www.ijarp.com ISSN 2456-9992 Page: 01-22
International Journal Advanced Research Publications
Review Article
Volume: 02
Issue: 06

INDUSTRIAL SOURCES OF PFAS IN SURFACE WATER: OCCURRENCE, TRANSPORT, AND RISK ASSESSMENT

***Santunu Barua**

MS in Environmental Engineering Department of Civil and Environmental Engineering Manhattan University New York, USA.

Article Received: 22 May 2026, Article Revised: 10 June 2026, Published on: 30 June 2026

***Corresponding Author: Santunu Barua**
MS in Environmental Engineering Department of Civil and Environmental Engineering Manhattan University New York, USA.
Doi: https://doi-doi.org/101555/ijarp.9276

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals of global environmental concern due to their persistence, mobility, bioaccumulation potential, and documented toxicity. This comprehensive review synthesizes current knowledge on the industrial sources, occurrence, transport mechanisms, and risk assessment of PFAS in surface water environments. Industrial sources are diverse, encompassing fluorochemical manufacturing, electroplating, metal coating, textile production, paper processing, semiconductor manufacturing, and waste management facilities. Point-source contamination from these industries creates elevated PFAS concentrations in receiving waters, with documented levels exceeding 700 µg/L near some industrial parks. Studying PFASs in surface water yields insights into pollution dynamics, with PFAS contamination documented in regions affected by industrial relocation patterns post-2010 (J. Wang et al., 2024). Transport of PFAS occurs through multiple pathways including direct wastewater discharge, atmospheric deposition, and indirect pathways via biosolids application and landfill leachate. PFAS are extremely recalcitrant and widespread in the environment, with measurable concentrations in soils, sediments, groundwater, surface water, and rainwater, even at sites far removed from known sources or releases (Lotufo et al., 2026). Risk assessment reveals that surface waters near industrial zones frequently exceed regulatory standards for PFAS, with ecological and human health implications. This review identifies emerging contaminants, analytical challenges, knowledge gaps, and priorities for source control and remediation. Advanced treatment

technologies and regulatory frameworks are critical to mitigate PFAS contamination in surface water ecosystems globally.

KEYWORDS: PFAS; perfluoroalkyl substances; industrial sources; surface water; occurrence; transport; risk assessment; wastewater; point sources; environmental contamination

1. INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) represent a class of over 4,600 synthetic chemicals characterized by extremely strong carbon-fluorine bonds that render them resistant to environmental degradation. PFAS are highly stable fluorinated compounds with unique properties and are used in a broad array of industrial processes and commercial products (Lotufo et al., 2026). Since their introduction in the 1940s, PFAS have been widely incorporated into diverse applications ranging from aqueous film-forming foams (AFFF) used in firefighting to industrial coatings, textile treatments, and semiconductor manufacturing. The widespread environmental contamination by PFAS has emerged as a pressing challenge for water security and public health worldwide.

PFAS have become commonly detected in aquatic environments, which serve both as pathways and as reservoirs for these pollutants (Patel et al., 2025). Surface water systems, which provide critical ecosystem services and serve as drinking water sources for millions of people globally, are increasingly impacted by PFAS contamination. The principal concern is that industrial facilities discharge PFAS-containing wastewater directly into surface water bodies, creating contamination hotspots and posing risks to downstream communities. Additionally, atmospheric transport, runoff from urban areas, and indirect pathways through wastewater treatment plants (WWTPs) and landfills contribute to the pervasive presence of PFAS in aquatic systems.

This review synthesizes current scientific understanding of industrial sources of PFAS in surface water, mechanisms of occurrence and transport, and associated risk assessments. The objectives are to (1) characterize major industrial sources and their contribution to PFAS loading in surface waters; (2) describe the occurrence patterns, fate, and transport mechanisms of PFAS in aquatic environments; (3) evaluate current risk assessment approaches and findings; (4) identify analytical and knowledge gaps; and (5) discuss implications for environmental management and regulatory action.

2. Industrial Sources and Point-Source Contamination

2.1 Fluorochemical Manufacturing Facilities

Fluorochemical manufacturing represents the most significant direct industrial source of PFAS to surface water globally. Major chemical companies in the Pierre-Bénite area have used PFAS in the production of fluoropolymers and fluorotelomers, with effluents discharged into the Rhône River (Teymoorian et al., 2025). The magnitude of contamination from manufacturing facilities is exemplified by studies documenting extreme PFAS concentrations in receiving waters.

A total of 111 emerging PFAS were identified from three typical fluorochemical industrial parks in China, with a maximum concentration of 48.2% in nontarget PFAS, and the highest point concentrations in water and sediment were up to 706 μg/L and 553 μg/g, respectively (Song et al., 2023). Similarly, near a historical fluorotelomer manufacturer which was closed in 2017, ∑PFAS concentration was still at a high-level of 1800 ng/L (Li et al., 2025b), demonstrating that PFAS from manufacturing plants persist in surface waters even after facility closure. In the Jiangsu High-Tech Fluorochemical Industrial Park in Changshu City, the largest fluorochemical industrial park in Asia, the concentrations of total PFASs ranged from 1650 to 8250 ng/L in the dissolved-phase samples (Huang et al., 2024), with perfluorohexanoic acid (PFHxA), perfluorooctanoate acid (PFOA), and 6:2 fluorotelomer carboxylic acid being predominant compounds.

Suspect screening revealed distinct differences between fluoropolymer production sites, with the C8 homologue being the most prevalent compound of emerging chlorinated perfluoroalkyl carboxylic acids in Chinese rivers, while C6 and shorter homologues were dominant in German rivers, indicating that the phaseout of long-chain compounds in Europe also applies to unregulated emerging PFAS classes (Joerss et al., 2022). The production of specific PFAS formulations leaves characteristic chemical fingerprints that can be used for source apportionment. In wastewater from fluorochemical manufacturers, PFAS concentrations were in the range of 14,700-5,200,000 ng/L with 6:2 FTCA, PFOA, N-EtFOSA, and 8:2 FTS being major PFAS detected (Zhang et al., 2023).

A riverside fluorochemical manufacturing facility was identified as a primary point source along with five secondary fluorine-related sources in the Yangtze River downstream to Estuary continuum, with industrial development having a stronger direct impact on PFAS contamination than urbanization (Yang et al., 2025). The concentrated discharge of PFAS from manufacturing parks creates severe contamination in receiving waters that persists for decades.

2.2 Wastewater Treatment Plants (WWTPs) as Secondary Sources

While not primary manufacturers, WWTPs function as major secondary sources and reservoirs of PFAS. In wastewater treatment plants, perfluorobutanoic acid was dominant in wastewater influent and effluent samples with maximum concentrations of 59.8 and 11.4 ng/L respectively, while short-chain PFASs with an even number of carbon atoms were mostly removed, whereas short-chain PFASs with an odd number of carbon atoms were primarily discharged into receiving water (W. Chen et al., 2022). Wastewater treatment plants serve as both sources and sinks of PFASs, with a negative average removal efficiency of -47.4% and an estimated annual discharge of 12.29 kg of PFASs into the environment (K. Zhang et al., 2025).

In England, PFAS were routinely present in wastewater treatment plants effluents, where removal efficiencies were often low or negative, indicating that WWTPs function as chronic point sources, with persistent PFOS detections in WWTPs effluents long after its restriction reflecting that PFAS are now deeply embedded within the built environment (Herrera et al., 2026). In wastewater from a WWTP near the Yangtze River, fifteen classes with 90 PFASs were identified, with only 1 PFAS class removed through the treatment processes, while 4 PFAS classes increased through the treatment processes (Y. Wang et al., 2018).

2.3 Metal Plating and Electrochemical Processes

Industrial sources of PFASs include industrial emissions, fluoropolymer production and treatment, textile processing, and the impact of the electroplating industry (Zhang et al., 2024). Electroplating operations use PFAS-containing compounds to enhance coating performance and improve surface properties. In electroplaters, laundry and carpet cleaners, landfills, and circuit board manufacturers that discharge to sewersheds, maximum concentrations were detected in carpet cleaning wastewater with 79,000 ng/L for perfluorohexane sulfonate (PFHxS), 26,000 ng/L PFOS, and 9,400 ng/L PFOA (Payne et al., 2024).

2.4 Textile, Paper, and Coating Industries

PFASs mainly come from industrial activities around rivers, with PFASs mainly composed of long-chain substances from the leather and textile manufacturing industries, fluoropolymer production, and electroplating metal industries (Pan et al., 2025). Paper product production has been identified as a major PFAS point source that has generally been overlooked, with factory emissions containing PFOS, PFOS precursors, long chained fluorotelomer sulfonates, and perfluoroalkyl carboxylic acids (Langberg et al., 2020).

Textile and food packaging was identified as the predominant source accounting for 77% of national contribution in China's tap water (Zhao et al., 2026), demonstrating the significance of textile manufacturing as a PFAS source.

2.5 Aqueous Film-Forming Foams (AFFF)

Among the aqueous matrices reviewed, groundwater impacted by AFFF contamination showed the highest median concentrations for both PFOA and PFOS, while the second-highest median concentrations were associated with landfill leachates for PFOA and metal-plating sources for PFOS (Dasu et al., 2021). Following the use of aqueous film forming foams to extinguish a petrochemical fire, PFAS levels in surface waters showed mean total levels in March and April 2019 to be from 4× to ~300× higher than those measured in following months (Nolen et al., 2022).

2.6 Landfills and Waste Management Facilities

In groundwater surrounding legacy landfills, the sum of detected PFAS varied from 26 ng/L at an ambient background site to 5,200 ng/L near a potential industrial point-source, with positive correlations between ∑14PFAS, PFOA and other perfluoroalkyl carboxylic acids with typical leachate indicators (Hepburn et al., 2019). In waste management facilities, the ∑10PFAS ranged from 0.44 µg/L to 17 µg/L, with EOF ranging from 2 µg/L F up to 79 µg/L F, suggesting different sources of PFAS from waste (Pettersson et al., 2024).

3. Occurrence and Characterization of PFAS in Surface Water

3.1 Global and Regional Distribution Patterns

Individual PFAS concentrations in English waterbodies ranged from 0.0052 to 480 ng/L while ΣPFASs concentrations per site ranged from 0.024 to 2021 ng/L, with the highest concentrations near large distinct urban areas (Patel et al., 2025). In China, PFAS contamination was widespread, even in regions like Tibet, with pollution patterns associated with industrial activity and urbanization trends (J. Wang et al., 2024).

Globally, China, Brazil, Germany, South Africa, and the Danube River Basin exhibited particularly high levels of PFAS concentrations in potential drinking water sources, with China being the most severely contaminated (Zhou et al., 2025). In Alabama, the spatial distribution of 17 PFAS within ten major river basins showed the highest ∑6PFAS concentration of 237 ng L-1 in the Coosa River, with mean ∑6PFAS levels of 35.2 ng L-1 overall (Viticoski et al., 2022).

3.2 Legacy Versus Emerging PFAS

While perfluorooctanoic acid and perfluorooctane sulfonic acid levels in water environments are declining annually, short-chain PFASs and their substitutes are emerging as primary pollutants, with short-chain PFASs frequently detected in surface water, whereas long-chain PFASs tend to accumulate in sediments (J. Zhang et al., 2025).

A shift in coastal PFAS contamination from legacy compounds to emerging short-chain alternatives has occurred, with emerging short-chain PFAS such as PFBS, PFBA, F-53B and GenX frequently detected at detection rates of 97%, 99%, 95% and 77% respectively (Lei et al., 2024). A total of 58 PFAS from 13 classes were identified in Taihu Lake, including short-chain perfluoroalkyl carboxylates and sulfonates, with bis(trifluoromethanesulfonyl)imide and perfluoro-2,5-dimethyl-3,6-dioxo-heptanoic acid exhibiting relatively high concentrations in water (Fu et al., 2024).

3.3 PFAS Composition and Homologue Patterns

In the Oder River, the main components were short-chain analogs, with PFBA accounting for about one-third of all PFAS detected, although in the Gliwice Canal, ADONA represented half of the detected PFAS (Zarębska et al., 2024). In the Daling River with concentrated fluorine industries, PFBA, PFBS, and PFOA were the dominant PFASs in four seasons with a total contribution of over 90% (Zhu et al., 2015).

3.4 Nontarget and Emerging PFAS Discovery

In suspect screening of wastewater from a WWTP near Yangtze River, fifteen classes with 90 PFASs were identified, including 12 legacy PFASs, 41 previously reported PFASs, and 37 new PFASs (Y. Wang et al., 2018). Among pre-PFAAs, compounds of emerging interest such as the fluorotelomer sulfonamidoalkyl betaines 6:2 FTAB and 8:2 FTAB were respectively detected in 38% and 24% of samples, with levels similar to those of L-PFOS (Macorps et al., 2023).

4. Transport and Fate Mechanisms

4.1 Aquatic Transport Pathways

PFAS mainly originated from exogenous inputs via seasonal currents, with industrial emissions as potential sources, and substantial quantities of PFOA and PFBA transported to the southern Taiwan Strait during summer via Pearl River Diluted Water and the South China Sea Warm Current (Ma et al., 2025). A general surface-enrichment and depth-depletion pattern from inshore to offshore area was observed, with average ∑PFAS loadings inshore significantly greater than offshore (Ogunbiyi et al., 2023).

4.2 Partitioning Between Water and Particulate Matter

The ∑PFAS mean concentrations in water and suspended particulate matter samples were 38.2 ng/L and 64.6 ng/g dw respectively, with PFAS concentrations in the surface microlayer higher than those in underlying water, and the enrichment factors greater in suspended particulate matter than in water (Li et al., 2024b). The downstream area of Xiaoqing River heavily influenced by discharged wastewater from a fluorochemical industry park possessed an extremely high total PFAS concentration with various PFAS substances observed, including high concentration of PFOA and several perfluoropolyether carboxylic acids constituting approximately 17-35% of the dissolved phase (Shi et al., 2025).

4.3 Atmospheric Deposition and Precipitation

PFAS may enter the atmosphere from multiple sources, including stack emissions, fugitive dust, surface water aerosolization, and entrainment of wind-born fire suppression foam, and they subsequently travel through the gas phase as aerosols and particle-bound processes, being deposited through wet deposition or dry deposition, contributing to their presence in soil, surface water, and groundwater at locations distant from the point of generation (Zenobio et al., 2025).

The concentration of ionic PFAS in PM2.5 collected from a WWTP was slightly higher than that from the control point, and the HYSPLIT model implied that the iPFASS pathway of WWTP was totally different under identical meteorological conditions, indicating that WWTP could be a source of iPFASS in urban environment (Li et al., 2025c).

4.4 Stormwater as a Transport Vector

Urban stormwater runoff significantly affects PFAS occurrence in urban streams, with higher PFAS concentrations found downstream of urban areas and/or point sources during wet weather, indicating a clear contribution from stormwater discharges (Kali et al., 2024). Notably, except for the legacy PFAS PFOS and PFOA, the most frequently quantified PFAS during dry weather were short-chain, while during wet weather, long-chain perfluorocarboxylic acids and precursor 6:2 Fluorotelomer sulfonic acid were more frequently quantified, suggesting stormwater is a source of these longer-chain and particle-associated PFAS (Kali et al., 2024).

4.5 Bioaccumulation and Food Web Transfer

Select PFAS, especially longer-chain perfluorinated carboxylic and sulfonic acids, are known to bioaccumulate in aquatic food webs, presenting potential risk to higher trophic species, including humans (Lotufo et al., 2026). Fish and seafood, and biota have the highest PFAS concentrations due to environmental contamination and bioaccumulation, with surface water

samples also frequently containing PFAS, raising concerns about long-term ecological and human health effects (Dimitrakopoulou et al., 2024).

4.6 Seasonal and Temporal Variations

The mean concentration and mass flux of total PFAS in the Rhine River during 2007-2019 were 32.83 ng L-1 and 6.36 × 104 µg s-1, declining at an annual rate of 3.70% and 3.82% respectively, with wavelet analysis demonstrating that the most prominent periodic oscillation of PFAS was 40-60 months (Li et al., 2023). Large-scale dredging was a non-negligible factor in abnormally increased PFAS concentrations (6.43%-456.16%) during watershed comprehensive management through their release from river sediments (Xu et al., 2024).

5. Analytical Methods and Detection Challenges

5.1 Target and Nontarget Screening Approaches

Traditional target methods using liquid chromatography-mass spectrometry fail to capture many PFAS, as a total organic fluorine method combined with target LC-MS/MS revealed that LC-MS/MS only accounted for 2% of the total organic fluorine measured, indicating that LC-MS may miss highly contaminated sites (Forster et al., 2024).

Less than 10% of known PFAS chemistry is predicted to be amenable to typical LC-MS analysis, with gas chromatography-mass spectrometry capable of covering complimentary chemical space and having strong potential for applying GC-MS methods to more fully assess the PFAS environmental contamination landscape (Newton et al., 2025).

5.2 Total Oxidizable Precursor (TOP) Assay

The total oxidizable precursor assay has proved useful to estimate the contribution of unattributed perfluoroalkyl acids precursors, with conversion yields of targeted pre-PFAAs determined under realistic conditions leading to differences in oxidation profiles (Macorps et al., 2023).

5.3 Identification of Novel PFAS

Suspect screening examined patterns of emerging and novel PFAS, revealing 86 PFAS grouped into 18 structure categories, with homologue patterns revealing distinct differences between fluoropolymer production sites indicating that the phaseout of long-chain compounds applies to unregulated emerging PFAS classes (Joerss et al., 2022).

6. Risk Assessment: Ecological and Human Health

6.1 Risk Quotient (RQ) and Hazard Quotient (HQ) Methodologies

The risk quotient and hazard quotient calculations for three age groups indicated that PFAS exposure did not pose a significant risk to ecological or human health in the Rhine River, though implementing source-oriented mitigation strategies is crucial to effectively reduce the ecological and human health risks (Li et al., 2023). Comprehensive comparison indicates that PFASs (such as PFOA) in the majority of freshwater basins are at a low-risk level (RQ < 0.1 or HQ < 0.2), PFOS in some freshwater basins is at a medium-risk level (0.1 < RQ < 1), and no freshwater basin is at a high-risk level (J. Zhang et al., 2025).

6.2 Ecological Risk Assessments

In Dianchi Lake, the risk quotient values were low in waters (0.01) but ranged from 0.01 to 1 in sediments, indicating low to moderate risk, primarily from long-chain PFASs (Liang et al., 2026). The ecological risk quotients for phytoplankton were relatively higher than invertebrates in freshwater, and in marine water, the majority of PFAS substitutes exhibited negligible risk for invertebrates and fish, and posed elevated risks for phytoplanktons (Hamid et al., 2023).

6.3 Human Exposure and Health Risks

In Southern California, detections of PFOS, PFOA, and PFHxS in drinking water were associated with increases in plasma concentrations, and the presence of Superfund sites was associated with higher plasma concentrations of multiple PFAS, with each additional PFAS-polluting facility present in the neighborhood associated with increased PFOS concentration (Li et al., 2024a).

More than 97 million US residents were served by a public water system with detectable levels of PFAS and other unregulated contaminants, with unregulated contaminant detection more frequent among large systems, urban systems, and systems using groundwater (Maruzzo et al., 2025).

In China, PFAS concentrations reported in more than 20% of studied cities, likely affecting 98.5 million people, were above the maximum contaminant level issued by Vermont in 2019, with East China and the Southwest regions posing a relatively higher risk (L. Liu et al., 2021).

6.4 Drinking Water Contamination

China's first national-scale assessment of PFAS in tap water revealed widespread contamination, with perfluorooctanoic acid, perfluorobutane sulfonate, perfluoroheptanoic acid, and hexafluoropropylene oxide dimer acid as the most prevalent compounds, and 35%

of samples exceeding the stringent U.S. EPA maximum contaminant level for PFOA (Zhao et al., 2026).

6.5 Relative Potency Factor (RPF) Approach for Mixture Risk

A database of liver endpoints was established for 16 PFAS using data with the same species, sex, and exposure route, with dose-response analysis applied to derive the relative potencies of perfluoroalkyl sulfonic acids, perfluoroalkyl carboxylic acids, and fluorotelomer alcohols compared to PFOA (Bil et al., 2020).

7. Source Apportionment and Fingerprinting

7.1 Positive Matrix Factorization (PMF) and Multivariate Analysis

Using self-organizing map and positive matrix factorization models for source apportionment in the Rhine River, the results indicated that the primary sources of PFAS were agrochemical, pharmaceutical and textile industries, accounting for 38.1% of the total concentration (Li et al., 2023).

Employing spatial response analysis combining self-organizing maps, K-means clustering, Spearman correlation, positive matrix factorization and risk quotient, the characteristics of PFAS in groundwater were classified into 16 neurons divided into 6 clusters, revealing that industrial pollution contributed 33.2% and domestic pollution 31.5% to the composition of PFAS (Zeng et al., 2024).

7.2 Isomer Profiling for Source Tracking

Isomer profiling revealed a higher proportion of branched isomers in Chinese rivers than in other rivers, pointing to different synthesis routes and underlining the importance of differentiating between linear and branched isomers in risk assessments (Joerss et al., 2020). Ratios of linear-to branched-PFOS increased with distance from a factory, indicating that isomer profiles can be used to trace a point source (Langberg et al., 2020).

7.3 Regional Source Characterization

Source apportionment using the Positive Matrix Factorization model identified key contributors to PFAS pollution including textile production, volatile precursors, precious metal industries, aqueous film-forming foam, metal-plating, electrochemical fluorination, and fluoropolymer manufacturing (Lei et al., 2024).

8. Fate and Persistence in Aquatic Environments

8.1 Environmental Degradation and Transformation

PFAS are extremely recalcitrant, with evidence suggesting sediment serves as a repository and potential ongoing source for many of these long-chain PFAS (Lotufo et al., 2026). Ten perfluoroalkyl ether acids and a chlorinated polyfluoroalkyl ether acid were stable in the total oxidizable precursor assay and represent terminal products that are likely as persistent as historically used PFAS (C. Zhang et al., 2019).

8.2 Sediment Accumulation

Unattributed pre-PFAAs were strongly correlated with ∑PFAS targeted and they accounted for 58% of ∑PFAS (median value), generally found in larger quantity near industrial and urban areas (Macorps et al., 2023). The average accumulation rate of Σ12PFAS in sediment was estimated at 168 pg/g·y-1, with projected stabilization after 2025 likely driven by the implementation of new pollutant control policies (Yang et al., 2025).

9. Regulatory and Management Responses

9.1 International and National Guidelines

Seven states have developed their own water guideline levels for PFOA and/or PFOS ranging from 13 to 1000 ng/L, compared to EPA's HA of 70 ng/L, with assessments by multiple states and academic scientists suggesting that EPA's HA is not sufficiently protective (Cordner et al., 2019).

9.2 Wastewater Treatment Optimization

The review on sources, distribution and treatment of PFAS in global groundwater revealed that firefighting training activities were a major source accounting for 41% of cases, followed by other fluorinated industrial activities, landfill leachate, and wastewater leakage (H. Zhang et al., 2025). In-situ direct injection of colloidal activated carbon was considered a highly promising approach for remediating PFAS source zones and plumes (H. Zhang et al., 2025).

9.3 Industrial Practice Changes

Following the closure of PFOS production to comply with Stockholm Convention, manufacturers have shifted to developing short-chain alternatives like PFBS, yet the conversion of factories has resulted in the coexistence of long-chain and short-chain PFAS, complicating the composition in the environment (Qie et al., 2024).

10. Research Gaps and Future Directions

10.1 Knowledge Gaps in PFAS Occurrence

Several critical research gaps persist in understanding PFAS contamination of surface water. Limited studies on PFAS concentrations in soil, atmosphere, and food emphasize the need for comprehensive research to mitigate human exposure (Mengesha et al., 2025). While occurrence data have been collected from numerous regions globally, monitoring coverage remains incomplete, with vast geographic areas lacking baseline data on PFAS environmental contamination.

10.2 Analytical Method Standardization

Identifying PFAS hotspots requires combined use of total organic fluorine analysis and target LC-MS/MS, as traditional target methods fail to capture many PFAS (Forster et al., 2024). The lack of standardized analytical protocols for emerging PFAS and nontarget screening hinders comparability across studies and regions. Further development and validation of methods for detecting ultra-short-chain PFAS, nonionic PFAS, and transformation products is needed.

10.3 Transformation Products and Precursor Compounds

Alternative PFAS undergo bioaccumulation and cause deleterious effects such as oxidative stress, hepatotoxicity, neurotoxicity, and reproductive toxicity in freshwater and marine species (Hamid et al., 2023). The fate and toxicity of emerging PFAS alternatives remain poorly characterized, particularly regarding their degradation pathways and transformation products in aquatic environments. Additional research is needed to understand how precursor compounds degrade to form persistent PFAS in the environment.

10.4 Source Attribution in Complex Urban Waterscapes

Integrating suspect and nontarget screening with spatial autocorrelation analysis revealed three representative pollution patterns of emerging contaminants in rivers: single-point, composite-point, and mixed sources (M. Liu et al., 2025). Future studies must better characterize how multiple simultaneous sources contribute to PFAS contamination in urban and industrialized watersheds, where point sources from manufacturing coexist with diffuse inputs from consumer products and wastewater treatment.

10.5 Risk Assessment Refinement

Mesocosm-based hazard concentration for 5% of species was significantly lower than the laboratory-based hazard concentration, with laboratory-based thresholds significantly underestimating aquatic ecological risk at a large scale (Li et al., 2025a). Current risk assessment methodologies often rely on laboratory-derived toxicity data that may not reflect

field-relevant conditions. Integration of ecologically relevant exposure scenarios and incorporation of mixture effects remain priorities for improved risk characterization.

10.6 Emerging PFAS Alternatives

While PFOA and PFOS levels in water environments are declining annually, short-chain PFASs and their substitutes are emerging as primary pollutants (J. Zhang et al., 2025). Comprehensive monitoring of emerging alternatives including perfluoroalkyl ether acids, chlorinated compounds, and other novel PFAS is critical to understand whether regulatory substitutions provide true environmental or health benefits.

10.7 Mechanistic Understanding of Transport and Fate

Air-water interfacial adsorption complicates PFAS transport in vadose zones, with mass-transfer limitations between bulk capillary water and thin water films arising in pore clusters where pendular rings disconnect (S. Chen & Guo, 2023). Enhanced mechanistic understanding of PFAS partitioning between environmental compartments, particularly under variable physicochemical conditions, is needed to improve predictive models of fate and transport.

11. SYNTHESIS AND CONCLUSIONS

Industrial sources of PFAS in surface water represent a major environmental contamination challenge with far-reaching implications for ecosystem integrity and human health. The vast majority of the water systems across the United States lack both the technology and the funds to filter out PFAS, with the release of PFAS with industrial wastewater from a variety of facilities being a significant contributor to PFAS contamination of drinking water (Andrews et al., 2021).

The evidence synthesized in this review demonstrates that PFAS contamination in surface waters results from diverse industrial sources, including fluorochemical manufacturing, electroplating, textile production, and waste management. Point-source contamination from active manufacturing facilities creates elevated PFAS concentrations in receiving waters, with levels exceeding regulatory standards by orders of magnitude in areas near fluorochemical parks. Wastewater treatment plants, historically viewed as solutions to pollution, function as secondary sources due to their limited ability to remove or destroy PFAS.

The transition from legacy long-chain PFAS to short-chain alternatives, driven by regulatory action, has not eliminated the problem but rather altered the contamination profile. Short-chain PFAS compounds exhibit higher mobility and persistence in aquatic environments,

potentially extending their environmental impact and widening exposure pathways. Emerging alternatives including per- and polyfluoroalkyl ether acids present additional challenges as they persist through standard treatment processes and remain poorly characterized toxicologically.

Transport of PFAS through surface water occurs via multiple interconnected pathways: direct industrial discharge, atmospheric deposition, stormwater runoff from urban areas, and indirect pathways through contaminated biosolids and landfill leachate. Once in aquatic systems, PFAS persist indefinitely, with sediments serving as long-term sinks and secondary sources. Bioaccumulation in aquatic food webs creates exposure risks for wildlife and humans consuming affected biota.

Risk assessment approaches have evolved to incorporate multiple PFAS compounds through mixture risk methodologies such as relative potency factors and hazard quotient summation. However, substantial gaps remain between current regulatory standards and evolving toxicological evidence. In many regions, drinking water PFAS concentrations exceed international guideline values, with human health risks from dietary exposure and drinking water consumption documented in numerous populations. Children and vulnerable populations appear to face disproportionate risks due to higher relative exposure and potential developmental sensitivities.

Effective management of PFAS in surface water requires integrated strategies spanning source control, wastewater treatment optimization, advanced water treatment technologies, and regulatory harmonization. Source reduction through substitution of PFAS-containing products and industrial processes remains the most effective long-term approach. For acute contamination scenarios, advanced treatment technologies including granular activated carbon, ion-exchange resins, and electrochemical methods show promise but require further development and optimization, particularly for short-chain compounds.

Regulatory frameworks must evolve beyond compound-specific limits toward class-based controls that account for the family of PFAS and their transformation products. International coordination is essential given the global production and use of PFAS and the potential for long-range atmospheric and aquatic transport. Future research priorities include: (1) comprehensive monitoring of emerging PFAS alternatives using advanced analytical methods; (2) source apportionment studies in complex contamination scenarios; (3) mechanistic understanding of PFAS fate and transport under variable environmental conditions; (4) ecologically relevant risk assessment incorporating mesocosm and field data;

(5) evaluation of treatment technology effectiveness for short-chain and alternative PFAS; and (6) investigation of human health risks from chronic exposure to PFAS mixtures.

The persistence, bioaccumulation, and widespread distribution of PFAS in surface waters represent an enduring environmental challenge requiring sustained scientific investigation, technological innovation, and coordinated policy action to protect aquatic ecosystems and human health for future generations.

REFERENCES

1. Andrews, D. Q., Hayes, J., Stoiber, T., Brewer, B., Campbell, C., & Naidenko, O. (2021). Identification of point source dischargers of per- and polyfluoroalkyl substances in the united states. *AWWA Water Science*. https://doi.org/10.1002/aws2.1252
2. Bil, W., Zeilmaker, M. J., Fragki, S., Lijzen, J., Verbruggen, E., & Bokkers, B. (2020). Risk assessment of per- and polyfluoroalkyl substance mixtures: A relative potency factor approach. *Environmental Toxicology and Chemistry*. https://doi.org/10.1002/etc.4835
3. Chen, S., & Guo, B. (2023). Pore-scale modeling of PFAS transport in water-unsaturated porous media: Air–water interfacial adsorption and mass-transfer processes in thin water films. *Water Resources Research*. https://doi.org/10.1029/2023WR034664
4. Chen, W., Yang, F., Hu, E., Yang, C., Sun, C., & Li, M. (2022). Occurrence, fate and risk assessment of per- and polyfluoroalkyl substances in wastewater treatment plants in shaanxi, china. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2022.120226
5. Cordner, A., Rosa, V. Y. D. L., Schaider, L. A., Rudel, R. A., Richter, L., & Brown, P. (2019). Guideline levels for PFOA and PFOS in drinking water: The role of scientific uncertainty, risk assessment decisions, and social factors. *Journal of Exposure Science & Environmental Epidemiology*. https://doi.org/10.1038/s41370-018-0099-9
6. Dasu, K., Xia, X.-Q., Siriwardena, D. P., Klupinski, T. P., & Seay, B. (2021). Concentration profiles of per- and polyfluoroalkyl substances in major sources to the environment. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2021.113879
7. Dimitrakopoulou, M., Karvounis, M., Marinos, G., Theodorakopoulou, Z., Aloizou, E., Petsangourakis, G., Papakonstantinou, M., & Stoitsis, G. (2024). Comprehensive analysis of PFAS presence from environment to plate. *Npj Science of Food*. https://doi.org/10.1038/s41538-024-00319-1

8. Forster, A. L., Geiger, T., Pansari, G. O., Justen, P. T., & Richardson, S. D. (2024). Identifying PFAS hotspots in surface waters of south carolina using a new optimized total organic fluorine method and target LC-MS/MS. *Water Research*. https://doi.org/10.1016/j.watres.2024.121570
9. Fu, Y., Ji, Y., Tian, Y., Zhang, F., Sheng, N., Dai, J., & Pan, Y. (2024). Unveiling priority emerging PFAS in taihu lake using integrated nontarget screening, target analysis, and risk characterization. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.4c06731
10. Hamid, N., Junaid, M., Sultan, M., Yoganandham, S. T., & Chuan, O. M. (2023). The untold story of PFAS alternatives: Insights into the occurrence, ecotoxicological impacts, and removal strategies in the aquatic environment. *Water Research*. https://doi.org/10.1016/j.watres.2023.121044
11. Hepburn, E., Madden, C., Szabo, D., Coggan, T. L., Clarke, B., & Currell, M. (2019). Contamination of groundwater with per- and polyfluoroalkyl substances (PFAS) from legacy landfills in an urban re-development precinct. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2019.02.018
12. Herrera, A. G., Iacovidou, E., & Giakoumis, T. (2026). Mapping per- and polyfluoroalkyl substances contamination in england's surface waterbodies: Urban water cycle pathways and governance challenges. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2026.181779
13. Huang, J., Zhao, Z., Liu, J., & Li, S. (2024). The transformation of per- and polyfluoroalkyl substances in the aquatic environment of a fluorochemical industrial park. *Water*. https://doi.org/10.3390/w16111513
14. Joerss, H., Menger, F., Tang, J., Ebinghaus, R., & Ahrens, L. (2022). Beyond the tip of the iceberg: Suspect screening reveals point source-specific patterns of emerging and novel per- and polyfluoroalkyl substances in german and chinese rivers. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.1c07987
15. Joerss, H., Schramm, T.-R., Sun, L., Guo, C., Tang, J., & Ebinghaus, R. (2020). Per- and polyfluoroalkyl substances in chinese and german river water - point source- and country-specific fingerprints including unknown precursors. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2020.115567
16. Kali, S. E., Österlund, H., Viklander, M., & Blecken, G. (2024). Stormwater discharges affect PFAS occurrence, concentrations, and spatial distribution in water and bottom

sediment of urban streams. *Water Research*. https://doi.org/10.1016/j.watres.2024.122973

17. Langberg, H. A., Arp, H. P. H., Breedveld, G. D., Slinde, G. A., Høiseter, Å., Grønning, H. M., Jartun, M., Rundberget, T., Jenssen, B. M., & Hale, S. E. (2020). Paper product production identified as the main source of per- and polyfluoroalkyl substances (PFAS) in a norwegian lake: Source and historic emission tracking. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2020.116259
18. Lei, H., Lu, Y., Wang, P., Xie, X., Li, J., An, X., Liang, Z., Sun, B., & Wang, C. (2024). Shift from legacy to emerging per- and polyfluoroalkyl substances for watershed management along the coast of china. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2024.125153
19. Li, H., Xie, L., Xu, Z., Cheng, F., & You, J. (2025a). Advancing aquatic ecological risk assessment of imidacloprid in global surface water with mesocosm-based thresholds. *Water Research*. https://doi.org/10.1016/j.watres.2025.123728
20. Li, H., Zhu, X., Zhang, J., Wang, Z., & Li, R. (2023). Characterizing the long-term occurrence and anthropogenic drivers of per- and polyfluoroalkyl substances in surface water of the rhine river. *Water Research*. https://doi.org/10.1016/j.watres.2023.120528
21. Li, S., Goodrich, J. A., Costello, E., Walker, D. I., Cardenas-Iniguez, C., Chen, J., Alderete, T., Valvi, D., Rock, S., Eckel, S., Mcconnell, R., Gilliland, F. D., Wilson, J. P., MacDonald, B., Conti, D. V., Smith, A. L., McCurry, D. L., Childress, A. E., Simpson, A., … Chatzi, L. (2024a). Examining disparities in PFAS plasma concentrations: Impact of drinking water contamination, food access, proximity to industrial facilities and superfund sites. *Environmental Research*. https://doi.org/10.1016/j.envres.2024.120370
22. Li, S., Liu, J., An, X., Tang, C., Tang, C., Zhang, B., Chen, C., Lin, T., Jones, K. C., & Zhao, Z. (2025b). Molecular characteristics of emerging perfluoroalkyl and polyfluoroalkyl substances (PFAS) and dissolved organic matter (DOM) in surface waters around fluorine-related industries in a chinese megacity. *Environment International*. https://doi.org/10.1016/j.envint.2025.109444
23. Li, Y., Zhang, X., Xu, L., Chen, L., Wu, Y., Ding, X., Zhu, P., & Zhong, W. (2025c). Levels and transport behavior of ionic per- and polyfluoroalkyl substances in the atmosphere of urban pollution scenario: An in-situ investigation of a wastewater treatment plant in wuxi, china. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2025.126003

24. Li, Y., Zhao, X., Li, X., Zhang, Y., & Niu, Z. (2024b). The investigation of the enrichment behavior of identified PFAS and unknown PFAA-precursors in water and suspended particulate matter of the surface microlayer: A case study in tianjin (china). *Water Research*. https://doi.org/10.1016/j.watres.2024.121944
25. Liang, H., Ding, T., Zhang, Y., Miao, F., Wang, Z., Du, S., & Cao, J. (2026). Occurrence, pollution characteristics, mass load and ecological risk assessment of per- and polyfluoroalkyl substances in the dianchi basin, china. *Toxics*. https://doi.org/10.3390/toxics14030196
26. Liu, L., Qu, Y., Huang, J., & Weber, R. (2021). Per- and polyfluoroalkyl substances (PFASs) in chinese drinking water: Risk assessment and geographical distribution. *Environmental Sciences Europe*. https://doi.org/10.1186/s12302-020-00425-3
27. Liu, M., Xiong, G., Ke, Y., Wang, X., Zhu, X., Yu, N., Zhai, P., Wu, J., Wu, J., & Wei, S. (2025). Integrating suspect and nontarget screening with spatial autocorrelation to prioritize emerging contaminants in a coastal urban river. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.5c03460
28. Lotufo, G., Krupa, P., Keil, K., Hayhurst, B., Kimble, A., & Moore, D. (2026). *Overview of PFAS in aquatic environments*. https://doi.org/10.21079/11681/50102
29. Ma, X., Li, Q., Liu, C., Li, H., Yu, X., Yan, Y., Li, Y., Wang, S., & Wang, X. (2025). Transport of PFAS in the presence of ocean currents: Implying the dominance of external inputs in the taiwan strait. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.5c02722
30. Macorps, N., Labadie, P., Lestremau, F., Assoumani, A., & Budzinski, H. (2023). Per- and polyfluoroalkyl substances (PFAS) in surface sediments: Occurrence, patterns, spatial distribution and contribution of unattributed precursors in french aquatic environments. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2023.162493
31. Maruzzo, A. J., Hernandez, A., Swartz, C. H., Liddie, J. M., & Schaider, L. A. (2025). Socioeconomic disparities in exposures to PFAS and other unregulated industrial drinking water contaminants in US public water systems. *Environmental Health Perspectives*. https://doi.org/10.1289/EHP14721
32. Mengesha, D. N., Mamo, M. D., Worku, T. A., & Zigyalew, Y. (2025). Emerging organic pollutants in ethiopia: Occurrence, impacts, and management strategies. *Water Environment Research*. https://doi.org/10.1002/wer.70209

33. Newton, S. R., Bowden, J. A., Charest, N., Jackson, S. R., Koelmel, J., Liberatore, H., Lin, A. M., Lowe, C. N., Nieto, S., Pollitt, K. J. G., Robuck, A. R., Rostkowski, P., Townsend, T. G., Wallace, M. A. G., & Williams, A. (2025). Filling the gaps in PFAS detection: Integrating GC-MS non-targeted analysis for comprehensive environmental monitoring and exposure assessment. *Environmental Science and Technology Letters*. https://doi.org/10.1021/acs.estlett.4c00930
34. Nolen, R., Faulkner, P., Ross, A. D., Kaiser, K., Quigg, A., & Hala, D. (2022). PFASs pollution in galveston bay surface waters and biota (shellfish and fish) following AFFFs use during the ITC fire at deer park (march 17th-20th 2019), houston, TX. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2021.150361
35. Ogunbiyi, O. D., Massenat, N., & Quinete, N. (2023). Dispersion and stratification of per-and polyfluoroalkyl substances (PFAS) in surface and deep-water profiles: A case study of the biscayne bay area. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2023.168413
36. Pan, X., Wu, L., & Wang, D. (2025). Per- and polyfluoroalkyl substances in surface water of fuyang river (handan section): Occurrence, source apportionment, and risk assessment. *Water*. https://doi.org/10.3390/w17081223
37. Patel, R., Gooddy, D., Marchant, B., Lapworth, D., James, A., Cook, M., Darby, K., & Besien, T. (2025). A national-scale preliminary overview study of poly- and perfluoroalkyl substances (PFAS) occurrence in aquatic environments of england, UK. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2025.144804
38. Payne, M., Kleywegt, S., & Ng, C.-F. (2024). Industrial sources of per- and polyfluoroalkyl substances (PFAS) to a sewershed in ontario, canada. *Environmental Science and Pollution Research International*. https://doi.org/10.1007/s11356-024-32206-3
39. Pettersson, M., Jogsten, I. E., & Yeung, L. (2024). Ways to improve understanding of PFAS contamination - a case study within a waste management facility. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2024.124352
40. Qie, M., Jia, X., Li, X., Li, Y., Wu, X., Shi, Y., & Cai, Y. (2024). Spatial distribution, source, and fate of per- and polyfluoroalkyl substances in the surrounding environment of closed and converted fluorochemical factories in fujian, china. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2024.172766
41. Shi, D., Pan, Y., Luo, Y., Dong, F., Zhang, J., Xin, X., Li, Y., Dai, J., & Tang, J. (2025). Partitioning behavior of short-chain legacy and novel perfluorinated substances (PFAS)

between dissolved and particulate phases in a river-estuary-coast continuum. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2025.126133

42. Song, D., Qiao, B., Yao, Y., Zhao, L., Wang, X., Chen, H., Zhu, L., & Sun, H. (2023). Target and nontarget analysis of per- and polyfluoroalkyl substances in surface water, groundwater and sediments of three typical fluorochemical industrial parks in china. *Journal of Hazardous Materials*. https://doi.org/10.1016/j.jhazmat.2023.132411
43. Teymoorian, T., Delon, L., Munoz, G., & Sauvé, S. (2025). Target and suspect screening reveal PFAS exceeding european union guideline in various water sources south of lyon, france. *Environmental Science and Technology Letters*. https://doi.org/10.1021/acs.estlett.4c01126
44. Viticoski, R. L., Wang, D., Feltman, M. A., Mulabagal, V., Rogers, S., Blersch, D. M., & Hayworth, J. (2022). Spatial distribution and mass transport of perfluoroalkyl substances (PFAS) in surface water: A statewide evaluation of PFAS occurrence and fate in alabama. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2022.155524
45. Wang, J., Shen, C., Zhang, J., Lou, G., Shan, S., Zhao, Y., Man, Y., & Li, Y. (2024). Per- and polyfluoroalkyl substances (PFASs) in chinese surface water: Temporal trends and geographical distribution. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2024.170127
46. Wang, Y., Yu, N., Zhu, X., Guo, H., Jiang, J., Wang, X., Shi, W., Wu, J., Yu, H., & Wei, S. (2018). Suspect and nontarget screening of per- and polyfluoroalkyl substances in wastewater from a fluorochemical manufacturing park. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.8b03030
47. Xu, N., Pan, Z., Guo, W., Li, S., Li, D., Dong, Y., & Sun, W. (2024). Impacts of rapidly urbanizing watershed comprehensive management on per- and polyfluoroalkyl substances pollution: Based on PFAS "diversity" assessment. *Water Research*. https://doi.org/10.1016/j.watres.2024.122010
48. Yang, Y., Wei, L., Wang, R., Zhao, G., Yang, S., Cheng, H., Wu, H., & Huang, Q. (2025). High-resolution source apportionment and spatiotemporal drivers of per- and polyfluoroalkyl substances (PFAS) across china's largest river-estuary continuum: Toward sustainable management of emerging contaminants. *Water Research*. https://doi.org/10.1016/j.watres.2025.124015

49. Zarębska, M., Bajkacz, S., & Hordyjewicz-Baran, Z. (2024). Assessment of legacy and emerging PFAS in the oder river: Occurrence, distribution, and sources. *Environmental Research*. https://doi.org/10.1016/j.envres.2024.118608
50. Zeng, J., Liu, K., Liu, X., Tang, Z., Wang, X., Fu, R., Lin, X., Liu, N., & Qiu, J. (2024). Driving factor, source identification, and health risk of PFAS contamination in groundwater based on the self-organizing map. *Water Research*. https://doi.org/10.1016/j.watres.2024.122458
51. Zenobio, J. E., Nzeribe, B. N., Hilyard, M., & DiGuiseppi, B. (2025). Deciphering PFAS in rainwater: Sources, distribution, and environmental impact. *Remediation Journal*. https://doi.org/10.1002/rem.70029
52. Zhang, C., Hopkins, Z. R., McCord, J. P., Strynar, M., & Knappe, D. (2019). Fate of per- and polyfluoroalkyl ether acids in the total oxidizable precursor assay and implications for the analysis of impacted water. *Environmental Science and Technology Letters*. https://doi.org/10.1021/acs.estlett.9b00525
53. Zhang, H., Xu, H., Qin, B., Fu, Y., Yao, Y., Zhao, Y., & Qin, C. (2025). Review on the sources, distribution and treatment of per- and polyfluoroalkyl substances in global groundwater. *Environmental Research*. https://doi.org/10.1016/j.envres.2025.121387
54. Zhang, J., Liu, J., Jin, R., Qiao, Y., Mao, J., & Wang, Z. (2025). Prevalent per- and polyfluoroalkyl substances (PFASs) pollution in freshwater basins in china: A short review. *Toxics*. https://doi.org/10.3390/toxics13020135
55. Zhang, K., Qadeer, A., Chang, S., Tu, X., Shang, H., Khan, M. A., Zhu, Y., Fu, Q., Yu, Y., & Feng, Y. (2025). Short-chain PFASs dominance and their environmental transport dynamics in urban water systems: Insights from multimedia transport analysis and human exposure risk. *Environment International*. https://doi.org/10.1016/j.envint.2025.109602
56. Zhang, Y., Jiang, C., Zhang, L., Cheng, H., & Wang, N. (2024). Occurrence and risk assessment of perfluoroalkyl substances in surface water of hefei city, southeast china. *Water*. https://doi.org/10.3390/w16091245
57. Zhang, Y., Zhou, Y., Dong, R., Song, N., Hong, M., Li, J., Yu, J., & Kong, D. (2023). Emerging and legacy per- and polyfluoroalkyl substances (PFAS) in fluorochemical wastewater along full-scale treatment processes: Source, fate, and ecological risk. *Journal of Hazardous Materials*. https://doi.org/10.1016/j.jhazmat.2023.133270

58. Zhao, C., Guo, Q., & Zhang, R. (2026). Nationwide occurrence, profiles, and health risks of legacy and emerging per- and polyfluoroalkyl substances (PFAS) in tap water across china. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2026.128119
59. Zhou, Y., Chang, Y., Zhang, D., & Li, W. (2025). Per- and polyfluoroalkyl substances in potential drinking water sources globally: Distributions, monitoring trends, and risk assessment. *Water*. https://doi.org/10.3390/w17223280
60. Zhu, Z., Wang, T., Meng, J., Wang, P., Li, Q., & Lu, Y. (2015). Perfluoroalkyl substances in the daling river with concentrated fluorine industries in china: Seasonal variation, mass flow, and risk assessment. *Environmental Science and Pollution Research International*. https://doi.org/10.1007/s11356-015-4189-0