



# Source identification and distribution of per- and polyfluoroalkyl substances (PFAS) in the freshwater environment of USA

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## Abstract

A family of anthropogenic organic pollutants with a long history of use, per- and polyfluoroalkyl substances (PFAS) are present in a wide range of environmental compartments, including drinking water, soil, biota, surface water, and groundwater. As a result of their persistent nature in the environment, PFAS have been found in several species of wildlife worldwide, such as invertebrates, aquatic organisms, amphibian species, aquatic plants, alligator, seabird, mammal tissues, as well as in human body. This review provides an in-depth assessment of the distribution of commonly detected PFAS in surface water within five distinct regions of the United States. Furthermore, the research aims to identify the key sources that contribute to the presence of PFAS and pinpoint data gaps in specific states, emphasizing the need for further research. The Southeastern region, particularly the states of Florida, South Carolina, North Carolina, and Virginia, has been observed to show a higher degree of PFAS contamination. The states of California, Colorado, Nevada, and Montana in the Western region, as well as Maryland, New Jersey, New York, and New Hampshire in the Northeast region also showed a higher presence of PFAS. In the Southwest region, we identified a significant lack of data, while in the Midwest, with the exception of Michigan, we observed a comparatively lower amount of PFAS in surface water. It is expected that including more PFAS in addition to the few commonly studied will increase the total concentration of PFAS, which aids in understanding the actual degree of PFAS pollution. The synthesis of fluoropolymers and the incorporation of PFAS in the manufacturing and production of consumer goods, together with the utilization of fluorinated AFFF, have been recognized as notable sources of PFAS. Possible strategies to decrease and eliminate PFAS from the US are discussed as well.

**Keywords** PFAS · USA · Surface water · Sources · Distribution

## Introduction

Per- and polyfluoroalkyl substances (PFAS) contain a class of thousands of different anthropogenic compounds distinguished by the presence of a fluorinated alkyl group with a different chain length. Since the 1940s, PFAS have been

extensively manufactured and used in many industrial and commercial items due to their distinctive characteristics, such as hydrophobicity, oleophobicity, and exceptional chemical and thermal resistance (Buck et al. 2011). Also, PFAS exhibit notable resistance to both biological and chemical degradation mechanisms (Wang et al. 2017; Ren et al. 2023), making them prevalent in various environmental matrices across the atmosphere, water, soil, sediment, and biota (Remucal 2019; Ren et al. 2022). These persistent ('forever') pollutants enter the freshwater environment through a variety of channels, including manufacturing plants, household waste, sewage treatment facilities, biosolids use, and aqueous film-forming foams. Concerns about PFAS have evolved significantly in recent years (Kolpin et al. 2021). As a result of their persistent nature in the environment, PFAS have been found in several species of wildlife around the world, including invertebrates, aquatic organisms, amphibian species, aquatic plants (Griffin et al.

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2023), alligator (Bangma et al. 2017; Guillette et al. 2022), sea birds, and mammal tissues (Robuck et al. 2020), as well as in human serum (Hall et al. 2022). Additionally, PFAS can enter the human body through numerous entry points, including food, drinks, personal care items, particles, and even indoor air (Hall et al. 2020; De Silva et al. 2021; Li et al. 2022b). Research from various sources has established a connection between exposure to PFAS and negative health outcomes in humans. These outcomes include disruptions to the endocrine system and reproductive health in women (Rickard et al. 2022), fatty liver disease (Sen et al. 2022), developmental toxicity, kidney, liver, and testicular cancer (Seyyedsalehi and Boffetta 2023), issues with the immune system, immunotoxicity, and genotoxicity (Blinc et al. 2024).

The ubiquitous distribution of PFAS in the environment is a consequence of the release of PFAS through multiple pathways. Exposure to PFAS in water in the US and other industrialized nations is mainly linked to PFAS-containing AFFF used at commercial airports and military bases (Andrews and Naidenko 2020). In addition, PFAS compounds are widely used in manufacturing and everyday life, although little is known about their environmental repercussions and dispersion behavior. Given the variety of possible sources and end uses, many potential contamination pathways exist at any given location (EPA 2019). PFAS production sites represent significant points of origin of surface water and groundwater contamination within the United States (Babayev et al. 2022). Consequently, millions of Americans have water supplies that exceed the maximum allowable levels of PFAS; AFFF has been widely acknowledged as a significant contributor to pollution in both present and historical contexts (Ruyle et al. 2021). Furthermore, PFAS are transported from one place to another by oceanic and atmospheric deposition.

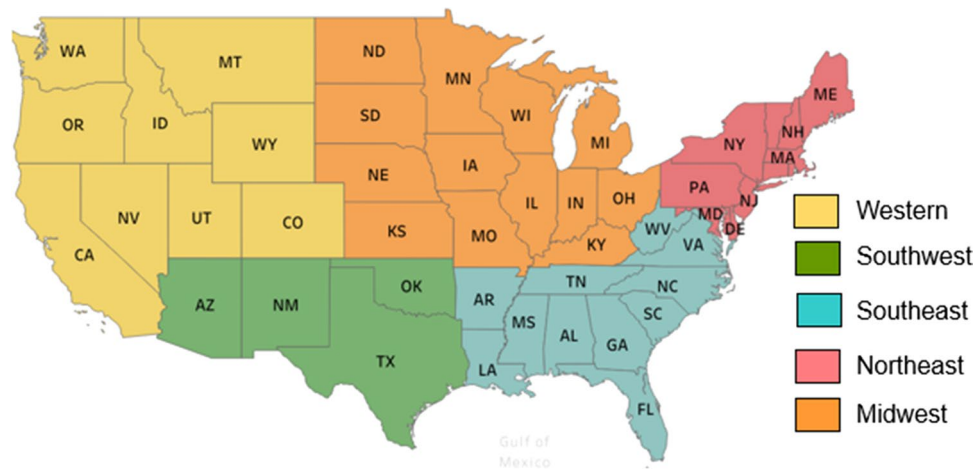
Conventional water treatment techniques find difficulties in eliminating PFAS from aquatic environments due to their distinctive properties (Taher et al. 2024). Effective techniques such as granular activated carbon (GAC), anion exchange, and high-pressure membranes can be quite expensive because of their high energy consumption and associated capital or operational expenses. Although many remediation strategies show promise in laboratory-scale research, their practical application is often limited in the field (Wanninayake 2021). However, recently advanced water treatment technologies, namely electrochemical oxidation, low-temperature plasma treatment, and sonolysis, have emerged as commercially available options for the destruction of PFAS from tap water (Blotvogel et al. 2023). Additionally, employing a hybrid approach that combines two or multiple

techniques may yield greater effectiveness compared to using a single technique in isolation (Wanninayake 2021). As an example, a recent study by Taher et al., (2024) highlights the potential of hybrid technology, which combines membrane technology with non-destructive or destructive procedures, as an effective approach for removing PFAS.

PFAS contamination is a multifaceted problem that produces a range of perspectives arising from different interests, knowledge, and experiences. Researchers express concerns about the health risks associated with it, environmental activists advocate for stricter regulations, industry representatives highlight its industrial usefulness, regulatory agencies strive to balance health and economic factors, and affected communities directly experience its effects. At the time of writing this manuscript, it appears that no comprehensive reports have been published that specifically examine and document the distribution of PFAS with sources in the United States. Extensive reviews of ambient levels of perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) in different environmental matrices (Vedagiri et al. 2018), as well as the presence of perfluorooctane sulfonic acid (PFOS) in US aquatic environments (Jarvis et al. 2021), have already been published. Surface water bodies, including creeks, lakes, and rivers, were reviewed to investigate and assess the distribution of PFAS throughout the state. Hence, the primary aim of this research is to present an in-depth analysis of the geographic distribution of PFAS in surface water across five different regions (Fig. 1) of the United States, namely the Northeast, Midwest, Southeast, Southwest, and West. Mainly, streams, lakes, and rivers were considered for investigation. Since most municipal water systems use surface or groundwater, drinking water data was considered when information about surface water was limited. Furthermore, the study seeks to identify the primary sources responsible for the presence of PFAS within each state. Also, this study contributes significantly to the research and control of PFAS at the point of origin. Overall, this research represents a significant contribution to the field of PFAS contamination assessment and control, providing novel insights on the extent, distribution, and sources of PFAS in surface water in the United States.

## PFAS testing methods and legal standards

The US EPA has released several methods, namely EPA Method 537, 537.1, 533 and draft method 1633, for the detection and quantification of PFAS in surface water. These methods are widely adopted in practice. To quantify PFAS at ng/L or ppt level, the conventional and



**Fig. 1** The map shows five distinct regions of the United States. This review was carried out based on this division of the states. Alabama (AL), Alaska (AK), Arizona (AZ), Arkansas (AR), California (CA), Colorado (CO), Connecticut (CT), Delaware (DE), Florida (FL), Georgia (GA), Hawaii (HI), Idaho (ID), Illinois (IL), Indiana (IN), Iowa (IA), Kansas (KS), Kentucky (KY), Louisiana (LA), Maine (ME), Maryland (MD), Massachusetts (MA), Michigan (MI), Minnesota (MN), Mississippi (MS), Missouri (MO), Montana (MT),

Nebraska (NE), Nevada (NV), New Hampshire (NH), New Jersey (NJ), New Mexico (NM), New York (NY), North Carolina (NC), North Dakota (ND), Ohio (OH), Oklahoma (OK), Oregon (OR), Pennsylvania (PA), Rhode Island (RI), South Carolina (SC), South Dakota (SD), Tennessee (TN), Texas (TX), Utah (UT), Vermont (VT), Virginia (VA), Washington (WA), West Virginia (WV), Wisconsin (WI), Wyoming (WY)

dominant technique is to use ultra performance liquid chromatography tandem mass spectrometry (UPLC-MS-MS) following sample preparation and extraction. UPLC-MS-MS, however, is costly and not widely accessible. In contrast, emerging inexpensive approaches have significantly lower sensitivity and cannot satisfy the legal detection limits, such as 4 ng/L for PFOA. Furthermore, the current range of analytical techniques and equipment capable of efficiently evaluating the exposure of PFAS in real-time field conditions is restricted. The advancement of inexpensive sensors can aid in the identification and evaluation of samples for the detection and prompt response (Rehman et al. 2023). The sensors, however, still face challenges of high detection limits and inability to measure multiple PFAS simultaneously.

This emerging group of pollutants has already been the subject of legal settlements valued at billions of dollars in several states within the United States (Barfoot et al. 2022). On April 10, 2024, the federal EPA released the final National Primary Drinking Water Regulation (NPDWR) and maximum contaminant level (MCLs) for six PFAS. Most of these MCLs are lower than what were established by several US states. This regulation aims to establish legally binding thresholds, known as maximum contaminants levels (MCLs), for six PFAS found

in drinking water. PFOA and PFOS are recognized as distinct contaminants, while perfluorohexane sulfonate (PFHxS), perfluorononanoic acid (PFNA), perfluorobutane sulfonate (PFBS), and Hexafluoropropylene oxide dimer acid (HFPO-DA), commonly known as GenX chemicals, constitute a mixture of PFAS. The MCLs for PFOA and PFOS are at 4 ng/L. Furthermore, the MCL hazard index of 1 has been suggested for a mixture of four other PFAS (EPA 2024).

## Point and non-point sources of PFAS contamination

A comprehensive understanding of the origins of PFAS pollution can help communities affected by PFAS formulate lasting solutions. The presence of PFAS in aquatic ecosystems can be linked to points and/or non-point sources. Both manufacturing facilities and municipal sewage treatment plants can serve as potential point sources of PFAS. For example, in the United States and elsewhere, PFAS industrial facilities are a major point source of groundwater contamination (Babayev et al. 2022). Furthermore, wastewater discharges from industrial use sites, including metal plating

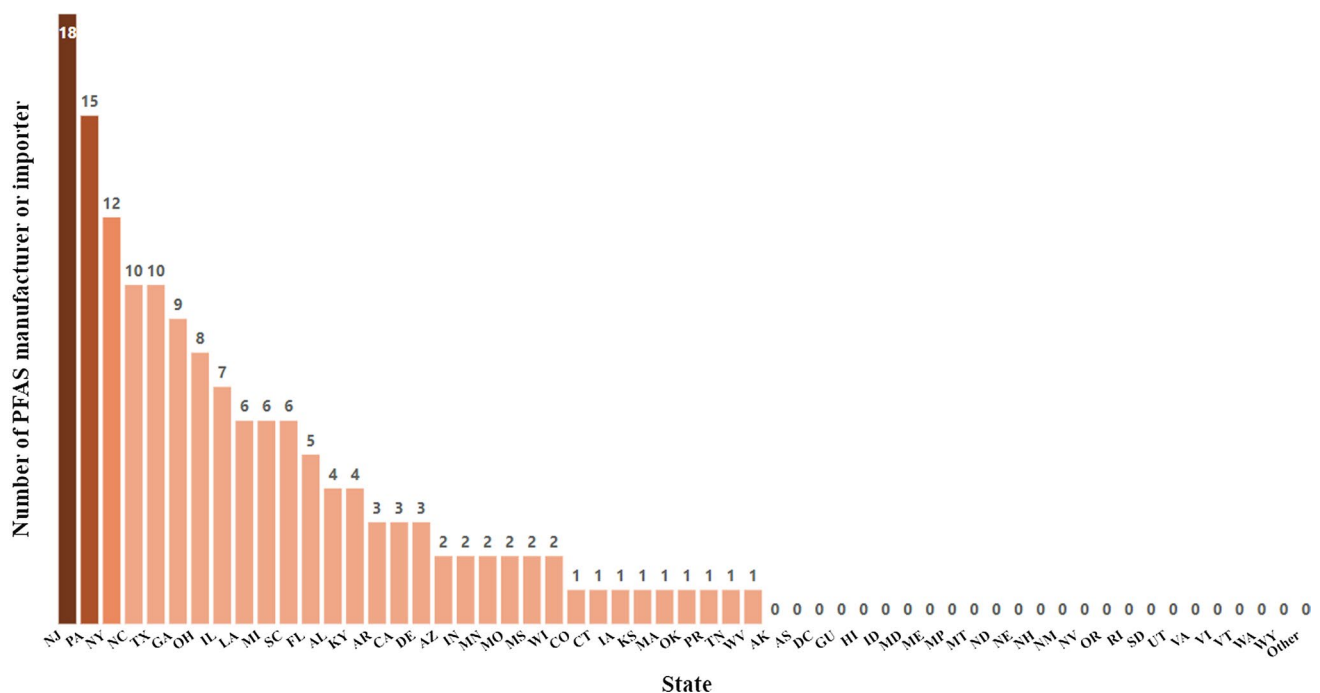
factories, places that have undergone AFFF usage, waste disposal facilities, and contaminated soils, are all possible additional point sources (Jarvis et al. 2021). Furthermore, products in the commercial and manufacturing industries that incorporate PFAS frequently find their way into landfills. Discharged PFAS from point sources have the potential to be adsorbed to soil via hydrophobic or electrostatic interactions, allowing them to stay in close proximity to the source for a long time (Barfoot et al. 2022). Over time, there will be a gradual release of PFAS from contaminated sites through leaching (Röhler et al. 2021).

Aquatic environments may be subject to various non-point sources of PFAS. These sources include dry and wet airborne deposition, the release of polluted groundwater originating from manufacturing facilities, discharges from impermeable surfaces within urban settings, street sweeps, street runoff (Ahmadireskety et al. 2022), the flow of affected groundwater resulting from the use of aqueous film-forming foam (AFFF) and the application of biosolids containing PFAS (Waterkeeper Alliance 2022). Several unidentified polyfluorinated precursors found in AFFF-impacted areas have the ability to turn into persistent perfluoroalkyl acids (PFAAs) through abiotic or biotic processes. As a result, these precursors could serve as a long-term source of environmental contamination. Furthermore, multiple studies have demonstrated a rise in PFAA levels in WWTPs effluents relative to influents. This increase is attributed to the biotransformation of precursor

substances in WWTPs and landfills (Dasu et al. 2022). PFAS can be transported through the atmosphere either by being released as volatile compounds or by being attached to airborne particulate matter (Barfoot et al. 2022). A comprehensive understanding of the manufacturing sequence of PFAS, the development of novel substitutes, the historical and present usage, and the subsequent disposal of merchandise facilitates the detection of potential origins of PFAS in the environment, as well as their potential routes of release (Dasu et al. 2022).

### Distribution of PFAS in different freshwater segments of the USA

The initial stage of assessing the potential impact of exposure to PFAS in a community involves the identification of PFAS. The majority of these highly fluorinated chemicals are readily soluble in water and can spread rapidly, posing a long-term hazard to aquatic ecosystems (Sima and Jaffé 2021). The transmission and breakdown of PFAS in the atmosphere result in their deposition and retention in terrestrial and aquatic ecosystems (Pfothenauer et al. 2022). Furthermore, these substances can also be transported by aerial or aquatic means, posing a risk of polluting drinking water sources. Also, the exchange of surface water and groundwater can take place in the direction of flow downstream from sources of PFAS (Tokranov et al. 2021). Figure 2



**Fig. 2** Diagram showing the number of PFAS manufacturers or importers for different states. According to this figure, New Jersey has the highest number of PFAS importers in the US (EPA, 2023b)



presents data indicating the quantity of PFAS manufacturers or importers across several states in the United States of America. The data unequivocally indicates that states with significant PFAS pollution, such as North Carolina, South Carolina, Georgia, and New Jersey, are frequently listed among the leading importers or manufacturers of PFAS. At the same time, certain exceptions have been observed in the states of Maryland, New Hampshire, Montana, and Virginia. These states are specifically affected by PFAS, despite the absence of any known importers of PFAS within their borders. Despite widespread contamination, a limited number of states have developed measures following a comprehensive assessment of their own conditions, while others are striving to comprehend the exposure to various environmental media. However, although most states regularly assess their drinking water, they have not yet assessed statewide contamination for surface water, groundwater soil, and sediment.

## Southeast region

### Distribution of PFAS in surface water

The states of Arkansas, Louisiana, Alabama, Mississippi, Georgia, Florida, Virginia, South Carolina, Tennessee, North Carolina, West Virginia, and the District of Columbia are all in the Southeast area. In Alabama, a recent study found that six PFAS (perfluoroheptanoic acid, PFHpA, PFOA, PFPeA, PFOS, PFBS, and perfluorohexanoic Acid, PFHxA) were identified in 65 samples of the 74 collected from rivers. The average combined level of these six PFAS compounds was measured at 35.2 ng/L in the ten main river basins (Viticoski et al. 2022). The maximum concentration of the 6 PFAS was 237 ng/L, and it was found in the Coosa River. The compound that was detected most frequently was short-chain perfluoropentanoic acid (PFPeA), which accounted for 88% of the detections. The compound with the highest concentration was perfluorobutanesulfonic acid (PFBS), measured at 79.4 ng / L.

In Tennessee, Waterkeeper Alliance (2022) reported PFAS at 28.8 ng/L in Jones Creek. In 2019, the Environmental Working Group (EWG) detected 12,285 ng/L of total PFAS in groundwater next to McGhee Tyson Airport in Blount County, Tennessee (EWG 2022). Unfortunately, there is a lack of available data associated with the extent of PFAS in soil and surface water at the statewide level in Tennessee. Responding to these reports, the Tennessee Department of Environment and Conservation (TDEC) is now undertaking a comprehensive project throughout the state. The project's goal is to test 29 distinct PFAS chemicals in all municipal water supplies (TDEC 2023).

In 2020, the Kentucky Department of Environmental Protection conducted a comprehensive assessment of PFAS contamination by collecting a total of 40 surface water samples from various locations throughout the state (KDEP 2021). Of the 40 analyzed samples, PFAS compounds were identified in 36. Within these samples, PFOS was detected most frequently, with the highest recorded value of 249 ng/L observed at a specific station located in the Cumberland River basin. At eight major river basins, the median concentration of all eight PFAS (PFBS, HFPO-DA, PFHpA, PFHxS, 4,8-dioxa-3H-perfluorononanoic acid (ADONA), PFOA, PFOS, and PFNA) was below 23 ng/L (KDEP 2021). The maximum concentrations of PFOS, PFHxS, PFHpA, PFNA, PFBS, and HFPO-DA were 249, 135, 47.1, 37.6, 21.8, and 8.29 ng/L, respectively. In 2019, processed water samples were collected from 41 of the 81 water treatment facilities, and PFAS chemicals were found in 19 of those samples.

Seven Georgia counties have tested positive for PFAS chemicals, with the highest level found in the Chattahoochee River in Cobb County (28.8 ngL<sup>-1</sup>) (Viticoski et al. 2022). The river is the primary source of water for at least 5 million people, providing a daily volume of 100 million gallons of water to Atlanta residents of the metropolitan area. The Georgia Environmental Protection Division (EPD) maintains a routine to monitor PFAS now and in the future. To ascertain probable sources of PFAS within the Chattooga River basin extending to Weiss Lake, the US EPA obtained additional samples of surface water at thirteen designated sampling locations in 2019. The combined concentration of PFOA and PFOS in Hinton Creek, Teloga Creek, Raccoon Creek upstream, and the Chattooga River was 312, 200, 95, and 75 ng/L, respectively. Furthermore, in 2023, the federal EPA began monitoring activities in the state of Georgia as part of the Unregulated Contaminant Monitoring Rule (UCMR 5). The findings of this monitoring effort indicate that drinking water in major cities and selected urban regions, such as Augusta, Columbus, and Atlanta, exceeds the newly implemented National Primary Drinking Water Regulations (NPDWR). For example, the hazard indexes for the Augusta-Richmond County water plant, the Bush field plant, and the Railroad Avenue well plant were recorded as 1.1, 5.2, and 1.46, respectively (EPD 2019). Cities in Georgia have allocated up to half a million dollars annually to implement additional drinking water treatment measures aimed at mitigating elevated levels of PFAS in the water supply. Several legal actions have been initiated against corporate entities responsible for environmental contamination.

PFAS have a widespread presence in several environmental compartments in the state of North Carolina (Ehsan et al.



**Table 1** Surface water concentration of the total PFAS of the southeast and southwest regions of the US (ng/L)

State	Location	Possible source	Media	Total PFAS	Concentration	References
Alabama	Coosa River	Carpet industries	SW	$\Sigma_6$ PFAS	237	Viticoski et al. (2022)
	Neely Henry Lake	Not specified	SW	* $\Sigma_5$ PFAS	124.2	Waterkeeper Alliance (2022)
	Buck Creek	Not specified	SW	$\Sigma_3$ PFAS	42.5	Waterkeeper Alliance (2022)
	Black Warrior River	WWTPs, Landfill	SW	$\Sigma_6$ PFAS	40.8	Viticoski et al. (2022)
	Mobile River	Not specified	SW	$\Sigma_3$ PFAS	26.4	Waterkeeper Alliance (2022)
Florida	Volusia Fire Rescue Center	AFFF	SW	PFOS + PFOA	6760	Waterkeeper Alliance (2022)
	Miami-Dade, Broward Palm Beach County	Military base, Airports, WWTPs	SW	$\Sigma_{30}$ PFAS	242	Li et al. (2022a, b)
	Miami Waterkeeper	Landfill, WWTPs	SW	$\Sigma_3$ PFAS	231	Waterkeeper Alliance (2022)
	Little River	Not specified	SW	$\Sigma_3$ PFAS	133.4	Waterkeeper Alliance (2022)
	Biscayne Bay and adjacent canals	WWTPs, Airport, Military base	SW	$\Sigma_{30}$ PFAS	106	Li et al. (2022a, b)
	St. Lucie River	WWTPs	SW	$\Sigma_6$ PFAS	66.4	Griffin et al. (2022)
	Spur Canal	Not specified	SW	$\Sigma_3$ PFAS	45.5	Waterkeeper Alliance (2022)
	Horton Park Boat Ramp	Boat ramp	SW	$\Sigma_6$ PFAS	20	Griffin et al. (2022)
	Withlacoochee River	Not specified	SW	$\Sigma_3$ PFAS	19.9	Waterkeeper Alliance (2022)
Georgia	Coosa Riverkeeper	Not specified	SW	$\Sigma_3$ PFAS	558	Waterkeeper Alliance (2022)
	Hinton Creek, Chattoogaville	Not specified	SW	PFOS + PFOA	312	EPD (2019)
	Teloga Creek, Broomtown	Not specified	SW	PFOS + PFOA	200	EPD (2019)
	Little Lotts Creek	Not specified	SW	$\Sigma_3$ PFAS	45.2	Waterkeeper Alliance (2022)
	Savannah River	Not specified	SW	$\Sigma_3$ PFAS	42.4	Waterkeeper Alliance (2022)
	Chattahoochee River	Not specified	SW	$\Sigma_6$ PFAS	28.8	Viticoski et al. (2022)
Kentucky	Cumberland River Basin	Not specified	SW	$\Sigma_8$ PFAS	424.4	KDEP (2021)
	Kentucky River Basin	Not specified	SW	$\Sigma_8$ PFAS	100.4	KDEP (2021)
	Green River Basin	Not specified	SW	$\Sigma_8$ PFAS	19.17	KDEP (2021)
	Big Sandy River Basin	Not specified	SW	$\Sigma_8$ PFAS	13.73	KDEP (2021)
Louisiana	Ascension, Modeste	Agriculture	SW	PFBA + PFOS	9.34	Water Collaborative (2022)
	Pointe Coupee, New roads	Agriculture	SW	PFBA	4.34	(Water Collaborative 2022)
Mississippi	Ascension, Donaldsonville	Agriculture	SW	PFOS	4.81	Water Collaborative (2022)
	Pearl River	Not specified	SW	$\Sigma_3$ PFAS	13.2	Waterkeeper Alliance (2022)
North Carolina	Georgia Branch	PFAS manufacturing plant	SW	$\Sigma_{13}$ PFAS	1197	(Pétre et al. 2022)
	Cape Fear River kings bluff	PFAS manufacturing plant	SW	$\Sigma_{40}$ PFAS	377	Pétre et al. (2022)
	South Buffalo Creek	Not specified	SW	$\Sigma_3$ PFAS	194.9	Waterkeeper Alliance (2022)
	Muddy Creek	Not specified	SW	$\Sigma_3$ PFAS	37.2	Waterkeeper Alliance (2022)
	Cape Fear River	PFAS manufacturing plant	SW	$\Sigma_3$ PFAS	43.3	Waterkeeper Alliance (2022)



**Table 1** (continued)

State	Location	Possible source	Media	Total PFAS	Concentration	References
South Carolina	Pocotaligo river	Not specified	SW	$\Sigma$ PFAS	7,663	SCDHEC (2023)
	Big Generostee creek	Not specified	SW	$\Sigma_6$ PFAS	936.2	SCDHEC (2023)
	Warrior Creek	Not specified	SW	$\Sigma_6$ PFAS	684.3	SCDHEC (2023)
	Fishing Creek	Not specified	SW	$\Sigma_6$ PFAS	306.3	SCDHEC (2023)
	Lake Conestee	Not specified	SW	$\Sigma_6$ PFAS	205	SCDHEC (2023)
	Sixmile Creek	Not specified	SW	$\Sigma_6$ PFAS	163.9	SCDHEC (2023)
	Broad River	Not specified	SW	$\Sigma_6$ PFAS	79.9	SCDHEC (2023)
	Saluda River	Not specified	SW	$\Sigma_6$ PFAS	41.6	SCDHEC (2023)
	Cooper River	Not specified	SW	$\Sigma_6$ PFAS	35.4	SCDHEC (2023)
Tennessee	Jones Creek	Not specified	SW	$\Sigma_5$ PFAS	28.8	Waterkeeper Alliance (2022)
Virginia	Cub run	Not specified	SW	$\Sigma_4$ PFAS	675.2	VADEQ (2023)
	West neck creek	Not specified	SW	$\dagger\Sigma_4$ PFAS	233.9	VADEQ (2023)
	White oak swamp	Not specified	SW	$\Sigma_4$ PFAS	125.1	VADEQ (2023)
	Accotink creek, Annandale	Not specified	SW	$\Sigma_4$ PFAS	90.3	VADEQ (2023)
	Pocaty river	Not specified	SW	$\Sigma_4$ PFAS	78	VADEQ (2023)
	Kingsland creek	Not specified	SW	$\Sigma_4$ PFAS	66.6	VADEQ (2023)
Washington DC	Kingman Lake	Not specified	SW	$\Sigma_5$ PFAS	23.6	Waterkeeper Alliance (2022)
	Anacostia River	Not specified	SW	$\Sigma_5$ PFAS	17.1	Waterkeeper Alliance (2022)
West Virginia	Opequon Creek	Not specified	SW	$\Sigma_5$ PFAS	29.3	Waterkeeper Alliance (2022)
	Ohio River	Not specified	SW	$\Sigma_5$ PFAS	7.9	Waterkeeper Alliance (2022)
Oklahoma	Tar Creek	Not specified	SW	PFOS	1.4	Waterkeeper Alliance (2022)
Texas	Whiteoak Bayou	Not specified	SW	$\Sigma_5$ PFAS	32	Waterkeeper Alliance (2022)
	Colorado River	Not specified	SW	$\Sigma_5$ PFAS	16.5	Waterkeeper Alliance (2022)

$\dagger\Sigma_4$ PFAS = PFOA, PFOS, PFBS, HFPO-DA (GenX)

\* $\Sigma_5$ PFAS = Total PFAS include PFOA, PFOS, PFHxA, PFPeA, PFBS

¥ $\Sigma_6$ PFAS = PFOA, PFOS, PFHxS, GenX, PFNA, PFBS

§ $\Sigma_8$ PFAS = PFNA, PFHxS, PFBS, ADONA, HFPO-DA, PFOS, PFHpA, PFOA

SW Surface water

2023) as shown by the data presented in Table 1. Total PFAS concentration was found to be the highest at Georgia Branch. In addition, an investigation has shown that the Cape Fear River in North Carolina has also been polluted with a PFAS content of 377 ng/L (Pétre et al. 2022). During the latter part of 2022, the North Carolina Department of Environmental Quality (NCDEQ) conducted a comprehensive sampling campaign for a duration of three months (NCDEQ 2023).

This initiative involved the collection of water samples from a total of fifty local and county water systems. The findings of the analysis reveal that with the exception of New Hanover, Jones, Dare, and Beaufort counties, all other counties have been contaminated by PFAS. Analysis of drinking water samples revealed PFOA and PFOS ranging from 1 to 25.3 ng/L and 0.95 to 41 ng/L, respectively. Furthermore, many studies have identified contamination in several

environmental compartments within North Carolina, including surface water (Pétre et al. 2022), groundwater (Guillette et al. 2022), soil, sediment (Saleeby et al. 2021), human blood (Kotlarz et al. 2020), and air (D'Ambro et al. 2021).

In a recent investigation in Florida, researchers analyzed 30 different PFAS in surface waters from places including Biscayne Bay, Key West, and the Everglades National Park. All 38 surface water samples analyzed were found to contain PFAS. The highest level of PFAS found in these samples was 169 ng/L. Furthermore, an elevated concentration of PFAS (> 60 ng/L) was predominantly detected in surface water samples sourced from contaminated coastal estuaries, as well as rivers within the Biscayne Bay area (Li et al. 2022a). In surface water samples, PFHpA, PFOS, PFPeA, PFBA, PFHxA, and PFHxS were mostly present with a mean total PFAS of 46.3 ng/L. Moreover, the average PFAS content in South Florida tap water has been found to be 83 ng/L on the east coast. The next highest average was measured on the west coast of southern Florida with 14.4 ng/L, then 8.0 ng/L in central Florida (Li et al. 2022a, b). Another recent study has found 21 out of 51 PFAS in Pensacola, Florida. These contained 6 PFASs (perfluoroalkyl sulfonic acids), 10 PFCAs (perfluoroalkyl carboxylic acids), 2 FASA (perfluoroalkane sulfonamide), 1 diPAP (polyfluoroalkyl phosphoric acid diesters), and 2 FTS (Fluorotelomer sulfonic acid). Individual PFAS concentration varied from 0.02 ng/L Perfluorododecanoic acid (PFDoA) to 269 ng/L (PFOS) (Da Silva et al. 2022). Griffin et al. (2022) assessed PFAS-related pollutants in Florida's surface water and soil across nine vulnerable aquatic systems. PFAS were identified at all sample sites, and the sediment showed higher levels of PFAS compared to the surface water (Griffin et al. 2022). Therefore, investigations have shed light on the widespread presence of these substances in many water bodies in Florida, posing possible detrimental consequences for health of humans and animals.

South Carolina has a markedly elevated degree of PFAS pollution compared to other regions within the United States. The South Carolina Department of Health and Environmental Control (SCDHEC) conducted an analysis of six common PFAS (PFNA, PFOA, PFBS, PFOS, PFHxS, and GenX) in surface water throughout the state, beginning in 2022. A total of 369 samples were collected for this analysis (SCDHEC 2023), out of which 365 were found to contain PFAS. The highest concentration of 7,663.94 ng/L was detected in the Pocotaligo river, while the lowest of 0.53 ng/L was observed in Parsonnage Creek and the mean of total PFAS was 92.26 ng/L. The available data unequivocally demonstrate that a significant amount of PFAS has contaminated

various surface water sources in South Carolina, including rivers, creeks, and swamps.

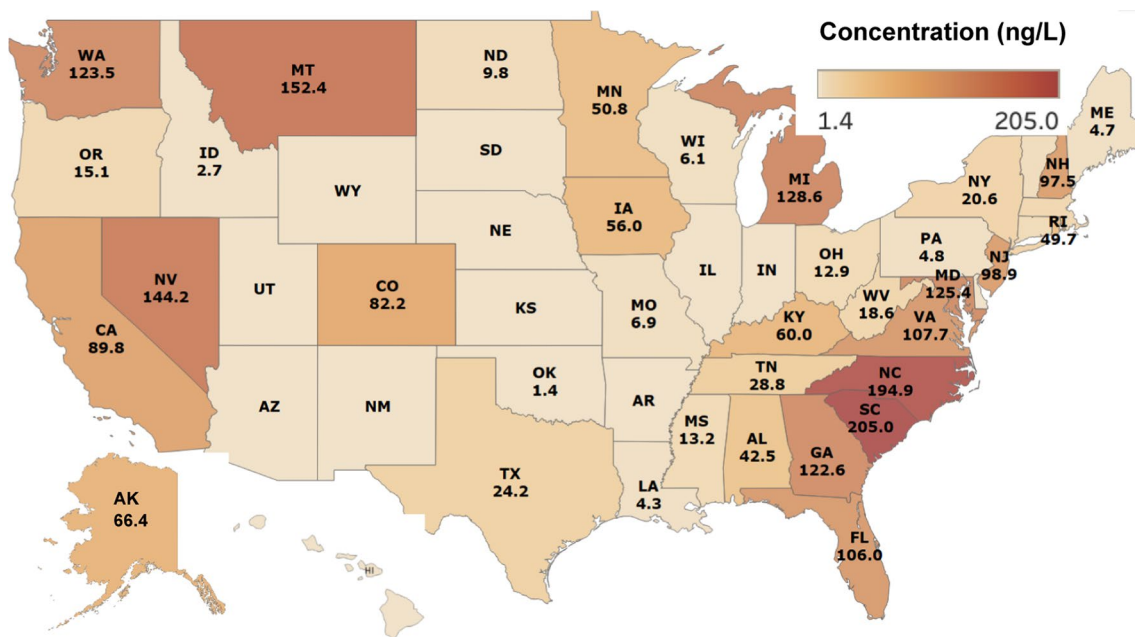
Like South Carolina, in 2022, the Virginia Department of Environmental Quality (VADEQ) conducted a comprehensive analysis of four PFAS compounds (PFOA, PFOS, PFBS, and HFPO-DA (GenX)) in 169 surface water samples throughout the state (VADEQ 2023). This four-compound appeared in 146 samples. The highest, median, and lowest identified total PFAS concentrations were 1,102, 8.7, and 0.44 ng/L, respectively. The PFAS contamination map reveals that areas close to Richmond and Alexandria showed a higher prevalence of contamination compared to other regions within the state (VADEQ 2023).

The West Virginia Department of Environmental Protection conducted an analysis of 23 PFAS at a total of 279 sites. PFAS concentrations in five locations exceeded 70 ng/L, with values of 1,540, 156, 104, 98, and 71 ng/L. 37 locations exhibited detections above the reporting level (4.1 ng/L) for PFOA, PFOS, or both substances. Among the 279 locations, 212 sites did not show detectable levels of PFAS that exceeded the reporting standard (Mitchell et al. 2022). Water bodies adjacent to the Ohio River in the western region of the state had the highest frequency of PFAS detections and the highest overall concentrations of PFAS. Hence, it can be inferred that West Virginia experiences a lesser degree of PFAS contamination compared to North Carolina or Virginia. Washington DC water sourced from the Potomac River has undergone extensive PFAS testing over several years, with consistently nondetectable results recorded until 2020. In 2021, the water treated by the Washington Aqueduct was tested in Virginia and the District of Columbia. The tests revealed the presence of PFOS and PFOA at 2.8 ng/L and 3.6 ng/L, respectively (DC 2023).

In conclusion, the states of Florida, South Carolina, North Carolina, and Virginia in the Southeast region of the United States experience significant impacts from PFAS (Table 1). In particular, these states are also among those with the highest PFAS concentration in the country (Fig. 3). It is also recognized that, in terms of PFAS research, these states are clearly ahead of the others. However, more research is still needed in this region in order to gain a better and more thorough understanding. Interestingly, PFAS concentrations in West Virginia are comparatively less than those in its neighboring states, Virginia and North Carolina. As shown in Table 1, the states of Alabama, Georgia, and Kentucky are all impacted by PFAS. Due to insufficient data on PFAS testing of tap water and surface water in the states of Arkansas, Louisiana, and Mississippi, a comprehensive evaluation of PFAS contamination in these three states was impossible.







**Fig. 3** The presented map illustrates the levels of PFAS concentration in the United States. PFAS concentrations were derived using the collected data for surface water only, which have been compiled from Tables 1, 2, 3 and 4. In this analysis, the median value (Tables 1, 2, 3 and 4) of the PFAS concentration of each state is considered. The

states of Arizona, Arkansas, Delaware, Hawaii, Illinois, Indiana, New Mexico, Utah, South Dakota, Kansas, Nebraska, and Wyoming have been excluded from consideration in this map due to the unavailability of PFAS concentration data of surface water

### Potential sources of PFAS in the southeast region

The Department of Environmental Protection (DEP) of Florida conducted an evaluation of the possible origin of PFAS. These sources include landfills, metal plating facilities, chemical manufacturers, electroplaters, solvent users, and notably, users of AFFF. The investigation comprised preliminary site evaluations, PFOS and PFOA sampling, waste site remediation, and gauging the usage of AFFF by the Department of Defense (DEP 2021). Apart from this, Li et al. (2022a, b) have identified military bases, a water treatment plant in Port St. Lucie, and airports as point sources in Florida. In South Carolina, the suspected sources of PFAS are Shaw Air Force Base and sludge from a textile mill that was used as fertilizer (Ecohub 2023). Within the state of Virginia, the DuPont Spruance plant, located in close proximity to Richmond, as well as various military and government installations such as NASA's Wallops Island facility, Norfolk Naval Station, Oceana Naval Station, Joint Base Langley–Eustis, and Fentress Auxiliary Landing Field, are potential sources of PFAS contamination identified by EPA (SELC 2022). In North Carolina, a study by Ehsan et al. (2023) identified several sources of PFAS, for instance, waste disposal facilities, firefighting foam, leachate from

landfills, domestic applications, and the Chemours PFAS production factory located in Fayetteville, NC. The primary sources of PFAS in Georgia are waste from carpet factories that are thrown into streams and firefighting foam used at the US Air Force sites (de Amorim et al. 2019). The state of Mississippi was never among the leading states in the PFAS manufacturing industry and currently lacks any operational PFAS manufacturing facilities. Unlike other states, Mississippi has a diverse array of industries that employ PFAS. In Alabama, a recent study established a connection between the presence of PFAS contamination and the carpet manufacturing industry in Dalton. Specifically, it was found that the effluents of these manufacturing plants are discharged to and treated by a city-owned wastewater treatment plant (Viticoski et al. 2022). Additionally, Alabama has a total of 173 active landfills, located predominantly in economically disadvantaged rural regions. These landfills accept hazardous waste from various states in the United States (Viticoski et al. 2022). In Tennessee, EWG has detected groundwater contamination in the vicinity of the Nashville Metropolitan Airport, Memphis International Airport, and McGhee Tyson Airport in Nashville, Knoxville, and Memphis, respectively (EWG 2022).



## Southwest region

### Distribution and sources of PFAS in surface water

Four states, New Mexico, Oklahoma, Texas, and Arizona, make up the Southwest region. The Arizona Department of Environmental Quality (ADEQ) collected 109 samples from 68 public water systems in 2018 to screen drinking water wells in Arizona that may have been contaminated with PFOA or PFOS. The findings showed that 94.5% of the wells sampled had non-detectable levels of PFOA/PFOS or levels below the health advisory level (HAL) established by the US EPA in 2016. Only six samples were found to exceed this advisory level (ADEQ 2023). Furthermore, in 2023, ADEQ tested 6 PFAS in drinking water (PFBS, PFOS, PFHxS, GenX, PFOA, PFNA) in 82 locations in the southeast region near Tucson, Arizona. Only three samples were found to have total PFAS at 8, 10, and 381.1 ng/L at Bella Vista, East Slope Water, and Apache AZ Electric Power, respectively. The total PFAS concentrations of all other samples were all lower than the laboratory reporting limit (ADEQ 2023). Currently, there are no PFAS chemical manufacturers in Arizona. The findings also suggest that PFAS were not used in widespread industrial applications. However, the industrial and manufacturing sectors, firefighting training sites, airports, and military bases were identified as likely high-use areas for PFAS in Arizona (ADEQ 2023).

In the same way, the New Mexico Environmental Department conducted a study from 2020 to 2021, collecting 98 samples from different groundwater and surface water sources in seventeen counties throughout the state to analyze the presence of PFAS. The findings revealed that among the 98 samples, PFAS were detected in 71 of them, with concentrations ranging from 1 to 156 ng/L (NMED 2021). Therefore, it is apparent that contamination of New Mexico's surface waters with PFAS is widespread, although further investigation is needed to provide a complete picture. Besides surface water and groundwater, PFAS were also found in soil at several AFFF release zones in Cannon AFB, New Mexico (DBS&A 2022).

In Oklahoma, at least nine locations have had a large amount of groundwater contaminated with PFAS. For example, in 2018, the Environmental Working Group (EWG) conducted groundwater tests at Tulsa International Airport, revealing a significant concentration of PFAS at 182,240 ng/L (EWG 2022). These locations are primarily military bases and airports. Apart from these locations, however, numerous water distribution systems run by municipalities and other government entities lack testing (Adcock 2023). For this state, only Tar Creek surface water

was tested for PFAS, with 1.4 ng/L of total PFAS detected (Waterkeeper Alliance 2022). No comprehensive data on PFAS testing of drinking water, surface water, soil, or sediment could be found for the state of Oklahoma. In 2023, two bills were introduced by the Oklahoma Legislature to improve testing and public notification about possible PFAS contamination by the state Department of Environmental Quality. Unfortunately, both bills did not pass the Senate (Adcock 2023).

Throughout the state of Texas, EWG has conducted tests of groundwater on several categories of PFAS in a minimum of 18 sites, specifically focusing on the utilization of firefighting foam in proximity to military installations. The total concentration of PFAS was found to be significantly higher, with the value measured at 2,859,600 ng/L at the Sheppard Air Force Base (EWG 2022). A recent study reported that surface water in Whiteoak Bayou and the Colorado River, Texas, had PFAS concentrations at levels of 32 and 5.2 ng/L, respectively (Waterkeeper Alliance 2022). Austin Water's sampling efforts revealed the absence of detectable levels of six PFAS compounds in their tap water (AW 2023). However, in the state of Texas, over the past 10 years, numerous oil and gas companies have injected a minimum of 43,000 pounds of PFAS into more than 1,000 wells that were subjected to hydraulic fracturing. The state of Texas has allowed the continuous and extensive use of PFAS in the extraction of oil and gas, lacking sufficient measures for testing, monitoring, and public disclosure (Javidan 2023). Meanwhile, we could not find any recent data related to PFAS tests on a statewide level for well water and surface water. Currently, the available data does not provide a comprehensive understanding of PFAS contamination in Texas. Therefore, it is essential for the governing bodies of Texas, New Mexico, and Oklahoma to take immediate measures to understand the distribution patterns of PFAS within their respective drinking, surface, and groundwater systems. Furthermore, these authorities must strive to determine the potential origins of PFAS contamination to implement strategies that can effectively mitigate additional exposure risks.

## Western region

### Distribution of PFAS in surface water

The states of Washington, Utah, California, Nevada, Montana, Colorado, Idaho, Wyoming, Alaska, Oregon, and Hawaii make up the western area of the United States. A recent study conducted by Bai and Son (2021) looked at eight sites along Lake Tahoe, Truckee River, and Pyramid Lake in Nevada, USA, to determine the levels of PFAS there.



The total concentration of PFAS in Truckee River water was 441.7 ng/L, whereas concentrations in Las Vegas Wash water were recorded as 2,234.3 ng/L. Furthermore, groundwater at Reno Tahoe International Airport, Naval Air Base, and Nellis Air in Nevada was found to have PFOS + PFOA at concentrations of 119,700, 167,000, and 47,400 ng/L, respectively, due to firefighting foam contamination (EWG 2022). Currently, the state of Nevada is using federal funding to conduct a comprehensive investigation of PFAS, which involves the collection of 200 samples from various locations within the state, with a particular focus on 160 samples derived from sources of drinking water (Rothberg 2023).

Similarly, freshwater samples were collected from a total of 16 different places downstream of wastewater treatment plants in the counties of San Luis Obispo, Ventura, Santa Barbara, and Los Angeles in central and southern California. In total, eight PFAS chemicals have been identified at the 16 sites. The median concentration of Perfluorodecanoic acid (PFDA), PFHpA, PFHxA, PFNA, Perfluorotridecanoic acid (PFTrDA), Perfluoroundecanoic acid (PFUnA), PFOA, and PFOS was 12, 59, 142, 16, 1.4, 3.5, 79, 13 ng/L, respectively (Desgens-Martin et al. 2023). PFAS levels in the Santa Ana River, tributaries, and selected storm channels varied between 5.7 ng/L for PFOA to 213 ng/L for PFHxA (Plumlee et al. 2022). Additionally, in 2020, the California Water Board began collecting data on 600 water system facilities located close to approximately 250 airports that have fire training facilities, as well as municipally owned solid waste landfills. 454 samples had PFOA levels below 20 ng/L, while 96 samples had concentrations between 20 and 40 ng/L. The concentration of PFOS in 399 samples varied between 0 and 20 ng/L, while the concentration in 125 samples varied between 20 and 40 ng/L (CAWB 2020).

In Colorado state, the levels of nine PFAS were measured in water, soil, and sediment from the Fountain Creek watershed in Colorado Springs. The average concentration of the sum of the nine PFAS in water was found to be 71.4 ng/L, with a range of 18.1 to 172.3 ng/L. Most soils (> 87%) and all sediment samples have been found to contain PFOA and PFOS (Quezada Davalos et al. 2023). In 2020, the Colorado Department of Public Health and the Environment performed surface water tests in the state of Colorado, specifically examining 71 locations for the presence of 18 different PFAS. The maximum recorded concentration of total PFAS was 257.2 ng/L, identified in close proximity to the South Platte River in Denver, Colorado (CDPHE 2020). At 62 of the 71 sites, the mean concentration of PFAS was 23.1 ng/L.

In 2020, on the basis of the data collected so far by the Utah Department of Environment Quality (DEQ), it has been observed that the presence of PFAS in drinking water

was relatively low. In the majority of instances, the outcomes were found to be lower than the method detection limit (MDL). The DEQ conducted measurements on 24 different types of PFAS in drinking water. In the majority of cases, the concentration of individual PFAS was found to be less than 1 ng/L. In the state of Utah, although it is currently unknown whether any PFAS are being produced, there exist entities that may involve the use of PFAS in manufacturing processes. Consequently, Utah is actively involved in the ongoing monitoring of PFAS, including its presence in surface water, wastewater sources, and fish (Utah DEQ 2023). In the same way, there is no documented record of PFAS production that occurs in the state of Wyoming, and only a limited number of industries that frequently employ PFAS are present in Wyoming. However, aquifers located in close proximity to sites exposed to AFFF have shown a greater chance of PFAS contamination (WDEQ 2018). In 2018, for example, a study performed by the EWG found PFOA and PFOS in groundwater near the Cheyenne Municipal Airport in Wyoming at a level of 94,400 ng/L (EWG 2022). Similarly, the state of Idaho has not seen extensive detection of PFAS in its environment. It is important to note, however, that potential PFAS pollution of Idaho's water supplies and other surroundings, especially soil and air, cannot be ignored (IDEQ 2021).

In 2021, the Montana Department of Environmental Quality (DEQ) started a water quality monitoring initiative with the objective of assessing the extent and scale of PFAS contamination in surface water at multiple locations that included the Helena, Bozeman, Billings, and Great Falls regions. Helena, Bozeman, Billings, and Great Falls each had a maximum total PFAS content of 26.05, 26.04, 278.5, and 12,920 ng/L (MDEQ 2022). In the same year, the Oregon Health Authority (OHA) also ran an initiative to track PFAS contents in the state's water supply. This project targeted public water systems that were believed to be vulnerable because of their proximity to potential PFAS contamination sources. The results revealed that among 140 drinking water systems in all counties in Oregon, only one case had PFAS at 31 ng/L, which was above the minimum reporting threshold (Oregon HAL PFOS, PFOA 30 ng/L) (OHA 2022). Aside from drinking water, we were unable to find any information on PFAS contamination in Oregon's surface water.

In the state of Washington, in 2016, samples were obtained from a total of 15 water bodies during the spring and fall seasons. These samples were collected to perform an analysis of 12 PFAS (Ecology 2022). PFAS were found at 7 of the 15 sites, with total PFAS concentrations varying from 2 to 153 ng/L (with a median value of 2 ng/L). They also performed an analysis of 12 PFAS present in stormwater



**Table 2** Surface water concentration of the total PFAS of the western region of the United States (ng/L)

State	Location	Possible source	Media	Total PFAS	Concentration	References
Alaska	Gustavus	AFFF	*RW	$\Sigma_{12}$ PFAS	120	Babayev et al. (2022)
	Ship Creek	Not specified	*SW	* $\Sigma_5$ PFAS	13.4	Waterkeeper Alliance (2022)
California	Santa Ana River	WWTPs	SW	PFAS + PFOA	970	Plumlee et al. (2022)
	San Diego Creek	Not specified	SW	$\Sigma_3$ PFAS	203.9	Waterkeeper Alliance (2022)
	Temescal Creek	Not specified	SW	$\Sigma_3$ PFAS	89.8	Waterkeeper Alliance (2022)
	Chollas Creek	Not specified	SW	$\Sigma_3$ PFAS	75.2	Waterkeeper Alliance (2022)
	Los Angeles River	Not specified	SW	$\Sigma_3$ PFAS	38.5	Waterkeeper Alliance (2022)
Colorado	Sand Creek	Wastewater discharge	SW	$\Sigma_{20}$ PFAS	257.2	CDPHE (2020)
	Fountain Creek	Wastewater discharge	SW	$\Sigma_{20}$ PFAS	148.2	CDPHE (2020)
	Creal Creek	Wastewater discharge	SW	$\Sigma_{20}$ PFAS	82.2	CDPHE (2020)
	Colorado spring	AFFF	SW	$\Sigma_9$ PFAS	71.4	Quezada Davalos et al. (2023)
Idaho	Mcllellan Reservoir	Wastewater discharge	SW	$\Sigma_{20}$ PFAS	10.96	CDPHE (2020)
	Henry's Fork	Not specified	SW	PFOA + PFHxA	2.7	Waterkeeper Alliance (2022)
Montana	Great Falls, Whitmore Ravine	WWTPs, Airport, AFFF, Industry, Military base	SW	$\Sigma_{16}$ PFAS	12,920	MDEQ (2022)
	Billings, Alkali Creek	WWTPs, Airport, AFFF, Industry, Military base	SW	$\Sigma_{10}$ PFAS	278.5	MDEQ (2022)
	Bozeman, Mandeville Creek	WWTPs, Airport, AFFF, Industry, Military base	SW	$\Sigma_8$ PFAS	26.4	MDEQ (2022)
	Helena, Prickly Pear Creek	WWTPs, Airport, AFFF, Industry, Military base	SW	$\Sigma_8$ PFAS	26.05	MDEQ (2022)
Nevada	Las Vegas wash 2 winter	Airport, WWTPs	SW	$\Sigma_{17}$ PFAS	591.9	Bai and Son (2021)
	Las Vegas wash 3 winter	Airport, WWTPs	SW	$\Sigma_{17}$ PFAS	407	Bai and Son (2021)
	Truckee River 5	Airport, WWTPs	SW	$\Sigma_{17}$ PFAS	203	Bai and Son (2021)
	Las Vegas wash 2 summer	Airport, WWTPs	SW	$\Sigma_{17}$ PFAS	85.4	Bai and Son (2021)
	Truckee River 8	Airport, WWTPs	SW	$\Sigma_{17}$ PFAS	82.3	Bai and Son (2021)
	Las Vegas wash 4 summer	Airport, WWTPs	SW	$\Sigma_{17}$ PFAS	76.8	Bai and Son (2021)
Oregon	Tualatin River	Not specified	SW	$\Sigma_3$ PFAS	15.1	Waterkeeper Alliance (2022)
Washington	West med lake	WWTPs	SW	$\Sigma_{12}$ PFAS	125	Ecology (2022)
	Sumner	WWTPs	SW	$\Sigma_{12}$ PFAS	122	Ecology (2022)

\*SW surface water, \*RW Residential water \*WWTPs wastewater treatment plant, \* $\Sigma_5$ PFAS = Total PFAS include PFOA, PFOS, PFHxA, PFPeA, PFBS

samples collected from urban and industrial basins. The results revealed that the total concentrations of PFAS varied between 31.9 and 114 ng/L. In comparison, total PFAS concentrations in effluent of wastewater treatment plants (WWTPs) were between 42.1 and 107 ng/L, with a median value of 68.9 ng/L (Ecology 2022).

PFAS data for Alaska is very limited. Babayev et al. (2022) collected residential water and serum from Gustavus, a small community in this state, and analyzed 39 PFAS compounds. The total PFAS content in drinking water went from undetectable to 120 ng / L, while serum PFAS concentrations ranged from 0.0170 to 13.1 ng/ml (median: 0.0823 ng/ml). Regarding Hawaii, in 2023, the Safe Drinking Water Branch (SDWB) of the Department of Health of Hawaii conducted tests on the presence of PFAS in the drinking

water of seven different places. The analysis revealed the presence of several commonly occurring PFAS compounds, including PFBA, PFBS, PFHpA, PFHxA, PFHxS, PFOA, PFOS, PFPeA, and Perfluoropentanesulfonate (PFPeS). The maximum total concentration of the 11 PFAS detected in the village of Del Monte Kunia was 264.8 ng/L. Other locations, however, exhibited PFAS concentrations that were below the HAL set by the EPA in 2016.

The states located within the western region are currently engaged in the stage of identifying the presence of PFAS in their respective drinking water, surface water, and groundwater, as described above. In particular, PFAS showed a more extensive distribution in the drinking water sources of California and surface water bodies in Colorado, Nevada (Table 2). There remains a significant information gap on the



extent of the presence of PFAS in the states of Wyoming and Idaho. Preliminary findings suggest that Utah and Oregon may be less affected than other western states, but additional research is needed to fully understand the spread of PFAS. In light of the geographical distribution of PFAS, state authorities are taking regulatory actions in certain instances.

### Potential sources of PFAS in the western region

The concentration of PFAS varies greatly from site to site but is typically quite high in high-risk areas. Although mining is still not recognized as a primary area of concern regarding PFAS impacts, there is growing recognition of mines as potential sources of PFAS contamination (Barfoot et al. 2022). EPA listed 54 operational mining and refining sites in Nevada as possible sources of PFAS (EPA 2024). In addition to these sites, the overall levels of PFAS in Nevada's watersheds can be influenced by various factors, such as source water, land use, municipal wastewater runoff, snowmelt, and military bases (Bai and Son 2021). All of these could explain the presence of PFAS in this state, although no manufacturing facilities for PFAS production have been documented in close proximity to Nevada watersheds. The same is true for PFAS in other western states, like Colorado (Quezada Davalos et al. 2023), California (CAWB 2020; Plumlee et al. 2022), Montana (MDEQ 2022), Washington and Alaska (Babayev et al. 2022).

## Midwest region

### Distribution of PFAS in surface water

The Midwest region of the United States includes the states of North Dakota, Nebraska, Missouri, Kansas, Wisconsin, Minnesota, Iowa, Illinois, South Dakota, Michigan, Ohio, and Indiana. In the early 2000s, PFAS contamination was detected in the eastern Twin Cities area. During the past two decades, the state of Minnesota has been engaged in a persistent struggle against PFAS. Subsequently, PFAS have been discovered throughout the state of Minnesota in a wide range of sediments, waters, fish, and soil (Scher et al. 2018). Around 140,000 Minnesotans may have had their drinking water contaminated with PFAS, according to the Minnesota Department of Health (MDH) (MDH 2022). In 2021, the MDH conducted tests on PFAS in surface water. It should be mentioned that 23 municipal water supplies in Minnesota depend on surface water sources, and 90 depend heavily on groundwater as their main source. In 17 surface water sites, a maximum of eight PFAS were detected in each sample. Among these PFAS, perfluorobutanoic acid (PFBA) was shown to be the most often detected compound. The levels of various PFAS in the raw water samples fluctuated from 0.762 ng/L to 32.9 ng/L, while the concentrations in the final product water samples varied from 0.768 ng/L to 33.2 ng/L

(Lambert et al. 2023). Similarly, the Wisconsin Department of Natural Resources conducted measurements of PFOS and PFOA concentrations in a total of 47 samples collected from lakes and 30 samples collected from major rivers starting in 2019 (DNR 2023a). Long Lake had the highest amount of PFOA and PFOS at 2.5 ng/L, while the other 46 samples all had amounts of PFOA and PFOS below 2 ng/L. Among the main rivers, the Root River has the highest combined levels of PFOA and PFOS, with a concentration of 7.73 ng/L. The majority of the other samples had PFAS levels of less than 5 ng/L. In 2023, eight drinking water samples obtained from various locations within the state were found to contain levels of PFAS that exceeded the health advisory threshold (70 ng/L) published by the Wisconsin Department of Health Services (DHS). Based on the aforementioned levels of PFAS and PFOA concentration observed across the state, it appears that Wisconsin does not exhibit a high degree of contamination. However, it is plausible that the concentration levels could increase if additional PFAS compounds are included in the list in the future.

The Michigan Department of Environment, Great Lakes and Energy (EGLE) conducted a comprehensive study from 2018 to 2021 by collecting a total of 2047 surface water samples from various lakes and streams in its state. This investigation was intended to examine 24 distinct PFAS to identify potential points of exposure (EGLE 2021). The results showed that the Kalamazoo River basin riparian area had the highest recorded concentration of a total of 24 PFAS, measuring 20,145 ng/L. The lowest concentration of 3.73 ng/L was detected in the Manistique River. These 2,047 samples had an average total PFAS concentration of 129 ng/L (EGLE 2021). Analysis of this large data set also revealed that the Kalamazoo Watershed, Doe Creek, and Huron river area had the highest levels of contamination among the several sites examined.

Surface water samples from the Bois de Sioux and Red rivers in North Dakota were collected in 2022 to determine the levels of PFAS. Among the 36 PFAS compounds analyzed, four were found to be present. In particular, perfluorobutanoic acid (PFBA) was detected in all samples, with a concentration range of 6.5–11 ng/L. The downstream of Grand Forks, North Dakota, was found to have the highest levels of PFAS. In addition, 120 samples were evaluated to observe PFAS contamination from various locations in North Dakota, including water treatment facilities, landfills, wastewater systems, industrial sites, groundwater aquifers, and laboratory samples cleaned with reverse osmosis. PFAS were found in groundwater aquifers (maximum 44 ng/L), drinking water (PFAS + PFOA < 3 ng/L), wastewater treatment plants, manufacturing facilities, and landfill leachate ponds. All PFOA and PFOS detections in drinking water tests were below 3 ng/L, which meets the latest released NPDWR health advisory level (NDDEQ 2021).



From 2021 to 2023, Indiana's Department of Environmental Management (IDEM) conducted PFAS testing on the state's raw and finished drinking water. In phase 1, finished water samples from Clark, Dubois, Hendricks, Jasper, Jefferson, Monroe, Morgan, Wabash, and Warrick counties all contained PFAS, although the concentrations were below the detection limit of 2 ng/L. Therefore, the authority marked the result as not detected, which might satisfy the interim EPA HAL proposed in June 2022. In phase 2, of 325 samples from various counties, PFAS were identified in 28 finished water, and nine samples had PFAS that exceeded the EPA HAL proposed in June 2022 (IDEM 2023). In a similar fashion, the Illinois state EPA conducted a study in 2021, and the results indicated that none of the 18 PFAS analyzed were detected in 1,264 samples, which was 88.5% of the total tested. A total of 70 samples showed the existence of one or more PFAS chemicals at levels that exceeded the recommended health-based guidance levels set by Illinois (PFOS 14 ng/L, PFOA 2 ng/L), and 82 samples were detected with one or more PFAS at concentrations that were higher than the minimum reporting limit (for all PFAS 2 ng/L) but fell below the health-based guidance levels (IDPH 2021).

Similarly, starting in 2013, all counties in Missouri underwent a PFAS monitoring initiative carried out by the state Department of Natural Resources for public drinking water. There were only 12 locations where PFAS concentrations were found to be higher than the federal EPA's interim HAL (PFOA 0.004 ng/L, PFOS 0.02 ng/L). The highest total PFAS level of 36 ng/L was found in Lewis County's Canton public water system (MoDNR 2022). Important new evidence of PFAS contamination in Missouri surface water has been uncovered by the Waterkeeper Alliance. Based on the detected concentration of 197.1 ng/L at Coldwater Creek, it is clear that an in-depth assessment of PFAS is needed at the state level.

Regarding the state of Iowa, the Department of Natural Resources collected 22 samples of lake water and 12 samples of river water throughout the state to test for 25 different PFAS compounds. A total of six compounds were identified in surface water samples, namely PFOS, PFBA, PFHxA, PFPeA, PFBS, and PFOA, with a maximum total concentration of 55.6 ng/L. Among these compounds, PFBA was found to be dominant, showing up in 29 out of a total of 40 samples (or 88%). The highest levels of PFBA, PFPeA, PFOS, PFOA, PFHxA, and PFBS were 32, 4, 9, 3, 8, and 2 ng/L, respectively (DNR 2023b). Agricultural areas in Iowa streams were also studied to determine the environmental prevalence of PFAS. Of the 60 stream sites that were sampled, at least one PFAS compound was detected at 19 sites. Additionally, ten different PFAS chemicals were found in all of the states (Kolpin et al. 2021).

The states of Michigan, Wisconsin, Illinois, Minnesota, Ohio, Indiana, and some parts of Pennsylvania and New

York are linked to the Great Lakes. As the largest freshwater system on Earth, the Great Lakes are a highly valuable resource for North America. Remucal (2019) reviewed the temporal and spatial fluctuations of widely researched perfluoroalkyl sulfonates (PFSA) and perfluoroalkyl carboxylates (PFCA) in the Great Lakes. The experiment was carried out by consolidating data obtained from various sources, including water samples, surface sediment samples, sediment cores, and samples from trout and eggs from herring gulls. Lake Superior had the lowest PFAS levels in all matrices. On the other hand, Lakes Erie, along with Ontario, exhibited higher concentrations, as they are subject to greater influence from industrial operations and wastewater discharge. Lake Superior had PFOS between 0.2 and 0.3 ng/L, Lake Michigan between 2.0 and 2.3 ng/L, and Lake Huron between 2.1 and 2.3 ng/L. Concerns have been raised that people residing in the Mid-Ohio River Valley may be susceptible to chemical PFOA via their drinking water as a result of industrial PFOA emissions in Parkersburg, West Virginia (Herrick et al. 2017). These concerns were validated by a median PFOA concentration of 7,600 ng/L in the blood of people living in the Mid-Ohio River Valley (Herrick et al. 2017). Similarly, the PFOA that industries discharged into the Ohio River affected the Ohio River Basin area, and the concentration of PFOA in the Ohio River downstream in September 2009 ranged from 9.2 to 19.1 ng/L (Paustenbach et al. 2006). Interestingly, it was observed that the use of granular activated carbon (GAC) correlated well with a decrease in PFOA in the bloodstream of Ohio residents (Herrick et al. 2017). As of August 2021, 1512 samples from Ohio's public water systems had been examined throughout the state. More than 97% of the samples did not show the existence of PFAS. For the remaining 3%, the detection of PFAS was below the action level defined as PFAS combined with PFOA > 70, GenX > 20, PFBS > 2100, PFHxA > 140, and PFNA > 21 ng/L (ODH 2021).

Minnesota, Missouri, Wisconsin, and Michigan are at the forefront of identifying and addressing PFAS contamination in both drinking water and surface water, surpassing other states in the Midwest region. These states exhibit better management, while Michigan also experiences higher levels of PFAS contamination. Available data indicate that Wisconsin, Missouri, Iowa, Ohio, and Minnesota have lower levels of PFAS contamination. This may not hold true for Indiana and Illinois due to the lack of extensive tests and data on surface water contamination. Furthermore, a significant data gap persists on the spatial distribution of PFAS in drinking water, surface water, and soil of the states of South Dakota, Nebraska, and Kansas, also located in the Midwest region.



## Potential sources of PFAS in Midwest region

Finding the origin of a problem is the first step to solving it and mitigating its impact (EPA 2019). The EPA has identified a total of 91,783 active industries in the US that engage in the import or manufacturing of products using PFAS (EPA 2023). These industries include oil & gas, waste management, chemical manufacturing, metal coating, petroleum, electronics, plastics, mining and refining, metal machinery manufacturing, printing, airports, textiles and leather, paints and coatings, papermills, cleaning product, national defense, industrial gas, fire protection, glass products, furniture and carpet, consumer products, cement manufacturing (EPA 2023).

Surface water and wastewater discharges were found to be significant contributors of PFOS and PFOA to Lake Ontario and Lake Michigan, while atmospheric deposition plays a comparatively minor role. According to a study, the tributaries are the main source of PFOA and PFOS in Lake Superior, accounting for 59% of the total (Remucal 2019; Miranda et al. 2023). In addition to PFAS in water, 35 soil samples close to a significant hazardous waste incinerator located in Ohio exhibited detectable levels of PFBS, PFOS, PFOA, and GenX. In particular, PFOS was detected in 97% of the samples analyzed. The measured concentrations of PFOS in these samples varied in a range of 0.05–8.3 (ng/g) (Martin et al. 2023). The PFAS in fish inhabiting the northern regions of Lake Michigan hinted at AFFF as a potential source (Lin et al., 2021), apart from several other sources of PFAS identified in relation to Lake Michigan (Miranda et al. 2023). For the mostly unaffected Lake Superior watershed, air deposition becomes a more significant source of PFAS (Pfothenauer et al. 2022; Remucal 2019).

PFAS from firefighting foams used at Wurtsmith Air Force Base in Oscoda, Michigan (MI) for training reasons over a 25-year period contaminated the groundwater below the base (Custer et al. 2019). Specific to Minnesota, the production of PFOS and PFOA by the Minnesota Mining and Manufacturing (3 M) company began in 1950 at its facilities located in Cottage Grove, Minnesota, United States (Scher et al. 2018). The manufacturing of these substances was discontinued in 2002 (Custer et al., 2013). Firefighting foams containing PFAS are no longer allowed to be used in Minnesota for training or testing purposes. Additionally, Minnesota has been actively collaborating with fire departments and other relevant stakeholders to promote the adoption of fluorine-free firefighting foams (F3) as a preferred alternative during emergency situations (Greene and Neuschler 2021). The Mississippi River, which passes through the Pig Eye Lake region, was contaminated with PFAS as a result of various pathways, such as direct discharge of wastewater, groundwater contamination, and runoff from surface waters originating from the 3 M manufacturing facility and

disposal sites. Therefore, similar to other regions, it is evident, based on recent studies, that various sources of PFAS have been identified in the Midwest region. These sources include wastewater discharges, atmospheric deposition, waste incinerators, firefighting foam (AFFF), PFAS manufacturing facilities, and industrial use, as well as contaminated groundwater.

## Northeast region

### Distribution of PFAS in surface water

The northeast region of the United States includes the states of Connecticut, Maine, Delaware, Maryland, New Hampshire, Massachusetts, New Jersey, Pennsylvania, New York, Vermont, and Rhode Island. In the state of Maine, a provisional regulation has been implemented, setting an interim threshold of 20 ng/L for six compounds of PFAS for drinking water in 2021, whether present alone or together. Subsequently, in 2022, Maine Water initiated a voluntary initiative to conduct comprehensive testing of its water systems for PFAS. The regulatory body conducted an analysis of a total of 25 samples of surface water and drinking water obtained from the Maine water system. The results of this analysis revealed that only two of the samples surpassed the interim threshold set by Maine, with concentrations of 154 and 34.8 ng/L, respectively. With a detection limit of 2 ng/L, PFAS were not evident in any of the remaining samples (Maine water 2022). Additionally, the Maine Department of Environmental and Community Health conducted a comprehensive analysis in 2022, examining a total of 700 finished samples from public water systems. This analysis specifically focused on the presence of six PFAS compounds, namely PFOA, PFOS, PFHxS, PFNA, PFHpA, and PFDA. Of the total, PFAS were not identified in 75% of cases (526 samples), where the reporting limit was established at 2 ng/L. The majority of the remaining samples had PFAS detection within the range of 2–20 ng/L (DWP 2022).

On 23 July 2020, legislation was passed in New Hampshire setting health-based maximum contaminant level (MCL) for four PFAS compounds. These MCLs were 12 ng/L for PFOA, 15 ng/L for PFOS, 18 ng/L for PFHxS, and 11 ng/L for PFNA. Since 2016, the New Hampshire Department of Environmental Services has consistently monitored and assessed the condition of surface water and groundwater in lakes and rivers across the state. Until now, the regulatory body has conducted analyses on at least 210 samples of surface water (NHDES 2022). A total of 71 samples (33%) were found to exceed the MCL set by the state. 21 samples (10%) were found to exceed the HALs of 70 ng/L established by the federal EPA, which was lower than 33% of the samples exceeding the EPA's 2016 HALs in 2019 (Panikkar et al. 2019). The remaining samples had PFAS below



the MCLs. It is noteworthy that a river near Merrimack had the largest overall PFAS content, measuring at 6,559.9 ng/L.

The Vermont Department of Environmental Conservation conducted PFAS monitoring at 19 sites in northern Vermont in 2021. Of them, 10 were located on Lake Memphremagog and its watershed (DEC 2021). Only two of the 36 PFAS compounds were found to be beyond the reporting limits (20 ng / L) in three sampling periods in 2021. The highest concentration of PFAS was detected on Black River Airport Road, 8.7 ng/L. The mean, minimum, and highest values of total PFAS were 4.6, 1.58, and 14.8 ng/L, respectively.

The updated regulatory standard for two primary PFAS compounds, namely PFOS and PFOA, in drinking water within the state of New York was set at 2.7 and 6.7 ng/L, respectively (ECOS 2023). The New York State Department of Health analyzed PFOS and PFOA concentrations in drinking water samples from 1773 public water systems in 2021. A total of 585 samples (33%) revealed the presence of PFOA. The highest recorded concentration of PFOA was 650 ng/L, seen in the Hoosick Falls Public Water System (PWS), while the lowest concentration was 0.59 ng/L, detected at the Windemere Highlands location. Similarly, PFOS was identified in a total of 455 samples (25%) ranging from 930 ng/L observed at Scotch Pine Manor to 1.3 ng/L detected at the Gardiner town house apartments (Buffalo news 2023). Moreover, Brase et al., (2022) analyzed 44 PFAS in surface water from two tributaries in the Hudson River, New York (one of which was previously contaminated with PFAS) and ultimately detected 17 analytes across all matrices, with PFOA leading (mean 17.4 ng/L) in surface water and PFOS in sediment/benthic macroinvertebrates. Eight different PFAS were found in surface water samples, including PFOA, PFOS, PFBA, PFHxA, PFHpA, PFBS, PFHxS, and PFNA, with the highest total eight PFAS concentration found in the Hoosic River's downstream section, at 29.3 ng/L. Beyond drinking water, the Massachusetts Department of Environmental Protection (MassDEP) and the United States Geological Survey (USGS) collaborated to study PFAS concentrations in Massachusetts rivers and streams. USGS conducted sampling and analysis of 24 different PFAS compounds at 64 sites in 27 rivers in 2020. PFAS were found in all 27 rivers that were sampled. The concentrations of individual PFAS varied from non-detectable levels to 109 ng/L, while the combined concentration of all 24 PFAS at a site varied from 0.3 to 399 ng/L. The highest concentrations of PFAS were detected downstream of wastewater effluent discharges. Rivers in less populated regions exhibited the lowest concentrations (USGS 2020). The MassDEP has also identified the existence of six distinct PFAS in 169 finished drinking waters. PFAS were found to exceed the MCL threshold of 20 ng/L (sum of six PFAS) (MassDEP, 2020). The state of Rhode Island has conducted drinking water sampling in a total of 26 cities and towns,

each of which has one or more public water systems. These tests were specifically performed to assess the presence of up to 19 longer-chain PFAS compounds. PFAS appeared in 81% of the samples, with the highest concentration of 228 ng/L detected in Burrillville Municipality (Sierra Club 2022).

The Connecticut Department of Public Health has established specific action levels for four PFAS: 16 ng/L for PFOA, 10 ng/L for PFOS, 49 ng/L for PFHxS, and 12 ng/L for PFNA. Connecticut Water conducted a comprehensive analysis of 87 public drinking water samples in the state between 2019 and 2022, specifically targeting these four PFAS. At least one PFAS was present in 44 samples, with Avon Water having the highest total PFAS concentration of 24 ng/L and Coventry Hills having the lowest total PFAS value of 2 ng/L (Connecticut water 2022). In addition, the Connecticut Department of Energy and Environmental Protection conducted an assessment of PFAS levels in eight surface water bodies in September 2021. The investigation measured concentrations of 34 PFAS covering ten locations in Connecticut, including the Connecticut River, Farmington River, Hockanum River, Naugatuck River, Pequabuck River, Quinnipiac River, Scantic River, and Still River (DEEP 2021). Except for Naugatuck River having total concentrations of 40 PFAS at 19.5 ng/L, the other rivers had PFAS at concentrations below the analytical detection limit of the instrument used in the study.

The New Jersey Department of Environmental Protection (NJDEP) has established MCL for PFOA, PFOS, and PFNA. These MCLs were 14 ng/L for PFOA and 13 ng/L for both PFOS and PFNA. Goodrow et al. (2020) conducted an evaluation of the presence of PFAS in surface water, sediments, and fish tissue in 11 specific waterbodies that were suspected of having PFAS contamination. According to the investigation, PFOA, PFHpA, and PFPeA were present in all sampling locations, and the concentrations of  $\Sigma$ PFAS varied between 22.9 and 279.5 ng/L. In 2021, a comprehensive assessment was carried out in 1,154 public water systems for PFAS. Among these systems, 13% exceeded the MCL established for PFAS (NJDEP 2022).

Regarding the state of Maryland, in August 2021, the Maryland Department of the Environment (MDE) collected 759 untreated drinking water samples from 313 public water systems and analyzed the presence of 18 PFAS under EPA Method 537.1. These samples were taken from a variety of reservoirs, aquifers, springs, and groundwater sources. Ten different PFAS were observed with various concentrations. The maximum concentrations of PFHxS were observed at 173 ng/L, whereas the combined values of PFOA and PFOS were between 74.54 and 113.32 ng/L (MDE 2022). In 2019, from various Pennsylvania streams, 161 surface water samples were collected. These samples were then subjected to analysis to identify the existence and content of





33 PFAS (Breitmeyer et al. 2023). At least one PFAS was observed in 76% of the streams studied. 12 out of 33 total compounds in these streams contained measurable levels of PFAS. The five compounds most commonly identified in streams were PFOA, PFHxA, PFOS, PFBS, and PFPeA. The observed median concentration of PFAS was 3.8 ng/L ranging from nondetectable to 102 ng/L. The MCL specified in the Delaware Regulations for Public Drinking Water Systems was 14 ng/L for PFOS and 21 ng/L for PFOA. The USGS, in collaboration with the Delaware Department of Natural Resources and Environmental Control, conducted an investigation of unfiltered drinking water sourced from groundwater to characterize the occurrence and distribution of 18 PFAS using EPA Method 537. A total of 44% of the investigated PFAS compounds were found to be present. The most commonly identified PFAS were PFOA, detected in 47% of cases, PFHxA, in 33% of cases; and PFOS and PFHxS, each detected in 27% of cases. Two of the wells had concentrations higher than the recommended lifetime level of 70 ng/L (Reyes 2021).

Based on the aforementioned information, it can be assumed that the states of New Hampshire, Maryland, New Jersey, Massachusetts, Rhode Island, and New York have elevated levels of contamination, as indicated by the detected levels of PFAS and their widespread distribution across these states (Table 4). Meanwhile, the states of Maine, Vermont, Connecticut, Pennsylvania, and Delaware had a comparatively lower level of contamination compared to other states in the Northeast region (Table 4). This observation presents an intriguing study opportunity to investigate the underlying factors that contribute to the reduced contamination levels in these states.

### Potential sources of PFAS in the Northeast region

In 2018, the Delaware Department of Natural Resources and Environmental Control (DNREC) identified three distinct categories of PFAS sources. These categories include primary sources, which encompass activities directly related to PFAS production. Secondary sources involve entities, such as waste management facilities, that contribute to the release of PFAS. Lastly, tertiary sources refer to biosolid applicators, which are responsible for the dissemination of PFAS to agricultural soil.

Geospatial analysis conducted on watersheds in the northeastern region of the United States has revealed that point sources, specifically textile mills, and airports, have emerged as the predominant contributors of PFAS in surface waters (Zhang et al. 2016). For example, Massachusetts, like many other states, used firefighting foam containing high amounts of PFAS for a number of years at military bases and airports. One major source of PFAS in Maine is the application of residuals such as industrial waste and biosolids (MFT

2023). The town of Merrimack, New Hampshire, is host to a manufacturing facility operated by Saint-Gobain, which specializes in the production of glass and fabrics coated with PFAS. There is strong evidence linking this facility to widespread PFAS pollution across the state (Panikkar et al. 2019; Lerner 2022). Furthermore, University of New Hampshire researchers identified wastewater treatment facilities in New Hampshire as a possible source of PFAS (Tavasoli et al. 2021). According to research conducted by the Department of Defense (DOD), groundwater at four locations in Maryland has been contaminated by PFAS. These sites include the old Fort Meade Tipton Airfield, the Chesapeake Beach Naval Research Laboratory, the former Naval Bayhead Annex in Annapolis, and the former Naval Research Laboratory in White Oak (MDE 2018). Now, MDE is looking at other possible sources that could be releasing PFAS into the environment. These sources include wastewater treatment plants, biosolids generated by such plants, and landfill leachate. Similarly, PFAS are prevalent throughout New Jersey as a result of both past and ongoing industrial operations, as well as the existence of military and civilian establishments using AFFF (Goodrow et al. 2020). Other industrial activities, such as plastic manufacturing in southwest Vermont and eastern New York State, resulted in the release of PFAS (from Teflon coating operations) into the air, which subsequently led to contamination of soil and groundwater at considerable distances that exceeded 8 km from the emission sources (Schroeder et al. 2021). In the state of Delaware, some of the treated wastewater streams containing PFAS are dumped on the surface of the soil, where they penetrate the soil and eventually contribute PFAS to the groundwater system (DNREC 2023). The geospatial study conducted in New York's watersheds indicates that a specific component or group of PFAS compounds can be traced back to a combination of point sources, namely airports and textile factories (Zhang et al. 2016). Possible sources of PFAS identified in Pennsylvania include an electronics manufacturing site and agricultural croplands (Breitmeyer et al. 2023).

### Implications for source control

Identifying sources of introduction of PFAS into the environment, implementing measures to prevent further releases, and monitoring and mitigating PFAS exposure are key strategies to address the problem of PFAS contamination. For example, in its PFAS Monitoring Plan, the Minnesota Pollution Control Agency listed 169 manufacturing and industrial establishments, 91 municipal wastewater treatment plants, 145 landfills, and other solid waste management facilities (MPCA 2023). In addition to the task of evaluating the distribution of PFAS in various environmental compartments such as surface water, groundwater, air, soil, and drinking



water, it is imperative that governmental agencies diligently ascertain the origin of PFAS contamination in order to effectively implement mitigation measures. Additionally, it is also essential to gradually stop the manufacturing and use of products that incorporate these substances while simultaneously looking for safer alternatives. For instance, starting in 2024, the state of Colorado will implement a prohibition on the commercial distribution of specific products that incorporate PFAS as a result of recent legislative measures (CDPHE 2023). All of these can be effective in decreasing PFAS concentration in the environment, as evidenced by the reduction in per- and polyfluoroalkyl acids (PFAAs) in fish populations as a result of discontinuation of industrial use of these chemicals (Point et al. 2021).

Continued monitoring of the release and dispersion of PFAS in the environment, particularly from sources that include biosolids, is essential due to their ability to enter food items such as milk and drinking water (Desgens-Martin et al. 2023). Most importantly, the quality of drinking water can be maintained by requiring states to establish maximum levels of contamination and by providing water treatment facilities with effective PFAS removal technologies (Voulgaropoulos 2022). For example, the states of Maine, New Hampshire, Massachusetts, Connecticut, New Jersey, Delaware, and New York have adopted MCL by establishing interim thresholds for certain PFAS chemicals. Liberty and Valley Utilities in Arizona expeditiously implemented the installation of granular activated carbon (GAC) treatment and ion exchange methods to promptly eliminate PFAS from affected drinking water sources (ADEQ 2023). Again, reduced contamination can be achieved through the implementation of precise regulatory requirements for waste disposal, elimination of AFFF use, and prohibition or substitution of most PFAS. Enhanced monitoring efforts in different states are also necessary to learn more about the prevalence of PFAS in water systems and to assess the possible effects on people and the environment. Additionally, the EPA suggests that three actions must be taken when the levels of the health advisory are exceeded. A potential course of action could involve conducting an assessment of PFAS levels, providing information to consumers, and implementing measures to restrict exposure (EPD 2019).

Close partnership among federal agencies and states, public water utilities, the private sector, and universities is essential to find long-term solutions. The Michigan PFAS Action Response Team (MPART) serves as a notable example of effective coordination in addressing the PFAS issue in the state of Michigan. The MPART comprises many specialized workgroups, such as those dedicated to airports, groundwater, landfill, land application, military, wastewater, surface water, and other relevant areas (MPART 2023). These workgroups are responsible for overseeing and coordinating PFAS efforts, conducting analyses, and conducting

research throughout the state. Preventing additional potential negative health and ecological impacts from use, release, or discharge, control, and elimination must be an essential task. A further example of this is that many PFAS applications are not necessary; thus, their ban would not have a major influence on society. The state of Minnesota has recently enacted legislation that prohibits the non-essential use of PFAS. Furthermore, it is critical to educate the general public about the ubiquitous presence of PFAS, as many companies, consumers, and firefighters have been using items containing PFAS without knowing or realizing the possible health concerns and liabilities associated with doing so (Greene and Neuschler 2021).

## Future distribution trends and challenges

In 2022, the Waterkeeper alliance groups conducted a surface water sampling across the US, where the presence of PFOA, PFHxA, PFOS, PFPeA, and PFBS was identified with the highest frequency (Waterkeeper Alliance 2022). Furthermore, Maryland, Georgia, Florida, North Carolina, California, and Alabama ranked first through sixth, respectively, for the greatest number of PFAS identified in surface water. For example, Maryland recorded the highest total detected number of PFAS, reaching 134. The outcome of this review aligns with the findings given by the Waterkeeper Alliance. The future dispersion of PFAS within various regions depends mainly on the level of PFAS use and state and federal legislation and monitoring efforts. Most states followed the HAL established by the EPA in 2016 and subsequently used this HAL as a basis for establishing their own standards. The potential approval of the newly proposed National Primary Drinking Water Regulation (NPDWR) on March 14, 2023, will impose additional regulatory measures to address the issue of PFAS pollution in a more stringent manner. Previous studies have shown that the gradual elimination of PFAS is proven effective in decreasing the accumulation of PFAS in organisms (Point et al. 2021). For example, between 2006 and 2018, there was a general trend towards lower PFOS and PFOA values in precipitation samples taken from the Great Lakes region, which may be related to the implementation of phase-outs and regulatory measures. Furthermore, considering that the PFOS and PFOA found in surface water and rainfall appear to originate mainly from human activities in the local area, the implementation of phaseouts and regulations will continue to effectively decrease their levels in the environment (Gewurtz et al. 2019). However, due to the wide range of applications for which the PFAS family of compounds has been found to be useful, PFAS have the potential to enter the environment through a wide variety of different industrial processes and end-use products (EPA 2019). Therefore, the



presence of numerous persistent legacy PFAS with diverse chemical compositions, including variations in chain length, functioning heads, branches, and linkages, poses a considerable obstacle to comprehending and predicting their effects on the environment (Pfothenauer et al. 2022).

Additionally, shorter-chain compounds are used in the process of eliminating longer-chain counterparts to mitigate potential environmental and ecotoxicological impacts (Desgens-Martin et al. 2023). However, there is empirical evidence that short-chain counterparts may demonstrate comparable or even greater persistence, potentially causing health hazards similar to those linked with their long-chain analogues (Li et al., 2020). Because of this, it is crucial to consider the possibility of contamination from untested, yet emergent, or novel PFAS. In fact, the environmental assessment conducted in the United States focused on a limited subset of PFAS compounds, including most of those currently accessible. Consequently, additional PFAS may be present within the environment of the United States but are not detected. Therefore, access to relevant details provided by the PFAS manufacturer, such as the structural composition of the PFAS and its manufacturing procedures, is crucial to the advancement of ongoing research in this field. Clearly, developing the infrastructure necessary to meet the new MCL proposed by the EPA for six PFAS poses a

significant challenge for water treatment facilities in different states. This is so because the installation of ion exchange resins or GAC for the remediation of PFAS-contaminated water imposes a substantial financial burden on water wholesalers and retailers. Apart from the six PFAS that may be legally enforced, thousands of similar PFAS structures are known to exist. Thus, the costs for lowering or eliminating all PFAS present in water may be too high to be operable.

## Conclusion

This review reveals the widespread presence of PFAS in rivers, tributaries, and drinking water in the vast majority of US states. Higher concentrations of PFAS were observed in the watersheds of the Southeast and Northeast regions. PFAS concentrations vary significantly depending on factors such as the origin, urbanization, and characteristics of aquatic water bodies. The findings of this review concerning the distribution of PFAS are as follows.

The current literature shows different levels of PFAS contamination in US surface water throughout the country. The observed ranges are as follows: Southeast (20–6,067 ng/L), Midwest (2.7–197.1 ng/L), West

**Table 3** Total concentration of PFAS in the Midwest region of USA (ng/L)

State	Location	Possible source	Media	Total PFAS	Concentration	References
Iowa	Mississippi river at Burlington	Not specified	SW	$\Sigma_6$ PFAS	56	DNR (2023b)
Michigan	Kalamazoo watershed	Not specified	SW	$\Sigma_{24}$ PFAS	20,145	EGLE (2021)
	Brandymore Drain	Not specified	SW	$\Sigma_{24}$ PFAS	12,559	EGLE (2021)
	Norton creek	Not specified	SW	$\Sigma_{24}$ PFAS	8219	EGLE (2021)
	Grand River	Not specified	SW	$\Sigma_{24}$ PFAS	871	EGLE (2021)
	Mona Lake	Not specified	SW	$\Sigma_{24}$ PFAS	128.6	EGLE (2021)
	Ecorse River	Not specified	SW	PFOS + PFOA	21.5	Armstrong (2020)
	Clinton river	Not specified	SW	PFOS + PFOA	8.96	Armstrong (2021)
	Rouge River	Not specified	SW	$\Sigma_5$ PFAS	6.9	Waterkeeper Alliance (2022)
	Lake macatawa	Not specified	SW	PFOS + PFOA	5.8	Armstrong (2020)
Missouri	Coldwater Creek	Landfill, Airport	SW	* $\Sigma_5$ PFAS	197.1	Waterkeeper Alliance (2022)
	Unity village treatment plant	Not specified	SW	$\Sigma_5$ PFAS	6.9	MoDNR (2022)
	215 Wheeler St	Not specified	SW	$\Sigma_5$ PFAS	0	MoDNR (2022)
Minnesota	Not specified	Not specified	SW	$\Sigma_5$ PFAS	50.8	Lambert et al. (2023)
North Dakota	Bois de Sioux River	Not specified	SW	PFBA	8.7	NDDEQ, (2022)
	Red River	Not specified	SW	PFBA	11	NDDEQ, (2022)
Ohio	Cairl Creek	Not specified	SW	$\Sigma_5$ PFAS	119.1	Waterkeeper Alliance (2022)
	Ohio River	Not specified	SW	$\Sigma_5$ PFAS	12.9	Waterkeeper Alliance (2022)
	Tributary to Cairl Creek	Not specified	SW	$\Sigma_5$ PFAS	12.7	Waterkeeper Alliance (2022)
Wisconsin	Milwaukee River	Not specified	SW	$\Sigma_5$ PFAS	10.3	Waterkeeper Alliance (2022)
	Root River	Not specified	SW	PFOS + PFOA	7.73	DNR (2023a)
	East Branch Milwaukee River	Not specified	SW	$\Sigma_5$ PFAS	2	Waterkeeper Alliance (2022)

\* $\Sigma_5$ PFAS = Total PFAS include PFOA, PFOS, PFHxA, PFPeA and PFBS. SW Surface water



**Table 4** Total PFAS concentration in the Northeast region of USA (ng/L)

State	Location	Possible source	Media	Total PFAS	Concentration	References	
Connecticut	Naugatuck River	Not specified	SW	$\Sigma_5$ PFAS	21.6	Waterkeeper Alliance (2022)	
	Naugatuck River	Wastewater	SW	$\Sigma_{34}$ PFAS	19.5	DEEP (2021)	
	Connecticut river	Wastewater	SW	$\Sigma_{34}$ PFAS	4.7	DEEP (2021)	
	Farmington River	Wastewater	SW	$\Sigma_{34}$ PFAS	14	DEEP (2021)	
Maine	Presumpscot River	Not specified	SW	* $\Sigma_5$ PFAS	4.71	Waterkeeper Alliance (2022)	
	Saco River	–	SW	$\Sigma_6$ PFAS	ND	Maine water (2022)	
	Silver Lake	–	SW	$\Sigma_6$ PFAS	ND	Maine water (2022)	
Maryland	Colonial Lane	Airport	SW	$\Sigma_{14}$ PFAS	3452.5	MDE, (2021)	
	Piscataway Creek	Airport	SW	$\Sigma_{40}$ PFAS	3050	Waterkeeper Alliance (2022)	
	Woodyard road crossing	Airport	SW	$\Sigma_{14}$ PFAS	2568.3	MDE, (2021)	
	Piscataway Creek	Airport	SW	$\Sigma_{14}$ PFAS	214	MDE, (2021)	
	La Trappe Creek	Not specified	SW	$\Sigma_5$ PFAS	36.9	Waterkeeper Alliance (2022)	
	Jones Falls	Not specified	SW	$\Sigma_5$ PFAS	23.7	Waterkeeper Alliance (2022)	
	Mill Creek	Not specified	SW	$\Sigma_5$ PFAS	16.1	Waterkeeper Alliance (2022)	
	Walston Branch	Not specified	SW	$\Sigma_5$ PFAS	14.8	Waterkeeper Alliance (2022)	
	Massachusetts	Ashumet Pond	Wastewater, contaminated groundwater	SW	PFOS + PFOA + PFHxS	151	Tokranov et al. (2021)
		North Head Long Pond	WWTFs, Industry	SW	$\Sigma_5$ PFAS	17	Waterkeeper Alliance (2022)
Tributary to MadaketHarbor		WWTFs, Industry	SW	$\Sigma_5$ PFAS	16.1	Waterkeeper Alliance (2022)	
New Hampshire	Merrimack River	Industry	SW	$\Sigma_6$ PFAS	6559.9	(NHDES 2022)	
	Brentwood Lake	Not specified	SW	$\forall\Sigma_6$ PFAS	6409	NHDES (2022)	
	Merrimack stream	Industry	SW	$\Sigma_6$ PFAS	917.6	NHDES (2022)	
	Newton pond	Not specified	SW	$\Sigma_6$ PFAS	97.57	NHDES (2022)	
	Pittsfield lake	Not specified	SW	$\Sigma_6$ PFAS	64.86	NHDES (2022)	
	Nottingham	Not specified	SW	$\Sigma_6$ PFAS	7.74	NHDES (2022)	
	New London Lake	Not specified	SW	$\Sigma_6$ PFAS	4.51	NHDES (2022)	
New Jersey	Little Pine Lake	AFFF	SW	$^{\S}\Sigma_{13}$ PFAS	279.5	Goodrow et al. (2020)	
	Mirror Lake	AFFF	SW	$\Sigma_{13}$ PFAS	180.9	Goodrow et al. (2020)	
	Pine Lake	AFFF	SW	$\Sigma_{13}$ PFAS	170.7	Goodrow et al. (2020)	
	Cohansey River	AFFF	SW	$\Sigma_{13}$ PFAS	27.2	Goodrow et al. (2020)	
	Lake Tappan	Not specified	SW	$\Sigma_5$ PFAS	21.4	Waterkeeper Alliance (2022)	
	Hackensack River	Not specified	SW	$\Sigma_5$ PFAS	20.2	Waterkeeper Alliance (2022)	
New York	Cayuga Creek	Landfills, Airports, Industry	SW	$\Sigma_5$ PFAS	301	Waterkeeper Alliance (2022)	
	Peconic River	Not specified	SW	$\Sigma_5$ PFAS	20.6	Waterkeeper Alliance (2022)	
	Black Brook	Not specified	SW	$\Sigma_5$ PFAS	27.3	(Waterkeeper Alliance 2022)	



**Table 4** (continued)

State	Location	Possible source	Media	Total PFAS	Concentration	References
Pennsylvania	Kreutz Creek	Landfill	SW	$\Sigma_5$ PFAS	2083.3	Waterkeeper Alliance (2022)
	Allegheny River	Not specified	SW	$\Sigma_5$ PFAS	6.2	Waterkeeper Alliance (2022)
	Glade Run	Not specified	SW	$\Sigma_5$ PFAS	3.5	Waterkeeper Alliance (2022)
	Tunungwant Creek	Not specified	SW	$\Sigma_5$ PFAS	4.3	Waterkeeper Alliance (2022)
Rhode Island	Spring Green Pond,	Not specified	SW	$\Sigma_5$ PFAS	193.9	Waterkeeper Alliance (2022)
	Mill Cove,	Airports, Industry	SW	PFHxS + PFNA	57	Zhang et al. (2016)
	Pawtuxet River	Not specified	SW	$\Sigma_5$ PFAS	42.3	Waterkeeper Alliance (2022)
	Buckeye Brook	Unknown	SW	$\Sigma_5$ PFAS	21.9	Waterkeeper Alliance (2022)
Vermont	Muddy Brook	Landfill	SW	* $\Sigma_5$ PFAS	14.8	VANR (2021)
	Lake Memphremagog	Landfill	SW	* $\Sigma_5$ PFAS	8.7	VANR (2021)
	Clyde river	Landfill	SW	* $\Sigma_5$ PFAS	1.8	VANR (2021)

SW Surface water ND Not Detected, \*WWTFs = Wastewater treatment facilities \* $\Sigma_5$ PFAS = Total PFAS include PFOS, PFOA, PFHxS, PFPeA, PFBS.  $\Sigma_6$ PFAS = PFHxA, PFHxS, PFOA, PFOS, PFNA, PFOSA.  $\Sigma_{13}$ PFAS = Total PFAS include PFBA, PFBS, PFPeA, PFHxA, PFHxS, PFHpA, PFOA, PFOS, Perfluorooctanesulfonamide (PFOSA) PFNA, PFDA, PFOA, Perfluorododecanoic acid (PFDoA)

(10.96–12,920 ng/L), and Northeast (4.7–6,559.9 ng/L). According to this study, the southeast is more contaminated than other regions. PFAS contamination is also prevalent in certain parts of West, Midwest, and Northeast regions, similar to the Southeast. There is a significant lack of data in the southwest region. Researchers and authorities continue to focus on a few PFAS structures while excluding others. Existing data are inadequate to explain PFAS contamination in Texas, Oklahoma, New Mexico, Arkansas, Louisiana, Mississippi, Wyoming, Idaho, Indiana, and Illinois. Thus, the governing body should promptly implement approaches that aim to understand the distribution patterns of PFAS in these states.

It can be inferred from Tables 1, 2, 3 and 4 that five to six common PFAS were measured in the surface water of most states, but many other PFAS were not taken into account. Meanwhile, it has been observed that, as the number of PFAS increased, there was usually a corresponding increase in the concentration of total PFAS. For example, Maryland (as shown in Table 4), Michigan (as shown in Table 3), Nevada, and Colorado (as shown in Table 2) measured a higher number of PFAS compounds, resulting in higher concentrations of total PFAS. This study suggests that measuring only five to six PFAS concentrations could paint an inadequate picture of PFAS contamination in different states. Thus, examining additional PFAS in surface, groundwater, and drinking water supplies throughout the state will help determine

the actual PFAS contamination. The state of Michigan serves as an exemplary case to illustrate this point.

Several states in the USA have recognized the presence of significant sources of PFAS. PFAS manufacturing facilities, landfills, firefighting foam use, airports, military bases, and naval stations, carpet factories, metal plating facilities, wastewater treatment plants, biosolids as fertilizer, mining and refining sites, atmospheric deposition, waste incinerators, and groundwater contamination are examples of these sources. In addition, urbanization and surface water near manufacturing sites contribute to PFAS pollution in several states.

There is a lack of literature that adequately documents the levels of PFAS in surface water in different states, and some states even do not have data available for comparison. An analysis of peer-reviewed literature and state environmental protection agencies' reports indicates that not all states are equally proactive in investigating the distribution of PFAS within their respective territories, and many states have a long way to go before they can even consider implementing a mitigation strategy. This report emphasizes the need for comprehensive assessments of PFAS contamination throughout the United States with a uniform approach.

Finally, to address the US surface water PFAS contamination problem, an integrated approach is recommended.



For effective management of PFAS pollution, identifying sources, preventing further releases, and monitoring and mitigating exposures are essential. However, insufficient PFAS governance allows these chemicals to persist in the environment, increasing remediation expenses. Monitoring the movement of these chemicals, effective mitigating strategies to decrease PFAS' concentrations, as well as eliminating their sources in the environment, will lead to favorable outcomes for water quality and the preservation of thriving communities within the United States.

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## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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