

SPECIAL SECTION

Mitigation of PFAS in U.S. Public Water Systems: Future steps for ensuring safer drinking water

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Abstract

The circulation and usage of per- and polyfluoroalkyl substances (PFAS) and PFAS-derived products, such as Teflon and aqueous film-forming foam (AFFF), have led to PFAS being found in organisms worldwide. PFAS are emerging chemical contaminants that are toxic and take a long time to break down in the environment. PFAS can cause adverse health effects, including kidney cancer, testicular cancer, and ulcerative colitis. Studies have shown a widespread presence of PFAS in public water systems and people across the United States. The main pollution sources that contribute to PFAS in water are the chemical manufacturing industry, AFFF runoff, and landfills. With the health issues associated, and the occurrence in water systems, action should be taken to reduce PFAS in drinking water. Despite the adverse health effects associated with PFAS, the Environmental Protection Agency has not yet set enforceable limits for the chemicals in drinking water. Future actions should tackle two areas: (1) reducing the contamination at the pollution source and (2) improving the quality of PFAS contaminated drinking water. Five recommendations are suggested for key stakeholders. Contamination can be reduced by setting stricter industrial controls for waste streams, phasing out AFFF usage, and banning the majority of PFAS. Drinking water quality can be improved through setting state-enforced maximum contaminant levels and equipping water treatment plants with adequate PFAS removal technologies. Application of these recommendations could help reduce the presence of PFAS in drinking water and ensure safer drinking water for communities across the United States.

KEYWORDS

drinking water, environmental policy, health and safety

The Washington Internships for Students of Engineering (WISE) is an internship program that was founded in 1980. WISE is an interdisciplinary program that enables engineering students from multiple professional engineering societies, including AIChE, to focus on a public policy issue for 9 weeks over the summer. Interns are tasked with independently writing, researching, and presenting an article on a public policy issue that is relevant to engineering. Additionally, interns learn about the legislative and decision-making process for complex issues.

1 | EXECUTIVE SUMMARY

The article focuses on two different areas: the United States (U.S.) public water systems and per- and polyfluoroalkyl substances (PFAS). PFAS are emerging chemical contaminants that are bioaccumulative, toxic, mobile, and persistent, and thus take a long time to break down in the environment. PFAS were initially created in 1938 and have been widely produced by the chemical manufacturing industry since the 1950s. The circulation and usage of PFAS in the consumer market

and for essential use purposes have led to PFAS being found in the environment and organisms worldwide. With respect to the United States, literature has shown a widespread presence of PFAS in public water supplies and treatment systems across the country. Due to the prolific use of PFAS in so many consumer products, from clothing to nonstick cooking equipment, PFAS is a common pollutant in wastewater treated by municipal wastewater treatment plants (WWTP). This pollution mainly occurs through WWTP post-treatment discharge and biosolids generated from the WWTP process that are disposed of through land application. From these wastewater pollution sources, PFAS are further released into the environment through discharge to navigable waters that are used as drinking water sources, or through erosion and wind dispersion after WWTP biosolids are land applied for disposal. However, the most concentrated PFAS pollution sources are recognized as the chemical manufacturing industry, runoff from aqueous film-forming foam (AFFF) used for firefighting, and leachate from landfills. In the past 20 years, ubiquitous concentrations of PFAS in the environment and PFAS toxicity and health studies have caused increased concern. Multiple toxicology and epidemiology studies have shown that PFAS can cause adverse health effects, including kidney cancer, testicular cancer, and ulcerative colitis.

Due to the pervasive occurrence of PFAS in United States public water supplies and treatment systems, and the health effects associated with PFAS exposure, action is needed. Various measures have already been enacted. In the 2000s, both the eight-carbon chain molecules perfluorooctanesulfonic acid (PFOS), used in AFFF and Scotchguard, and perfluorooctanoic acid (PFOA), used in Teflon, were voluntarily phased out by United States manufacturers in cooperation with the U.S. Environmental Protection Agency (EPA). In 2016, the EPA set a Lifetime Drinking Water Health Advisory for PFOA and PFOS to serve as a non-enforceable guidance to drinking water stakeholders. Currently, bills have been introduced and are being reviewed in the House of Representatives and the Senate. However, further action must be taken to tackle the presence of PFAS in drinking water. The actions should both: (1) reduce contamination at the pollution source, and (2) improve quality of PFAS contaminated drinking water. Five recommendations are provided for consideration by policymakers:

1. As required by the Safe Drinking Water Act (SDWA) delegation, individual states must enforce EPA's SDWA maximum contaminant levels (MCLs) for the two PFAS contaminants PFOA and PFOS upon EPA's adoption of these MCLs. In the meantime, states should ensure compliance with EPA's PFAS health advisories and consider adopting their own specific state standards for characterized PFAS of concern.
2. The author urges the EPA to regulate waste streams of chemical plants manufacturing or incorporating PFAS chemicals into products, including: PFAS in stack emissions, management of existent PFAS in landfills, prevention of future PFAS landfill leachate contamination, and initiation of PFAS task forces for all chemical plants that use PFAS in their processes.
3. To protect the public water supply, both surface and groundwater sources, use of fluorine containing AFFF should be prohibited. An extensive portfolio of effective fluorine-free foams should be developed, and PFAS-containing foam should be phased out of use.
4. Although stopping contamination at its source can reduce PFAS in drinking water, PFAS is still present in drinking water. To ensure compliance with EPA's PFAS health advisories and soon, MCLs, public water supply treatment plants should be equipped with appropriate PFAS treatment technologies. Three technologies to consider are granular activated carbon, reverse osmosis filters, and ion-exchange resins. For areas with high concentrations of PFAS in water and inadequate water infrastructure, bottled water and household filters should be provided.
5. To significantly reduce the future presence of PFAS in the environment and thus, drinking water, a large-scale "Nothing but the Essentials" ban on PFAS should be introduced. PFAS-free substitutes without the undesirable characteristics of PFAS—persistent, mobile, bioaccumulative, and toxic—should be developed and introduced into the market.

Adopting these recommendations could reduce the release of PFAS into the environment and thus surface water and groundwater drinking water sources. This would reduce environmental exposure to PFAS and better protect the public water supply for communities across the United States.

2 | BACKGROUND

2.1 | The chemistry behind PFAS

PFAS is an acronym for per- and polyfluoroalkyl substances. PFAS are also referred to as perfluorinated compounds (PFCs).¹ PFAS are a group of man-made chemicals created in 1938.² Generally, PFAS are made up of a carbon chain with fluorine atoms attached.³ Perfluoroalkyl substances, such as perfluorooctanoic acid (PFOA), consist of a fluorinated carbon chain with a functional group attached to the last carbon.⁴ Polyfluoroalkyl substances, such as polytetrafluoroethylene (PTFE), have at least one carbon attached to a fluorine (Figure 1).⁴

PFAS have various properties due to their chemical makeup. Primarily, PFAS can act as surfactants, making them water-repellent and oil-repellent.⁵ Additionally, due to the stable carbon-fluorine chemical bond, PFAS are chemically nonreactive and heat resistant.⁵ For consumer products, these properties aid in water resistance, grease resistance, soil resistance, and making surfaces nonstick.⁵ From their discovery in 1938 to present day, PFAS have been widely integrated into consumer markets. Several products that contain PFAS with these properties are the following⁶:

- Oil-resistant coatings (grease-resistant paper, fast food wrappers/containers, and pizza boxes)
- Stain and water-resistant coatings

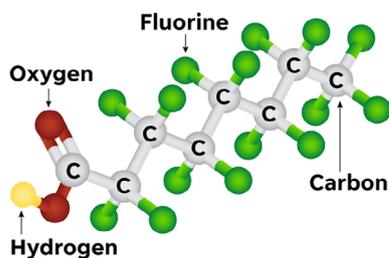


FIGURE 1 Chemical makeup of PFAS³

- Cleaning products
- Personal care products and cosmetics
- Paints, varnishes, and sealants
- Aqueous film-forming foams

In addition to these desirable properties, PFAS have characteristics that give reason for concern. The carbon-fluorine bond in PFAS is thermally and chemically very stable, and among the shortest and strongest of known chemical bonds. Due to the strong bond, PFAS are persistent, as they are not easily broken down and remain in the environment for a long time.^{7,8} Smaller, short-chain PFAS have increased mobility, allowing them to travel long distances through the environment.⁹ The mobility and persistence of the chemicals cause several PFAS to be bioaccumulative, meaning they accumulate in organisms over time.^{9,10} PFAS have also recently been found to be toxic and cause adverse health effects, which is further discussed in Section 3.4.1.

2.2 | PFAS historical perspective

To adequately understand the issue of PFAS in drinking water, a historical perspective of the origin and use of PFAS must be reviewed. In 1938, a fluoropolymer chemical called PTFE was discovered by Roy J. Plunkett, a chemist who worked at DuPont. The chemical had various useful properties, as it was chemically stable, non-corrosive, and had a very high melting point.² Most prominently, PTFE was low friction, hence its “slippery” and non-stick nature. The fluoropolymer was patented and registered as DuPont’s Teflon product in 1945.¹¹ In 1946, Teflon was introduced into the consumer market and advertised for its non-stick properties. The discovery of PTFE initiated the creation, production, and use of other per- and polyfluoroalkyl substances.

In the late 1940s, both DuPont and 3 M started producing large amounts of PFAS materials. 3 M began its large-scale production of PFOA. DuPont produced over 900 tons of PTFE-based Teflon per year at their Washington Works facility in Parkersburg, West Virginia. In the 1950s and 1960s, two PFAS compounds, PFOA and perfluorooctanesulfonic acid (PFOS), started to be implemented into the production of protective coatings, water-resistant products, and stain-resistant products. These products included Scotchgard and non-stick commercial cookware made from Teflon.¹² Outside of the

realm of commercial products, PFAS was also used to produce firefighting technologies. In the 1960s, the Naval Research Laboratory (NRL) and 3 M developed an aqueous film-forming foam (AFFF) to extinguish large petroleum fires. Following the 1967 USS Forrester fire in North Vietnam which caused 134 casualties, the Navy mandated that AFFF was carried on all vessels to ensure fire safety.¹³

The continuous use and production of PFAS led to the eventual contamination of water sources across the United States.¹⁴ A past example is 3 M’s Cottage Grove plant in Minnesota, which produced PFAS.¹⁵ From its production start in the 1950s to the 1970s, 3 M’s Cottage Grove plant legally dumped perfluorochemical waste in landfills near Lake Elmo of Minnesota.^{15,16} This resulted in the PFAS leaching into the groundwater and contaminating the community water supply.¹⁶ In 1998, a farmer in Parkersburg, West Virginia, reported the death of multiple cattle and suspected DuPont’s nearby Washington Works plant, which produced PFOA, as the source.¹⁷ The lawsuit found that **7100** tons of highly-concentrated PFOA waste had been dumped by DuPont into a nearby landfill.¹⁷ It was confirmed that the Washington Works plant released contaminants into nearby water sources.¹⁷

Moving into the 21st century, greater attention was brought to the potential environmental and health effects of the two primary PFCs used in the supply chain: PFOA and PFOS. In 2001, an article showed the widespread presence of PFOS in wildlife worldwide, illustrating the persistent and bioaccumulative nature of PFOS.¹⁸ This article raised international concern about PFAS and its effects.¹⁹ As a result, 3 M vouched to voluntarily phase out PFOA from production by 2002.²⁰ By 2006, the EPA’s 2010/2015 PFOA Stewardship Program was initiated, setting a goal to eliminate PFOA emissions from eight companies in the United States.²¹ A 2007 study found that four PFAS were detected in the blood of 98% of the U.S. population.²²

Despite the phaseouts of two legacy, long-chain PFAS, PFOA, and PFOS, in the United States, these two chemicals can still enter the consumer economy through internationally imported products.²³ Additionally, due to the phaseouts of the legacy PFAS, short-chain PFAS alternatives have been implemented into products and manufacturing processes. Although these shorter chain “replacement” PFAS serve as an alternative, recent studies have shown that these non-legacy chemicals have similar properties to their longer chain constituents and may pose an even greater threat to human health.²⁴

The history of PFAS thus far shows the emergence of the chemicals in modern consumer markets and lifestyles. Additionally, it demonstrates the rising concern associated with both legacy and replacement PFAS, giving a glimpse at the need for future policy action.

2.3 | Public water systems

The scope of the article focuses on PFAS presence in public water supply and treatment systems, as these systems provide drinking

water to a large number of Americans. A public water system is a pipe-based water system that provides drinking water to at least 25 people for at least 60 days per year or has “at least 15 service connections.”²⁵ Over 148,000 public water systems in the United States serve approximately 317 million consumers.^{25,26} There are multiple types of water systems where people access drinking water. Community water systems, the most common type, provide tap water for drinking to over 286 million people.²⁷ Both surface water and groundwater are important sources for providing drinking water to people in the United States, as community water systems get their water from these sources.²⁷

To ensure drinking water is potable, the water collected from these sources must be treated at water treatment plants (Figure 2). As the water is pumped into the plant, various floating solids, such as wood, leaves, and other large debris, are filtered out using screening.²⁹ Then, sediment and organic material are removed through coagulation and flocculation. In coagulation, chemicals called coagulants are added to the water, neutralizing the charges in the particles and allowing them to stick together. Once the particles are aggregated, the water is transferred to a flocculation basin. In the basin, slow mixing causes the formation of floc particles, which are clumps of the particles. The water is then transferred to sedimentation basins, where the floc particles accumulate at the bottom of the basin due to gravity. These gathered floc particles become sludge. The sludge is normally taken to a landfill or holding facility.³⁰

After larger particles are removed, the water is moved to filtration for the removal of remaining particles and microbes. Filtration occurs by running the water through layers of fine, granulated particles, using either sand, gravel, or carbon beds as filters.^{29,31} Finally, disinfection occurs, where chlorine compounds are used to eliminate microorganisms

from the water. Additionally, some plants may add alkaline substances to the water to maintain its pH and prevent corrosion of pipes.³¹ At the end of the process, water is either pumped and distributed through the city's pipe distribution system, or stored for future use.³⁰

Water treatment plants in public water systems must comply with standards set by the Safe Drinking Water Act (SDWA).³² The current drinking water regulations are listed under the National Primary Drinking Water Regulations (NPDWR), Part 141 of Title 40 Code of Federal Regulations (40 CFR Part 141), adopted by the EPA pursuant to its authority under the Safe Drinking Water Act, 42 U.S.C. §300f et seq.^{20,33} These regulations have enforceable limits, called maximum contaminant levels (MCLs), for over 90 contaminants that can be found in drinking water.²⁰

2.4 | The Safe Drinking Water Act

Congress enacted the Safe Drinking Water Act (SDWA) in 1974.³⁴ The purpose of the law was to “protect public health regulating the nation's public drinking water supply.”³⁵ In 1996, Congress amended the law to recognize source water protection, operator training and provide for funding treatment system improvements. More prominently, the SDWA authorizes the EPA to promulgate regulations setting forth national drinking water standards to mitigate health risks associated with contaminants.³⁶ These drinking water standards require water systems to test for regulated contaminants and ensure that these contaminants are at or below the set MCLs.³⁵ The SDWA targets four types of potential contaminants in drinking water: physical, chemical, biological, and radiological.³⁷ If these contaminants are not adequately managed and treated in a public water system such

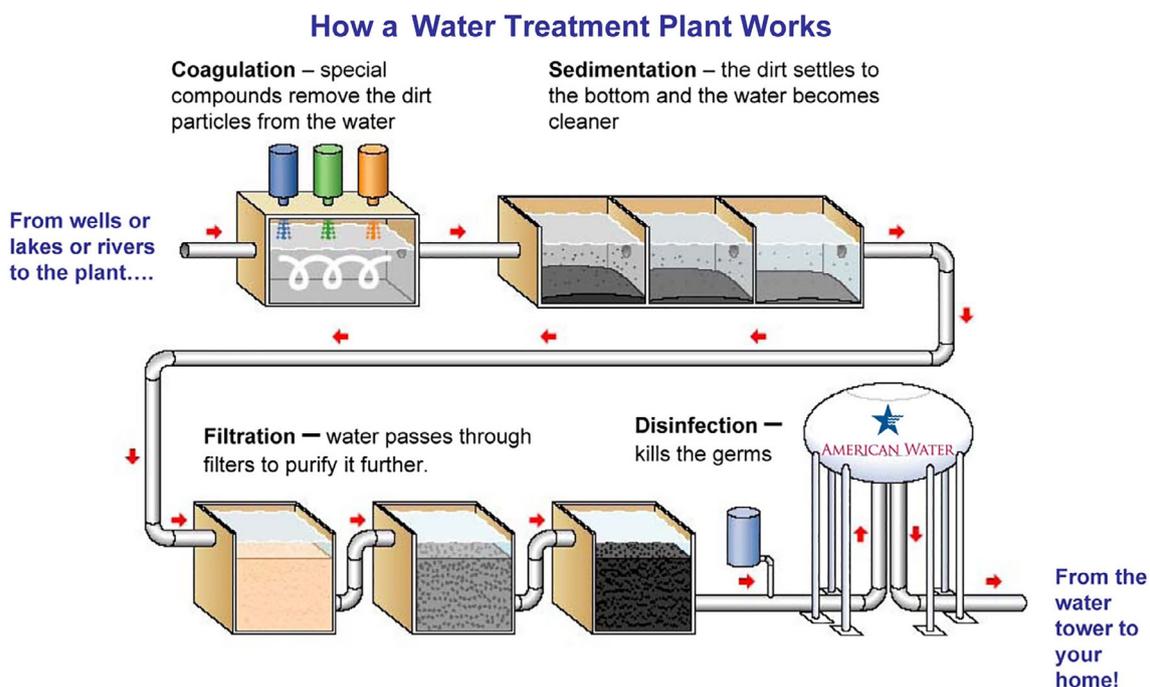


FIGURE 2 Illustration of the Water Treatment Process²⁸

that they remain at concentrations below the EPA's set MCLs, the contaminants can pose a health risk to humans.

Through evaluation of potential contaminants of concern, their associated health risks, and their frequency of occurrence, the EPA can determine that it will adopt an MCL for a contaminant.³⁸ For this to occur, the contaminant must have potential for causing a health issue, have a frequent occurrence in multiple public water systems, and regulatory action must have potential for reducing health risks associated with the contaminant.³⁸ Currently, EPA has not yet adopted MCLs for PFAS as part of the NPDWR, though EPA has determined that it will adopt MCLs for PFOA and PFOS.³⁹

2.5 | Health effects of PFAS

Multiple epidemiology and toxicology studies have been conducted on the health effects associated with PFAS. These studies have been primarily funded by the National Institute of Environmental Health Sciences (NIEHS).

The National Toxicology Program conducted multiple rat toxicology studies on the potential health effects of PFAS. A 28-day study found that both long- and short-chain PFAS affect liver and thyroid hormones.⁴⁰ Another study illustrated increased numbers of pancreatic tumors in male and female rats and increased number of liver tumors in male rats for rats exposed to PFAS during gestation or post-weaning.⁴⁰ PFAS impacted and changed mitochondrial function, with long-chain PFAS having more effect on mitochondrial function than short-chain PFAS. In a neurodevelopment study, it was observed that certain PFAS (PFOS, PFBS, and PFOA) had potential to impact neurodevelopment due to modification of neural cell differentiation.⁴¹ These studies suggest that high doses of exposure to certain PFAS can cause health issues, however, due to differences between mouse models and humans, these health risks from the rat studies are not conclusive for human health risk.

Due to the large amount of attention given to PFAS after the voluntarily PFOA and PFOS phase-out, many academic health effect studies were initiated in the 2000s. A large amount of current human health data for PFAS, specifically PFOA, has been obtained from the C8 Health Project, which studied the affected population that lived in vicinity of Dupont's Washington Works facility in West Virginia.¹⁹ This population's drinking water was contaminated with PFOA from 1984 to 2004.⁴² The C8 Health Projects found a positive association between PFOA exposure levels and testicular and kidney cancer, suggesting possible carcinogenicity associated with PFOA.¹⁹ Additionally, the study found other potential health effects associated with PFOA exposure: pregnancy-induced hypertension, high cholesterol, ulcerative colitis, and thyroid disease.¹⁹ Various other studies have shown an increased occurrence of bladder cancer, kidney cancer, prostate cancer, liver cancer, leukemia, and kidney disease.¹² The Agency for Toxic Substances and Disease Registry also lists two other potential health effects related to birth and pregnancy: small decreases in birth weights and pre-eclampsia in pregnant women.⁴³

Although research is still being conducted on health effects caused by PFAS exposure, the current studies show a reason for concern, as there are strong correlations between various PFAS and adverse health effects. One of the main pathways of human exposure to PFAS is drinking water.¹⁹

3 | KEY CONCERNS – DRINKING WATER CONTAMINATION

The occurrence and persistence of PFAS in public water systems in the United States give rise to three main areas of concern. First, there are many existing and accumulated PFAS in public water systems, affecting drinking water quality. Second, PFAS-containing compounds are still produced, distributed in United States commerce, used in consumer goods, and released into the environment. Third, emerging studies point to many potential adverse health effects of PFAS posed by these known sources of PFAS. This combination of factors signifies a public health urgency to develop policy strategies that will remove existing PFAS from public water systems and prevent future PFAS contamination of public water systems.

3.1 | Contamination of PFAS in public water systems

Contamination has been occurring in public water systems since the 1950s. PFAS are soluble in water, making it easy for them to dissolve in drinking water sources.⁴⁴ The main concentrated PFAS contamination sources are industry, AFFF run-off from fire training at air force bases, airports and other locations, and landfills.¹⁹

As shown in Figure 3, PFAS-containing consumer products are an additional source of PFAS contamination in humans.¹⁹ Due to the scope of this article, only the impact of concentrated PFAS contamination sources on drinking water systems will be discussed.

Figure 4 showcases the contamination occurrence of PFAS in different locations across the United States and the associated pollution source.

From 1999 to 2017, there was an increasing number of PFAS-contaminated sites among all four contamination sources. The two most prominent sources were industry, specifically chemical manufacturing plants, and byproducts of using AFFF for fire training at air force bases, airports, and by fire stations.¹⁹ These plants and AFFF-applied sites contribute to the presence of PFAS in waste management systems due to lack of containment and proper disposal.

Additionally, the EPA's third Unregulated Contaminant Monitoring Rule (UCMR 3) showed that over 75% of detected PFAS were found in 13 different states: California, New Jersey, North Carolina, Alabama, Florida, Pennsylvania, Ohio, New York, Georgia, Minnesota, Arizona, Massachusetts, and Illinois.¹⁴ Figure 5 shows the levels of detection across the United States for PFOA and PFOS, illustrating the widespread occurrence of PFAS in drinking water across the

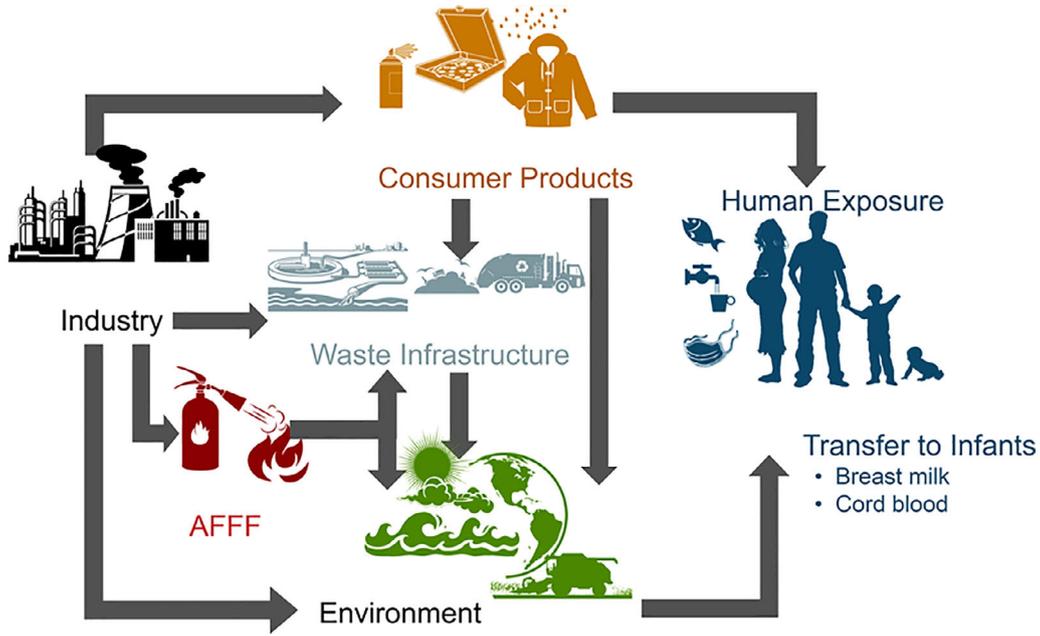


FIGURE 3 The multiple pathways that PFAS can enter drinking water and affect human health¹⁹

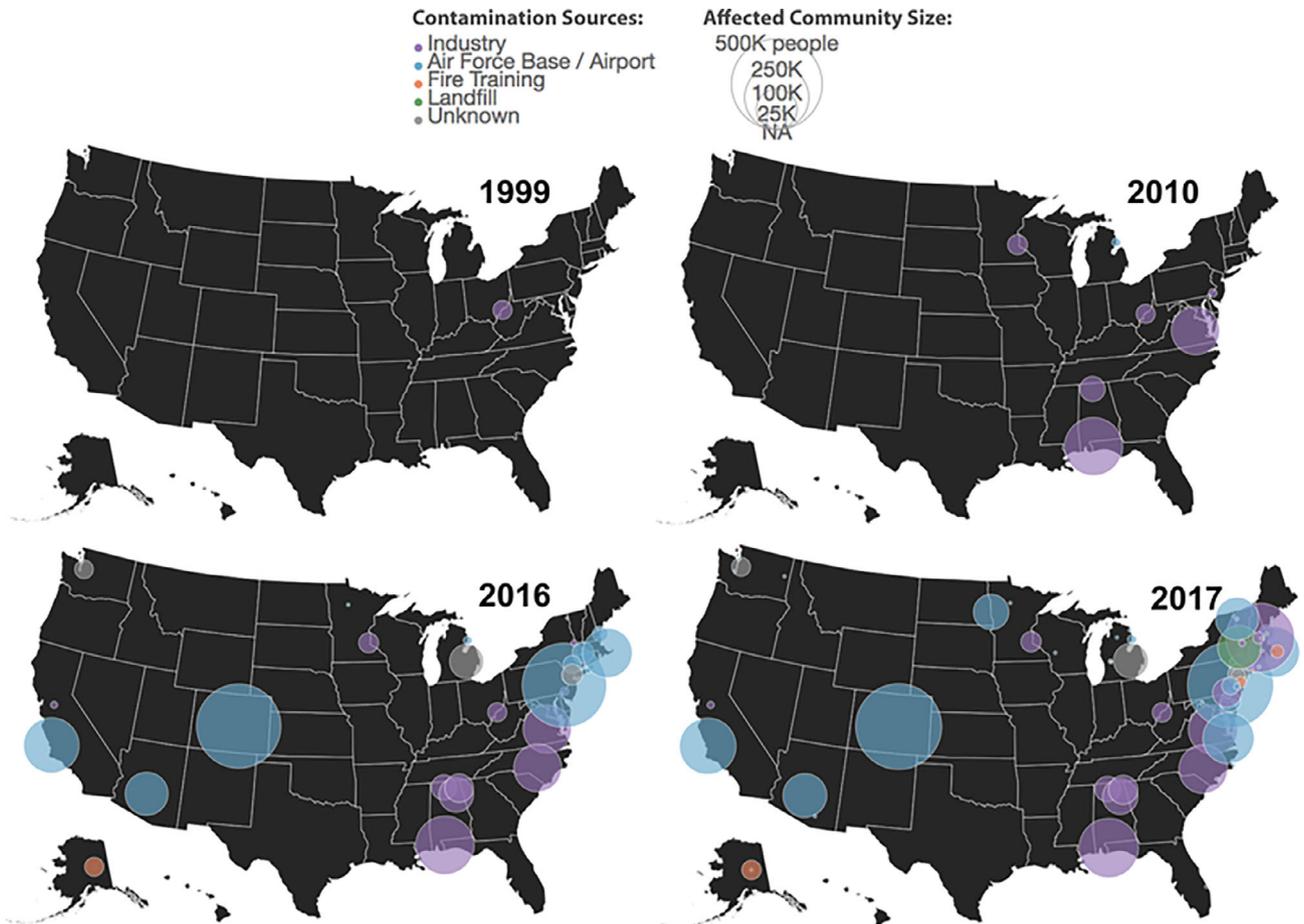


FIGURE 4 Locations in the United States with contaminated PFAS Sites¹⁹

United States. The following sections will address how PFAS have gotten into drinking water and characterize the pathways.

3.2 | Industry contamination

Industry is a significant source of PFAS in drinking water.¹⁴ The industrial category consists of industrial facilities that use PFAS in their manufacturing, produce PFAS, or process PFAS.⁴⁵ Over the course of 70 years, industry has contributed greatly to PFAS pollution of groundwater and drinking water. Studies have pointed to increased concentrations of PFAS in drinking water for regions with fluorochemical-related sites nearby.¹⁴ Specifically, every additional industrial site within an area was associated with an 81% increase of PFOA levels in drinking water.¹⁴ Figure 6 visualizes the association between specific industrial sites and the detection of six different fluorochemical compounds.¹⁴ The industrial sites are sourced from the EPA's 2010/2015 Stewardship program (see Appendix Table A1).²¹ The PFAS detection data originates from the EPA's

Unregulated Contaminant Monitoring Rule (UCMR), also discussed in Section 3.5.2.

There are multiple pathways in which PFAS can enter drinking water systems from industrial sources. The primary pathway of PFAS release is through waste disposal. First, the chemicals can enter the water system through liquid waste disposal in wastewater and stormwater discharge. This shifts the PFAS contamination to secondary contamination sources: wastewater treatment plants (WWTPs) and waste infrastructure. Additionally, PFAS in disposed solid waste, such as treatment sludge in landfills, can contribute to contamination of groundwater through soil infiltration and surface water through runoff. The third pathway of PFAS contamination by industry is accidental leaks and spills.⁴⁵ The final pathway is from stack emissions. A stack is an industrial chimney that releases gas emissions and disperse harmful pollutants over a broad area.⁴⁶ PFAS gas emissions released from industrial stacks can potentially result in the deposition of PFAS particles on land and surface water.²⁵ Figure 7 further illustrates the pathways in which PFAS enters water sources from industry.

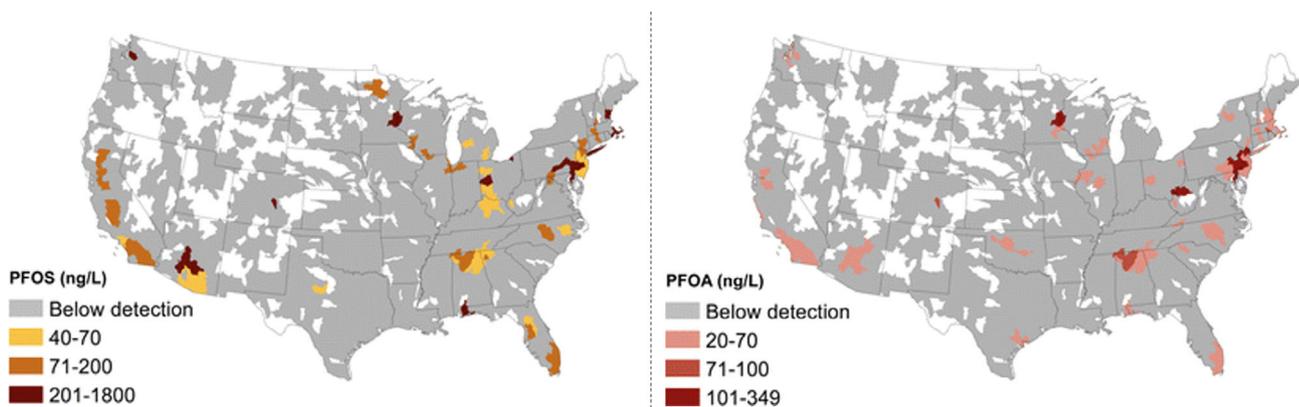


FIGURE 5 Adapted figure of PFOA and PFOS detection in drinking water across the United States¹⁴

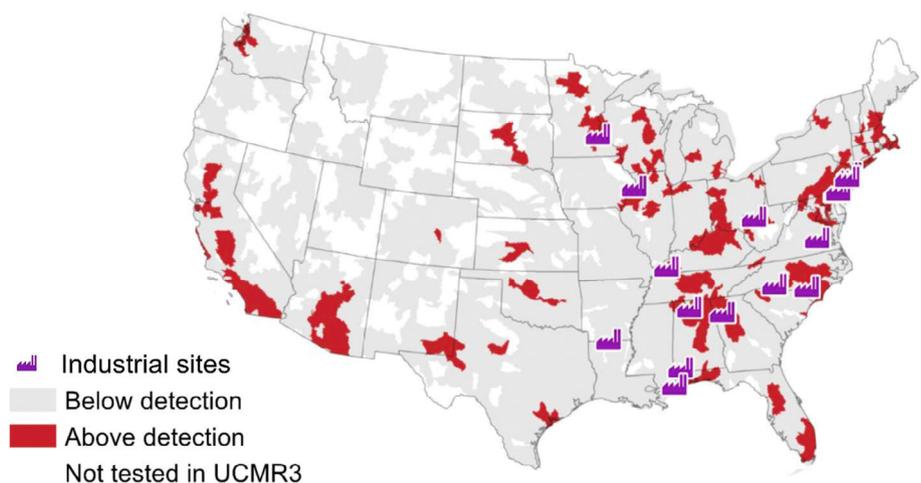


FIGURE 6 Adapted figure of select fluorochemical industrial sites and PFAS detection data¹⁴

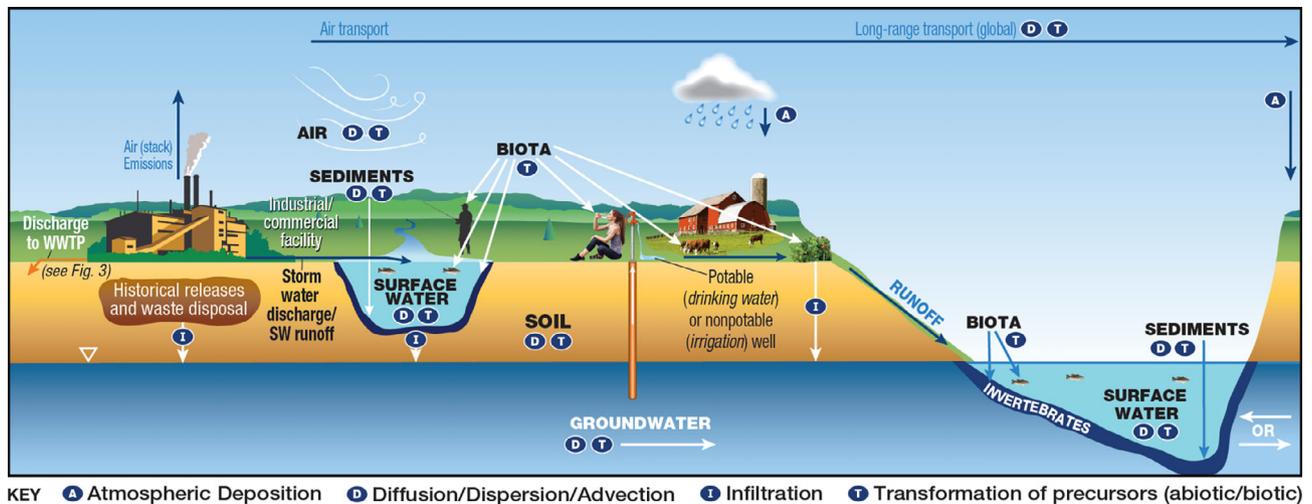


FIGURE 7 Adapted figure of a Conceptual Site Model for the industrial pathways of PFAS contamination⁴⁵

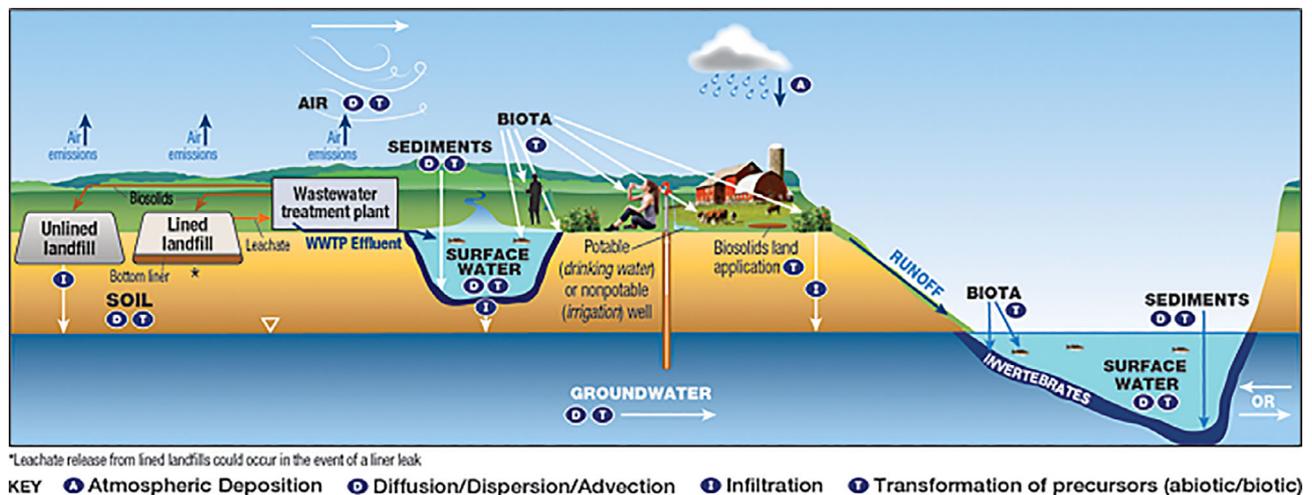


FIGURE 8 Release of PFAS through Waste Management Facilities⁴⁵

3.3 | PFAS in waste management infrastructure

Due to both industry and consumer actions, PFAS can enter drinking water through various waste management systems. There are multiple pathways in which PFAS can go into waste infrastructure: landfills, land application of biosolids, and WWTPs.

Figure 8 shows a conceptual site model for waste management facilities, specifically landfills and WWTPs. It demonstrates how contaminants can be released into the environment through waste streams. The two main sources, landfills, and WWTPs, both can contribute to the contaminant release of PFAS into groundwater and surface water. Additionally, agricultural land application of the treatment plant biosolids that contain trace amounts of PFAS can contribute to the runoff of PFAS into drinking water.

3.3.1 | Pathways into waste infrastructure: industry and consumers

Overall, *industry* is the main contributor to PFAS entering waste infrastructure. Companies that make PFAS-containing products dispose of their manufacturing waste products through various waste disposal systems, mainly landfills and WWTPs. Past industrial documentation from 3 M shows evidence of PFAS waste disposal into landfills and WWTPs.¹⁶ The appendix summarizes 3 M's "Fluorochemical Use, Distribution, and Release Overview" report (see Appendix Text A1).

Industry also acts as an indirect contributor, as fluorochemical companies create consumer products with PFAS. These products are eventually used and disposed of by *consumers* and enter landfills. Both

PFAS from direct industry disposal and consumer products contribute to the formation of PFAS-containing landfill leachate.⁴⁷ Landfill leachate from solid waste landfills is a large contributor of PFAS into water sources.⁴⁸ Landfill leachate is a liquid that forms when moisture, such as rainwater, filters through landfill waste and forms highly toxic wastewater.^{49,50} Through weather and time, mechanical breakdown of these products occurs and the PFAS exit landfills as landfill leachate. The liquid PFAS leachate that exits the solid waste landfills enters nearby water sources and becomes contaminated wastewater.

This section conveys that industry is the main source due to its direct contributions through industrial waste and indirect contributions to consumer waste. Action is needed to reduce drinking water contamination from PFAS waste disposal and landfills.

3.4 | AFFF contamination

In addition to industry directly contributing to PFAS contamination, industry indirectly affects PFAS in drinking water through a key product: aqueous film-forming foam (AFFF). Industry produces AFFF, a life-saving firefighting foam used by fire departments, military sites, and specific airports for training and emergency purposes.

Class B AFFF is used to suppress hazardous, flammable liquid-based fires, primarily stemming from hydrocarbon fuels.⁵¹ AFFF is used for both firefighting training exercises and for emergency live oil fires.¹⁹ AFFF is used in multiple types of sites: military fire training sites, civilian airports, fire departments, firefighting training facilities, petroleum refineries, fuel storage facilities, and chemical manufacturing plants.⁵¹ In these scenarios, AFFF is sprayed on oil, jet fuel, and petroleum fires to suppress and extinguish the fires in less than 30 seconds.⁵² It is used by mixing the foam with water and spraying the foam mixture onto the fire.⁵³ As shown in Figure 9, PFAS can enter waterways through AFFF runoff.⁵¹

The use of AFFF in fire-training exercises and firefighting activities has resulted in both controlled and uncontrolled releases of the fluorinated foam into groundwater.⁵⁴ It was found that the amount of military fire training sites in an area are positively associated with a concentration increase of six different polyfluorinated compounds in drinking water.¹⁴ Markedly, every additional military fire training site in an area accounted for a 35% increase of PFOS levels, a 20% increase of PFHxS levels, and a 10% increase of PFOA levels in drinking water.¹⁴ This suggests that military fire training sites that use PFAS-containing AFFFs are a prominent contributor to the presence and persistence of PFAS in drinking water systems. A future challenge is reducing the release of AFFF from sites that use PFAS-containing AFFF.

3.4.1 | AFFF requirements

Currently, AFFF used in military fire training exercises must adhere to performance requirements of military standard Mil-F-24385F.⁵⁵ The Mil-F-24385F performance standards require that AFFF agents extinguish smaller heptane fires (28 ft²) within 30 seconds using foam mixed with potable water or seawater. For larger fires (50 ft²), the AFFF agent must be able to extinguish the fire within 50 seconds using foam mixed with seawater.⁵² Additionally, the military standard specifically requires that the firefighting agent is diluted with fresh or seawater at two concentrations: three-part concentrate and 97-part volume water, or six-part concentration and 94-part volume water.⁵² The military specification applies to military sites and FAA-regulated airports. Additionally, the Federal Aviation Administration (FAA) has set standards for containing jet fuel-based fires with aircraft fire extinguishing agents. These guidelines are contained within the FAA's Advisory Circular (AC) for Aircraft Fire Extinguishing Agents.⁵⁵ The guidelines adhere to the military's Mil-F-24385F.

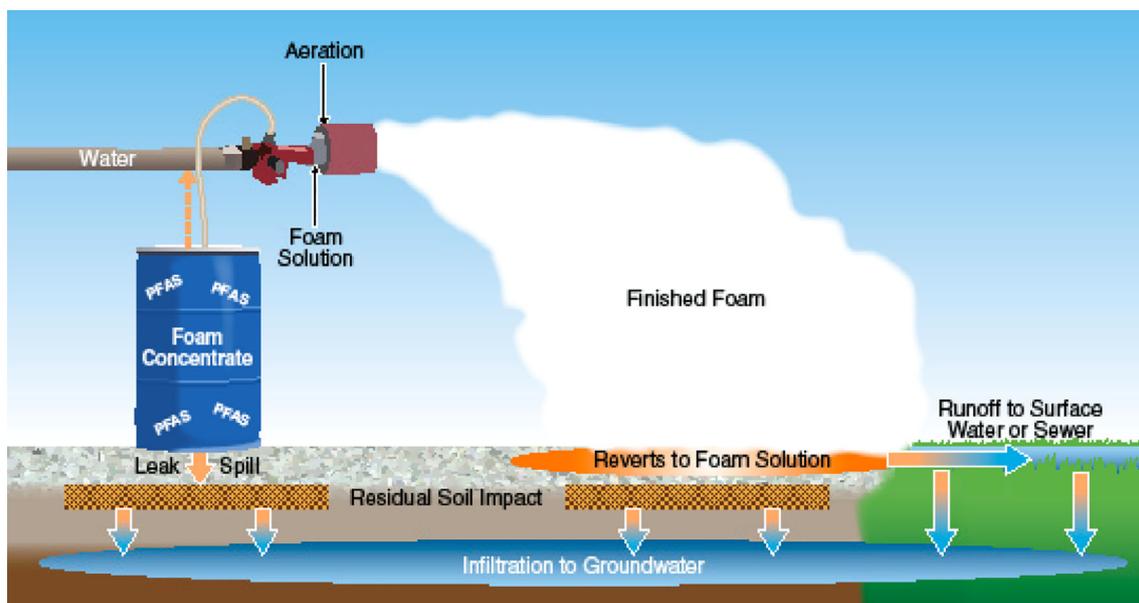


FIGURE 9 Release of firefighting foam into water sources⁵³

3.5 | Recent PFAS actions and plans

Due to the attention on PFAS, various regulations have been implemented in the past decade. Currently, several regulations give monitor and guidance on PFAS in drinking water.

3.5.1 | Drinking water advisories

Section 3.4 reviewed the Safe Drinking Water Act. The SDWA does not yet enforce the limits of any PFAS in drinking water. However, in 2016, the EPA set Lifetime Drinking Water Health Advisories for both PFOA and PFOS of 70 parts per trillion (ppt).⁵⁶ Moreover, in February 22, 2021, EPA reissued its fourth Contaminant Candidate List (CCL4) providing its final determination to regulate PFOA and PFOS with SDWA MCLs.³⁹ With CCL4, EPA also determined specifically that it would not regulate 1,1-dichloroethane, acetochlor, methyl bromide (bromomethane), metolachlor, nitrobenzene, and RDX. Federally, while there are no MCLs for PFAS yet, EPA's Health Advisory serves as guidance to state agencies, drinking water system operators, tribal officials, and local officials until EPA adopts MCLs for PFOA, PFOS, and other PFAS.^{39,56}

3.5.2 | Unregulated Contaminant Monitoring Rule

For drinking water contaminants that are currently not regulated, such as PFAS, data is collected on the presence of the contaminants in water systems through the EPA's Unregulated Contaminant Monitoring Rule (UCMR). UCMR requires water systems operators to test for 30 unregulated contaminants every 5 years.³⁸ In 2012, the EPA released UCMR 3, which required approximately 5000 water systems to test for six different PFAS (including PFOA and PFOS) between January 2013 and December 2015 (see Appendix Table A2).³⁸ A 1.3% of the water systems under this classification found PFOA and/or PFOS content at concentrations above the EPA's health advisory level of 70 ppt.³⁸ The information gathered in UCMR 3 aims to serve as a basis for "future regulatory actions to protect public health."⁵⁷

In March 2021, the EPA published UCMR 5. UCMR 5 contains 29 PFCs.⁵⁸ Data will be collected from January 2023 to December 2025 for UCMR 5.⁵⁸ The large presence of PFAS in UCMR 5 signifies the current administration's initiative towards addressing the presence of PFAS in drinking water.

3.5.3 | EPA PFAS Action Plan

In 2019, EPA released its PFAS Action Plan. This report was a comprehensive analysis and action plan of future tasks to reduce PFAS in the environment and develop greater analysis and detection tools. One action item of interest is the development PFAS Under the Drinking Water State Revolving Fund (DWSRF). This fund aims to provide financial aid to drinking water systems, both public and private, that

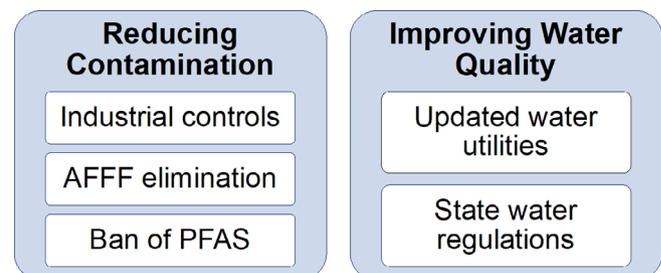
have been affected by PFAS contamination. The fund must be used towards either achieving NPDWR compliance or achieving the health protection objectives of the SDWA.⁵⁹

3.6 | Problem statement

As shown by Section 4.1, the detection of PFAS in drinking water has occurred across the United States. Additionally, various adverse health effects are associated with exposure to PFAS. Every day that passes leads to a greater risk of health effects for those exposed to higher concentrations of PFAS. The sources of PFAS in the U.S. drinking water have been largely identified and characterized. Despite occurrence and adverse health effects associated with PFAS, there are no currently enforceable nationwide limits that have been implemented, and PFAS policy is still developing. Therefore, action is needed to remove PFAS from drinking water by controlling pollution sources and developing treatment strategies for existing PFAS.

4 | POLICY RECOMMENDATIONS

The main issue is that PFAS are currently contaminating public water systems and have contaminated public water systems since the 1950s. Various epidemiology and toxicology studies have shown that this contaminated drinking water consumption can have health risks. There have been many different proposed solutions to this issue. As PFAS in drinking water is a complex issue, it is difficult to spearhead one specific solution. The following section will list policy recommendations for alleviating the issue and investigate the implications of each recommendation. The recommendations fall into two categories: reducing contamination from pollution sources and improving water quality where PFAS is already present in drinking water.



4.1 | Ensuring safer drinking water

4.1.1 | Drinking water regulations

The first action that should be taken is the implementation of enforceable state drinking water regulations for characterized PFAS. Currently, the EPA has a set lifetime drinking water health advisory of 70 ppt for two PFAS: PFOA and PFOS.⁵⁶ Although non-enforceable,

this technical information from the EPA can serve as a standard for states to make state-enforced drinking water standards for PFOA and PFOS until EPA can adopt MCLs for these two contaminants pursuant to its February 22, 2021 CCL4 determination.⁵⁵

Immediate actions

The Unregulated Contaminant Monitoring Rule (UCMR) acts as an informative document for data of unregulated contaminants potentially present in drinking water.⁶⁰ Although the EPA cannot adopt limits on contaminants without sufficient data, states and their environmental agencies can adopt their own stricter, more protective limits than the EPA.

From 2013 to 2015, UCMR 3 investigated and measured the occurrence of six PFAS: PFOS, PFOA, PFNA, PFHxS, PFHpA, and PFBS.⁶⁰ UCMR 3 showed the detectable amounts of these six PFAS in 4064 public water systems across the United States.¹⁴ State adoption and implementation of state-specific maximum contaminant concentrations is highly recommended for states with high concentrations of PFAS compounds in their drinking water, based on UCMR 3.²⁰ These states are California, New Jersey, North Carolina, Alabama, Florida, Pennsylvania, Ohio, New York, Georgia, Minnesota, Arizona, Massachusetts, and Illinois.¹⁴ The state-specific maximum contaminant concentrations should be set and enforced by each state's environmental agency.

Immediate future action

The EPA currently has analytical methods for 29 PFAS: EPA Method 533 and EPA Method 537.1.⁵⁸ UCMR 5 outlines an information summary of the 29 PFAS. Sample collection for UCMR 5 is planned to occur for 2 years, from January 2023 to December 2025.⁶¹ After December 2025, once UCMR 5 is published with sample detection data for the 29 PFAS, states that are most affected should develop for PFAS of highest occurrence. This regulatory action would include the following actions:

1. Mapping areas with the greatest PFAS release by industry, fire training sites, and corresponding WWTPs
 - Out of the 29 PFAS, occurrence data of each compound will identify the PFAS compounds of concern.
2. Setting drinking water standards in the form of state-specific maximum contaminant concentrations based on the state's PFAS of concern
3. Implementing a state monitoring campaign for quarterly monitoring of the PFAS of concern
 - The monitoring would utilize the analytical methods listed in EPA Method 533 and EPA Method 537.1. The monitoring would be conducted by the state's environmental agency.

Long-term future actions

As more analytical methods are developed, this procedure should be repeated for each new PFAS that can be analyzed. New state-specific maximum concentrations should be set as more UCMR's are released on a five-year basis.

One obstacle for future long-term actions is that there are still many newer, uncharacterized PFAS with little to no toxicology data that are being used as substitutes for legacy PFAS. For the EPA and state agencies to act properly, the EPA and NIEHS should establish a basis of research and toxicity classification for PFAS. For this to occur, the House Committee on Energy and Commerce could introduce appropriation bills to increase funding to key agencies, namely the EPA and NIEHS. Increasing funding for PFAS classification purposes allows the EPA and other agencies to better characterize risks associated with a wider range of PFAS used in industry and by consumers.

Setting state-specific maximum contaminant concentrations is only one of the steps that can be taken to alleviate the issue of PFAS in public water systems. Action should also be taken to reduce the source of PFAS entering drinking water. The following sections illustrate how various sources of PFAS can follow steps to reduce the presence of known and measurable PFAS in drinking water.

4.2 | Reducing industry contamination: targeted regulatory measures to reduce industry PFAS emissions

Section 4.2 introduces one of the main sources of PFAS into drinking water: industry. To reduce the presence of PFAS in drinking water, the release of PFAS by industrial sources should be closely monitored and managed. The three industrial sources of focus are air emissions, landfill release, and leaks and spills.

4.2.1 | Regulation of stack emissions

Past literature points to stack emissions, which are industrial gas emissions, as a possible contributor to PFAS in water sources.⁴⁵ Although more studies need to be conducted on the exact role of industrial gas emissions on water contamination, regulations should be implemented to reduce the release of PFAS from stacks. The following actions should be considered for industrial plants that produce, use, or process PFAS.

For all fluorochemical plants that have high detection of PFAS in nearby drinking water, based on UCMR data, air emissions monitoring should be implemented to measure PFAS in industrial gas emissions. Currently, the EPA has several standard analytical methods for measuring PFAS in stack emissions. The methods listed in the appendix can be used to test for the presence of over 50 PFAS compounds (see Appendix Table A3).⁶² The testing is to be managed by the state's environmental agency, the responsible company, and individual contractors hired by the company. If measurable amounts of PFAS at a set level are detected in stack emissions from a facility, regulations in the form of air pollution limits should be enacted and enforced to restrict output of PFAS.

Like the absence of current EPA SDWA MCLs for PFAS, there are also no EPA air emission regulations for PFAS. Though, a byproduct of PFAS combustion, hydrofluoric acid, is a listed "hazardous air

pollutant.” Thus, as with PFAS drinking water standards, state agencies should adopt their own state-specific PFAS air emission requirements.

To protect public water systems and drinking water supply sources, it is highly recommended that state-specific PFAS air emission regulations require appropriate pollution control technologies to be implemented at industrial fluorochemical facilities that use, produce, and process PFAS. For facilities with high PFAS emissions, thermal oxidizers and acid-gas scrubbers could be installed to remove PFAS and combustion byproducts from the process and effectively dispose of the PFAS in air emissions. Past state legislation has exhibited success in this area. In 2020, after a NC DEQ Consent Order required control of PFAS air emissions, Chemours installed a thermal oxidizer facility. The thermal oxidizer was able to remove over 99.999% of PFAS from air emissions, showing the effectiveness of the technology.⁶³ State environmental agencies, delegated with authority to implement portions of the United States Clean Air Act, 42 U.S.C. § 7401 et seq., can adopt more stringent air emission regulations and issue such air permit requirements on their own.⁶⁴

4.2.2 | Landfill management

Another source of industry PFAS contamination is PFAS-containing landfill leachate being released and entering the water supply.⁴⁵ As of present, PFAS are considered non-hazardous waste. Due to this classification, PFAS from industry and consumers can be disposed of into municipal solid waste landfills (MSWLFs).⁶⁵ For PFAS in landfills, two approaches should be considered.

Managing existent PFAS in landfills

The first approach is managing the already existing PFAS in landfills. As noted, both industry and consumers dispose of PFAS into municipal solid waste landfills. Although all modern municipal solid waste landfills (MSWLFs) have liners and leachate collection systems, PFAS leachate has been found in landfills and the surrounding environment.⁸ To prevent further contamination, a PFAS Detection and Restriction in Landfills Program (DaRLP) should be developed for MSWLFs nationwide, to be applied with the current requirements for MSWLFs in 40 C.F.R. Part 258.⁶⁶

1. As a general precaution, all MSWLF within a given radius of drinking water sources used by public water systems should have their leachate tested for PFAS.
 - o The amount and types of PFAS tested will be limited to the approved analytical methods by the EPA. As the EPA develops and approves more analytical methods for PFAS detection, such as SW-846 Method 8327, more PFAS can be potentially detected.⁶⁷
2. If PFAS are detected at levels above EPA method detection limits, the MSWLF groundwater monitoring plan required pursuant to 40 C.F.R. 258.51 will be reviewed to ensure it will protect nearby public water systems.⁶⁶

3. Should ongoing groundwater monitoring detect PFAS, then a PFAS groundwater remediation and containment plan should be developed.
4. After implementing the plan, compliance with the remediation and containment plan should be checked routinely, possibly every 12 months, to ensure minimal leachate leakage.
5. All landfills, affected or not, should be checked at least once within a decade.

These steps are highly recommended to prevent possible future groundwater contamination by leachate and should be capable of implementation by individual states as a means of more strict regulation without action by EPA. However, states can petition for rulemaking to request modifications to EPA's MWSLF regulations in order to specifically address PFAS in the existing groundwater monitoring requirements for MSWLFs.

Prevention of future landfill leachate contamination

The second approach is the prevention of future drinking water contamination by PFAS landfill leachate. Collected landfill leachate can be treated at WWTPs. However, there is a lack of effective removal technologies. In order to prevent (1) large-scale landfill PFAS leachate leakage from MSWLFs and (2) the subsequent ineffective removal of PFAS in WWTPs, disposal of PFAS into MSWLFs should be reduced. To safely contain PFAS and avoid any potential leakage, PFAS waste produced directly from industry should be designated as hazardous waste within the next 5 years. Hazardous waste is waste that can have negative health and environmental effects.⁶⁸ Due to the high variety of consumer waste, PFAS embedded in consumer waste products are more difficult to control. Therefore, this hazardous waste designation should only apply to PFAS waste produced by industry. This designation would allow “cradle-to-grave” regulation of the hazardous PFAS waste, from formation to disposal.⁶⁸ By disposing of industry PFAS waste streams as hazardous waste, less PFAS will enter MSWLFs, and one pathway of PFAS into drinking water is reduced. Treatment of disposal of the contained hazardous PFAS waste presents a future challenge that should be evaluated by the EPA and key PFAS disposal research organizations.

The State of New Mexico petitioned EPA to regulate PFAS as Hazardous Waste. On October 26, 2021, EPA responded to New Mexico's request stating that it will initiate rulemaking to regulate PFOA, PFOS, GenX, and PFBS as “hazardous constituents” under the Resource Conservation and Recovery Act (RCRA). EPA will also initiate rulemaking to clarify that RCRA gives EPA authority to require investigation and cleanup for wastes designated as hazardous under the law. This allows enforcement of RCRA for these constituents through RCRA's corrective action process.⁶⁹

4.2.3 | Release, leak, and spill prevention measures

As required by the National Defense Authorization Act of 2020 on June 22, 2020, EPA promulgated a final rule adding three PFAS

compounds to the list of chemicals covered by the Emergency Planning and Community Right-to-Know Act (EPCRA) Toxics Release Inventory (TRI) and created a framework for annual PFAS additions to the TRI. Entities subject to EPA's TRI reporting requirements were required to report PFAS releases by July 1, 2021 for the reporting year 2020.⁷⁰

Because some PFAS constituents are now regulated and contamination by these constituents can give rise to legal liability, it is suggested that companies within the PFAS industry have a PFAS task force that implements release, leak, and spill prevention measures. Task forces of this nature could be a part of the facility's Environment, Health, and Safety (EHS) department and have the following responsibilities:

- Budget appropriations of PFAS containment technologies
- Routine monitoring of plant waste streams
- Immediate action towards detected PFAS in waste streams
- Collaboration with state and federal environmental agencies to ensure contaminants are being properly managed and surrounding communities are being protected

Industrial facilities that use PFAS in their manufacturing, produce PFAS, or process PFAS are highly recommended to initiate a PFAS task force.

4.2.4 | Reducing industry contamination: summary

The suggested policy recommendations can reduce the industrial release of PFAS into drinking water sources. Other guidance and recommendations should be explored to get a full view of the issue and potential solutions.

4.3 | Reducing AFFF in drinking water

AFFF has been in use since the 1960s and is a critical component of firefighting safety. It was initially produced by 3 M and the NRL.¹³ AFFF is used at various sites for extinguishing hydrocarbon fires: petroleum plants, military training facilities, firefighting training, and fire departments.⁵¹ As mentioned in the background, AFFF is one of the main contributors to PFAS in drinking water. The AFFF enters the drinking water through seeping into groundwater and through runoff into surface water.⁵¹ There are multiple avenues for addressing and reducing AFFF PFAS contamination.

4.3.1 | “No PFAS in firefighting training foam” legislation

The National Defense Authorization Act of 2020 (2020 NDAA) prohibits “uncontrolled release” of fluorinated AFFF at military sites starting on October 1, 2024. An uncontrolled release is the “release

of a hazardous substance from its container.”⁷¹ The law means that all AFFF used in non-emergency situations must be contained, except for AFFF used in emergency responses.^{51,72} For AFFF to be used in training exercises, thorough and proper containment, capture, and disposal mechanisms must be set up to prevent AFFF release into the environment. Additionally, the law allows the use of fluorine-free extinguishing agents in training exercises instead of solely AFFF.

2020 NDAA presents a suggestion towards eliminating AFFF in training, however, it falls short, as PFAS-containing AFFF can still be used if containment measures are taken. Washington state and North Carolina are two states that have enacted legislation to take this suggestion one step further by eliminating the use of PFAS-containing AFFF in all training exercises, regardless of containment measures. As military fire training and firefighting training occurs in a controlled environment, there is virtually no risk associated. Therefore, the surfactant does not need to be as effective and can be fluorine-free. Due to the lack of risk, the state legislation enacted by Washington state and North Carolina should be used as a model for establishing similar legislation on a federal level.

A “No PFAS in Firefighting Training Foam” legislation should be introduced, in which the use of AFFF for non-emergency measures should be eliminated, regardless of containment measures, to reduce any risk of contamination. Non-emergency measures include the firefighting training exercises performed by military training sites and fire departments. Emergency measures are classified as any oil-based fire, alternatively known as a liquid pool fire, that unexpectedly breaks out and has the potential to cause great structural damage, environmental harm, and injuries/casualties. The bill could be introduced by the House Committee on Armed Services, House Committee on Veterans' Affairs, House Committee on Science, Space, and Technology, and/or the House Committee on Transportation and Infrastructure.

Implementation

With the proposed complete ban of fluorine-containing foams for fire training purposes, a substitution will need to be used in place of fluorine-containing foam. The main purpose of fire training exercises is to ensure the trainees use proper technique. The training foams for liquid pool fires should have similar characteristics to previously used fluorinated foams. There are multiple types of fluorine-free foams. Several alternatives are listed below:

- GreenFire Fighting Foam (GFFF)⁷³
- Fomtec Fluorine Free Foam⁷⁴
- SOLBERG VERSAGARD AS-100⁷⁵

Appropriate proportioning devices must be used to dispense the foams and effectively extinguish oil-based Class B fires. In finding foams for training purposes, foams do not need to meet the military specifications. However, even for these alternatives, containment methods should be set up to reduce foam runoff and entrance of possible contaminants into the water system. Containment systems include pre-installed water barriers, permanent retention basins, firefighting water barriers, hoods and sealing pads, and mobile storage

tanks.⁷⁶ By containing the foam-containing water through HAZMAT methods (i.e., damming, diking, diversion, and retainment), the potentially contaminated water can be transported to a proper water treatment facility.

By enacting “No PFAS in Firefighting Training Foam” legislation, there would be less PFAS use in firefighting sites and departments. PFAS exposure would be reduced for firefighters, military personnel, and trainees. Additionally, AFFF producers will see profit losses, as many PFAS-containing AFFF are used in training exercises.⁷⁷ Currently qualified product distributors for fluorinated foams that meet MilSpec MIL-F-24385F are listed in the appendix (see Appendix Table A4).⁷⁸

The majority of companies with qualified fluorinated foam products for Class B fire military specifications have fluorine-free substitutions that could be used to replace the loss of revenue from AFFF sales. Research and development into fluorine-free foams is highly recommended for companies that do not have alternatives to PFAS-containing foams.

4.3.2 | Replacement of all fluorinated foams with fluorine-free foams

In the next 5 years, fluorinated firefighting foams should be phased out and replaced with fluorine-free foam. Although NDAA 2020 prohibits “uncontrolled release” of fluorinated AFFF at military sites starting on October 1, 2024, it grants an exception for emergency use.^{51,72} By 2027, there should no longer be an exception for the “uncontrolled release” of fluorinated AFFF in emergency use, and only non-fluorinated foams should be allowed. A portfolio of safe and effective fluorine-free foams should be developed. Recent legislation in the Federal Aviation Act of 2020 has allowed fluorine-free foams to extinguish live fires at FAA-certified airports.⁷⁹ With this legislation, airports can explore various fluorine-free options and progressively build a portfolio.

The safe and effective fluorine-free foams portfolio should be developed and validated by December 2024. This identification should be spearheaded and sponsored by the NRL and the DOD’s Strategic Environmental Research and Development Program.⁸⁰ Once effective fluorine-free candidates are identified, the candidates can be tested at FAA-certified airports with varying fuel fires starting in October 2024. Similar to the initial fluorine-free foam use at the London Heathrow airport in 2015, select airports should switch to solely using fluorine-free foams and observe effectiveness over a 15-month evaluation period.⁸¹ In this period, all use of fluorine-free foams, both emergency and training use, should be monitored and recorded. If a candidate shows early signs of ineffectiveness, the candidate will be removed for safety assurance. After 15 months, the Department of Defense and the NRL should examine the evaluation reports and approve or disapprove of a fluorine-free candidate. As more fluorine-free airports are tested and a basis for extinguishing liquid pool fires is set, the legislation should extend to military sites, petrochemical plants, and fire training facilities.

Potential obstacles

A current obstacle with replacing the PFAS-containing AFFF is that fire extinguishing agents for Class B fires must meet specifications from MIL-F-24385F. In the United States thus far, only fluorinated foams have met all the specifications contained in MIL-F-24385F. Studies are being conducted to establish fluorine-free foams that have the same effectiveness as fluorinated AFFFs. Although non-fluorinated foams have yet to meet every specification within the MilSpec, multiple alternatives have been tested for and have met the *fire extinction metrics* of MIL-F-24385F. The NRL has done exploratory research with fluorine-free foams. Two of the tested foams, 3:2 Cap/Gluc and Cap, have been able to fully extinguish a live “pool fire” in under 30 seconds.^{82,83} However, these foams do not meet all the standards listed in MIL-F-24385F, as each foam must have specific liquid properties.

It is recommended that the military specifications for MIL-F-24385F are reevaluated and potentially amended to expand the range of liquid properties. The amendment should shift focus to fire extinction metrics. For example, if a suppressant can extinguish a smaller 28 ft² pool fire within 30 seconds, in addition to meeting burnback requirements, the foam meets specifications. Through amending the MilSpec, the door opens for equally effective, fluorine-free foams to meet standards and be used in emergency live pool fires.

In the interim

Until an equally effective fire extinguishing agent is found for Class B Fires, AFFF should continue to be used for all emergency fires to ensure safety and decrease risk. For live situations with emergency fires, containment setup may not be possible, as safety and extinguishing the fire is the top priority. If possible, the runoff and remaining firefighting agents should be cleaned up immediately after the situation is deemed safe. All sites with fire training should have an in-house wastewater center and water containment system to deal with AFFF used in live, emergency fires. By containing the PFAS-containing water, the contaminated or potentially contaminated water can be transported to a proper water treatment facility.

4.4 | PFAS in the water supply

4.4.1 | Safe drinking water—water treatment plants

The EPA’s National Primary Drinking Water Regulations do not currently regulate PFAs, though EPA has committed to adopting MCLs for PFOA and PFOS.²⁰ If these primary standards are set in the immediate future, the standards are still not enforceable until 3 years after the EPA’s finalization.³⁶ Congressional legislation for the enforcement of water treatment systems should happen immediately to mitigate future negative health and environmental effects. The legislation should take place as follows.

As previously mentioned, public water supply and treatment systems provide potable drinking water to communities of varying sizes. Current water treatment plants for community water systems require several steps for treatment and purification, as outlined in Section 3.3. These water treatment plants are useful for removing microorganisms, particles, and other enforced contaminants from drinking water; however, many are ineffective in removing PFAS from drinking water.

Subsequently, there is a great need to equip public water systems with effective PFAS treatment technologies. To tackle this effort, first, an official portfolio of acceptable and effective treatment methods for PFAS removal should be established by the EPA. Studied removal technologies that could be included in the portfolio are listed below.

Example: PFAS removal technologies portfolio



Granular activated carbon

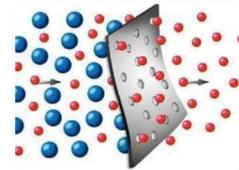
Granular activated carbon (GAC) is a highly porous material that can be used to filter out PFAS in water through adsorption. Adsorption is the movement of a substance from a gas or liquid phase to the surface of a solid.^{84,85} GAC consists of various high-carbon organic materials, such as coal and wood.⁸⁶ GAC is effective at treating and removing long-chain PFAS, such as PFOA and PFOS. However, GAC is not as effective at removing shorter chain PFAS from water.⁸⁷ After the PFAS compounds are adsorbed to the binding sites and the GAC is spent, the filter beds must be properly disposed of through either incineration or other methods. Despite these drawbacks, GAC removes many of the listed enforced contaminants, making it an attractive option for water systems due to its versatility.⁸⁸



Ion exchange resins

Ion exchange resins consist of beads made up of highly porous material that is insoluble in water, acid, and base solutions. Ion exchange resins remove PFAS from solution through the use of anion exchange. The positively charged resin attracts the negatively charged PFAS compounds, causing them to bind to the resin.⁸⁹ There are two resin types: single-use and regenerable resins.⁸⁹ Single-use resins have

been found to be more effective in the treatment of low-concentrations of PFAS, while regenerable resins are more effective in the treatment of high-concentrations of PFAS. Single-use resins are more applicable to drinking water treatment systems.⁸⁷ Although ion exchange resins are generally more effective in removing PFAS than GAC, they are also more costly than GAC, signifying a greater financial burden for water systems.⁸⁶



Reverse osmosis

In reverse osmosis, PFAS-contaminated water is pushed through a semipermeable membrane through the application of pressure.⁸⁷ Reverse osmosis is more than 90 percent effective at removing PFAS from water.⁸⁶ One consideration is that reverse osmosis filters sodium chloride from water, while other treatment techniques, such as nanofiltration, retain essential minerals.⁸⁶ Multiple technical challenges are associated with reverse osmosis, including membrane fouling, temperature parameters, and feedwater quality. Although effective, reverse osmosis requires a large amount of energy to power high-pressure pumps, making it a costly and energy-intensive option.^{87,89} Reverse osmosis systems are commonly used in household purification systems, signifying a potential opportunity for PFAS-contaminated water purification for those communities that do not have adequate water infrastructure.⁸¹

End of example portfolio

Public water systems can choose to implement one of the approved treatment methods listed in the portfolio based on the resources and funds available. Due to the cost of technology implementation, the implementation should only be enforced for public water systems that have at least one of the following classifications:

- have already been impacted by measurable PFAS contamination, such as PFOA, PFOS, and PFHxS
- are within the vicinity of known PFAS sources, such as military training bases and industrial facilities

4.4.2 | Additional action: system challenges

Although some public water systems have the resources and infrastructure to integrate PFAS removal technologies, other small water systems can face multiple issues, such as aging infrastructure, lack of expertise, lack of financial resources, and lack of resources.⁹⁰ For these systems that lack the appropriate infrastructure and resources, alternative action should be taken to ensure safe drinking water. In these scenarios, individual water filtration

systems and/or bottled water should be provided to the households within the affected area.

Individual water filtration systems should contain charcoal filters (granular activated carbon) or reverse osmosis filters. Due to the water filtration inefficiency, reverse osmosis filters should only be used for one water source, for example, a kitchen sink or similar water dispenser. GAC systems should be used for entire households.⁹¹

4.4.3 | Funding

For public water systems where industry pollution is the source of PFAS contamination, the legislation should require that responsible parties are held accountable for funding these filtration systems and/or bottled water. To fund removal technologies for a state's water treatment plants, taxes should be increased for fluorochemical companies in the state. The increased tax income from these companies should be used to assist water utilities in equipping their treatment plants with adequate technologies. For communities that have utilities with insufficient resources and infrastructure, the tax revenue will go to providing drinking water to communities through the purchase of bottled water and effective home filters. Additionally, loans can be taken from the DWSRF to more imminently fund treatment plant removal technologies and improve drinking water quality.⁹²

In the past, similar statewide legislation has been enacted to provide potable water to those whose water sources have been contaminated by PFAS. In North Carolina, a prominent PFAS issue has been the GenX contamination of North Carolina's Cape Fear River by the Chemours Fayetteville works plant. In 2017, 19 households were found to have concentrations of GenX, a short-chain PFAS, above the state's provisional health goal. To ensure safe drinking water, state officials mandated that Chemours give bottled water to the affected households.⁹³ Considering this issue, representative Deb Butler of New Hanover County, NC, recently spearheaded water treatment through a new bill, H444, that would hold industry PFAS contaminants responsible for water treatment.⁹⁴ The bill was introduced to ensure safe drinking water supplies for those affected by GenX and specified PFAS contamination.⁹⁵ On a federal level, measures like these should be taken to ensure safe drinking water across the nation. If federal action is not immediately taken, in the interim, similar bills should be introduced and enacted in state legislatures for states that have high PFAS concentrations in their public water supply.

4.4.4 | Future technologies and challenges

PFAS removal

Current technologies can remove PFAS; however, they are limited in the amount and type of PFAS that can be removed. Additionally, all methods, although varying in price, are cost intensive. There is space for future research and development into treatment technologies for PFAS removal. Funding should be appropriated to research institutions and universities for technology development to remove existing and emerging PFAS.

PFAS disposal

The three technologies in the preceding PFAS Removal Technologies Portfolio—granular activated carbon, ion exchange resins, and reverse osmosis—can adsorb PFAS and remove the compounds from water. However, these materials still contain PFAS. PFAS destruction technologies should be developed so that PFAS can be effectively removed from the environment and waste streams. Further, once the PFAS are removed from water, the materials containing the PFAS waste should be managed. The current PFAS destruction method is incineration, where the PFAS materials are incinerated at extremely high temperatures and theoretically dissociated into the basic elements (i.e., carbon, fluorine, etc.).⁸⁹ However, more research should be conducted to investigate if the PFAS are truly incinerated, or if they are merely degraded to shorter-chain fluorinated compounds.

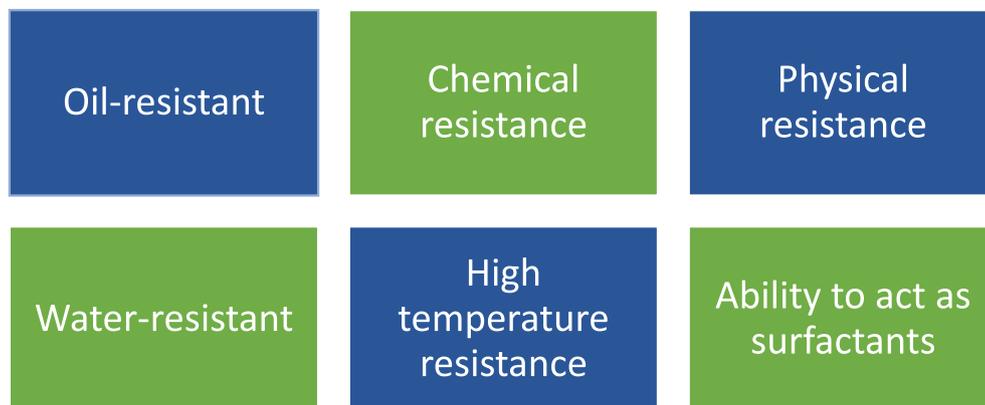
Finally, as more research is conducted and more effective technologies are developed, grants should be given to affected water treatment facilities. These grants will enable water treatment facilities to equip themselves with effective remediation technologies and further remove PFAS from drinking water.

4.5 | “Nothing but the Essentials” PFAS ban

The ultimate solution for removing PFAS from drinking water is eliminating the use of PFAS within the industrial sector, and subsequently, the consumer market. By banning all PFAS, the point source of contamination would be removed, mitigating new contamination that could occur in public water systems. The ban would consist of a large-scale ban on PFAS industrial use, whether it is in producing PFAS precursor chemicals, manufacturing products with the PFAS surfactant properties, and using PFAS in production-related activities. A ban on all PFAS would serve as a preventative measure, focused on mitigating potential future risks based on the negative health effects of legacy perfluorochemicals. Removing all PFAS from the market and production is a complex issue that must be thoroughly assessed. Deliberate and carefully considered action should be taken to tackle a PFAS ban strategically.

In May 2021, the EU's European Chemical Agency (ECHA) published an update for the Chemical Sustainability Strategy (CSS), which calls for an eventual ban on all PFAS unless deemed to be essential.^{96,97}

The United States should follow the EU's strategy and enact a legislation that bans PFAS within the next 10 years, by 2032. The legislative plan should be developed within the House Committee on Energy and Commerce to draft a “Nothing but the Essentials” ban for PFAS. Although immediate action is needed to eliminate future drinking water contamination, time should be given so that actions are deliberately investigated to prevent potential negative outcomes. In order to eliminate PFAS from the supply chain, substitutes for PFAS should be implemented. PFAS are found in multiple consumer products, including fast food wrappers, water-resistant coatings, and cleaning products, due to their physical properties. PFAS are desirable in consumer and safety products due to their numerous characteristics, listed below.⁹



Substitutions for PFAS need to consider the aforementioned characteristics. There should be various types of substitutions for each characteristic. To supply products that have nearly identical properties, adequate appropriations should be put towards developing new chemicals that can imitate the key properties of PFAS.

Additionally, the search for and implementation of new chemicals that do not contain polyfluorinated carbons contains a challenge within itself: the potential toxicological and health effects associated with the new chemicals. There are several main issues associated with PFAS. Listed below are the undesirable characteristics associated with PFAS.⁹

- Persistent in the environment after partial degradation
- Mobility in the environment (multiple mediums: air, water, and soil)
- Bioaccumulative
- Toxic: associated with multiple health issues.

Substitutions for PFAS should not have these undesirable, negative traits. Past short-term solutions were focused on substituting the primary long-chain compounds of focus, PFOA and PFOS, for short-chain PFCs. Due to having shorter half-lives, these short-chain replacement compounds were considered to not have the negative effects associated with PFOA and PFOS. However, research has shown that short-chain PFAS compounds can also be bioaccumulative, persistent, and toxic.⁹⁸

A past example of an adverse PFAS substitution was the replacement of PFOA with GenX. As a result of the PFOA phase-out, the short-chain GenX was used as a replacement for making Teflon-like materials. Later studies showed that GenX was bioaccumulative, persistent, and mobile in the environment. Additionally, recent animal laboratory studies have shown GenX is associated with health effects such as liver cancer, pancreatic cancer, and testicular cancer.⁹⁹ Although no human health effects have been observed yet, these preliminary animal studies show reason for concern of future human health effects. This example shows the importance of thorough investigation for potential PFAS substitutions. Markedly, future substitutions must be screened to ensure that there are no adverse effects.

To ensure the proposed substitutions are not toxic, multiple health, toxicity, and safety studies must be conducted. Once substitutes are located, the bill must provide appropriations to various agencies, primarily the NIEHS, the National Toxicology Program, and the EPA.

5 | CONCLUSION

The topic of PFAS in drinking water is nuanced and has many items to consider. The author has suggested the following measures be taken to reduce PFAS in drinking water:

1. Individual states should enforce MCLs for measurable PFAS in their drinking water on both an immediate and long-term basis.
2. The waste streams of chemical plants involved with PFAS should be strictly regulated.
3. There should be more regulation focused on reducing AFFF in drinking water, including the phase out of PFAS-containing foam and development of a comprehensive portfolio of effective fluorine-free foams.
4. To remove PFAS contaminants and improve drinking water quality, water treatment plants should be equipped with adequate PFAS treatment technologies. For areas with high concentrations of PFAS in drinking water sources and inadequate water infrastructure, bottled water and household filters should be provided.
5. To significantly reduce the future presence of PFAS in drinking water, a large-scale “Nothing but the Essentials” ban on PFAS should be introduced. PFAS-free substitutes without the undesirable characteristics of PFAS—persistent, mobile, bioaccumulative, and toxic—should be developed and introduced into the market.

Implementation of the aforementioned suggestions could result in reduced PFAS in drinking water and safer drinking water. The author recognizes that there are many more aspects that need to be explored and hopes that the background and recommendations can spur further discussion on the matter.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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