# Transport Behavior and Degradation Methods of Antibiotic Contaminants in Aquatic Environments

Mo Yufei

Shijiazhuang University, Shijiazhuang 050035, Hebei, China

**Abstract:**Antibiotics continuously enter aquatic environments through domestic sewage, hospital effluent, pharmaceutical wastewater, and runoff from livestock and aquaculture operations, subsequently migrating among the aqueous phase, suspended particulate matter, and sediments. This paper analyzes adsorption–desorption, hydrodynamic transport, photolysis, biodegradation, and related processes and compares biological treatment, adsorption, membrane separation, and advanced oxidation technologies. The findings indicate that pollution-control assessments should distinguish phase transfer, disappearance of the parent compound, and complete mineralization. Source reduction, combined treatment processes, and the integrated assessment of transformation products and antimicrobial-resistance risks should be strengthened.

**Keywords:** antibiotic contamination; aquatic environment; transport and transformation; advanced oxidation; antibiotic resistance genes

## Introduction

Antibiotics are widely used in human medicine, livestock production, and aquaculture. These pharmaceuticals are generally not completely metabolized in the body, and the unchanged compounds and their metabolites can be excreted in urine and feces. Residues that are not completely removed by conventional wastewater treatment subsequently enter rivers, lakes, groundwater, and sediments through treated effluent and sludge.

Unlike isolated episodes of high-concentration contamination, antibiotics frequently occur as mixtures of multiple compounds characterized by low concentrations and continuous inputs. They therefore exhibit typical “pseudo-persistence.”

Research on antibiotic contamination should not focus exclusively on concentrations in water samples. On the one hand, antibiotics may adsorb onto suspended particulate matter, settle, and subsequently be released when flow conditions change. On the other hand, a reduction in the concentration of a parent compound may result from adsorption, membrane retention, or transformation and does not necessarily indicate complete mineralization. Some transformation products retain biological activity, while environmental exposure at low concentrations may exert selective pressure for antimicrobial resistance.

Drawing on five traceable publications, this paper analyzes pollution sources, partitioning among environmental media, transport behavior, influencing factors, and treatment technologies. It subsequently proposes a control pathway based on mass balance and risk reduction.

## 1 Sources and Distribution of Antibiotic Contamination in Aquatic Environments

### 1.1 Pollution Sources and Entry Pathways

Sources of antibiotics in aquatic environments can be divided into point and nonpoint sources. Point sources include municipal wastewater treatment plants, hospital effluent, pharmaceutical manufacturers, and concentrated discharges from livestock farms. Pharmaceuticals used in households and healthcare facilities enter sewer networks after excretion, and wastewater treatment plants differ considerably in their removal of different antibiotic classes. Pharmaceutical wastewater may be characterized by high concentrations, high salinity, and strong inhibition of biological processes.

Nonpoint sources primarily include surface runoff and soil leaching following the application of livestock manure or sewage sludge, as well as the dispersion of antibiotics directly administered in aquaculture.

Different sources exhibit different temporal patterns. Municipal wastewater represents a relatively continuous base-flow input. Hospital and industrial discharges may create localized concentration hotspots, whereas agricultural nonpoint-source pollution is controlled by rainfall, fertilization periods, and irrigation practices. Improper disposal of expired medicines can also increase emissions.

Pollution inventories should therefore integrate antibiotic consumption, excretion fractions, wastewater-collection rates, treatment efficiencies, and runoff coefficients. Source strength should not be inferred solely from antibiotic concentrations measured in river-water samples.

### 1.2 Occurrence Characteristics in Aquatic Environments

Antibiotics generally occur in environmental waters at concentrations ranging from ng/L to μg/L, although higher concentrations may be present near pollution sources. Li et al. conducted a meta-analysis of studies on antibiotics in aquatic environments in China. The analysis included 128 publications, of which 116 investigated surface water and 12 investigated groundwater, and reported the detection of at least 94 antibiotics. For most antibiotics, median concentrations were below 100 ng/L in surface water and below 10 ng/L in groundwater [1]. These findings demonstrate the widespread occurrence of antibiotic contamination while also revealing that existing monitoring has been concentrated more heavily in eastern China and in surface waters.

Spatially, elevated concentrations are more likely near wastewater outfalls, intensive livestock and aquaculture areas, pharmaceutical industrial zones, and water bodies with limited exchange. Temporally, reduced dilution capacity during dry periods often increases the relative influence of point sources. During wet periods, inputs may increase because of agricultural runoff and sediment disturbance.

Antibiotics differ in their seasonal patterns of use, degradation rates, and affinities for different environmental media. A single sampling event therefore cannot represent the annual contaminant load. Monitoring should encompass the aqueous phase, suspended matter, and sediments, while flow-weighted loads should be used to support assessments of pollution trends.

### 1.3 Ecological and Antimicrobial-Resistance Risks

Antibiotics primarily act on microorganisms and can alter microbial communities, carbon and nitrogen cycling, and primary production in water bodies and sediments. Certain antibiotics may also affect algae, aquatic plants, and invertebrates.

However, mixture contamination, pulse exposure, and transformation products may cause single-compound risk quotients to underestimate actual effects.

Antibiotic residues, antibiotic-resistant bacteria, and antibiotic resistance genes are interrelated but nonequivalent risk objects. Exposure below the clinical minimum inhibitory concentration may still affect microbial competition and gene selection. High microbial densities, nutrients, and mobile genetic elements within wastewater-treatment systems may further facilitate the dissemination of resistance.

Assessment systems should therefore measure pharmaceutical concentrations, antimicrobial activity, resistant bacteria, and representative resistance genes simultaneously. Antibiotic removal efficiency should not be used as a substitute for conclusions regarding antimicrobial-resistance risk.

## 2 Transport and Transformation of Antibiotics in Aquatic Environments

### 2.1 Partitioning Among Water, Particulate Matter, and Sediments

After entering a water body, antibiotics are dynamically partitioned among the dissolved phase, colloids, suspended particulate matter, and sediments. Adsorption mechanisms include hydrophobic interactions, electrostatic interactions, hydrogen bonding, π–π interactions, surface complexation, and cation bridging.

Fluoroquinolones and tetracyclines contain multiple ionizable functional groups and generally bind readily to clay minerals, metal oxides, and organic matter. Some sulfonamides occur in anionic forms under neutral or slightly alkaline conditions and exhibit relatively weak adsorption onto surfaces carrying charges of the same sign. They are therefore more mobile in water.

The pH affects the charge states of both pharmaceutical molecules and particle surfaces. Dissolved organic matter may compete for adsorption sites or increase apparent solubility through complexation. Ions such as $Ca^{2+}$ and $Mg^{2+}$ can promote the adsorption of certain pharmaceuticals through cation bridging. Sediments can therefore function both as contaminant sinks and as secondary sources when pH, salinity, redox conditions, or hydrodynamic conditions change.

### 2.2 Hydrodynamic Transport and Natural Transformation

Dissolved antibiotics are transported primarily through advection and dispersion, whereas particle-bound antibiotics move with the transport, settling, and resuspension of suspended matter. In rivers, flow velocity, discharge, and residence time determine the opportunities for dilution and transformation. Exchange is slower in lakes and reservoirs, making sediment accumulation more pronounced. Groundwater lacks intense light, flows slowly, and maintains relatively stable temperatures; consequently, some persistent antibiotics may travel considerable distances.

A decline in antibiotic concentrations downstream from a wastewater outfall may simultaneously result from dilution, adsorption, and degradation. In the absence of conservative tracers and flow data, such concentration changes cannot be used directly to calculate degradation rates.

Natural transformation processes include hydrolysis,

direct or indirect photolysis, biodegradation, and redox reactions. β-Lactam rings are relatively susceptible to hydrolysis, while some tetracyclines can undergo epimerization. Reactive oxygen species generated by photosensitizers may promote photodegradation.

Turbidity and water depth reduce light penetration. Organic matter may act as a photosensitizer, but it may also screen light or scavenge free radicals. Microbial degradation is influenced by temperature, dissolved oxygen, substrate concentration, and community acclimation. For many antibiotics, cometabolism may be more important than utilization of the antibiotic as the sole carbon source. Kümmerer emphasized that antibiotics differ substantially in environmental fate and biodegradability and that the behavior of a single antibiotic class cannot represent all pharmaceuticals [2].

## 3 Principal Factors Affecting Transport and Degradation

### 3.1 Molecular Structure and Physicochemical Properties

Molecular weight, solubility, vapor pressure, the acid dissociation constant ((pK_a)), the octanol–water partition coefficient, and functional groups jointly determine environmental behavior. Most antibiotics have low vapor pressures, and volatilization is therefore generally not a major removal pathway. Their ionization states, however, substantially affect water solubility, adsorption, and membrane retention.

For zwitterionic compounds, the use of (\log K_{ow}) for the neutral compound alone may produce misleading estimates of mobility. The proportions of different ionic species should instead be calculated according to the environmental pH.

Chemical structure also determines reactive sites. Compounds containing aromatic rings, double bonds, amino groups, or thioether groups exhibit different reactivities toward ozone, hydroxyl radicals, and reactive chlorine species. Destruction of the parent molecular structure does not necessarily mean that organic carbon has been completely converted to $CO_2$. Intermediate products generated through dealkylation, hydroxylation, ring opening, and related reactions may temporarily accumulate.

In addition to measuring parent-compound removal, degradation studies should monitor total organic carbon, inorganic ions, major transformation products, and residual antimicrobial activity.

### 3.2 Aquatic Matrices and Environmental Conditions

The pH is an important variable governing antibiotic speciation, adsorption, and oxidation reactions. When the pH differs from the isoelectric point of a material, the surface charge of the adsorbent changes. In advanced oxidation processes, pH also affects catalyst activity, ozone decomposition, and iron cycling.

Natural organic matter may compete for adsorption sites and consume free radicals, although it may also generate excited-state species and reactive oxygen species during photochemical processes. Bicarbonate, chloride, phosphate, and high salinity may all alter reaction pathways.

Increasing temperature generally accelerates reactions and diffusion but may reduce the solubility of certain gaseous oxidants. Dissolved oxygen and oxidation–reduction potential determine aerobic, anoxic, or anaerobic degradation pathways. Suspended particles and turbidity influence both light penetration and contaminant bioavailability.

High degradation efficiencies obtained in laboratory-grade ultrapure water cannot necessarily be extrapolated directly to actual wastewater. Performance must be verified using real matrices, environmentally relevant concentrations, and continuous operating conditions.

### 3.3 Hydrological Processes and Human Activities

Rainfall can dilute continuous point-source concentrations in rivers, but it can also wash residues from manure-amended land, livestock-production areas, and soils into water bodies. Combined sewer overflows during heavy rainfall may bypass treatment facilities. During dry periods, the self-purification capacity of a water body decreases, while wastewater-treatment-plant effluent constitutes a larger proportion of river discharge.

Dam and sluice operations alter residence times and sedimentation processes. Sediment dredging and flood disturbance may remobilize particle-bound antibiotics into the aqueous phase.

Regional differences are jointly shaped by patterns of antibiotic use, wastewater-collection rates, treatment technologies, and discharge management. Improving end-of-pipe treatment without controlling source strength from healthcare facilities, livestock production, and pharmaceutical manufacturing will expose treatment facilities to persistently high contaminant loads.

Studies should combine multitemporal monitoring, watershed-scale mass balances, conservative tracers, or hydrodynamic models to distinguish changes in source strength, dilution, and actual degradation.

## 4 Degradation and Removal Methods for Antibiotic Contamination

### 4.1 Biological Treatment, Adsorption, and Membrane Separation

Activated sludge, biofilms, and constructed wetlands remove antibiotics through microbial degradation, cometabolism, and adsorption onto sludge. Their advantages include operational maturity and suitability for treating large volumes of water. Their disadvantages include unstable performance for persistent compounds or compounds with strong antimicrobial activity.

Extending the sludge retention time, maintaining appropriate dissolved-oxygen conditions, and cultivating functional microbial communities may improve the removal of certain pharmaceuticals. However, adsorption onto sludge is merely a phase-transfer process, and the residual sludge must still be disposed of safely.

Apparent negative removal may result from the reconversion of conjugated metabolites into their parent compounds during treatment, asynchronous influent and effluent sampling, or analytical variability.

Adsorption uses materials such as activated carbon, biochar, clay, and resins to concentrate antibiotics. It offers flexible operation and stable effluent quality. Performance is affected by specific surface area, pore size, surface functional groups, pH, and coexisting organic matter. Saturated adsorbents must be regenerated or disposed of; otherwise, the contaminants may subsequently desorb.

In membrane separation, microfiltration and ultrafiltration primarily remove antibiotics indirectly through their association with particulate matter or retention by membrane-fouling layers. Nanofiltration and reverse osmosis can increase rejection through size exclusion, electrostatic repulsion, and hydrophobic interactions. However, these processes generate concentrated reject streams and are associated with energy consumption and membrane fouling.

Watkinson et al. monitored 28 human and veterinary antibiotics in Brisbane, Australia. The median influent concentrations of cephalexin and ciprofloxacin were 4.6 and 3.8 μg/L, respectively. Conventional activated-sludge treatment followed by microfiltration–reverse osmosis reduced antibiotics in the aqueous phase by an average of 92% [3]. These data demonstrate the effectiveness of combined treatment. However, the decrease in aqueous-phase concentrations included degradation, sludge adsorption, and membrane retention and cannot be interpreted as 92% complete mineralization.

### 4.2 Advanced Oxidation and Combined Treatment Processes

Ozonation, UV/$H_2O_2$, Fenton and photo-Fenton processes, semiconductor photocatalysis, electrochemical oxidation, and activated persulfate processes generate hydroxyl radicals, sulfate radicals, or other reactive species that attack the aromatic and heterocyclic structures of antibiotic molecules.

Advanced oxidation processes have rapid reaction rates and are suitable for advanced treatment and high-risk point sources. However, their large-scale application is constrained by energy consumption, chemical consumption, catalyst recovery, matrix-induced quenching, and the toxicity of transformation products. Low-dose UV irradiation used alone primarily serves as a disinfection process and has limited direct photolytic capacity for some antibiotics.

Under conditions representative of drinking-water treatment, Adams et al. examined seven antibiotics and found that powdered activated carbon, reverse osmosis, chlorine oxidation, and ozonation were effective, whereas coagulation–flocculation–sedimentation, softening, disinfection-level UV irradiation, and ion exchange were relatively ineffective [4].

After comparing multiple treatment technologies for aqueous matrices, Homem and Santos reported that ozonation, Fenton and photo-Fenton processes, and semiconductor photocatalysis were among the most extensively investigated methods. Combined processes were more likely to balance removal performance and operational requirements [5].

Table 1. Representative evidence and interpretive boundaries of treatment methods

| Evidence | Study object and conditions | Principal findings |
|---|---|---|
| Meta-analysis of aquatic environments in China [1] | 128 publications covering surface water and groundwater | At least 94 antibiotics were detected; median concentrations of most antibiotics were below 100 ng/L in surface water and below 10 ng/L in groundwater |

| Evidence | Study object and conditions | Principal findings |
|---|---|---|
| Field study of wastewater treatment plants [3] | Twenty-eight antibiotics; activated sludge and microfiltration–reverse osmosis | Median influent concentrations of cephalexin and ciprofloxacin were 4.6 and 3.8 μg/L, respectively; average aqueous-phase removal was 92% |
| Drinking-water treatment experiments [4] | Seven antibiotics in laboratory-spiked water samples | Powdered activated carbon, reverse osmosis, chlorine, and ozone were effective; conventional coagulation–sedimentation and disinfection-level UV were relatively ineffective |
| Review of degradation technologies [5] | Biological treatment, adsorption, membrane processes, and advanced oxidation | Ozonation, Fenton and photo-Fenton processes, and photocatalysis have been extensively studied, while combined treatment shows greater potential |

In engineering applications, processes should be combined according to water quality and intended use. Municipal wastewater can undergo enhanced biological treatment to reduce the principal organic load, followed by ozonation or activated-carbon treatment as an advanced polishing step. High-concentration wastewater from pharmaceutical manufacturers and hospitals should be separately collected and preoxidized before entering a combined wastewater system. Nanofiltration or reverse osmosis may be applied to high-quality reclaimed water, but the resulting concentrate must be treated simultaneously.

Process evaluations should report pharmaceutical mass removal, total organic carbon, antimicrobial activity, transformation products, antibiotic resistance genes, energy consumption, and life-cycle environmental burdens.

## 5 Life-Cycle Control and Research Prospects

Antibiotic-pollution management should progress from isolated end-of-pipe removal to life-cycle control encompassing the source, process, treatment endpoint, and receiving environment.

At the source, rational antibiotic use, prescription management, reduced antibiotic consumption in livestock production, and the collection of expired medicines should be promoted. High-risk wastewater from pharmaceutical manufacturing, hospitals, and large-scale livestock operations should be managed separately.

During the process stage, emission inventories should be established using online water-quality parameters and periodic targeted analyses. Priority monitoring locations should include the influent and effluent of wastewater treatment plants, sludge, receiving waters, and sediments. End-of-pipe technologies should be selected according to the contaminant profile, rather than by pursuing the highest laboratory removal efficiency achieved by a single technology.

Four research priorities should be addressed. First, nontarget screening and mass-balance methods covering parent compounds, metabolites, and transformation products should be established to determine where contaminants go after the parent compound disappears. Second, long-term continuous experiments should be conducted at environmentally relevant concentrations and in real water matrices to identify matrix effects and catalyst deactivation. Third, pharmaceuticals, resistant bacteria, and resistance genes should be incorporated into an integrated risk-assessment framework, and selection and horizontal gene transfer during treatment should be investigated. Fourth, hydrological models, passive sampling, and source-apportionment techniques should be combined to quantify the relative contributions of point sources, nonpoint sources, and sediment rerelease.

Treatment selection should be based on three criteria: effectiveness, cost, and risk. For low-concentration pollution in large volumes of water, source reduction and combined biological–adsorption treatment should be prioritized. High-concentration, persistent wastewater may require pretreatment and advanced oxidation. Where reclaimed-water safety requirements are high, membrane barriers may be used together with appropriate concentrate management.

The ultimate control objective should extend beyond reducing parent-compound concentrations to achieving simultaneous reductions in antimicrobial activity, ecological toxicity, and the potential for antimicrobial-

resistance transmission.

## Conclusion

Antibiotics continuously enter aquatic environments through wastewater discharge, runoff, and leaching and subsequently migrate among the aqueous phase, particulate matter, sediments, and biota. Their environmental fate is jointly controlled by molecular ionization, adsorption affinity, water quality, hydrodynamics, and microbial processes. Sediments can function as both contaminant sinks and sources of secondary release.

Conventional biological treatment, adsorption, and membrane technologies each have defined operational boundaries. Advanced oxidation can destroy molecular structures but must be evaluated in relation to energy requirements and the risks posed by transformation products.

Future management should be founded on watershed-scale mass balances and should integrate source reduction with multistage combined treatment. An integrated assessment of parent compounds, transformation products, toxicity, and antimicrobial resistance is required to shift antibiotic management from concentration control toward the control of actual environmental risks.

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