CHOICES

AAEA Agricultural & Applied Economics Association

Volume 39. Quarter 3

Forever Chemicals and Challenges to Drinking Water Systems

Samantha L. Snyder, Xinde James Ji, Weizhe Weng, Di Fang, Suzanne Thorsbury, Michael T. Olexa, and Sean Olivnik

JEL Classifications: Q53; Q58
Keywords: Drinking water systems, Forever chemical, PFAS, Safe Drinking Water Act

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals used for their unique repellant properties. Popularly labeled as “forever chemicals,” the first PFAS was discovered in 1938 and entered commercial use as a nonstick agent in Teflon. Today, more than 12,000 PFAS chemicals are known to exist, with perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) being the most widely used and studied compounds. PFAS compounds have found extensive applications in various consumer products—including cookware, food packaging, clothing, and makeup—because of their resistance to heat, water, and stains. PFAS are also used to make a fire-suppressing foam, Aqueous Film Forming Foam (AFFF), intended for airport and military use, where hazardous, flammable-liquid fires may occur. These same characteristics have led to increasing concerns over the persistence of PFAS compounds in water and food sources with impacts on long-term health and environmental outcomes, with estimates suggesting that almost half of the tap water in the United States is contaminated with these chemicals (Smalling et al., 2023).

Forever chemicals have attracted growing regulatory attention for their extensive environmental presence, resistance to natural degradation processes, ability to bioaccumulate, and potential toxicity in humans (Ehsan et al., 2023). Recently, the U.S. Environmental Protection Agency (EPA) has taken a series of actions to tackle the challenge presented by PFAS, especially related to drinking water, one of the most prevalent sources of PFAS exposure to the U.S. public. Among other regulatory actions, the EPA finalized National Primary Drinking Water Regulations (NPDWR) for six PFAS chemicals in April 2024, establishing legally binding concentrations of PFAS for public drinking water systems under the Safe Drinking Water Act (SDWA) (EPA, 2024).

Who Is at Risk?

Although PFAS exposure is widespread in the U.S. population, high levels of exposure (considered concentrations above 20 ng/ml and 2 ng/ml for sensitive populations) are most common in those who regularly consume contaminated water, food, and air or use products made with PFAS (NIEHS, 2023).[1] A National Health and Nutrition Examination Survey of serum samples from more than 2,000 individuals found that 98% of the samples contained some detectable level of PFAS (Calafat et al., 2007).

Several studies have concluded that drinking water is one of the primary sources of PFAS exposure in humans (Hopkins et al., 2018; Hu et al., 2016; Mulhern et al., 2022, Stoiber et al., 2020). Consequently, individuals who drink more tap water per pound of body weight tend to be at an increased risk compared to the average person (Domingo and Nadal, 2019; Teaf et al., 2019). Infants can also be exposed to PFAS through breastfeeding if the mother has consumed products contaminated with PFAS or through baby formula if the water used to make the formula is contaminated (Anderko and Pennea, 2020). Exposure from drinking water is a top concern for environmental regulators as there is a current lack of cost-effective treatment systems equipped to remove PFAS from drinking water.

PFAS exposure levels vary across a wide range of factors, including geography, age, and occupation. Individuals working in industries or living near manufacturing sites that regularly handle PFAS, including aerospace and construction sectors, are most at risk for the adverse health risks associated with higher levels of exposure (Høisæter and Breedveld, 2022). Nevertheless, PFAS exposure is not confined to those near manufacturing sites; these chemicals can disperse into off-site water, soil, and air sources as well as bioaccumulate in wildlife and humans.

---

[1] ng/mL stands for nanograms per milliliter. One nanogram is one billionth of a gram, or 0.000000000035274 ounce.

According to the EPA, the most prominent locations of off-site PFAS contamination include firefighting training sites, medium and large airports subject to "Part 139" regulation[2], national defense and military bases, chemical plants and storage facilities, and waste management sites. PFAS possess high thermal and physical stability properties, making them ideal for extinguishing fires quickly. Firefighting training sites, large civilian airports, and military bases regularly use AFFF, which contains a mixture of PFOA, PFOS, and other PFAS chemicals. Manufacturing facilities are also a significant source of PFAS contamination. Chemicals can be released into the environment through both primary and secondary products, either as residuals or as impurities during production. Facilities that apply surface coatings on various consumer products to make them water-, stain-, or heat-resistant are also of particular concern. Due to the regulatory complexities surrounding PFAS, many manufacturing facilities lack adequate measures to handle PFAS contamination, resulting in the unintentional release of chemicals (Dasu et al., 2022).

Readers are referred to the EPA's PFAS analytics tool (https://comptox.epa.gov/dashboard/chemical-lists/pfasmaster) for an integrated mapping tool of potential PFAS sources and testing results. Additionally, the Environmental Working Group provides an interactive PFAS contamination map (https://www.ewg.org/interactive-maps/pfas_contamination/map/) that maps PFAS concentration in drinking water as well as potential sources.

What Are the Health Impacts?

Evidence linking PFAS exposure with multiple adverse health conditions has mounted rapidly over the last decade (Baker and Knappe, 2022, Braun, 2023). Epidemiological research reveals probable links between PFOA exposure and high cholesterol levels, thyroid disease, and kidney and testicular cancers (Anderko and Pennea, 2020). Chronic autoimmune and compromised immune system function have also been identified as potential effects of exposure (Guillette et al., 2020). Of particular concern is the potential health impacts of PFAS on reproductive health and children (Anderko and Pennea, 2020). Although research is ongoing, studies indicate that PFAS exposure can cause fluctuations in adolescent growth, learning abilities, behavior, fertility rates, immune system response, and cholesterol levels (Anderko and Pennea, 2020).

PFAS are notorious for their tendency to bioaccumulate in wildlife, which presents an added dimension of concern for individuals who regularly ingest food or water potentially contaminated by these substances. This issue is particularly pertinent for the consumption of fish derived from polluted water bodies (FDEP, 2023). Moreover, when released into the environment, PFAS can be absorbed by water, soil, and plants, potentially causing further food chain contamination.

Regulatory Environment

In April 2024, the EPA took one of the most consequential steps to date toward tackling PFAS contamination in water systems by finalizing an enforceable federal drinking water standard using the National Primary Drinking Water Regulation (NPDWR), with regulatory authority granted to the EPA by the Safe Drinking Water Act. The rule was first proposed in March 2023. Despite documented health and environmental impacts, PFAS regulations were largely unenforceable at the federal level before 2023. While the Safe Drinking Water Act grants the EPA the authority to regulate the nation's drinking water supply federal drinking water, regulations regarding PFAS were historically limited to selective monitoring and issuing Health Advisory Guidelines (HAL).[3] The last round of completed PFAS monitoring was between 2013 and 2015 under the Unregulated Contaminant Monitoring Rule (UCMR 3) (https://www.epa.gov/dwucmr/third-unregulated-contaminant-monitoring-rule). It required Public Water Systems (PWS) to monitor for six types of PFAS. In 2016, the EPA established an HAL of 70 ppt for PFOS and PFOA individually or combined (https://www.epa.gov/sites/default/files/2016-06/documents/drinkingwaterhealthadvisories_pfoa_pfos_updated_5.31.16.pdf). These levels were intended to guide state agencies and the public. They do not trigger mandatory monitoring measures or significant remediation procedures. It was not until 2022—6 years later—that the interim updated HALs for PFOA and PFOS were significantly lowered to 0.004 and 0.02 ppt, respectively. Neither HAL includes other types of PFAS chemicals.

The absence of federal PFAS guidance has made it difficult for state and local agencies to establish unified policies to address drinking water contamination (Stoiber et al., 2020). Consequently, dozens of states have created their own PFAS health guidelines and standards to guide contaminated site cleanups and treat drinking water (Cordner et al., 2019). To address PFAS at the state level, legislators nationwide have attempted to

---

[2] The Federal Aviation Administration specifically requires medium- to large-size airports to use AFFF and to conduct periodic firefighting drills as part of the Part 139 airport certification process (14 CFR Part 139). More information on the Part 139 certification process can be found on the FAA website: https://www.faa.gov/airports/airport_safety/part139_cert/what-is-part-139.

[3] Some prior regulatory actions include issuing strategic plans. In 2019, the EPA released the PFAS Action Plan, outlining the agency's approach to address these contamination concerns. Two years later, the EPA established a federal council to enhance the agency's understanding of PFAS and mitigate potential environmental and health risks. In the same year, the EPA created the PFAS Strategic Roadmap to set agency goals for PFAS regulation and legislation between 2021 and 2024.

reduce PFAS exposure by regulating source material, enforcing contamination limits, and initiating remediation projects. Several states—including California, Michigan, and Vermont—have issued or proposed PFOA and PFOS drinking water limits lower than the EPA's HAL of 70 ppt (https://www.saferstates.com/ and https://www.ncsl.org/environment-and-natural-resources/per-and-polyfluoroalkyl-substances#state). For example, Michigan adopted its initial PFAS drinking water regulations in 2020, setting standards for PFOA at 8 ppt and PFOS at 16 ppt.[4]

The EPA's recently finalized rule establishes an enforceable federal drinking water standard using the National Primary Drinking Water Regulation, which is one of the most consequential steps to date toward tackling PFAS contamination in water systems (https://www.epa.gov/newsreleases/biden-harris-administration-finalizes-critical-rule-clean-pfas-contamination-protect). The proposed rule incorporates maximum containment levels (MCLs), maximum containment level goals (MCLGs), and HALs for six PFAS compounds, including PFOA, PFOS, PFNA, PFHxS, PFBS, and GenX chemicals. Table 1 discusses the similarities and differences among MCLs, MCLGs, and HALs. The key difference between the proposed rule and prior regulations is that it includes enforceable MCLs for PFAS in addition to MCLGs and HALs. Drinking water providers are required to abate the level of PFAS to or below the MCLs.

Table 2 presents the regulatory limits in the finalized rule. The EPA proposed an MCL of 4.0 parts per trillion (ppt) for PFOA and PFOS, the lowest quantifiable level given current analytical methods. MCLs for additional groups of chemicals, including PFNA, PFHxS, and GenX chemicals, are set at 10 ppt. A hazard index of 1.0 is set for mixtures of PFNA, PFHxS, PFBS, and GenX chemicals.[5] All public water systems will have 3 years (2024–2027) to complete initial monitoring under the new PFAS standards and notify consumers if levels exceed the MCLs, and 5 years (by 2029) to take remediation action to comply with all MCLs.

Benefits and Costs of the EPA's Proposed Rule

The proposed PFAS rule is expected to yield significant public benefits, primarily in health risk reductions. The EPA has conducted a regulatory impact analysis (RIA) in which they document quantifiable and nonquantifiable economic benefits from the proposed rule (EPA, 2023).

Table 1. Differences between MCLs, MCLGs, & HALs

Maximum Contaminant Level (MCL)	Maximum Contaminant Level Goal (MCLG)	Health Advisory Guidelines (HAL)
Sets highest contamination levels deemed safe for drinking water given currently available technology	Sets goal for drinking water contaminants at levels at which there are no known health risks	Considers an individual's lifetime exposure to drinking water contaminants and determines concentrations at/below levels at which health risks aren't expected to occur
• Legally enforceable: if state isn't abiding by MCL, state must implement water treatment systems • Set as close to MCLG as feasibly possible • Considers available technology and treatment methods required to remove a contaminant from drinking water	• Unenforceable • Strictly health-based • Doesn't consider currently available analytical methods to measure and treat PFAS • Levels at or below concentrations in which there are no known anticipated adverse health effects • Typically set lower than MCLs	• Not regulatory • Unenforceable • Intended to provide information about PFAS health effects, most up to date analytical tools, and effective treatment methods for state agencies and public officials • Addresses other PFAS sources, including air, diet, and consumer products • If PWS detect levels higher than HAL, utilities advised to inform consumers and take remediation action

Note: Readers are referred the EPA website for further details on MCL, MCLG, and HAL: https://www.epa.gov/sdwa/drinking-water-health-advisories-has.

---

[4] Readers are referred to the Rockerfeller Institute of Government's PFAS Policy Dashboard (https://rockinst.org/issue-areas/climate-environment/pfas-policy-dashboard/, accessed 7/21/2023) for a list of state-level PFAS regulations.

[5] The Hazard Index (HI) is a tool used to understand the health implications of chemical mixture exposures. In the case of PFAS, the toxicity of the four additional PFAS chemicals—PFNA, PFHxS, PFBS, and GenX—are compared to the toxicity of PFOA and PFOS. An HI greater than 1.0 indicates that the individual or combined toxicity of the four chemicals is greater than the toxicity of PFOA and/or PFOS at 4.0 ppt. If that is the case, the public water system will be in violation and agencies must take action to abate PFAS.

Table 2. Regulatory Limits in the 2024 PFAS Rule

Chemical	Maximum Contaminant Level Goal (MCLG)	Maximum Contaminant Level (MCL)
PFOA	0	4.0 ppt
PFOS	0	4.0 ppt
PFHxS	10 ppt	10 ppt
HFPO-DA (GenX chemicals)	10 ppt	10 ppt
PFNA	10 ppt	10 ppt
Mixture of two or more: PFHxS, PFNA, HFPO-DA, and PFBS	Hazard Index of 1 (unitless)	Hazard Index of 1 (unitless)

Note: Reproduced from EPA document: https://www.epa.gov/system/files/documents/2024-04/drinking-water-utilities-and-professionals-technical-overview-of-pfas-npdwr.pdf.

Among other benefits, the proposed rule will lead to reduced health burdens for a variety of diseases. The EPA's analysis relies on previously conducted scientific studies to measure and quantify the expected health benefits by using epidemiological and animal studies. Adverse health burdens from PFOA and PFOS have been quantified for four health conditions—cardiovascular disease, low birth weight, renal cell carcinoma, and bladder cancer—assessed as avoided cases of illness and deaths related to the exposure of PFAS from drinking water (EPA, 2023). The monetary effects of other diseases are currently not quantified due to a lack of information about either the strength of scientific information or appropriate economic information to monetize those disease burdens.[6] Overall, the total annualized monetized benefits of the proposed rule are $1,232.98 million (in 2021 dollars).

Bringing drinking water into compliance with the proposed rule is projected to incur sizable economic costs: PFAS in drinking water systems are difficult to treat using conventional methods (DeMeo and Caspary, 2020). Alternatively, public water systems will need to install additional treatment technologies such as activated carbon (GAC), ion exchange (IX), nanofiltration (NF), or reverse osmosis (RO). The EPA expects approximately 66,000 PWS around the nation to be subject to the proposed rule, and an estimated 3,400–6,300 PWS to exceed one or more MCLs. The annualized cost to bring national PWS in compliance with the standard is projected to be between $772 million and $1.2 billion, depending on the applied discount rate and the MCL. This assessment considers sampling, implementation, treatment, monitoring, and administration costs. Additionally, the EPA estimates that the annual costs of rule implementation could increase by $30–$61 million per year depending on whether PWS are required to dispose of and classify PFAS treatment as hazardous waste.

The Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act, P.L. 117-58) has dedicated $9 billion of funding for communities to deal with challenges from PFAS and other emerging chemicals. Of that money, $1 billion can be used for private well owners.

Concluding Remarks

PFAS pose significant challenges to human health and the environment. Although PFAS exposure has been associated with adverse impacts in the literature, further research is needed to fully understand the potential health effects and the associated economic costs. Collaboration among researchers, government agencies, and industry leaders will be essential to address the multifaceted challenges associated with PFAS. As state and local governments navigate remediation costs, PFAS contamination in drinking water supplies continues to pose health and environmental risks. Federal regulations regarding PFAS have been historically limited, with voluntary standards that vary across the nation and federal health advisories that lack enforceability. The EPA's proposed PFAS National Primary Drinking Water Regulation takes a significant step toward a cohesive, legally enforceable regulatory framework. While implementing PFAS regulations imposes potential cost burdens on local utilities and municipalities, federal assistance is available to support compliance efforts. Additionally, some parties are seeking financial compensation through legal action to aid in the cost of compliance. We hope this article can inform the general public and policymakers about potential sources of PFAS and their associated impacts on human health and the environment, with special attention paid to high-risk communities through effective outreach strategies and comprehensive policy development.

---

[6] Health conditions that lead to mortality burdens were monetized using a standard value of statistical life (VSL) metric. Morbidity burdens are much harder to quantify. EPA uses medical cost information for cardiovascular diseases (in O'Sullivan, 2011) and low birth weight (in Klein et al., 2018). Methods to monetize other PFAS-related diseases are less well established.

For More Information

Anderko, L., & Pennea, E. (2020). Exposures to per-and polyfluoroalkyl substances (PFAS): Potential risks to reproductive and children's health. *Current problems in pediatric and adolescent health care*, *50*(2), 100760.

Andrews, D.Q., and O.V. Naidenko. 2020. “Population-Wide Exposure to Per- and Polyfluoroalkyl Substances from Drinking Water in the United States.” *Environmental Science & Technology Letters* 7(12):931–936.

Baker, E.S., and D.R. Knappe. 2022. “Per- and Polyfluoroalkyl Substances (PFAS)—Contaminants of Emerging Concern.” *Analytical and Bioanalytical Chemistry* 414(3):1187–1188.

Braun, J.M. 2023. “Enhancing Regulations to Reduce Exposure to PFAS—Federal Action on ‘Forever Chemicals.’” *New England Journal of Medicine* 388:1924–1926.

Calafat, A.M., L.Y. Wong, Z. Kuklenyik, J.A. Reidy, and L.L. Needham. 2007. “Polyfluoroalkyl Chemicals in the U.S. Population: Data from the National Health and Nutrition Examination Survey (NHANES) 2003–2004 and Comparisons with NHANES 1999–2000.” *Environmental Health Perspectives* 115(11):1596–1602.

Cordner, A., V.Y. De La Rosa, L.A. Schaider, R.A. Rudel, L. Richter, and P. Brown. 2019. “Guideline Levels for PFOA and PFOS in Drinking Water: The Role of Scientific Uncertainty, Risk Assessment Decisions, and Social Factors.” *Journal of Exposure Science & Environmental Epidemiology* 29(2):157–171.

Dasu, K., X. Xia, D. Siriwardena, T.P. Klupinski, and B. Seay. 2022. “Concentration Profiles of Per- and Polyfluoroalkyl Substances in Major Sources to the Environment.” *Journal of Environmental Management* 301:113879.

DeMeo, R.A., and J. Caspary. 2020. “Pfapocalypse Now: The PFAS Firestorm and Implications for Florida.” *Florida Bar Journal.* 94:46–47.

Domingo, J.L., and M. Nadal. 2019. “Human Exposure to Per- and Polyfluoroalkyl Substances (PFAS) through Drinking Water: A Review of the Recent Scientific Literature.” *Environmental Research* 177:108648.

Ehsan, M.N., M. Riza, M.N. Pervez, M.M.O. Khyum, Y. Liang, and V. Naddeo. 2023. “Environmental and Health Impacts of PFAS: Sources, Distribution and Sustainable Management in North Carolina (USA).” *Science of The Total Environment* 878:163123.

Florida Department of Environmental Protection (FDEP). (2023). DEP’s Efforts to Address PFAS in the Environment. https://floridadep.gov/waste/waste-cleanup/content/dep%E2%80%99s-efforts-address-pfas-environment.

Guillette, T.C., J. McCord, M. Guillette, M.E. Polera, K.T. Rachels, C. Morgeson, ... and S.M. Belcher. 2020. “Elevated Levels of Per- and Polyfluoroalkyl Substances in Cape Fear River Striped Bass (*Morone saxatilis*) Are Associated with Biomarkers of Altered Immune and Liver Function.” *Environment International* 136:105358.

Høisæter, Å., and G.D. Breedveld. 2022. “Leaching Potential of Per- and Polyfluoroalkyl Substances from Source Zones with Historic Contamination of Aqueous Film Forming Foam-a Surfactant Mixture Problem.” *Environmental Advances* 8:100222.

Hopkins, Z. R., Sun, M., DeWitt, J. C., & Knappe, D. R. (2018). Recently detected drinking water contaminants: GenX and other per-and polyfluoroalkyl ether acids. *Journal‐American Water Works Association*, *110*(7), 13-28.

Hu, X.C., D.Q. Andrews, A.B. Lindstrom, T.A. Bruton, L.A. Schaider, P. Grandjean, ... and E.M. Sunderland. 2016. “Detection of Poly- and Perfluoroalkyl Substances (PFASs) in US Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants.” *Environmental Science and Technology Letters* 3(10):344–350.

Klein, R., & Lynch, M. (2018). *Development of Medical Cost Estimates for Adverse Birth Outcomes*.

Mulhern, R., B. Grubbs, K. Gray, and J.M. Gibson. 2022. “User Experience of Point-of-Use Water Treatment for Private Wells in North Carolina: Implications for Outreach and Well Stewardship.” *Science of the Total Environment* 806:150448.

National Institute of Environmental Health Sciences (NIEHS). 2023. “Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS).” Available online: https://www.niehs.nih.gov/health/topics/agents/pfc/index.cfm [Accessed May 20, 2023].

O’Sullivan, A. K., Rubin, J., Nyambose, J., Kuznik, A., Cohen, D. J., & Thompson, D. (2011). Cost estimation of cardiovascular disease events in the US. *Pharmacoeconomics*, *29*, 693-704.

Smalling, K.L., K.M. Romanok, P.M. Bradley, M.C. Morriss, J.L. Gray, L.K. Kanagy, ... and T. Wagner. 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.

Stoiber, T., S. Evans, A.M. Temkin, D.Q. Andrews, and O.V. Naidenko. 2020. “PFAS in Drinking Water: An Emergent Water Quality Threat.” *Water Solutions* 1(40):e49.

Teaf, C.M., M.M. Garber, D.J. Covert, and B.J. Tuovila. 2019. “Perfluorooctanoic Acid (PFOA): Environmental Sources, Chemistry, Toxicology, and Potential Risks.” *Soil and Sediment Contamination: An International Journal* 28(3):258–273.

U.S. Environmental Protection Agency (EPA). 2023, June 7. “Our Current Understanding of the Human Health and Environmental Risks of PFAS.” Available online: https://www.epa.gov/pfas/our-current-understanding-human-health-and-environmental-risks-pfas [Accessed May 20, 2023].

———. 2024. “Biden-Harris Administration Finalizes Critical Rule to Clean up PFAS Contamination to Protect Public Health.” Available online: https://www.epa.gov/newsreleases/biden-harris-administration-finalizes-critical-rule-clean-pfas-contamination-protect [Accessed Apr 24, 2024].

———. n.d. *Comptox Chemicals Dashboard: Master List of PFAS Substances (Version 2)*. Available online: https://comptox.epa.gov/dashboard/chemical-lists/pfasmaster [Accessed May 18, 2023].

———. n.d. *PFAS Analytic Tools*. Available online: https://awsedap.epa.gov/public/extensions/PFAS_Tools/PFAS_Tools.html [Accessed May 20, 2023].

U.S. Environmental Protection Agency Office of Water. 2023. *Economic Analysis for the Proposed Per- and Polyfluoroalkyl Substances National Primary Drinking Water Regulation*. EPA-822-P-23-001.

Wanninayake, D.M. 2021. “Comparison of Currently Available PFAS Remediation Technologies in Water: A Review.” *Journal of Environmental Management* 283:111977.

About the Authors: Samantha L. Snyder is a Graduate Student with the Warrington School of Business at the University of Florida. Xinde James Ji (xji1@ufl.edu) is an Assistant Professor with the Food and Resource Economics Department at the University of Florida. Weizhe Weng is an Assistant Professor with the Food and Resource Economics Department at the University of Florida. Di Fang is an Associate Professor with the Food and Resource Economics Department at the University of Florida. Suzanne Thornsbury is a Professor with the Food and Resource Economics Department at the University of Florida. Michael T. Olexa is a Professor with the Food and Resource Economics Department, University of Florida. Sean Olivnik is a JD Candidate with the University of Florida Levin School of Law.

Acknowledgments: We thank the editor and the anonymous reviewer for their helpful comments. All errors are our own.