrogeologic conditions.

6 | EXISTING REMEDIATION TECHNOLOGIES: THE CHALLENGES OF PFAS REMEDIATION

Uncertainties related to toxicity, the absence or variation in enforceable standards, and the potential number of regulated compounds, as well as the limitations of new and existing remedial technologies, make the planning, design, and implementation of PFAS remediation strategies extremely complex and challenging. Dr.

Stephen Covey (author of *The 7 Habits of Highly Effective People*) suggested that one should always begin with the end in mind (Covey, 2015). For PFAS remediation, the “end,” that is the final objectives or goals, appear to be in constant flux due to the plethora of proposed state or federal regulations and guidelines, as are the tools available to achieve that end. Despite significant uncertainty in what the endpoint of a given PFAS remediation strategy should be, protecting human health and the environment is the fundamental objective of the environmental industry. Because there are currently very few proven technologies that can effectively remediate PFAS, remediation approaches need to balance appropriate levels of protection with the inherent challenges associated with PFAS treatment. To assist the industry in tackling this challenge, several groups have compiled information on the state of the practice of PFAS remediation technologies (Concawe, 2016; National Ground Water Association, 2017; ITRC, 2018b). However, these documents focus primarily on the status of development (mature, emergent, etc.), with little discussion on developing comprehensive remediation strategies at PFAS sites.

To date, most PFAS treatment has focused on drinking water and mitigating or preventing exposure. Because the current technologies focus on separation (primarily sorption, ion exchange, or sequestration) the net result is to just concentrate PFAS on other media without destroying them. Although effective, sorption technologies are expensive and not compound selective, and generally rely on groundwater extraction and aboveground treatment (i.e., pump and treat) approaches that the industry has spent the last several decades moving away from by a series of innovations, not the least of which is in situ treatment. Although drinking water issues have been addressed at dozens of sites, a coherent strategy to address aquifer and soil remediation has yet to emerge. As explained below, these areas will prove daunting and will require a paradigm shift in how we address this unique and intimidating challenge.

6.1 | Due to the uncertainties surrounding PFAS, a balanced approach to remediation is warranted

A balanced approach to PFAS management is most appropriate; one which addresses existing (or imminent) risks considered unacceptable based on the available science but also avoids remedial actions that may be premature and later deemed unnecessary as the science develops. The initial assessment of PFAS contamination risks should not be limited to those associated with human health and environment. For instance, public perception and long-term financial liabilities resulting from the initial site management actions should also be considered.

Once all risks, along with any applicable regulatory compliance criteria, have been identified and considered, the remediation strategy should be carefully planned within the context of the risk profile and ever-changing landscape of PFAS remediation technology and regulatory enforcement. For instance, while immediate point-of-use treatment may be required to eliminate existing exposure routes, a more deliberate approach may be appropriate for source

remediation and mitigating continued plume migration. An underlying problem with this approach is that existing source and plume mitigation technologies are generally inefficient and expensive.

Although concentrated source zones may warrant mass reduction, remedy selection is a tenuous endeavor as many available remedies have potentially adverse consequences. Case in point, in situ chemical oxidation and in situ stabilization technologies used to treat other contaminant classes for decades, have the potential to actually increase PFAS mobility if applied improperly. In terms of thermal destruction efficiency and combustion byproducts, these matters have not been sufficiently evaluated. Finally, the future of excavation and offsite disposal is in doubt due to increasing difficulties being encountered by landfills in containing PFAS-impacted leachate and in finding effective, affordable treatment for PFAS-impacted leachate.

With respect to plume remediation, the state of the science is rapidly evolving; however, the remediation of plumes with footprints spanning hundreds or thousands of acres is not practical. Indeed, even if emerging technologies become commercially available, the degree of plume remediation achieved for other contaminant classes may never be practical for PFAS. Developing feasible plume management strategies will require more regulatory certainty, more cost-effective remediation technologies, and a better understanding of PFAS transport and fate.

6.2 | PFAS are a family of compounds so varied in chemical properties that effective treatment will typically require multiple technologies/treatment trains

PFAS represent a significant challenge for treatment (in situ or ex situ) in groundwater or soil because they are a diverse group of compounds with widely varying properties. Existing treatment technologies may not be able to treat all PFAS, and may have limited applicability within the diverse group of compounds that comprise PFAS. For instance, some compounds within the PFAS family can be relatively sorptive, but some also can degrade to form smaller chain, less sorptive and more mobile forms. As a result, not all of the complex mixtures of PFAS in the environment will be effectively mitigated by any single treatment technology and the distribution of PFAS may have significant spatial heterogeneity requiring different forms of treatment. To date, remediation has been largely limited to ex situ removal from water, be it through sequestration onto GAC or ion exchange resins. These spent media then require disposal or incineration as a final stage. No single destructive remedial technique has been implemented that can adequately break apart the highly deactivated fluorinated alkyl chain, short of incineration, and even that is poorly documented at present.

The uncertainty surrounding PFAS toxicity has increased the burden on remedial technologies by imposing cleanup levels that are several orders of magnitude lower than concentrations where remedial technologies are typically effective or cost-efficient, especially destructive technologies. Therefore, it is not surprising

that the consensus at the PFAS Experts Symposium was that effective PFAS remediation will likely require a combination of treatment technologies and the optimal approaches must ultimately result in complete destruction rather than sequestration. Therefore, rather than attempting to destroy all PFAS in the media of interest with a single technology, treatment practitioners should consider implementing multiple technologies based on specific compound (structure), media, economic, and/or other factors to determine optimum combinations that provide maximum benefits. For example, sorption onto single-use ion exchange media may be cost-effective and ultimately destructive if the small mass of spent resin is then incinerated. Or a regenerable ion exchange system coupled with nonthermal plasma for treatment of the regenerant fluids may prove to be a cost-effective, fully destructive treatment train.

On a larger scale, plume migration could be reduced with injection of colloidal activated carbon; however, without a significant degree of source control, the colloidal carbon could eventually become saturated and ineffective. Source area mass flux reduction through hydraulic containment or in situ stabilization could provide a temporary solution but, in most cases, does not represent a permanent solution. In the distal, less concentrated portions of PFAS plumes where concentrations are too low for efficient plume-wide treatment, but still too high for human consumption, point-of-use treatment could be implemented to address potential ingestion exposure concerns. Because PFAS plumes are large and often diffuse, this plume-wide, multiple component treatment train approach capitalizes on the strengths of each technology by applying it where it can best be utilized either alone or in combination with other technologies to most efficiently mitigate large-scale PFAS impacts.

6.3 | PFAS represent a truly unique challenge that requires a paradigm shift in approach to groundwater remediation

Toward the ultimate goal of remediating PFAS in groundwater, there are three factors which confound current technologies and approaches. First, PFAS are far more resistant to conventional destructive treatment technologies that have proven cost-effective for other well-established contaminant classes such as chlorinated VOCs and petroleum hydrocarbons. Although it is too early to discount the future development of destructive technologies such as chemical oxidation, chemical reduction, and biological treatment, the current capability of these technologies is limited to partial treatment or pretreatment. Second, at many sites, the nature of PFAS use and mechanisms of their release into the environment have resulted in extremely widespread and diffuse impacts to environmental media. PFAS groundwater plumes can be large and amorphous. Their transport and fate are complex but overall far-reaching, as well as not consistently understood. Urban and industrial communities are often challenged with comingled PFAS contamination from multiple, diverse sources. The sheer volume of PFAS-impacted environmental media presents a physical/chemical

challenge for any technologies attempted. Third, precaution based upon the limitations of available toxicity data has led to the establishment of very low concentration health advisories and cleanup standards, down to double-digit ppt. Combining the three factors of recalcitrance, large scale, and low goals results in a remediation challenge of incomparable scale and cost, unlike anything the environmental industry has encountered in the past. The new paradigm must consider the practicability of PFAS aquifer remediation. Although society works toward eliminating future inputs of PFAS to the environment and as remediation practitioners apply proven technologies to address direct exposures to protect human health (principally ingestion of drinking water) and the environment, we may be forced by economic or scientific constraints to manage PFAS in the environment with a longer-term outlook, as they eventually attenuate to a level below detection. Protection of receptors, coupled with a reduction in mass flux from source areas, may in fact be all that can be achieved within the limitations of physical and chemical processes with this unique and challenging group of man-made compounds.

The ppt-level cleanup objectives presently required for PFAS, combined with the lack of proven destructive in situ remediation technologies and limited information on natural complete degradation processes, may make active in situ remediation exceptionally costly and impracticable at many PFAS sites.

As described in the statement above, difficulties in completely remediating PFAS sites could lead to a paradigm shift, from active source remediation as has been used at most non-PFAS sites to an adaptive strategy, such as that developed by the ITRC, at complex non-PFAS sites. The ITRC defines “complex sites” as sites “...where remedial approaches are not anticipated to bring the site to closure or facilitate transitioning to sustainable long-term management within a reasonable time frame” (ITRC, 2017). ITRC (2017) recommends using an adaptive management approach, where active remediation is performed in an iterative fashion because of the uncertainties in the response of the system. However, when active remedies reach a point of diminishing return, a transition from active remediation to long-term management is prescribed as long as the long-term management strategy controls exposure pathways.

Because of the pernicious combination of (a) ppt-level cleanup objectives, (b) the lack of proven destructive in situ remediation technologies, (c) limited information on natural PFAS degradation processes in the subsurface, (d) the mobility and persistence of PFAS, and (e) the large size of some PFAS plumes, a *triage approach* may be warranted for managing the risks posed by PFAS sites. A hypothetical example of a PFAS site triage system is provided below:

1. Minor PFAS sites may be addressed by complete source treatment (e.g., excavation) combined with natural attenuation of PFAS plumes with low PFAS concentrations and groundwater cleanup by pump and treat or other technologies for plumes with high PFAS concentrations. In the case of PFAS, natural attenuation would not likely involve destructive reactions, but be driven by processes such as matrix diffusion, sorption, and dilution.

2. Intermediate sites may be managed by partial source remediation/removal/control while PFAS plumes will be managed either by allowing natural attenuation of plumes that do not pose near term risks or active control (e.g., hydraulic containment, physical barriers) to prevent expansion of plumes with high PFAS concentrations or to prevent PFAS drinking water ingestion exposure for plumes with near term risk to receptors.
3. Major sites (e.g., semi-regional plumes) may be addressed by partial removal or control of some of the known sources, but because of the large extent of the PFAS plume, alternative water supply or point-of-use treatment is employed for both domestic and municipal users of PFAS-impacted groundwater.

In other words, in the universe of PFAS sites, complete cleanup (i.e., achieving stringent cleanup objectives) using in situ remediation technologies may be relatively uncommon, and PFAS natural attenuation, containment, and point-of-use treatment may become key tools for managing risks at many PFAS plumes.

7 | REMEDIATION RESEARCH

Although a wide range of PFAS remediation technologies show promise or have been tested at the laboratory bench test or field pilot test level, very few technologies are field-demonstrated and generally accepted. The current state of the science remains physical removal or stabilization. For water, physical removal entails extraction followed by adsorption (via activated carbon and/or ion exchange resins) or reverse osmosis, with subsequent disposal or incineration of the resulting concentrated PFAS phase. For soil, physical removal involves excavation followed by disposal at a permitted landfill or incineration. Soil stabilization with reagents such as carbon, clay minerals, Portland cement, or some combination of these materials is a promising technology for treating soils by inhibiting further migration but does not remove PFAS from the environment. The recalcitrance of PFAS to chemical or biological degradation is well recognized, with biological degradation being more tenuous.

Additional challenges for remediation include the diversity of PFAS chemical structures and properties, uncertain transformation pathways that could result in the formation of hazardous intermediate or final products, and the variety of sources and transport mechanisms that result in an unclear understanding of what or where to focus remedial efforts.

The two groups funding the most research on PFAS remediation technologies are the USEPA and the DOD (through its Strategic Environmental Research and Development Program [SERDP] and the Environmental Security Technology Certification Program [ESTCP]). During the PFAS Experts Symposium, Dr. Libelo from USEPA identified that the Agency will be characterizing PFAS sources such as fire training/emergency response sites, manufacturing facilities, production facilities, and disposal sites; evaluating technologies for remediating PFAS-impacted soils, waters, and

sediments; and generating performance and cost data with collaborators to develop models and provide tools to determine optimal treatment choices. Ultimately, USEPA plans to provide tools, data, and guidance regarding cost, efficacy, and implementability for remedy selection and performance monitoring. Due to widespread PFAS contamination at military bases, SERDP and ESTCP have been and continue to fund PFAS remediation research. At the Symposium, Andrea Leeson, SERDP and ESTCP's Deputy Director and Environmental Restoration Program Manager, provided an overview of the dozens of PFAS research projects these organizations have completed or are currently managing. More information on the SERDP/ESTCP research projects can be accessed from the SERDP/ESTCP website at <https://www.serdp-estcp.org/Featured-Initiatives/Per-and-Polyfluoroalkyl-Substances-PFASs>.

7.1 | The immense diversity of PFAS and the corresponding diversity of their chemical properties poses a challenge to many remediation technologies

A recent review identified and categorized 4,730 PFAS-related compounds with Chemical Abstracts Service registry numbers (Organisation for Economic Co-Operation and Development, 2018). All remediation technologies exploit the physicochemical properties of a chemical compound to transform, immobilize, or remove contaminants. Because PFAS reflect a broad diversity of chemical structures and corresponding physicochemical properties, there are few remediation technologies that can effectively address more than a relatively narrow range of PFAS. This problem is compounded by a lack of full characterization of the PFAS that may be present at many sites. Although a remediation technology may appear effective for the narrow list of up to 24 PFAS, the efficacy of technology on other PFAS that may be present but not specifically measured is unknown.

7.2 | Transformation pathways for destructive remedial technologies are not well characterized; incomplete mineralization may result in the formation of intermediate compounds that present new risks

The objective of many PFAS remedial technologies is to chemically transform the compounds (e.g., via biotic or abiotic oxidative or reductive reactions) to less toxic products. Simply demonstrating that the concentration of a specific compound is reduced is not sufficient for PFAS because the reduction in the target PFAS concentration could reflect sorption, partial transformation, or some process other than complete transformation to nontoxic products. Fluorine balance is difficult to achieve due to the nature of fluorine chemistry, the very low concentrations of PFAS typically present, and transformation products relative to analytical limitations. The full transformation pathway is rarely elucidated in technology development studies. Determination of the intermediate

and final transformation products is important to evaluate if PFAS are fully or only partially degraded, if the intermediate and/or final products are themselves of concern (e.g., with respect to mobility, toxicity, etc.), and what environmental characteristics may affect the transformation reactions.

7.3 | The wide-range of PFAS sources and transport mechanisms, and resulting distribution in the environment, results in poor understanding of what to remediate

There are a wide range of known PFAS sources to the environment, including intentional or accidental discharge (e.g., fire-fighting foam), indiscriminate disposal of manufacturing wastes, landfilling of commercial products such as fire and stain-resistant fabrics, coated food packaging materials, productive reuse of wastes before the presence of PFAS was recognized (e.g., distribution of biosolids for agricultural fields or use of treated wastewater for irrigation), and aerial transport and deposition. PFAS distribution in the environment may range from the scale of discrete point sources to areas of impacted soil and groundwater that extend for miles. Because of the diversity of potential PFAS sources and transport mechanisms, identifying what to remediate (e.g., the primary source that results in an exposure risk) may not be well understood.

7.4 | Ex situ stabilization may be effective in the future for pretreating PFAS waste before landfill disposal

Until reliable in situ PFAS destruction technologies are developed, pump and treat will be indispensable to plume management. And until reliable ex situ destruction methods are found, PFAS will continue to be removed from extracted groundwater using GAC, which is then commonly placed in landfills, which are the repositories for PFAS that are the most secure and protective. For these reasons, stabilizing contaminated materials to reduce PFAS leachability is vital to responsibly managing PFAS in the environment. Alternatively, ion exchange resins are used to treat extracted groundwater, albeit considerably less frequently than GAC. However, exhausted ion exchange resins are also either landfilled or regenerated using a process that produces a high concentration PFAS solution that must be managed, typically by incineration.

Other than injecting colloidal GAC, no studies to date demonstrate that in situ techniques, such as injecting oxidation, reduction, or bioremediation amendments, and/or in situ soil blending, can significantly reduce the leaching of PFAS from the vadose zone and PFAS flux in groundwater. Several Symposium participants expressed concern regarding injectable colloidal activated carbon due to the emplaced carbon becoming saturated and eventually releasing the adsorbed PFAS. Or, that the carbon becomes saturated with other

non-PFAS naturally occurring organic matter or other contaminants, and the PFAS passes through the injected carbon.

Ex situ stabilization shows promise for PFAS-contaminated materials that must be landfilled, potentially including: soils, sediments, AFFF liquid wastes, biosolids, spent carbon and other sorptive media, reverse osmosis reject, and electrocoagulation floc. Although toxicity characteristic leaching procedure (TCLP) criteria have not been promulgated for PFAS, proper landfill management suggests that higher concentration PFAS-containing wastes first be stabilized to reduce PFAS leachability. Ongoing research suggests that ex situ stabilization can reduce the leachability of PFAS to low ppt concentrations in TCLP leachate, but large amendment doses are often necessary. A critical question that must be addressed is how reversible is PFAS sorption onto different sorbents.

7.5 | Future PFAS remediation research

Treatment technologies proven effective for PFAS removal from environmental media are currently limited. For some environmental media (e.g., AFFF and highly contaminated soil), cost-prohibitive high-temperature incineration is currently the only proven and viable option. As cost-effective options are increasingly needed for PFAS remediation, research has focused toward the development of technologies that can (a) remove or immobilize PFAS, (b) destroy PFAS, (c) reduce the generation of remediation derived waste streams, and (d) be applied in situ. Examples of PFAS research underway include the following:

- Low-cost, single-use, PFAS-specific, or regenerable sorbents to reduce/eliminate spent sorbent changeouts.
- Foam fractionation or flocculation technologies to reduce high concentrations of PFAS (ppb range and higher) before additional PFAS treatment that is designed to achieve low (ppt) discharge requirements.
- On-site destruction by electrochemical oxidation, reductive defluorination, plasma, sonication, high-temperature smoldering, and enzyme-induced degradation have been studied at bench scale. Scalability, applicability, feasibility, generation of unwanted by-products, and high costs have limited the current capability for widespread commercial implementation of these technologies.
- In situ immobilization (as outlined above).
- In situ destructive technologies, such as bioremediation and abiotic chemical transformation (e.g., chemical oxidation), remain commercially unavailable and there are very limited options currently in development.

Another research direction is to understand how remediation processes can impact PFAS transport and fate due to partial transformation, particularly of precursors. Additionally, there is very little known about PFAS transport and fate in certain media, such as biosolids and sediment. The need for remediation of these media requires evaluation of PFAS leachability and associated potential

environmental impact. The feasibility of removing PFAS in these media has not been widely evaluated but warrants future research.

8 | CONCLUSION

This Symposium summary article highlights the myriad of challenges posed by PFAS contamination issues, many of which are interlinked in ways the remediation field has never experienced. These linkages include the following:

- Increased regulatory scrutiny and quickly developing policies, regulations, and guidance as a result of media attention and public pressure—*which link to:*
- Conservative approaches to develop regulatory guidance and standards in the wake of somewhat limited toxicological data and related uncertainties, which result in stringent numerical criteria for drinking water protection and cleanup—*which lead to:*
- Attempting to understand complex transport mechanisms, particularly at the air/water and water/solids interfaces, that result in uncommon adsorptive behavior of many PFAS as well as difficulties in understanding the transport mechanisms of ppt levels of a surfactant migrating in aquifer systems—*combined with:*
- Transformation of precursors presenting the possibility of “ghost” appearances of regulated perfluorinated species away from source areas—*which is complicated by:*
- The lack of accepted analytical methods for media other than water and the notion that high dissolved and total solids contents can interfere with regulatory accepted analytical methods for water—*which is confounded by:*
- The prospect that new PFAS could be discovered that are as toxic, or more toxic, and as prevalent, or more prevalent, as those currently regulated—*which is also complicated by:*
- The potential that there may be synergistic toxic effects of multiple PFAS, thus, posing further issues related to exposures and controls —*and finally:*
- The absence of cost-effective treatment technologies for in situ and point-of-use treatment and recognition by industry leaders that PFAS sites are going to be more difficult and expensive to manage than other complex sites.

This list is the tip of what appears to be an iceberg of interlinked PFAS issues. What lurks ahead from a regulatory and technical perspective certainly poses a concern to both the regulated and regulatory community as well as their legal and technical advisors. Many of the Symposium participants voiced concerns about the expense of attempting to remediate PFAS sites compared to the benefits to society, particularly in light of the impracticability of remediating many PFAS sites. Several participants called for a change in the regulatory paradigm consisting of reducing PFAS contamination sources and then controlling exposures through point-of-use or alternative water supplies as opposed to broad-based pump-and-treat solutions. However, the sobering reality is that, until such a

regulatory paradigm shift occurs, remediation practitioners will be faced with addressing PFAS sites using the best available science, engineering, and ingenuity.

REFERENCES

- Britt, S. (2005). Testing the in-well horizontal laminar flow assumption with a sand-tank well model. *Ground Water Monitoring & Remediation*, 25, 73–81.
- Concawe. (2016). *Environmental fate and effects of poly- and perfluoroalkyl substances (PFAS)*. Brussels: Author.
- Convertino, M., Church, T. R., Olsen, G. W., Liu, Y., Doyle, E., Elcombe, C. R., ... Evans, T. R. J. (2018). Stochastic pharmacokinetic-pharmacodynamic modeling for assessing the systemic health risk of perfluorooctanoate (PFOA). *Toxicological Sciences*, 163(1), 293–306.
- Covey, S. R. (2015). *The 7 habits of highly effective people*. Salt Lake City, UT: FranklinCovey.
- Dincutoiu, I., Górecki, T., & Parker, B. L. (2003). A novel technique for rapid extraction of volatile organohalogen compounds from low permeability media. *Environmental Science & Technology*, 37(17), 3978–3984.
- Dincutoiu, I., Górecki, T., & Parker, B. L. (2006). Microwave-assisted extraction of trichloroethylene from clay samples. *International Journal of Environmental Analytical Chemistry*, 86(15), 1113–1125.
- Freyberg, D. L. (1986). A natural gradient experiment on solute transport in a sand aquifer: 2. Spatial moments and the advection and dispersion of nonreactive tracers. *Water Resources Research*, 22(13), 2031–2046.
- Górecki, M., & Parker, B. L. (2005). Cross-Contamination in the analysis of VOCs in rock samples. Poster: Pittcon, Orlando, FL, February 27–March 4.
- Hu, X. C., Andrews, D. Q., Lindstrom, A. B., Bruton, T. A., Schaidler, L. A., Grandjean, P., ... Sunderland, E. M. (2016). Detection of poly- and perfluoroalkyl substances (PFASs) in U.S. drinking water linked to industrial sites, military fire training areas, and wastewater treatment plants. *Environmental Science & Technology Letters*, 3(10), 344–350.
- Interstate Technology & Regulatory Council (ITRC). (2017). *Remediation management of complex sites*. Retrieved from <https://rmcs-1.itrcweb.org>
- Interstate Technology & Regulatory Council. (2018a). *Site characterization considerations, sampling precautions, and laboratory analytical methods for per- and polyfluoroalkyl substances (PFAS)*. Washington, DC: Author.
- Interstate Technology & Regulatory Council. (2018b). *Per- and polyfluoroalkyl substances (PFAS) fact sheets*. Washington, DC: Author.
- Kärman, A., Elgh-Dalgren, K., Lafossas, C., & Møskeland, T. (2011). Environmental levels and distribution of structural isomers of perfluoroalkyl acids after aqueous fire-fighting foam (AFFF) contamination. *Environmental Chemistry*, 8(4), 372–380.
- Lacombe, S., Sudicky, E. A., Frappe, S. K., & Unger, A. J. A. (1995). Influence of leaky boreholes on cross-formational groundwater flow and contaminant transport. *Water Resources Research*, 31(8), 1871–1882.
- Li, Y., Fletcher, T., Mucs, D., Scott, K., Lindh, C. H., Tallving, P., & Jakobsson, K. (2018). Half-lives of PFOS, PFHxS and PFOA after end of exposure to contaminated drinking water. *Occupational and Environmental Medicine*, 75(1), 46–51.
- Lindstrom, A. B., Strynar, M. J., & Libelo, E. L. (2011). Polyfluorinated compounds: Past, present, and future. *Environmental Science & Technology*, 45, 7954–7961.
- Mackay, D. M., Freyberg, D. L., Roberts, P. V., & Cherry, J. A. (1986). A natural gradient experiment on solute transport in a sand aquifer: 1. *Water Resources Research*, 22(8), 2017–2029.
- National Ground Water Association. (2017). *Groundwater and PFAS: State of knowledge and practice*. Westerville, OH: Author.
- Organisation for Economic Co-Operation and Development. (2018). *Toward a new comprehensive global database of per- and polyfluoroalkyl substances (PFASs): Summary report on updating the OECD 2007 list of per- and polyfluoroalkyl substances (PFASs)*, Series on risk management No. 39. Retrieved from [https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV-JM-MONO\(2018\)7&doclanguage=en](https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV-JM-MONO(2018)7&doclanguage=en)
- Sterling, S. N., Parker, B. L., Cherry, J. A., Williams, J. H., Lane, J. W., Jr., & Haeni, F. P. (2005). Vertical cross contamination of trichloroethylene in a borehole in fractured sandstone. *Ground Water*, 43(4), 557–573.
- US Environmental Protection Agency (USEPA). (1993). *Guidance for evaluating the technical impracticability of ground-water restoration*. Office of Solid Waste and Emergency Response, Report No. OSWER 9234.2-25. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2012). *Summary of technical impracticability waivers at national priority list sites*. Office of Solid Waste and Emergency Response, Report No. OSWER 9230.2-24. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2015). *Overview of new EPA Superfund groundwater guidance and tools*. Office of Superfund Remediation and Technology Innovation. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2016a). Lifetime health advisories and health effects support documents for perfluorooctanoic acid and perfluorooctane sulfonate. *Federal Register*, 81(101), 33250–33251.
- US Environmental Protection Agency (USEPA). (2016b). *Health effects support document for perfluorooctanoic acid (PFOA)*, EPA 822-R-16-003. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2016c). *Health effects support document for perfluorooctane sulfonate (PFOS)*, EPA 822-R-16-002. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2018a). *Draft—Human health toxicity values for perfluorobutane sulfonic acid (CASRN 375-73-5) and related compound potassium perfluorobutane sulfonate (CASRN 29420-49-3)*. EPA-823-R-18-307. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2018b). *Draft—Human health toxicity values for hexafluoropropylene oxide (HFPO) dimer acid and its ammonium salt (CASRN 13252-13-6 and CASRN 62037-80-3)*. EPA-823-P-18-001. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2019a, February 14). *EPA's per- and polyfluoroalkyl substances (PFAS) action plan*, EPA 823R18004. Washington, DC: Author.
- US Environmental Protection Agency (USEPA). (2019b, April 25). *Draft interim recommendations to address groundwater contaminated with perfluorooctanoic acid and perfluorooctane sulfonate*. Washington, DC: Author.
- World Health Organization. (2017). *Keeping our water clean: The case of water contamination in the Veneto Region, Italy*. WHO Regional Office for Europe. Copenhagen: Author.
- Zeilmaker, M. J., Fragki, S., Verbruggen, E. M. J., Bokkers, B. G. H., & Lijzen, J. P. A. (2018). *Mixture exposure to PFAS: A relative potency factor approach*, RIVM Report 2018-0079. Bilthoven: National Institute for Public Health and the Environment

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