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Emerging Contaminants in Groundwater Resources: From Occurrence and Risk Assessment to Advanced Remediation

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Abstract

Groundwater is a major source of drinking water, irrigation and industrial supply, yet its apparent protection from surface disturbances can be misleading. A diverse group of emerging contaminants (ECs)—including pharmaceuticals and personal-care products, endocrine-disrupting compounds, pesticides, per- and polyfluoroalkyl substances (PFAS), microplastics, antimicrobial-resistance determinants, industrial chemicals and engineered nanomaterials—can enter aquifers through wastewater infiltration, landfill leachate, agricultural recharge, industrial releases, septic systems and managed aquifer recharge. Their occurrence at trace concentrations does not necessarily imply negligible risk because persistence, mobility, mixture effects and chronic exposure can complicate risk assessment. Recent groundwater-focused reviews emphasize PFAS, microplastics, pharmaceuticals and microorganisms as major emerging pollutant classes, while newer work highlights the importance of hydrogeochemistry, source characterization and site-specific transport processes.

This review analyzes the sources, occurrence, transport, transformation, exposure pathways and health implications of emerging contaminants in groundwater and critically evaluates remediation technologies. The review concludes that prevention, source control and risk-based monitoring should precede remediation; where remediation is necessary, treatment selection should be based on contaminant chemistry, aquifer properties, hydrogeological connectivity, exposure pathways and lifecycle impacts. Future systems should combine high-resolution monitoring, reactive transport modelling, artificial intelligence-assisted plume prediction and sustainable treatment trains.

Keywords: Groundwater, emerging contaminants, PFAS, pharmaceuticals, pesticides, microplastics, endocrine disruptors, health risk, remediation, advanced oxidation.

1. Introduction

Groundwater is a critical component of global freshwater security because aquifers provide relatively stable water supplies during seasonal changes and drought. However, the same subsurface environment that protects groundwater from rapid physical disturbance can delay contaminant detection and make remediation difficult. Once a persistent chemical enters an aquifer, transport can occur over long distances through advective flow, dispersion and diffusion, while sorption, transformation and redox reactions determine the concentration and persistence observed at monitoring or abstraction wells. [1]

Emerging contaminants are not necessarily newly invented chemicals. The term generally refers to substances that are newly recognized, insufficiently regulated, or inadequately understood with respect to environmental occurrence and risk. Recent groundwater reviews identify PFAS, micro- and nanoplastics, pharmaceuticals and personal-care products, and microorganisms among important classes. [2]

The challenge is particularly important because groundwater is frequently used for drinking without advanced treatment. Contamination may therefore create direct human exposure through ingestion, while bathing and food production can contribute additional pathways. Recent reviews also emphasize that urban wastewater infiltration, landfills, agricultural practices and industrial activity can introduce multiple contaminant classes simultaneously. PFAS illustrate the difficulty of emerging groundwater pollution. Their strong carbon–fluorine bonds contribute to exceptional persistence, and recent global groundwater reviews compiled hundreds of contaminated sites, identifying firefighting activities, fluorinated industrial activity, landfill leachate and wastewater leakage among important sources. [3]

This review therefore treats groundwater contamination as a coupled hydrogeochemical, toxicological and engineering problem. The objective is not simply to list contaminants or technologies, but to connect source, transport, exposure, risk and intervention. Such an approach is essential for selecting remediation measures that are technically effective and environmentally defensible. [4]

2. Review Scope and Methodology

Literature searches focused on combinations of groundwater, emerging contaminants, PFAS, pharmaceuticals, pesticides, microplastics, endocrine-disrupting chemicals, health risk, hydrogeochemical transport, permeable reactive barriers, adsorption, ion exchange, advanced oxidation, electrochemical treatment, bioremediation and managed aquifer recharge.

Evidence was organized into six analytical layers: contaminant classes; sources and entry pathways; subsurface fate and transport; exposure and health risk; detection and monitoring; and remediation and management. Particular attention was given to studies that compare treatment mechanisms, discuss full-scale feasibility, or identify limitations that may affect real aquifer applications. [5]

3. Major Classes of Emerging Groundwater Contaminants

Contaminant class	Representative compounds/materials	Important sources	Key concern
PFAS	PFOA, PFOS, PFHxS, short-chain PFAS	Firefighting foams, industry, landfills, wastewater	Persistence, mobility, chronic toxicity

Pharmaceuticals	Antibiotics, analgesics, antidepressants	Wastewater, septic systems, animal production	Bioactivity, mixtures, antimicrobial resistance
Personal-care products	UV filters, preservatives, fragrances	Domestic wastewater, land application	Persistence and endocrine activity
Pesticides	Herbicides, insecticides, fungicides	Agriculture, irrigation return flow	Toxicity, mobility, transformation products
Endocrine disruptors	Bisphenols, alkylphenols, steroid hormones	Plastics, wastewater, industry	Hormonal and developmental effects
Microplastics	PE, PP, PS, PET particles	Wastewater, landfill leachate, runoff	Transport, sorption, physical/chemical effects
Nanomaterials	Metal/metal-oxide nanoparticles, engineered carbon	Industry, consumer products, research	Mobility and uncertain chronic effects
AMR-related contaminants	Antibiotic residues, resistance genes, pathogens	Wastewater, hospitals, agriculture	Selection and spread of resistance
Industrial chemicals	Solvents, surfactants, flame retardants	Manufacturing, spills, landfills	Persistence and toxicity

4. Sources and Entry Pathways

Wastewater infiltration and septic systems - Treated and untreated wastewater can introduce pharmaceuticals, hormones, surfactants, PFAS, microorganisms and transformation products to groundwater. Recharge through leaking sewers, septic systems and irrigation with reclaimed water may be particularly important in shallow unconfined aquifers. Managed aquifer recharge can also transport contaminants when source water contains persistent chemicals; a recent systematic review identifies plastics, pesticides, pharmaceuticals, PPCPs and PFAS as contaminants of concern in MAR systems.

Landfills and leachate - Landfill leachate can contain complex mixtures of organic matter, metals, PFAS, microplastics and pharmaceutical residues. Landfill leachate is a major source of PFAS, microplastics and pharmaceuticals/PPCPs, with contaminant levels influenced by landfill characteristics and environmental conditions. [6]

Agricultural recharge - Pesticides, veterinary medicines, nutrients and transformation products can migrate through the vadose zone following rainfall or irrigation. Soil texture, organic carbon, preferential flow, pesticide chemistry and groundwater depth strongly influence transport. Atmospheric deposition and infiltration of urban runoff can transport persistent organic chemicals and particulate contaminants into recharge zones. The importance of these pathways increases where permeable surfaces and shallow aquifers coincide. [1]

Industrial sources - Industrial releases may contain solvents, PFAS, plastic additives, surfactants, dyes and other persistent compounds. Point-source releases can produce concentrated plumes, whereas diffuse industrial activity can create broader low-concentration contamination. [5]

5. Hydro geochemical Fate and Transport

Groundwater contamination is controlled by the interaction of contaminant properties and aquifer characteristics. Advective transport follows groundwater movement, while dispersion spreads solutes across flow paths. Diffusion can be important in low-permeability zones, creating long-term mass transfer back into flowing groundwater.

Sorption - Hydrophobic compounds may sorb to organic carbon, while ionic interactions can dominate for charged molecules. Sorption can retard migration but does not necessarily eliminate risk because desorption may occur when pH, ionic strength or dissolved organic carbon changes.

Redox conditions - Redox potential, dissolved oxygen, nitrate, sulfate, iron and manganese influence microbial and abiotic transformation. Some pharmaceuticals and pesticides degrade rapidly under particular redox conditions but persist under others.

PFAS mobility - PFAS behavior is influenced by chain length, functional group, mineral surfaces, organic matter, air–water interfaces and co-contaminants. Short-chain PFAS are often more mobile than long-chain analogues, complicating plume containment and treatment. Recent reviews emphasize that PFAS plumes can behave differently from conventional hydrocarbon plumes and remain challenging to remediate.

Transformation products - Parent compounds may transform into metabolites or daughter products that are more mobile or toxic than the original chemical. Risk assessment based only on target parent compounds can therefore underestimate total chemical burden.

Microplastics as contaminant carriers - Microplastics can interact with hydrophobic organic chemicals and metals and may transport associated contaminants through porous media. Their behavior depends on size, density, surface aging, biofilm development and aquifer grain interactions. [1, 5, 6, 9, 11]

6. Occurrence and Monitoring

Monitoring emerging contaminants is difficult because concentrations may occur at ng/L–µg/L levels and contaminants can be highly heterogeneous in space and time. Targeted analytical methods are powerful but require predefined analyte lists, while suspect and non-target screening can reveal unexpected compounds. [1, 8]

Analytical approach	Main application	Strength	Limitation
LC-MS/MS	Pharmaceuticals, PFAS, polar organics	High sensitivity/selectivity	Standards and targeted lists required
HRMS	Suspect/non-target screening	Broad chemical coverage	Complex data interpretation
GC-MS	Volatile/semi-volatile organics	Mature spectral libraries	Less suitable for highly polar compounds
ICP-MS/OES	Trace metals	Sensitive elemental analysis	No molecular identity
FTIR/Raman	Microplastics	Particle identification	Lower sensitivity for very small particles
Ion chromatography	Inorganic ions	Robust anion/cation analysis	Limited organic specificity
Passive samplers	Time-integrated monitoring	Useful for temporal variability	Calibration and deployment issues

Groundwater literature reviews identify LC-MS, GC-MS and spectroscopic methods among the principal analytical tools used for emerging contaminants.

7. Human Health Risks

Health-risk assessment should distinguish hazard from actual risk. Hazard describes the intrinsic ability of a contaminant to cause harm, whereas risk depends on concentration, exposure route, duration, population susceptibility and uncertainty. Groundwater contaminants can reach people through drinking water, food irrigation, dermal contact and inhalation of volatile compounds during domestic use. PFAS have attracted substantial concern because of persistence and widespread exposure. Pharmaceuticals are biologically active by design. Chronic low-dose exposure through drinking water remains an area of scientific uncertainty, while ecological effects and antimicrobial-resistance selection are additional concerns. Risk varies considerably by compound and exposure context. Pesticides may affect neurological, endocrine, reproductive and developmental systems depending on the chemical. Their risk is strongly dependent on dose and exposure duration. Recent groundwater-focused literature emphasizes the need to understand transport processes and mitigation in agricultural systems. Endocrine-active compounds can affect hormonal signaling at low concentrations, making conventional dose–response assumptions difficult in some contexts. Mixture exposure and vulnerable life stages are important considerations. Human health evidence for microplastics and engineered nanomaterials is still developing. Groundwater receiving wastewater or agricultural inputs can contain antibiotics, resistant bacteria and resistance genes. Even when antibiotic concentrations are low, mixtures of antimicrobial compounds and biological communities may contribute to selection and dissemination of resistance. [1, 5, 6, 8, 13]

8. Ecological and Aquifer-System Impacts

Groundwater ecosystems contain microbial communities that participate in carbon, nitrogen, sulfur and metal cycling. Emerging contaminants may alter these communities even when concentrations are below conventional drinking-water thresholds. Contaminants can also discharge from aquifers into springs, wetlands, rivers and coastal zones, creating ecological exposure beyond the original groundwater plume. Persistent chemicals may accumulate in sediments or biota, while transformation products can extend the duration of exposure. Microplastics can modify microbial attachment surfaces and influence the transport of associated chemicals. The ecological significance of these processes remains an active research area. [11]

9. Conventional Remediation Strategies

Pump-and-treat extracts contaminated groundwater for ex-situ treatment. It is robust and controllable but can be energy intensive and slow for strongly sorbed contaminants. It may also create a long remediation tail as contaminants diffuse from low-permeability zones. Activated carbon is widely used for adsorbing hydrophobic organic contaminants and has important applications for PFAS and pharmaceuticals. The key limitation is transfer of contaminants from water to a spent carbon phase; regeneration or disposal must therefore be addressed. Ion-exchange resins can selectively remove charged contaminants. They are particularly relevant to PFAS and certain inorganic species, but resin capacity, competing ions and spent-resin management affect lifecycle performance. Nanofiltration and reverse osmosis can provide high rejection of many dissolved contaminants. However, energy demand and concentrate management can be substantial, making membranes more suitable as part of a treatment train than as a universal groundwater remedy. Air stripping can be effective for volatile contaminants but is not appropriate for nonvolatile persistent compounds. Off-gas treatment may be necessary. [5,10]

10. Advanced and In-Situ Remediation

Hydroxyl radicals, sulfate radicals and other reactive species can transform organic contaminants. UV-based, ozone-based, persulfate-based and photocatalytic processes are potential options. The main concerns are energy consumption, oxidant demand, matrix scavenging and formation of transformation products. Electrochemical technologies can generate reactive species directly at electrodes and can be engineered for contaminant destruction. They are promising for persistent organics but electrode stability, energy demand and by-product control remain important. Bioremediation uses indigenous or introduced microorganisms to transform contaminants. Electron donors, acceptors or nutrients may be supplied to stimulate degradation. It can reduce energy demand compared with intensive pumping but depends strongly on contaminant biodegradability and aquifer conditions. Plants can immobilize, uptake or transform selected contaminants and can be useful for shallow groundwater or contaminated zones near the surface. Long treatment times and seasonal limitations can restrict application. Natural attenuation relies on dilution, dispersion, sorption and biological or abiotic transformation. It is appropriate only when contaminant concentrations and exposure risks can be demonstrated to decline without unacceptable plume migration. [10]

11. PFAS-Specific Remediation

PFAS are unusually challenging because many members of the class resist conventional biodegradation and oxidation. A practical distinction is therefore needed between separation and destruction. Adsorption, ion exchange and membranes can separate PFAS from water, but the contaminant remains in a concentrated residual. Destructive technologies seek to break carbon–fluorine bonds and mineralize the compounds. Adsorption, membrane filtration, electrochemical treatment, redox approaches, bioremediation and treatment trains are the major PFAS-remediation pathways. [6]

12. Pharmaceutical and Pesticide Remediation

Pharmaceuticals and pesticides generally offer a wider range of transformation pathways than PFAS. Biological treatment can be effective for biodegradable compounds, while adsorption and advanced oxidation provide additional barriers for recalcitrant molecules. For pesticide-contaminated groundwater, prevention remains particularly important because diffuse agricultural contamination is difficult to capture after entry into an aquifer. Buffer zones, precision application, optimized irrigation, reduced chemical loading and improved waste handling can reduce future plume formation. Recent pesticide literature emphasizes process understanding and mitigation alongside remediation. Treatment should also consider transformation products. A process that removes the parent compound but creates a persistent toxic intermediate may not provide genuine risk reduction. [6]

13. Microplastics, Nanomaterials and Complex Mixtures

Microplastics present a different remediation challenge because they are particles rather than conventional dissolved solutes. Physical filtration, membrane separation and sedimentation may remove larger particles, while smaller particles can migrate through porous media. Aging can change particle density, surface chemistry and sorption behavior. Nanomaterials can exhibit colloidal transport and strong interactions with minerals and natural organic matter. Their mobility may change with ionic strength and surface coatings. Standard dissolved-contaminant models may therefore be insufficient. Real aquifers rarely contain a single contaminant. PFAS, pharmaceuticals, metals, hydrocarbons and natural organic matter can coexist and compete for reactive surfaces. Co-contaminants can alter treatment performance, so remediation studies using single-solute laboratory water should be interpreted cautiously. [8]

14. Risk-Based Site Management

A defensible groundwater program should prioritize contamination according to exposure and consequence rather than concentration alone. A conceptual site model should identify sources, hydrostratigraphy, flow directions, receptors, exposure pathways and uncertainty. [7]

15. Sustainable Remediation and Life-Cycle Considerations

Remediation should not simply transfer contaminants from groundwater to another waste stream. A sustainable strategy evaluates energy use, chemical inputs, greenhouse-gas emissions, secondary waste, land requirements, worker safety and long-term maintenance. Sustainable remediation may favor prevention and source control over aggressive plume treatment where exposure risk is low and natural attenuation is reliable. Conversely, where a plume threatens a drinking-water source, rapid containment may be justified even when energy use is higher. [9, 10]

16. Integrated Treatment Trains

No single remediation technology is universally suitable. Treatment trains can combine capture, concentration, destruction and polishing. For example, groundwater may be pumped through activated carbon or ion exchange, followed by a destructive treatment of the concentrated residual. Similarly, a PRB may provide primary plume interception while an ex-situ polishing system protects a sensitive receptor. Hybrid treatment is especially relevant for PFAS because separation technologies are relatively mature while complete destruction is technically more difficult. Recent reviews emphasize treatment-train approaches as a promising pathway.

For pharmaceutical mixtures, biological treatment followed by activated carbon or oxidation can combine low-energy bulk removal with a polishing barrier. For agricultural contaminants, prevention and source reduction should remain the primary strategy, with targeted in-situ treatment for persistent hotspots. [5, 6,10,12]

17. Policy and Regulatory Considerations

Emerging contaminants create a regulatory challenge because scientific evidence and analytical capability often advance faster than legal standards. The absence of a numerical standard does not mean absence of risk; it means risk management must rely on broader evidence and precautionary principles.PFAS demonstrate the importance of regulatory evolution. WHO is continuing scientific evaluation of priority PFAS and health effects, reflecting the need to update guidance as toxicological evidence develops. Regulatory systems should support standardized monitoring, transparent reporting, source-control requirements, polluter-pays mechanisms, risk-based remediation and adaptive standards. For managed aquifer recharge, contaminant screening should be incorporated into source-water acceptance criteria rather than relying only on post-infiltration monitoring. [3,13]

18. Future Directions

Future research should move from isolated laboratory demonstrations toward integrated field pilots. The most valuable studies will report influent and groundwater chemistry, energy use, secondary waste, contaminant mass balance, transformation products, uncertainty and long-term performance.

19. Conclusions

Emerging contaminants in groundwater represent a complex environmental and public-health challenge because contaminants may occur at low concentrations while remaining persistent, mobile and biologically active. PFAS, pharmaceuticals, pesticides, endocrine-disrupting chemicals, microplastics, nanomaterials and antimicrobial-resistance-related contaminants can reach aquifers through wastewater infiltration, agriculture, industrial releases, landfills, septic systems and managed aquifer recharge. Recent literature confirms that groundwater contamination is increasingly recognized as a global concern and that contaminant behavior is strongly controlled by source conditions and hydrogeochemistry. The most defensible management strategy begins with prevention and source control, followed by risk-based monitoring and targeted remediation. Activated carbon, ion exchange, membranes and PRBs are valuable separation or containment tools, whereas advanced oxidation, electrochemical methods and biological processes can provide transformation or destruction for selected compounds. PFAS remain particularly challenging because separation is generally easier than complete destruction. The future of groundwater protection will depend on integration. High-resolution analytical chemistry, hydrogeological modelling, GIS, AI-assisted prediction, sustainable remediation and adaptive regulation should operate as a connected system. Remediation performance should be evaluated not only by concentration reduction but also by contaminant mass, exposure risk, energy demand, secondary waste and long-term aquifer recovery. Such a framework can protect groundwater resources while avoiding unnecessary environmental and economic burdens.

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