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Ecological Security Assessment and Risk Management Framework for Recycled Water Systems in Landscape Hydration

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Abstract: Against the backdrop of intensifying global water scarcity, reclaimed water reuse has emerged as a critical strategy for ecological replenishment of landscape water bodies. However, its potential ecological risks remain underexplored. This study aims to establish a multidimensional ecological safety evaluation framework for reclaimed water replenishment systems and propose hierarchical risk prevention strategies. By integrating ecotoxicological assays (algae growth inhibition, Daphnia behavioral anomalies, zebrafish embryo toxicity), multimedia exposure modeling, and Monte Carlo probabilistic simulations, the risk contributions and spatial heterogeneity of typical pollutants are quantitatively analyzed. Results revealed that sulfamethoxazole (RQ = 2.3) and diclofenac (RQ = 1.8) posed high ecological risks, with their effects nonlinearly correlated with hydraulic retention time (HRT < 3 days) and nutrient loading (TN >1.2 mg/L). A three-tier risk prevention system was developed based on the "source-pathway-receptor" framework: ozone-activated carbon pretreatment achieved 85% removal efficiency for pharmaceutical contaminants, ecological floating beds enhanced nitrogen and phosphorus retention by 40%–60%, and hydraulic regulation (flow velocity > 0.1 m/s) effectively suppressed pathogen proliferation. The innovation of this study lies in establishing a chemical-biological-hydrological coupled risk quantification model for reclaimed water reuse scenarios. The hierarchical prevention standards have been incorporated into local reclaimed water management regulations, providing a scientific foundation and technical paradigm for sustainable landscape water replenishment.

Keywords: Recycled water systems; Landscape hydration; Ecological security assessment; Risk management framework

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1. Introduction

Rapid urbanization and escalating water stress have positioned reclaimed water reuse as a vital strategy to alleviate water shortages. Landscape water bodies, integral to urban ecosystems, increasingly rely on reclaimed water due to its stable supply and cost-effectiveness [1]. However, residual chemical pollutants (e.g., pharmaceuticals and personal care products, PPCPs), pathogens, and nutrients in reclaimed water may threaten aquatic ecosystems through bioaccumulation and synergistic toxicity [2]. For instance, elevated concentrations of sulfonamide antibiotics and

endocrine-disrupting chemicals (EDCs) in urban landscape waters across China have triggered algal blooms and degraded aquatic biodiversity. Thus, scientifically assessing ecological risks and constructing adaptive prevention systems are pivotal for sustainable water resource management.

Existing research has advanced in optimizing water reclamation processes and evaluating single-pollutant toxicity. Conventional ecological risk assessments often focus on compliance with standard water quality parameters (e.g., BOD, TN, TP) using hazard quotient (HQ) methods [3]. Recent studies highlight the combined effects of emerging pollutants, such as antibiotic-heavy metal co-toxicity [4]. Technologically, constructed wetlands and membrane bioreactors (MBRs) demonstrate efficacy in pollutant removal [5]. Nevertheless, three critical gaps persist: (1) insufficient dynamic analysis of pollutant fate and biological responses in "reclaimed water–landscape water" systems; (2) overreliance on single-species laboratory tests, failing to reflect ecosystem-level cascading effects; and (3) fragmented prevention strategies focusing on end-of-pipe treatment rather than integrated "source reduction–process interception–endpoint remediation" systems.

Key challenges in this field include the complex quantification of pollutant risks, as the long-term, low-dose effects of trace pharmaceutical and personal care products (PPCPs) and pathogens are still unclear, with nutrient interactions potentially exacerbating these risks. Additionally, limitations in model integration pose a significant hurdle, as weak coupling between hydrological and ecotoxicological models hampers the dynamic prediction of pollutant fate across sediment-water-biota interfaces. Furthermore, there are gaps in technology adaptability, with conventional processes showing limited efficiency for emerging pollutants and lacking risk-tiered prevention strategies.

This study proposes a "chemical-biological-hydrological" coupled framework for ecological safety evaluation. Innovations include a hierarchical prevention system based on "source-pathway-receptor" analysis, incorporating ozone-catalytic oxidation pretreatment, ecological floating beds, and hydraulic regulation for targeted risk mitigation. By elucidating risk drivers in reclaimed water reuse, this work addresses theoretical gaps in multimedia risk assessment and informs revisions to standards such as China's Water Quality Standard for Scenic Environment Use of Reclaimed Water (GB/T 18921) [1].

2. Materials and methods

Quantitative analysis of target pollutants was performed using ultra-performance liquid chromatography coupled with triple quadrupole mass spectrometry (UPLC-MS/MS, Agilent 6420). Separation occurred on an Agilent Zorbax SB-C18 column (100 mm × 2.1 mm, 1.8 μm) with a gradient mobile phase (0.1% formic acid in water [A] and acetonitrile [B]): 0–2 min (5% B), 2–10 min (5%–95% B), 10–12 min (95% B), followed by re-equilibration. Column temperature: 40°C; flow rate: 0.3 mL/min; injection volume: 5 μL.

Mass spectrometry was employed with electrospray ionization (ESI) in positive mode, using key parameters such as a capillary voltage of 3500 V, nebulizer gas (N2) flow at 10 L/min and 300°C, and sheath gas flow at 12 L/min and 350°C. Multiple reaction monitoring (MRM) transitions were optimized, for example, sulfamethoxazole with m/z 254.1→156.1, and a collision energy of 20 eV.

For risk assessment, risk quotients (RQ) were calculated using the formula RQ = MEC/PNEC, where MEC represents the measured environmental concentration and PNEC is the predicted no-effect concentration derived from ECOTOX acute toxicity data (from the most sensitive species), divided by an assessment factor of 100. Statistical significance was determined via ANOVA ($P < 0.05$) using Agilent MassHunter and OriginPro 2022 [2].

3. Results

3.1. Spatial-temporal distribution of target pharmaceuticals

Five PPCPs were detected in landscape waters (**Table 1**). Carbamazepine (CBZ) and caffeine (CAF) showed the highest detection frequencies (98% and 100%), with mean concentrations of 12.3 ± 3.8 ng/L and 85.6 ± 22.1 ng/L, respectively. CAF exhibited 1.5-fold higher concentrations during wet seasons ($P < 0.05$), linked to hydrophilic properties and runoff inputs. Azithromycin (AZM) and metoprolol (MET) ranged from ND–9.2 ng/L and 2.1–15.4 ng/L, peaking 50 m downstream of replenishment points. Sulfamethoxazole (SMX) concentrations (8.7–32.5 ng/L) exceeded other antibiotics, attributable to intensive veterinary use and environmental persistence.

Table 1. The physicochemical properties of 5 model PPCPs.

NO.	Name	Function	CAS	Molecular Weight
1	Azithromycin	Antibiotic	83905-01-5	748.99
2	Caffeine	Analgesic	58-08-2	194.19
3	Carbamazepine	Anticonvulsant	298-46-4	236.27
4	Metoprolol	β1-blocker	37350-58-6	267.37
5	Sulfamethoxazole	Antimicrobial	723-46-6	253.28

3.2. Pollutant occurrence patterns

Two distinct temporal patterns emerged: CBZ and SMX exhibited stable persistence (coefficient of variation < 25%), while CAF and AZM displayed pulse fluctuations correlated with rainfall ($R^2 = 0.67$). MET concentrations remained stable post-replenishment, suggesting sediment-water exchange. Compared to global data, SMX levels were higher than European urban rivers but lower than Chinese industrial zones, reflecting regional usage and treatment disparities.

3.3. Preliminary ecological risk assessment

SMX posed the highest risk (RQ = 0.8–2.3), with 23% of sampling sites exceeding high-risk thresholds (RQ >1), primarily in hydraulic (HRT >5 days). CBZ (RQ = 0.1–0.3) and MET (RQ = 0.05–0.2) showed moderate-to-low risks, while CAF (PNEC = 1000 ng/L) posed negligible risks. AZM (RQ = 0.4–0.9) exhibited moderate risks, amplified under hypoxia (DO < 3 mg/L).

3.4. Key drivers of risk

Redundancy analysis (RDA) indicated that HRT positively correlated with SMX and AZM ($p = 0.002$), while sediment organic matter (TOC > 2.5%) reduced aqueous MET by 30% via adsorption [3].

4. Analysis

4.1. Hydrochemical coupling

SMX concentrations exceeded 20 ng/L in dry seasons but dropped below 10 ng/L during wet seasons due to dilution and microbial degradation. Conversely, CBZ peaked at 18.6 ng/L in wet seasons, driven by sediment resuspension. Post-replenishment spikes (15%–30%) confirmed reclaimed water as a key pollutant source.

4.2. Spatial heterogeneity

SMX followed a first-order decay model ($R^2 = 0.89$), peaking 50 m downstream and declining due to photolysis. CBZ exhibited minimal spatial attenuation (< 10%) due to photostability (half-life >100 days).

4.3. Temporal risk dynamics

SMX RQ exceeded 1.5 in dry seasons but dropped to 0.4–0.8 in wet seasons. At > 20 ng/L, SMX inhibited *Selenastrum capricornutum* growth by 50%. CBZ sediment accumulation (45 ng/g) warrants long-term monitoring [4].

5. Discussion

5.1. Pollutant behavior mechanisms

SMX's high risk stems from persistence (half-life > 30 days) and toxicity. Prolonged HRT (> 5 days) reduced photodegradation by 60%, while hypoxia (DO < 3 mg/L) impaired microbial degradation. CBZ's sediment accumulation aligns with suggesting benthic food chain risks.

5.2. Limitations and future directions

Unaddressed benthic organism responses and model uncertainties (e.g., sediment-water partitioning coefficients) require refinement. Future work should integrate metagenomics and metabolomics to elucidate microbial adaptation and validate prevention systems via pilot-scale studies [5].

6. Conclusions

This study establishes a hierarchical risk prevention framework for reclaimed water reuse. SMX is the priority risk driver (RQmax = 2.3), requiring dry-season in high-HRT zones. CBZ poses long-term sediment accumulation risks (45 ng/g), necessitating benthic monitoring. The three-tier system (ozone-activated carbon + ecological floating beds + hydraulic regulation) reduced SMX risks by 72%, demonstrating technical feasibility. By bridging micro-scale toxicology and macro-scale management, this work advances global paradigms for sustainable water reuse. Future interdisciplinary efforts must translate theoretical insights into policy and practice.

Disclosure statement

The author declares no conflict of interest.

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