InterPore JOURNAL

Invited Commentary

CHALLENGES AND OPPORTUNITIES FOR POROUS MEDIA RESEARCH TO ADDRESS PFAS GROUNDWATER CONTAMINATION

Bo Guo[1], Mark L. Brusseau[1,2]

[1]Department of Hydrology and Atmospheric Sciences, University of Arizona, USA; [2]Department of Environmental Science, University of Arizona, USA

Correspondence to:
Bo Guo at
boguo@arizona.edu

How to Cite:
Guo, B., & Brusseau, M. L. Challenges and opportunities for porous media research to address PFAS groundwater contamination . InterPore Journal, 1(2), ipj240824–2.
https://doi.org/10.69631/ipj.v1i2nr35

RECEIVED: 11 July 2024
ACCEPTED: 6 Aug. 2024
PUBLISHED: 24 Aug. 2024

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) have become one of the most important contaminants due to their ubiquitous presence in the environment and potentially profound impacts on human health and the environment even at parts per trillion (ppt) concentration levels. A growing number of field investigations have revealed that soils act as PFAS reservoirs at many contaminated sites, with significant amounts of PFAS accumulating over several decades. Because PFAS accumulated in soils may migrate downward to contaminate groundwater resources, understanding the fate and transport of PFAS in soils is of paramount importance for characterizing, managing, and mitigating long-term groundwater contamination risks.

Many PFAS are surfactants that adsorb at air–water and solid–water interfaces, which leads to complex transport behaviors of PFAS in soils. Concomitantly, PFAS present in porewater can modify surface tension and other interfacial properties, which in turn may impact variably saturated flow and PFAS transport. Furthermore, some PFAS are volatile (i.e., can migrate in the gas phase) and/or can transform under environmental conditions into persistent PFAS. These nonlinear and coupled processes are further complicated by complexities of the soil environment such as thin water films, spatial heterogeneity, and complex geochemical conditions.

In this commentary, we present an overview of the current challenges in understanding the fate and transport of PFAS in the environment. Building upon that, we identify a few potential areas where porous media research may play an important role in addressing the problem of PFAS contamination in groundwater.

KEYWORDS

Porous media, PFAS, Per- and polyfluoroalkyl substances, Fluid–fluid interfaces, Fate and transport, Soil, Groundwater, Adsorption

1. THE PFAS CONTAMINATION PROBLEM

PFAS is an acronym that stands for per- and polyfluoroalkyl substances, which are a family of thousands of synthetic chemicals widely used since the 1950s (53). Large-scale manufacturing and applications (such as non-stick and stain-resistant coating, waterproofing treatment, and firefighting foams) (53) have led to their ubiquitous presence in the environment, contaminating surface water, soils, sediments, and groundwater. A growing body of field data demonstrates that vadose zones (below land surface and above groundwater table) at PFAS-contaminated sites have become significant PFAS reservoirs after accumulating mass over decades (14), posing a long-term threat to groundwater resources underneath.

The problem of PFAS contamination is distinctive compared to most of the previous contaminants due to a combination of the following aspects. First, PFAS have been widely used for many industrial applications and consumer products over many decades. Long-term releases from various pathways and sources at different concentration levels (e.g., local concentrated sources of aqueous film forming (AFFF)-impacted sites versus wider and much less concentrated sources of agricultural lands receiving PFAS-containing biosolids) have resulted in their widespread presence in the environment. For example, at least 6,189 sites are known to be contaminated by PFAS in the United States (37) and 45% of the United States drinking water was estimated to contain PFAS (96). Similarly, 22,934 contaminated sites have been reported across 32 European countries, with several countries (Belgium, Netherlands, Italy, Denmark, Germany, United Kingdom, and France) having more than 1,000 sites (28, 101). Note that these numbers may reflect only a fraction of the problem due to incomplete sampling and investigation. Second, unprecedentedly restrictive concentration levels have been established, or are being discussed by regulatory agencies internationally. These concentration levels are several orders of magnitude lower than regulatory levels established for most prior contaminants (74). For example, the maximum contaminant levels for PFOS and PFOA have been set to 4 parts per trillion (ppt) in the United States (102). Even more restrictive regulations are used in some European countries such as Denmark (34) (i.e., 2 ppt for the sum of four PFAS). Third, PFAS consist of thousands of species with significantly different physicochemical properties (e.g., anionic vs. cationic vs. zwitterionic vs. neutral species, different functional groups, and carbon chain lengths) and transport behaviors. Fourth, because vadose zones at many contaminated sites are PFAS reservoirs (14), understanding and quantifying PFAS fate and transport in the vadose zone are central for characterizing, managing, and mitigating long-term groundwater contamination risks. These characteristics pose significant challenges in addressing the problem of PFAS contamination.

Furthermore, most PFAS are surfactants that tend to accumulate at fluid–fluid and solid–fluid interfaces (60). These interfacially-active properties lead to their relatively unique transport behaviors in the environment, particularly in the vadose zone due to abundant air–water and solid–water interfaces in soils. Concomitantly, PFAS accumulating at fluid–fluid and solid–fluid interfaces can also modify the properties of the interfaces (60), including surface tension and wettability. The changes in interfacial properties may in turn impact variably saturated water flow and the transport of PFAS in the vadose zone (45, 110). Any effective characterization and remediation of contaminated vadose zones will require conceptualizations that incorporate these critical interfacial processes. In this commentary, we discuss these complexities of PFAS fate and transport in the vadose zone, and identify the challenges and opportunities where porous media research may be relevant.

2. COMPLEXITY OF THE PFAS PROBLEM FROM A FATE AND TRANSPORT PERSPECTIVE

Air–water interfaces in the vadose zone may arise from the bulk water (e.g., pendular rings) between soil grains (i.e., bulk capillary air–water interfaces) and the thin water films on grain surfaces (**Fig. 1**). Under most field-relevant conditions, the latter accounts for more than 90% of air–water interfaces (19, 20, 30, 55, 58, 76). Air–water interfacial adsorption has been demonstrated to be a major mechanism controlling the fate and transport of PFAS in the vadose zone by laboratory column transport experiments (10, 18, 22, 70, 71, 99), field observations (16, 89), and mathematical modeling (43, 45, 46, 94, 105, 109, 110, 111).

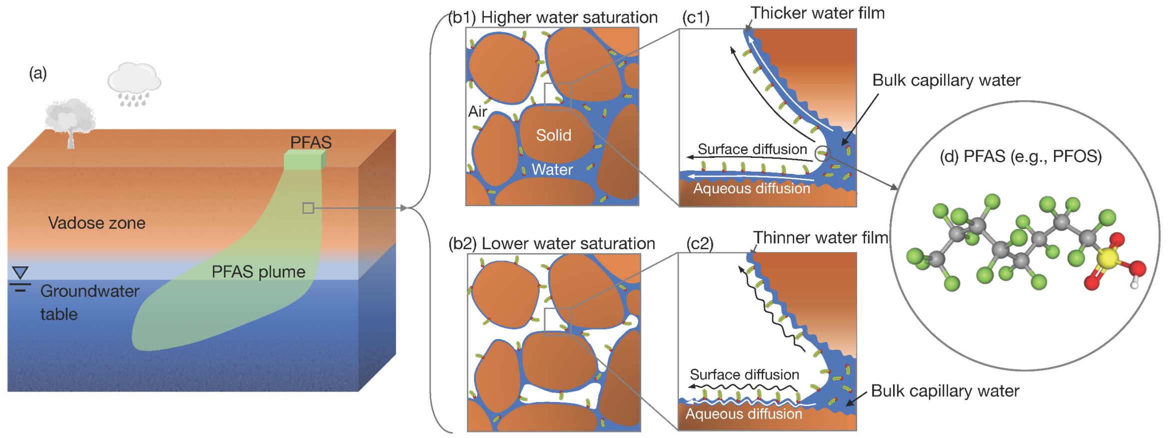

Figure 1: Interfacial retention processes for per- and polyfluoroalkyl substances (PFAS) in the vadose zone. **(a)** Schematic for PFAS contamination in the vadose zone and groundwater, **(b)** adsorption of PFAS at air–water interfaces arising from bulk capillary water and thin water films in soils under different wetting conditions, **(c)** mass transfer of PFAS between bulk capillary water and thin water films, and **(d)** an example PFAS molecule (e.g., perfluorooctane sulfonic acid (PFOS)), where the colors denote different atoms: gray = carbon, green = fluorine, red = oxygen, yellow = sulfur, and white = hydrogen. In panel **(d)**, the molecule consists of a hydrophobic and oleophobic tail (the fluorocarbon chain on the left) and a hydrophilic head (the sulfonic acid functional group on the right). *Figure originally reported in Chen & Guo (25) and used here with permission of the authors and Wiley.*

These studies highlight the importance of understanding and quantifying partitioning of PFAS at air–water interfaces in soils and how it controls PFAS transport in the vadose zone.

Fluid–fluid interfaces have been long recognized as an important factor controlling flow, transport, and reactions in porous media (9). The processes at fluid–fluid interfaces include adsorption and desorption of interfacially-active solutes (38, 56, 59, 86, 98), attachment and detachment of colloids (41, 63, 100, 106), and mass transfer between fluid phases (72, 81). One of the earlier drivers to quantify air–water interfacial area was to test a functional relationship among capillary pressure, saturation, and fluid-fluid interfacial area in a porous medium derived from thermodynamic principles (48, 49, 50). A corollary of this functional relationship suggests that accounting for air–water interfacial area may eliminate hysteretic behaviors observed in capillary pressure and saturation relationships during cyclic drainage and imbibition processes (48, 49, 50, 82). Driven by this fundamental investigation and other more applied problems (e.g., dissolution of non-aqueous phase liquids [NAPL] in groundwater), multiple experimental methods have been developed to measure fluid–fluid interfacial areas in porous media since the late 1990s. One group of methods uses pore-scale imaging to explicitly count interfacial areas, such as X-ray computed tomography (XMT) (5, 15, 32, 33, 90, 107, 108). Another group uses interfacially-active tracers to indirectly measure and compute fluid–fluid interfaces, either by retardation in the breakthrough curves during transport experiments or via the mass of a tracer at fluid–fluid interfaces (6, 21, 25, 38, 59, 86, 88). These interfacially-active tracers can be in the gas or liquid phase. Usually, the gas-phase tracer is an alkane (i.e., not charged) and the liquid-phase tracer an anionic hydrocarbon surfactant (i.e., negatively charged). Additionally, air–water interfacial area can also be estimated from measured soil water characteristic curves using a thermodynamic approach based on energy balance (65, 73).

X-ray computed tomography (and other imaging-based methods) can separate thin-film fluid–fluid interfaces from bulk capillary interfaces. For a water saturation smaller than 0.5, the former measured by XMT is generally much greater than the latter in natural porous media (5, 15). The actual thin-film fluid–fluid interfacial area is typically much greater, as XMT tends to underestimate the thin-film fluid–fluid interfacial area in sand and soil media. This underestimation occurs because XMT does not capture the additional thin-film interfacial area resulting from microscale grain surface roughness (15, 20). For example, by combining XMT and liquid-phase tracer methods, Brusseau et al. (20) reported that thin-film fluid–fluid interfacial areas in a sandy soil accounted for more than 90% of the total fluid–fluid

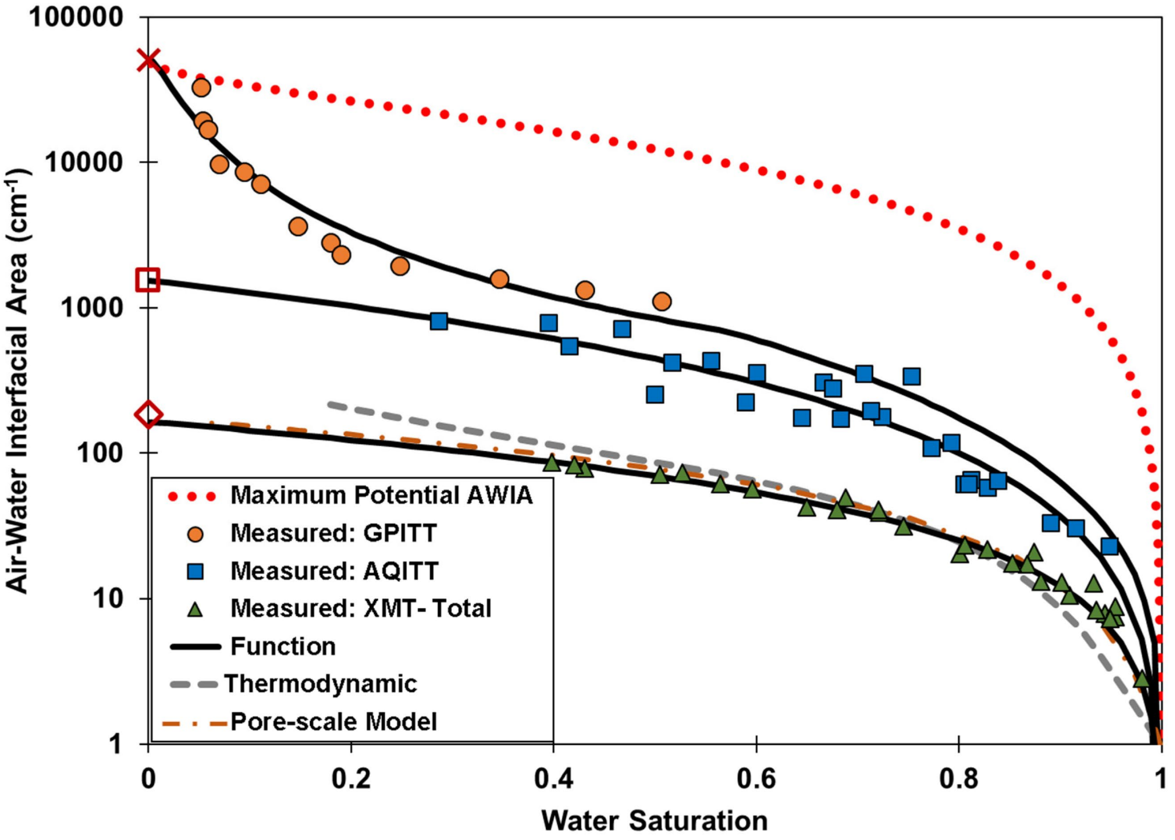

Figure 2: Air–water interfacial area as a function of water saturation for a sand determined by different measurement methods and models. "GPITT" denotes gas-phase interfacial tracer test, "AQITT" denotes aqueous interfacial tracer test. "XMT-total" is the total air–water interfacial area (bulk capillary and film-associated air–water interfacial area) measured by XMT. "Function" refers to an empirical fit. "Thermodynamic" denotes the results computed from the thermodynamic approach (65, 73). "Pore-scale Model" refers to the air–water interfacial area computed by the model from Jiang et al. (55). Figure originally reported in Brusseau (13) and used here with permission of the author and Elsevier.

interfacial area at water saturations less than 0.5. Furthermore, the fluid–fluid interfacial area measured by gas-phase tracer methods is greater than that by liquid-phase tracers, especially under drier conditions (20, 30, 77). The significant difference between fluid–fluid interfacial areas measured by liquid- and gas-phase tracers is not yet fully understood, although it has been hypothesized that gas-phase tracers may access additional air–water interfacial domains (13, 30). **Figure 2** provides an example of the differences in air–water interfacial areas determined by various methods (13).

While the prior works quantifying the air–water interfacial area made the distinction between the bulk capillary and thin-water-film air–water interfaces, the two types of air–water interfaces are not differentiated in most transport model conceptualizations for the retention and transport of interfacially-active contaminants. These model concepts often build upon two premises that significantly underrepresent the role of thin water films: 1) adsorption at the bulk capillary and thin-film air–water interfaces can be treated the same; and 2) interfacially-active contaminants in the thin water films and the bulk capillary water are in chemical equilibrium. These assumptions may be challenged in the vadose zone, especially under drier conditions. Recent theoretical analysis (112) illustrated that the adsorption of PFAS at thin-film air–water interfaces can strongly deviate from that at a bulk capillary air–water interface due to complex surface forces from the solid surface (i.e., electrostatic and Van der Waals forces). Additionally, slow mass transfer in thin water films can greatly reduce the accessibility of thin-film air–water interfaces for PFAS, and thereby introduce nonequilibrium conditions between thin water films and bulk capillary water (26) (**Fig. 1**). Surface diffusion of the adsorbed PFAS along air–water interfaces, while rarely discussed in the hydrology and PFAS literature, was identified as a primary mechanism for transferring PFAS mass along the thin water films and between the thin water films and bulk water (26). The potentially slow mass transfer along the thin water films may also provide a plausible explanation for some of the differences observed between the air–water interfacial areas measured by liquid- and gas-tracer methods. Because thin water films account for most air–water interfaces in the vadose zone, not representing the above thin-film-mediated fundamental processes may predict significantly different field-scale migration of PFAS.

It is important to point out that the impact of air–water interfaces has been studied previously for the transport of interfacially-active constituents before PFAS, such as the attachment and detachment of colloidal particles at air–water interfaces (11, 62, 85, 95). The impact of water films on colloidal transport was also examined, but the modeled mechanisms are simple—films trap and immobilize colloids with a diameter greater than their thickness (11, 106)—without representing any of the complex surface forces. Additionally, non-PFAS surfactants in the subsurface were also studied for various applications including enhanced oil recovery (36, 80), surfactant-enhanced aquifer remediation (35, 78), and the impact of surfactant on unsaturated water flow (31, 51, 97, 98). Somewhat surprisingly, all the earlier surfactant-related work primarily focused on how surfactants affect fluid flow and dissolution with minimal discussion of air–water interfacial adsorption (see more detailed discussion in Guo et al. (45)). In contrast, the impact of air–water interfacial adsorption on transport has been a focal point of the recent PFAS work.

In addition to the different interfacial area domains and thin water films, PFAS transport in the vadose zone involves several other complexities. First, PFAS interfacial partitioning is sensitive to geochemical conditions (e.g., water chemistry and interactions with other interfacially-active constituents). For example, the partitioning of PFAS at air–water interfaces can vary greatly under different ionic strengths and electrolyte compositions (22, 23, 29, 42, 44, 61, 92, 112). The presence of co-PFAS and other interfacially-active solutes may also modify the strength of air–water interfacial partitioning (42, 44, 52, 93). Second, in addition to accumulating at air–water interfaces, it was also hypothesized that PFAS may form supramolecular structures (4) such as aggregated structures, micelles, and vesicles. Although micelles and vesicles are unlikely to form due to porewater concentrations at PFAS-contaminated sites being much lower than the critical micelle concentrations (16, 44), self-assemblies of different PFAS molecules may still occur in complex PFAS mixtures. If present, the movement of these supramolecular structures can transport PFAS themselves as well as partitioning mass with the other phases (aqueous phase, air–water interfaces, and solid surfaces). Third, strong transient flow dynamics coupled with spatial heterogeneity may introduce transport behaviors unique to PFAS due to partitioning to air–water interfaces and mass redistribution among the different phases. An example is the amplified acceleration of PFAS transport along preferential flow pathways with reduced air–water interfacial retention due to greater water saturation collapsing air–water interfaces (110, 111).

Finally, while most of the current PFAS fate and transport work focuses on anionic PFAS (i.e., perfluoroalkyl acids, [PFAAs]), other types of PFAS including cationic, zwitterionic, and neutral compounds have been shown to be present at contaminated sites (3, 8, 39, 68, 75, 84, 91). Unlike the environmentally persistent PFAAs, some of these PFAS can react under environmental conditions—driven by either abiotic or biotic processes—and eventually transform into PFAAs (27, 67, 83). The fate and transport of these PFAA “precursors” in the vadose zone remain poorly understood. Additionally, some of the neutral PFAS have relatively high vapor pressure and may partition to the gas phase as PFAS vapor (2, 17). The migration of vapor-phase PFAS and their partitioning with the other phases represent another set of potentially important processes for PFAS transport in the vadose zone (17).

3. CHALLENGES AND OPPORTUNITIES FOR POROUS MEDIA RESEARCH

While significant progress has been made in recent years to advance our understanding of PFAS fate and transport in the vadose zone, many critical areas are underexplored, and substantial challenges remain. Here, we discuss some of the major challenges from both fundamental research and practical application perspectives.

3.1. Quantification of air-water interfacial area

Various methods including direct imaging-based and indirect tracer-based approaches were developed to measure or estimate air–water interfacial area at varying water saturations as discussed in **Section 2**. However, there are still internal inconsistencies among these different methods, e.g., different methods may measure different air–water interfacial areas under the same conditions for the same media. Furthermore, the characterization of air–water interfacial area has only been done on a very limited number of soils. Since air–water interfaces play an important role in controlling the transport of interfacially-active substances like PFAS, it is critical to conduct comprehensive investigations of the air–water interfacial area across a wide range of soils and under different wetting conditions, as recently discussed (13). Detailed characterizations of the air–water interfacial area could enable the development of process-based models or robust empirical correlations based on more readily available parameters. These improved quantifications are expected to significantly enhance the modeling of PFAS fate and transport in the vadose zone.

3.2. Coupled nonlinear multi-physics processes

The transport of PFAS in soils is a multi-physics problem that involves various nonlinear processes in the vadose zone. For example, while surfactant-induced flow may not be significant for many lower concentration sites (45, 110), it could modify the transport behavior of PFAS at some of the highly contaminated AFFF-impacted sites (45, 103, 110), especially during the early period of PFAS release from fire training activities. Additionally, PFAS at contaminated sites are typically present as mixtures of numerous individual PFAS and other substances. Initial experimental studies have examined the effects of PFAS mixtures and hydrocarbon surfactants on interfacial tension (23, 47, 87, 93, 104) and transport (1, 52, 54, 66, 69). The Langmuir model extended for multiple components has been employed to describe potential competitive adsorption among different components (7, 42, 52, 54, 66). However, the multicomponent Langmuir model is thermodynamically inconsistent unless all components have equal maximum adsorption capacities (12, 40, 44, 57, 64). A more rigorous thermodynamically consistent model was recently developed for multicomponent adsorption of PFAS (44). However, all the studies to date focus primarily on PFAS mixtures with no opposite charges. The potentially synergistic interactions among PFAS with opposite charges (e.g., between anionic and cationic PFAS), and how they affect the fate and transport of PFAS in the vadose zone remain minimally explored. This is also the case for the transport of PFAS in the vapor phase and the transformation of PFAA precursors. In addition to the processes discussed above, PFAS transport in the vadose zone is driven by transient and nonlinear variably saturated flow, which has been considered one of the most computationally challenging processes in hydrology (24, 79). Understanding and quantifying how these processes and their coupling control PFAS transport in the vadose zone will require comprehensive experimental and field data, along with the development of new mathematical models and numerical methods.

3.3. Physical chemistry of PFAS interfacial partitioning and mass transfer in the thin water films

While the importance of thin water films has been recognized in porous media literature for fluid displacement, they are often considered insignificant for solute transport because they represent a tiny fraction of the total fluid volume and hence a negligible amount of the solute mass. This conceptualization needs to be revised for PFAS transport because the majority of the PFAS mass may be associated with the thin water films (26) due to the significant amounts of air–water interfaces arising from the thin water films. Whether these thin water films can be accessed by PFAS, and under what conditions they occur, may directly affect PFAS transport in the vadose zone (26, 111). Furthermore, the physical chemistry of PFAS partitioning at the air–water interface in the vicinity of a complex solid surface may deviate from that at bulk air–water interfaces (112). These detailed processes occurring in thin water films are potentially critical, but they are only begun to be explored.

3.4. Scale translation & development of practical modelling approaches

An outstanding challenge prevalent in all subsurface-related problems is the significant disparity between the scales at which dominant physical and chemical processes occur (nanometers to millimeters) and that at which we make observations and engineering decisions (tens of centimeters to meters or larger). This is also the case for PFAS transport in the vadose zone. Ultimately, site characterization and remediation applications require models developed for the field scale that can be practically applied to real-world contaminated sites. These practical models must be computationally efficient and relatively simple to parameterize, which means that they likely cannot account for all the complexities discussed in **Section 2**. We will need to identify the sub-pore and pore-scale processes with a first-order impact and approximate them at greater scales. Experimental data and more advanced models that represent a greater level of complexities may be used to aid the development of these practical models (26).

We note that the aspects discussed above are not an exhaustive list of important topics related to PFAS transport in the vadose zone. Rather, they represent a sample of the topics that we think the porous media community may find interesting. Addressing each of these challenges will likely require an integrated investigation through experiments, field observations, and development of theory and computational models from sub-pore-scale, pore-scale, and greater scales. Just like the prior non-PFAS research efforts that helped to prepare us for tackling the PFAS contamination problem, the fate and transport research of PFAS will likely generate new knowledge and tools that may find use in addressing emerging environmental problems in the future, with the interfacially-active micro- and nano-plastics being a potential example.

4. CONCLUSION

This commentary provides an overview of the complexities and challenges for understanding and quantifying the fate and transport of PFAS in the environment, with a particular focus on the vadose zone. We have focused on issues unique to PFAS compared to previous contaminants and how these processes manifest in the complex environment of porous media. It is evident that addressing PFAS contamination can greatly benefit from the expertise of the porous media community, both from fundamental and practical perspectives. This commentary highlights some of the opportunities where the porous media community could make substantial contributions.

STATEMENTS AND DECLARATIONS

Acknowledgements

This work was in part supported by National Science Foundation CAREER Award (2237015) to B. Guo and by the Environmental Security Technology Certification Program (ESTCP Project ER21-5041) to B. Guo and M. L. Brusseau.

Author Contributions

Bo Guo: Conceptualization, Methodology, Formal analysis, Funding acquisition, Writing – original draft.
Mark L. Brusseau: Formal analysis, Funding acquisition, Writing – reviewing & editing.

Conflicts of Interest

There are no conflicts of interest to declare.

ORCID IDs

Bo Guo https://orcid.org/0000-0002-8825-7331
Mark L. Brusseau https://orcid.org/0000-0002-6937-2975

Correction from March 24, 2025:

Please note that during the production process, citation errors affected eight references within the text. These have now been corrected to accurately reflect the intended sources.

REFERENCES

1. Abraham, J. E. F., Mumford, K. G., Patch, D. J., & Weber, K. P. (2022). Retention of PFOS and PFOA mixtures by trapped gas bubbles in porous media. *Environmental Science & Technology*, 56(22), 15489–15498. https://doi.org/10.1021/acs.est.2c00882
2. Abusallout, I., Holton, C., Wang, J., & Hanigan, D. (2022). Henry's Law constants of 15 per- and polyfluoroalkyl substances determined by static headspace analysis. *Journal of Hazardous Materials Letters,* 3, 100070. https://doi.org/10.1016/j.hazl.2022.100070
3. Adamson, D. T., Nickerson, A., Kulkarni, P. R., Higgins, C. P., Popovic, J., Field, J., Rodowa, A., Newell, C., DeBlanc, P., & Kornuc, J. J. (2020). Mass-based, field-scale demonstration of PFAS retention within AFFF-associated source areas. *Environmental Science & Technology*, 54(24), 15768–15777. https://doi.org/10.1021/acs.est.0c04472
4. Anderson, R. H., Feild, J. B., Dieffenbach-Carle, H., Elsharnouby, O., & Krebs, R. K. (2022). Assessment of PFAS in collocated soil and porewater samples at an AFFF-impacted source zone: Field-scale validation of suction lysimeters. *Chemosphere*, 308, 136247. https://doi.org/10.1016/j.chemosphere.2022.136247
5. Araujo, J. B., & Brusseau, M. L. (2020). Assessing XMT-measurement variability of air-water interfacial areas in natural porous media. *Water Resources Research*, 56(1), e2019WR025470. https://doi.org/10.1029/2019WR025470
6. Araujo, J. B., Mainhagu, J., & Brusseau, M. L. (2015). Measuring air–water interfacial area for soils using the mass balance surfactant-tracer method. *Chemosphere*, 134, 199–202. https://doi.org/10.1016/j.chemosphere.2015.04.035
7. Arshadi, M., Garza-Rubalcava, U., Guedes, A., Cápiro, N. L., Pennell, K. D., Christ, J., & Abriola, L. M. (2024). Modeling 1-D aqueous film forming foam transport through the vadose zone under realistic site and release conditions. *Science of The Total Environment*, 919, 170566. https://doi.org/10.1016/j.scitotenv.2024.170566
8. Baduel, C., Mueller, J. F., Rotander, A., Corfield, J., & Gomez-Ramos, M.-J. (2017). Discovery of novel per- and polyfluoroalkyl substances (PFASs) at a fire fighting training ground and preliminary investigation of their fate and mobility. *Chemosphere*, 185, 1030–1038. https://doi.org/10.1016/j.chemosphere.2017.06.096
9. Bear, J. Dynamics of Fluids in Porous Media; Elsevier: New York, 1972.
10. Bigler, M., He, X., & Brusseau, M. L. (2024). PFAS transport under lower water-saturation conditions characterized with instrumented-column systems. *Water Research*, 260, 121922. https://doi.org/10.1016/j.watres.2024.121922
11. Bradford, S. A., & Torkzaban, S. (2008). Colloid transport and retention in unsaturated porous media: A review of interface-, collector-, and pore-scale processes and models. *Vadose Zone Journal*, 7(2), 667–681. https://doi.org/10.2136/vzj2007.0092
12. Broughton, D. B. (1948). Adsorption isotherms for binary gas mixtures. *Industrial & Engineering Chemistry*, 40(8), 1506–1508. https://doi.org/10.1021/ie50464a036
13. Brusseau, M. L. (2023). Determining air-water interfacial areas for the retention and transport of PFAS and other interfacially active solutes in unsaturated porous media. *Science of The Total Environment*, 884, 163730. https://doi.org/10.1016/j.scitotenv.2023.163730
14. Brusseau, M. L., Anderson, R. H., & Guo, B. (2020). PFAS concentrations in soils: Background levels versus contaminated sites. *Science of The Total Environment*, 740, 140017. https://doi.org/10.1016/j.scitotenv.2020.140017
15. Brusseau, M. L., Araujo, J. B., Narter, M., Marble, J. C., & Bigler, M. (2024). Microtomographic measurements of total air-water interfacial areas for soils. *Water Resources Research*, 60(5), e2023WR036039. https://doi.org/10.1029/2023WR036039
16. Brusseau, M. L., & Guo, B. (2022). PFAS concentrations in soil versus soil porewater: Mass distributions and the impact of adsorption at air-water interfaces. *Chemosphere*, 302, 134938. https://doi.org/10.1016/j.chemosphere.2022.134938
17. Brusseau, M. L.; Guo, B. (2024). Vapor-Phase Transport of Per and Polyfluoroalkyl Substances: Processes, Modeling, and Implications. *Science of the Total Environment*, 947, 174644. https://doi.org/10.1016/j.scitotenv.2024.174644

18. Brusseau, M. L., Guo, B., Huang, D., Yan, N., & Lyu, Y. (2021). Ideal versus nonideal transport of pfas in unsaturated porous media. *Water Research*, 202, 117405. https://doi.org/10.1016/j.watres.2021.117405
19. Brusseau, M. L., Peng, S., Schnaar, G., & Costanza-Robinson, M. S. (2006). Relationships among air-water interfacial area, capillary pressure, and water saturation for a sandy porous medium. *Water Resources Research*, 42(3), 2005WR004058. https://doi.org/10.1029/2005WR004058
20. Brusseau, M. L., Peng, S., Schnaar, G., & Murao, A. (2007). Measuring air−water interfacial areas with x-ray microtomography and interfacial partitioning tracer tests. Environmental Science & Technology, 41(6), 1956–1961. https://doi.org/10.1021/es061474m
21. Brusseau, M. L., Popovičová, J., & Silva, J. A. K. (1997). Characterizing gas−water interfacial and bulk-water partitioning for gas-phase transport of organic contaminants in unsaturated porous media. Environmental Science & Technology, 31(6), 1645–1649. https://doi.org/10.1021/es960475j
22. Brusseau, M. L.; Van Glubt, S. (2021). The Influence of Molecular Structure on PFAS Adsorption at Air-Water Interfaces in Electrolyte Solutions. *Chemosphere*, 281, 130829. https://doi.org/10.1016/j.chemosphere.2021.130829
23. Brusseau, M. L., & Van Glubt, S. (2019). The influence of surfactant and solution composition on PFAS adsorption at fluid-fluid interfaces. *Water Research*, 161, 17–26. https://doi.org/10.1016/j.watres.2019.05.095
24. Celia, M. A., Bouloutas, E. T., & Zarba, R. L. (1990). A general mass-conservative numerical solution for the unsaturated flow equation. *Water Resources Research*, 26(7), 1483–1496. https://doi.org/10.1029/WR026i007p01483
25. Chen, L., & Kibbey, T. C. G. (2006). Measurement of air−water interfacial area for multiple hysteretic drainage curves in an unsaturated fine sand. *Langmuir*, 22(16), 6874–6880. https://doi.org/10.1021/la053521e
26. Chen, S., & Guo, B. (2023). Pore-scale modeling of PFAS transport in water-unsaturated porous media: Air–water interfacial adsorption and mass-transfer processes in thin water films. *Water Resources Research*, 59(8), e2023WR034664. https://doi.org/10.1029/2023WR034664
27. Choi, Y. J., Helbling, D. E., Liu, J., Olivares, C. I., & Higgins, C. P. (2022). Microbial biotransformation of aqueous film-forming foam derived polyfluoroalkyl substances. *Science of The Total Environment,* 824, 153711. https://doi.org/10.1016/j.scitotenv.2022.153711
28. Cordner, A., Brown, P., Cousins, I. T., Scheringer, M., Martinon, L., et al. (2024). PFAS contamination in Europe: Generating knowledge and mapping known and likely contamination with "expert-reviewed" journalism. *Environmental Science & Technology*, 58(15), 6616–6627. https://doi.org/10.1021/acs.est.3c09746
29. Costanza, J., Arshadi, M., Abriola, L. M., & Pennell, K. D. (2019). Accumulation of PFOA and PFOS at the air–water interface. *Environmental Science & Technology Letters*, 6(8), 487–491. https://doi.org/10.1021/acs.estlett.9b00355
30. Costanza-Robinson, M. S., & Brusseau, M. L. (2002). Air-water interfacial areas in unsaturated soils: Evaluation of interfacial domains. *Water Resources Research*, 38(10). https://doi.org/10.1029/2001WR000738
31. Costanza-Robinson, M. S., & Henry, E. J. (2017). Surfactant-induced flow compromises determination of air-water interfacial areas by surfactant miscible-displacement. *Chemosphere*, 171, 275–283. https://doi.org/10.1016/j.chemosphere.2016.12.072
32. Culligan, K. A., Wildenschild, D., Christensen, B. S. B., Gray, W. G., & Rivers, M. L. (2006). Pore-scale characteristics of multiphase flow in porous media: A comparison of air–water and oil–water experiments. *Advances in Water Resources*, 29(2), 227–238. https://doi.org/10.1016/j.advwatres.2005.03.021
33. Culligan, K. A., Wildenschild, D., Christensen, B. S. B., Gray, W. G., Rivers, M. L., & Tompson, A. F. B. (2004). Interfacial area measurements for unsaturated flow through a porous medium. *Water Resources Research*, 40(12), 2004WR003278. https://doi.org/10.1029/2004WR003278
34. Danish EPA. (4 Aug 2024). Limit values for PFAS in the environment. https://mst.dk/erhverv/sikker-kemi/kemikalier/graensevaerdier-og-kvalitetskriterier
35. Delshad, M., Pope, G. A., & Sepehrnoori, K. (1996). A compositional simulator for modeling surfactant enhanced aquifer remediation, 1 formulation. *Journal of Contaminant Hydrology*, 23(4), 303–327. https://doi.org/10.1016/0169-7722(95)00106-9
36. Delshad, M.; Pope, G. A.; Sepehrnoori, K. (2000) UTCHEM Version 9.0 Technical Documentation. Center for Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, Texas, 78751. http://gmsdocs.aquaveo.com/UTCHEM_Users_Guide.pdf
37. EWG. (4 August 2024). PFAS Contamination in the U.S.; 2024. https://www.ewg.org/interactive-maps/pfas_contamination/
38. Faisal Anwar, A. H. M., Bettahar, M., & Matsubayashi, U. (2000). A method for determining air–water interfacial area in variably saturated porous media. *Journal of Contaminant Hydrology*, 43(2), 129–146. https://doi.org/10.1016/S0169-7722(99)00103-5
39. Field, J. A., & Seow, J. (2017). Properties, occurrence, and fate of fluorotelomer sulfonates. *Critical Reviews in Environmental Science and Technology*, 47(8), 643–691. https://doi.org/10.1080/10643389.2017.1326276

40. Frey, D. D., & Rodrigues, A. E. (1994). Explicit calculation of multicomponent equilibria for ideal adsorbed solutions. *AIChE Journal*, 40(1), 182–186. https://doi.org/10.1002/aic.690400121
41. Gao, B., Saiers, J. E., & Ryan, J. N. (2004). Deposition and mobilization of clay colloids in unsaturated porous media. *Water Resources Research*, 40(8), 2004WR003189. https://doi.org/10.1029/2004WR003189
42. Gao, Y., Le, S.-T., Kibbey, T. C. G., Glamore, W., & O'Carroll, D. M. (2023). A fundamental model for calculating interfacial adsorption of complex ionic and nonionic PFAS mixtures in the presence of mixed salts. *Environmental Science: Processes & Impacts*, 25(11), 1830–1838. https://doi.org/10.1039/D2EM00466F
43. Gnesda, W. R., Draxler, E. F., Tinjum, J., & Zahasky, C. (2022). Adsorption of PFAAs in the vadose zone and implications for long-term groundwater contamination. *Environmental Science & Technology*, 56(23), 16748–16758. https://doi.org/10.1021/acs.est.2c03962
44. Guo, B., Saleem, H., & Brusseau, M. L. (2023). Predicting interfacial tension and adsorption at fluid–fluid interfaces for mixtures of PFAS and/or hydrocarbon surfactants. *Environmental Science & Technology*, 57(21), 8044–8052. https://doi.org/10.1021/acs.est.2c08601
45. Guo, B., Zeng, J., & Brusseau, M. L. (2020). A mathematical model for the release, transport, and retention of per- and polyfluoroalkyl substances (Pfas) in the vadose zone. *Water Resources Research*, 56(2), e2019WR026667. https://doi.org/10.1029/2019WR026667
46. Guo, B., Zeng, J., Brusseau, M. L., & Zhang, Y. (2022). A screening model for quantifying PFAS leaching in the vadose zone and mass discharge to groundwater. *Advances in Water Resources,* 160, 104102. https://doi.org/10.1016/j.advwatres.2021.104102
47. Guo-Xi, Z., Bu-Yao, Z., Ya-Ping, Z., & Li, S. (1984). The surface adsorption and micelle formation of the mixed aqueous solutions of fluorocarbon and hydrocarbon surfactants: II. Sodium perfluorooctanoate-sodium decylsulfate system. *Acta Chimica Sinica*, 2(2), 111–118. https://doi.org/10.1002/cjoc.19840020205
48. Hassanizadeh, S. M., & Gray, W. G. (1990). Mechanics and thermodynamics of multiphase flow in porous media including interphase boundaries. *Advances in Water Resources*, 13(4), 169–186. https://doi.org/10.1016/0309-1708(90)90040-B
49. Hassanizadeh, S. M., & Gray, W. G. (1993). Thermodynamic basis of capillary pressure in porous media. *Water Resources Research*, 29(10), 3389–3405. https://doi.org/10.1029/93WR01495
50. Hassanizadeh, S.M., & Gray, W. G. (1993). Toward an improved description of the physics of two-phase flow. *Advances in Water Resources*, 16(1), 53–67. https://doi.org/10.1016/0309-1708(93)90029-F
51. Henry, E. J., & Smith, J. E. (2003). Surfactant-induced flow phenomena in the vadose zone: A review of data and numerical modeling. *Vadose Zone Journal*, 2(2), 154–167. https://doi.org/10.2113/2.2.154
52. Huang, D.; Saleem, H.; Guo, B.; Brusseau, M. L. (2022). The Impact of Multiple-Component PFAS Solutions on Fluid-Fluid Interfacial Adsorption and Transport of PFOS in Unsaturated Porous Media. *Science of The Total Environment*, 806, 150595. https://doi.org/10.1016/j.scitotenv.2021.15059
53. ITRC. (Sept. 2023). ITRC PFAS Technical and Regulatory Guidance Document. https://pfas-1.itrcweb.org/
54. Ji, Y., Yan, N., Brusseau, M. L., Guo, B., Zheng, X., Dai, M., Liu, H., & Li, X. (2021). Impact of a hydrocarbon surfactant on the retention and transport of perfluorooctanoic acid in saturated and unsaturated porous media. *Environmental Science & Technology*, 55(15), 10480–10490. https://doi.org/10.1021/acs.est.1c01919
55. Jiang, H., Guo, B., & Brusseau, M. L. (2020). Pore-scale modeling of fluid-fluid interfacial area in variably saturated porous media containing microscale surface roughness. *Water Resources Research*, 56(1), e2019WR025876. https://doi.org/10.1029/2019WR025876
56. Karkare, M. V., & Fort, T. (1996). Determination of the air−water interfacial area in wet "unsaturated" porous media. *Langmuir*, 12(8), 2041–2044. https://doi.org/10.1021/la950821v
57. Kemball, C., Rideal, E. K., & Guggenheim, E. A. (1948). Thermodynamics of monolayers. *Transactions of the Faraday Society*, 44, 948. https://doi.org/10.1039/tf9484400948
58. Kibbey, T. C. G., & Chen, L. (2012). A pore network model study of the fluid-fluid interfacial areas measured by dynamic-interface tracer depletion and miscible displacement water phase advective tracer methods. *Water Resources Research*, 48(10), 2012WR011862. https://doi.org/10.1029/2012WR011862
59. Kim, H.; Rao, P. S. C.; Annable, D. (1997). Determination of Effective Air-Water Interfacial Area in Partially Saturated Porous Media Using Surfactant Adsorption. *Water Resources Research,* 33 (12), 2705–2711. https://doi.org/10.1029/97WR02227
60. Kissa, E. (2001). Fluorinated Surfactants and Repellents. (2nd ed). CRC Press, Vol. 97. ISBN 0-8247-0472-X
61. Le, S.-T., Gao, Y., Kibbey, T. C. G., Glamore, W. C., & O'Carroll, D. M. (2021). A new framework for modeling the effect of salt on interfacial adsorption of PFAS in environmental systems. *Science of The Total Environment*, 796, 148893. https://doi.org/10.1016/j.scitotenv.2021.148893
62. Lenhart, J. J., & Saiers, J. E. (2002). Transport of silica colloids through unsaturated porous media: Experimental results and model comparisons. *Environmental Science & Technology*, 36(4), 769–777. https://doi.org/10.1021/es0109949

63. Lenhart, J. J., & Saiers, J. E. (2004). Adsorption of natural organic matter to air−water interfaces during transport through unsaturated porous media. *Environmental Science & Technology*, 38(1), 120–126. https://doi.org/10.1021/es034409a
64. LeVan, M. D., & Vermeulen, T. (1981). Binary Langmuir and Freundlich isotherms for ideal adsorbed solutions. *The Journal of Physical Chemistry*, 85(22), 3247–3250. https://doi.org/10.1021/j150622a009
65. Leverett, M. C. Capillary Behavior in Porous Solids. Transactions of the AIME 1941, 142 (01), 152–169. https://doi.org/10.2118/941152-G
66. Liao, S., Arshadi, M., Woodcock, M. J., Saleeba, Z. S. S. L., Pinchbeck, D., et al. (2022). Influence of residual nonaqueous-phase liquids (NAPLs) on the transport and retention of perfluoroalkyl substances. *Environmental Science & Technology*, 56(12), 7976–7985. https://doi.org/10.1021/acs.est.2c00858
67. Liu, J., & Mejia Avendaño, S. (2013). Microbial degradation of polyfluoroalkyl chemicals in the environment: A review. *Environment International*, 61, 98–114. https://doi.org/10.1016/j.envint.2013.08.022
68. Liu, M., Munoz, G., Vo Duy, S., Sauvé, S., & Liu, J. (2022). Per- and polyfluoroalkyl substances in contaminated soil and groundwater at airports: A canadian case study. *Environmental Science & Technology*, 56(2), 885–895. https://doi.org/10.1021/acs.est.1c04798
69. Lyu, X., Li, Z., Wang, D., Zhang, Q., Gao, B., Sun, Y., & Wu, J. (2022). Transport of perfluorooctanoic acid in unsaturated porous media mediated by SDBS. *Journal of Hydrology*, 607, 127479. https://doi.org/10.1016/j.jhydrol.2022.127479
70. Lyu, X., Liu, X., Sun, Y., Gao, B., Ji, R., Wu, J., & Xue, Y. (2020). Importance of surface roughness on perfluorooctanoic acid (PFOA) transport in unsaturated porous media. *Environmental Pollution*, 266, 115343. https://doi.org/10.1016/j.envpol.2020.115343
71. Lyu, Y., Brusseau, M. L., Chen, W., Yan, N., Fu, X., & Lin, X. (2018). Adsorption of PFOA at the air–water interface during transport in unsaturated porous media. *Environmental Science & Technology*, 52(14), 7745–7753. https://doi.org/10.1021/acs.est.8b02348
72. Miller, C. T., Poirier-McNeil, M. M., & Mayer, A. S. (1990). Dissolution of trapped nonaqueous phase liquids: Mass transfer characteristics. *Water Resources Research*, 26(11), 2783–2796. https://doi.org/10.1029/WR026i011p02783
73. Morrow, N. R. (1970). Physics and thermodynamics of capillary action in porous media. I*ndustrial & Engineering Chemistry*, 62(6), 32–56. https://doi.org/10.1021/ie50726a006
74. Newell, C. J., Adamson, D. T., Kulkarni, P. R., Nzeribe, B. N., & Stroo, H. (2020). Comparing PFAS to other groundwater contaminants: Implications for remediation. *Remediation Journal*, 30(3), 7–26. https://doi.org/10.1002/rem.21645
75. Nickerson, A., Rodowa, A. E., Adamson, D. T., Field, J. A., Kulkarni, P. R., et al. (2021). Spatial trends of anionic, zwitterionic, and cationic pfass at an AFFF-impacted site. *Environmental Science & Technology*, 55(1), 313–323. https://doi.org/10.1021/acs.est.0c04473
76. Or, D.; Tuller, M. (1999). Liquid Retention and Interfacial Area in Variably Saturated Porous Media: Upscaling from Single-Pore to Sample-Scale Model. Water Resources Research, 35 (12), 3591–3605. https://doi.org/10.1029/1999WR900262
77. Peng, S., & Brusseau, M. L. (2005). Impact of soil texture on air-water interfacial areas in unsaturated sandy porous media. Water Resources Research, 41(3), 2004WR003233. https://doi.org/10.1029/2004WR003233
78. Pennell, K. D., Abriola, L. M., & Weber, W. J. (1993). Surfactant-enhanced solubilization of residual dodecane in soil columns. 1. Experimental investigation. Environmental Science & Technology, 27(12), 2332–2340. https://doi.org/10.1021/es00048a005
79. Pinder, G.; Celia, M. (2006). Subsurface Hydrology; John Wiley & Sons. https://www.geokniga.org/bookfiles/geokniga-subsurface-hydrology.pdf
80. Pope, G. A., & Nelson, R. C. (1978). A chemical flooding compositional simulator. *Society of Petroleum Engineers Journal*, 18(05), 339–354. https://doi.org/10.2118/6725-PA
81. Powers, S. E., Loureiro, C. O., Abriola, L. M., & Weber, W. J. (1991). Theoretical study of the significance of nonequilibrium dissolution of nonaqueous phase liquids in subsurface systems. *Water Resources Research*, 27(4), 463–477. https://doi.org/10.1029/91WR00074
82. Reeves, P. C., & Celia, M. A. (1996). A functional relationship between capillary pressure, saturation, and interfacial area as revealed by a pore-scale network model. *Water Resources Research*, 32(8), 2345–2358. https://doi.org/10.1029/96WR01105
83. Ruyle, B. J., Thackray, C. P., Butt, C. M., LeBlanc, D. R., Tokranov, A. K., Vecitis, C. D., & Sunderland, E. M. (2023). Centurial persistence of forever chemicals at military fire training sites. *Environmental Science & Technology*, 57(21), 8096–8106. https://doi.org/10.1021/acs.est.3c00675
84. Ruyle, B. J., Thackray, C. P., McCord, J. P., Strynar, M. J., Mauge-Lewis, K. A., Fenton, S. E., & Sunderland, E. M. (2021). Reconstructing the composition of per- and polyfluoroalkyl substances in contemporary aqueous film-

forming foams. *Environmental Science & Technology Letters*, 8(1), 59–65. https://doi.org/10.1021/acs.estlett.0c00798

85. Saiers, J. E., & Lenhart, J. J. (2003). Colloid mobilization and transport within unsaturated porous media under transient-flow conditions. *Water Resources Research*, 39(1), 2002WR001370. https://doi.org/10.1029/2002WR001370
86. Saripalli, K. P., Kim, H., Rao, P. S. C., & Annable, M. D. (1997). Measurement of specific fluid−fluid interfacial areas of immiscible fluids in porous media. *Environmental Science & Technology*, 31(3), 932–936. https://doi.org/10.1021/es960652g
87. Schaefer, C. E., Culina, V., Nguyen, D., & Field, J. (2019). Uptake of poly- and perfluoroalkyl substances at the air–water interface. *Environmental Science & Technology*, 53(21), 12442–12448. https://doi.org/10.1021/acs.est.9b04008
88. Schaefer, C. E., DiCarlo, D. A., & Blunt, M. J. (2000). Experimental measurement of air-water interfacial area during gravity drainage and secondary imbibition in porous media. *Water Resources Research*, 36(4), 885–890. https://doi.org/10.1029/2000WR900007
89. Schaefer, C. E., Lavorgna, G. M., Lippincott, D. R., Nguyen, D., Christie, E., Shea, S., O'Hare, S., Lemes, M. C. S., Higgins, C. P., & Field, J. (2022). A field study to assess the role of air-water interfacial sorption on PFAS leaching in an AFFF source area. *Journal of Contaminant Hydrology*, 248, 104001. https://doi.org/10.1016/j.jconhyd.2022.104001
90. Schnaar, G., & Brusseau, M. L. (2005). Pore-scale characterization of organic immiscible-liquid morphology in natural porous media using synchrotron x-ray microtomography. *Environmental Science & Technology*, 39(21), 8403–8410. https://doi.org/10.1021/es0508370
91. Schumacher, B. A., Zimmerman, J. H., Williams, A. C., Lutes, C. C., Holton, C. W., et al. (2024). Distribution of select per- and polyfluoroalkyl substances at a chemical manufacturing plant. *Journal of Hazardous Materials*, 464, 133025. https://doi.org/10.1016/j.jhazmat.2023.133025
92. Silva, J. A. K., Martin, W. A., Johnson, J. L., & McCray, J. E. (2019). Evaluating air-water and NAPL-water interfacial adsorption and retention of Perfluorocarboxylic acids within the Vadose zone. *Journal of Contaminant Hydrology*, 223, 103472. https://doi.org/10.1016/j.jconhyd.2019.03.004
93. Silva, J. A. K., Martin, W. A., & McCray, J. E. (2021). Air-water interfacial adsorption coefficients for PFAS when present as a multi-component mixture. *Journal of Contaminant Hydrology*, 236, 103731. https://doi.org/10.1016/j.jconhyd.2020.103731
94. Silva, J. A. K.; Šimůnek, J.; McCray, J. A Modified HYDRUS Model for Simulating PFAS Transport in the Vadose Zone. Water (Basel) 2020, 12 (10), 2758. https://doi.org/10.3390/w12102758
95. Šimůnek, J., He, C., Pang, L., & Bradford, S. A. (2006). Colloid-facilitated solute transport in variably saturated porous media: Numerical model and experimental verification. *Vadose Zone Journal*, 5(3), 1035–1047. https://doi.org/10.2136/vzj2005.0151
96. Smalling, K. L., Romanok, K. M., Bradley, P. M., Morriss, M. C., Gray, J. L., et al. (2023). Per- and polyfluoroalkyl substances (PFAS) in United States tapwater: Comparison of underserved private-well and public-supply exposures and associated health implications. *Environment International*, 178, 108033. https://doi.org/10.1016/j.envint.2023.108033
97. Smith, J. E., & Gillham, R. W. (1994). The effect of concentration-dependent surface tension on the flaw of water and transport of dissolved organic compounds: A pressure head-based formulation and numerical model. *Water Resources Research*, 30(2), 343–354. https://doi.org/10.1029/93WR02745
98. Smith, J. E., & Gillham, R. W. (1999). Effects of solute concentration–dependent surface tension on unsaturated flow: Laboratory sand column experiments. *Water Resources Research*, 35(4), 973–982. https://doi.org/10.1029/1998WR900106
99. Stults, J. F., Choi, Y. J., Schaefer, C. E., Illangasekare, T. H., & Higgins, C. P. (2022). Estimation of transport parameters of perfluoroalkyl acids (PFAAs) in unsaturated porous media: Critical experimental and modeling improvements. *Environmental Science & Technology*, 56(12), 7963–7975. https://doi.org/10.1021/acs.est.2c00819
100. Torkzaban, S., Hassanizadeh, S. M., Schijven, J. F., & Van Den Berg, H. H. J. L. (2006). Role of air-water interfaces on retention of viruses under unsaturated conditions. *Water Resources Research*, 42(12), 2006WR004904. https://doi.org/10.1029/2006WR004904
101. The Forever Pollution Project. (7 August 2024).The Forever Pollution Project: Journalists tracking PFAS across Europe. https://foreverpollution.eu/
102. US EPA. (4 August 2024). Final PFAS National Primary Drinking Water Regulation. https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas.
103. Vahedian, F., Silva, J. A. K., Šimůnek, J., & McCray, J. E. (2024). Influence of tension-driven flow on the transport of afff in unsaturated media. *ACS ES&T Water*, 4(2), 564–574. https://doi.org/10.1021/acsestwater.3c00611

104. Vecitis, C. D., Park, H., Cheng, J., Mader, B. T., & Hoffmann, M. R. (2008). Enhancement of perfluorooctanoate and perfluorooctanesulfonate activity at acoustic cavitation bubble interfaces. *The Journal of Physical Chemistry C*, 112(43), 16850–16857. https://doi.org/10.1021/jp804050p
105. Wallis, I., Hutson, J., Davis, G., Kookana, R., Rayner, J., & Prommer, H. (2022). Model-based identification of vadose zone controls on PFAS mobility under semi-arid climate conditions. *Water Research*, 225, 119096. https://doi.org/10.1016/j.watres.2022.119096
106. Wan, J., & Tokunaga, T. K. (1997). Film straining of colloids in unsaturated porous media: Conceptual model and experimental testing. *Environmental Science & Technology*, 31(8), 2413–2420. https://doi.org/10.1021/es970017q
107. Wildenschild, D., Rivers, M. L., Porter, M. L., Iltis, G. C., Armstrong, R. T., & Davit, Y. (2015). Using synchrotron-based X-ray microtomography and functional contrast agents in environmental applications. In S. H. Anderson & J. W. Hopmans (Eds.), SSSA Special Publications (pp. 1–22). American Society of Agronomy and Soil Science Society of America. https://doi.org/10.2136/sssaspecpub61.c1
108. Wildenschild, D., & Sheppard, A. P. (2013). X-ray imaging and analysis techniques for quantifying pore-scale structure and processes in subsurface porous medium systems. *Advances in Water Resources*, 51, 217–246. https://doi.org/10.1016/j.advwatres.2012.07.018
109. Zeng, J., Brusseau, M. L., & Guo, B. (2021). Model validation and analyses of parameter sensitivity and uncertainty for modeling long-term retention and leaching of PFAS in the vadose zone. *Journal of Hydrology*, 603, 127172. https://doi.org/10.1016/j.jhydrol.2021.127172
110. Zeng, J., & Guo, B. (2021). Multidimensional simulation of PFAS transport and leaching in the vadose zone: Impact of surfactant-induced flow and subsurface heterogeneities. *Advances in Water Resources*, 155, 104015. https://doi.org/10.1016/j.advwatres.2021.104015
111. Zeng, J., & Guo, B. (2023). Reduced accessible air–water interfacial area accelerates pfas leaching in heterogeneous vadose zones. *Geophysical Research Letters*, 50(8), e2022GL102655. https://doi.org/10.1029/2022GL102655
112. Zhang, W., & Guo, B. (2024). Anomalous adsorption of PFAS at the thin-water-film air-water interface in water-unsaturated porous media. *Water Resources Research*, 60(3), e2023WR035775. https://doi.org/10.1029/2023WR035775