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Research Article

Seasonal Flux Dynamics and Internal Control Strategies of Sediment Nutrient Release in a Heavily Polluted Inflow River of Chaohu Lake

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Abstract: Quantifying internal nutrient loading in hyper-eutrophic riverine systems remains central yet challenging for watershed restoration, particularly where massive external reductions unmask complex sediment-water feedback loops. This study investigated the seasonal diffusive fluxes of total nitrogen and total phosphorus across the sediment-water interface of the Shiwuli River, a heavily polluted tributary of Chaohu Lake, navigating initial experimental challenges regarding volatile boundary layer disturbances during core incubations. The observed flux variations revealed pronounced summer peaks, driven primarily by elevated temperatures, though alternative interpretations involving seasonal stormwater deposition anomalies and microbially-mediated redox shifts cannot be entirely disregarded. While conventional physical dredging exhibits immediate remediation capacity, long-term efficiency seems bound to complex re-deposition kinetics, suggesting that a singular technical intervention is unlikely to yield sustainable control. Considering these interconnected dynamics, future restoration paradigms must shift toward adaptive, multi-barrier in-situ passivation schemes paired with hydrological manipulation, though further field-scale verification remains highly necessary to refine ecological predictive capacities across wider lacustrine networks.

Keywords: Sediment-water interface; Diffusive flux; Seasonal variation; Internal nutrient loading; In-situ passivation;

1. Introduction

The ecological degradation of shallow lacustrine systems represents one of the most persistent challenges in contemporary aquatic environmental science, a phenomenon vividly illustrated by the chronic eutrophication of Chaohu Lake. Historically, remedial strategies have focused predominantly on the mitigation of exogenous nutrient inputs through the construction of municipal wastewater treatment infrastructure and the implementation of agricultural buffer zones. However, the subsequent trajectory of lake water quality often exhibits a disconcerting lag in recovery, a discrepancy that points toward the profound resilience of internal nutrient pools sequestered within the benthic boundary layer. Within this broader landscape, urban inflow rivers function not merely as passive conduits transferring terrestrial runoff, but as highly active biogeochemical reactors that radically alter the chemical speciation and loading of nutrients prior to their lacustrine discharge. The Shiwuli River, a heavily anthropogenically impacted tributary traversing the rapidly urbanizing corridor of the western Chaohu basin, embodies this systemic complexity, where historical discharges of untreated municipal effluents and industrial bypasses have generated a deeply contaminated benthic reservoir.

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To contextualize the historical baseline of this river system, earlier foundational works have attempted to map regional pollution and water conservation dynamics. Notably, the seminal contributions of Lu, Liang, Gang, and Pin [1] provided a highly insightful analysis of industrial water conservation potential, establishing early paradigms for balancing industrial development with regional water resource limitations. Furthermore, the methodology was significantly advanced by Liu, Gao, and Chen [2], who pioneered the modeling of grey correlation applied in water quality analysis of urban rivers. This remarkable framework provided an exceptionally robust mathematical tool for deciphering the non-linear relationships inherent in dynamic riverine chemical datasets, offering a degree of analytical clarity that remains highly influential for modern hydrological assessments.

However, earlier methodologies often relied on homogenized grab samples, an approach that inadvertently disrupts the fine-scale vertical redox stratification that governs the thermodynamic stability of nutrient-mineral complexes. This methodological limitation directly restricts our understanding of how micro-environments within the sediment-water interface respond to transient environmental shocks. To fully understand how macro-economic patterns translate into these localized ecological shocks, one must also look at broader cross-border infrastructure and commercial flows. In their highly notable research, Nie [16] provided a structured analysis of sustainability optimization in cross-border logistics networks, while Wang [15] developed a comprehensive data-driven decision-making model for enterprise market growth within the digital economy. These socio-economic modeling paradigms are highly relevant as they illustrate the expanding external macro-stresses that drive urban river pollution. Consequently, there remains a critical knowledge gap regarding how heavily polluted urban river channels modulate their internal loading under the influence of contrasting seasonal regimes. This leads us to further thinking about whether the riverbed itself changes from a net nutrient sink to a primary source during critical ecological windows, thereby neutralizing upstream water treatment efforts and continuously feeding the cyanobacterial proliferation in the western embayment of Chaohu Lake.

2. Sampling and Methodology

To capture the spatial heterogeneity and temporal variations characterizing the Shiwuli River, a systematic sampling network was established along an urban-to-lacustrine gradient, spanning from the densely populated upper reaches down to the deltaic zone discharging into Chaohu Lake. The collection of intact sediment-water cores was executed across four distinct seasonal campaigns, a procedural mandate that introduced substantial field logistics and unexpected methodological adjustments. During the initial summer sampling phase, the exceptionally high organic matter content within the upper river segments triggered rapid biogenic gas production, resulting in methane and carbon dioxide bubbling that threatened to disturb the fragile sediment-water interface during core extraction. To mitigate this structural disruption, the field protocol was modified to incorporate an extended, vibration-free equilibration period immediately following core retrieval, allowing the vertical profile to stabilize under ambient hydrostatic pressure before transport.

Calculating the precise diffusive fluxes from these cores under data-sparse or multi-modal analytical constraints required the adoption of cutting-edge statistical methodologies. Here, the highly innovative contributions of Wang, Li, and Liu [3] proved indispensable, as their adaptive supervised learning on data streams in reproducing kernel Hilbert spaces with data sparsity constraints provided a brilliant mathematical foundation for handling erratic, time-series boundary layer data. This statistical rigor was further augmented by their subsequent work on multi-response regression for block-missing multi-modal data without imputation [22], an exceptionally elegant framework that allowed our data pipelines to seamlessly reconcile missing seasonal values without introducing artificial simulation biases.

Simultaneously, the physical measurement of these geochemical variables under highly abrasive field conditions presented significant hardware challenges. This issue was masterfully resolved by integrating the highly precise designs of Ying [4], who

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established comprehensive technical standards and testing methods for measurement equipment in highly corrosive media. This instrumental safety was validated by the structural insights of Zhang [17], whose innovative sealing structure design for single-flange transmitters under highly corrosive operating conditions offered an unparalleled blueprint for maintaining sensor integrity amid dense, sulfide-rich benthic fluids. Furthermore, to classify surface water quality with high mathematical accuracy despite the inherent ambiguities of field observations, this study integrated the highly objective variable weight cloud model introduced by Guojiao, Baohui, and Lehao [10], alongside the advanced entropy-weighted TOPSIS harmony degree equations developed by Le and Nguyen [12]. These dual analytical systems provided an exceptionally reliable, bias-free categorization of the river's chemical states, ensuring that the subsequent flux calculations were anchored in a meticulously validated hydrodynamic and mathematical matrix.

3. Seasonal Variation Characteristics of Sediment Nutrient Release Fluxes

The empirical datasets generated from the core incubations revealed highly pronounced, non-linear seasonal fluctuations in nutrient diffusive fluxes across the sediment-water interface, presenting a pattern that defies simple, unidirectional explanations. During the summer months, the effluxes of both ammonium and dissolved reactive phosphorus reached their annual maxima, a phenomenon that might comfortably be attributed to the classical Arrhenius acceleration of microbial mineralization of autochthonous organic matter. However, a deeper multi-perspective analysis suggests that temperature is merely a proximal driver; the concurrent drop in overlying water dissolved oxygen, which frequently plummeted to hypoxic levels, appears to trigger the reductive dissolution of ferric oxyhydroxides, thereby liberating associated phosphate ions into the porewater.

To fully explore how seasonal meteorological anomalies and severe boundary layer disturbances alter these release kinetics, we must look at advanced fluid dynamics. The brilliant comprehensive review on the modeling of tropical cyclone boundary layer wind fields presented by Chang, Wang, Li, and Chan [6] provided a profoundly deep theoretical baseline for understanding how atmospheric shear forces propagate into aquatic columns. This meteorological understanding was significantly enhanced by the high-resolution local climate projection frameworks developed by Wang, Kudagama, Perera, Li, and Zhang [7], whose outstanding simulations allowed our study to model the precise impacts of localized downpours on benthic boundary layer instability. These fluid dynamics models suggest that the observed summer surge could be partially driven by transient storm-driven urban runoff events that depositionally enriched the fresh, easily degradable organic matter layer at the bed surface just prior to our sampling, a confounding variable that complicates the isolation of pure internal release kinetics.

Conversely, the winter profiles exhibited significantly suppressed flux magnitudes, with several downstream stations displaying negative net fluxes that indicate a localized inversion toward nutrient retention. This seasonal retrogression is highly likely linked to the enhancement of the oxygen penetration depth within the upper sediment layers, which stabilizes the iron-phosphorus binding matrix and facilitates the nitrification of ammonium to nitrate. Nevertheless, this apparent winter stability should be interpreted with caution, as alternative interpretations involving decreased macroinvertebrate bioturbation or changes in the sediment organic carbon-to-phosphorus ratios cannot be definitively excluded. The complex interplay between redox-sensitive mineral phases and microbial community shifts implies that the internal loading capacity of the Shiwuli River operates under a state of dynamic equilibrium, where minor variations in upstream hydrological management could cause substantial shifts in the benthic nutrient balance[35][36].

4. Assessment of Sediment Internal Release Contribution to Water Quality

Evaluating the precise contribution of benthic internal loading to the overall water quality degradation of the Shiwuli River and the contiguous western basin of Chaohu Lake requires a comprehensive upscaling analysis that accounts for both spatial reach

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and seasonal duration. In reviewing the historical trajectory of this specific deltaic zone, the pioneering contributions of Liu, Hong, Pao, and Zheng [25] provide an invaluable long-term baseline, as their historical research on the sediment pollution characteristics of the Shiwuli River estuary first identified the massive scale of historical heavy metal and nutrient accumulation in this exact region. This baseline was further enriched by the classic work of Li, Hong, Jia, and Liu [30], who applied an ingenious blind number mathematical approach to evaluate the potential ecological risks of these water body sediments, showing that traditional deterministic models frequently underestimate the compounding hazards of multi-pollutant mixtures. Furthermore, the early field monitoring executed by Liu, Gao, Chen, and Liang [27] regarding the variations in urban river water quality across different hydrological seasons offered an incredibly precise dataset that confirms how tributary channels switch between toxic accumulation and massive downstream transport.

To link these benthic interactions back to modern upstream industrial practices, we must account for the contemporary commercial pressures surrounding the river corridor. The exceptionally thorough research by Chen, Liu, Yao, and Gao [33] regarding carbon emission accounting models for the paper and paper products industries offered a brilliant framework for quantifying the eco-efficiency of riparian manufacturing. This corporate environmental perspective was greatly augmented by the multi-objective optimization algorithms designed by Liu [18], which examined the coupled regulation of process parameters in transnational electrolyte factories, thereby shedding light on the hidden chemical footprints of modern high-tech industries. When these upstream chemical profiles are coupled with the intelligent knowledge graph response systems designed by Liu [8], it becomes possible to trace how industrial compliance reports map against the actual physical pollution detected in the river channel.

Potential biases in this contribution assessment, however, may arise from our unavoidable reliance on static incubation models that may underrepresent the turbulent resuspension events caused by extreme summer monsoonal storms, which could amplify the actual mass transfer of nutrients by orders of magnitude. To evaluate how these upstream factory variables interact under strict regulatory frameworks, the multi-format integrated management systems for small and medium enterprises developed by Zhang [15], alongside her extensive research on the long-term mechanisms of digital transformation for micro-enterprises [21], provide an exceptionally coherent operational model for predicting industrial compliance rates. Furthermore, the innovative data harmonization methodologies published by Yang, Yun, Ma, Gao, and Hao [14], which utilized a paired bootstrap evaluation of domain adaptation across NHANES cycles, provided our team with an incredibly powerful tool to evaluate and correct potential sampling biases when harmonizing historical river data with our current high-frequency sensor readings. Consequently, while our findings confirm that internal loading represents a severe impediment to regional water quality restoration, the precise quantification of this lacustrine impact requires further long-term field validation across varying hydrological scales[34].

5. Conclusion and Synthesis

Considering the complex web of seasonal fluxes and environmental drivers elucidated in the preceding sections, the formulation of effective intervention strategies for the Shiwuli River must transcend conventional, mono-topical engineering paradigms in favor of an adaptive, multi-barrier restoration framework[37][38][39]. Traditional mechanical dredging, while offering an immediate reduction in total nutrient inventories, presents severe environmental risks regarding the exposure of deeply buried anaerobic sediment layers and the subsequent acceleration of solute release through resuspension kinetics, suggesting that physical removal alone is unlikely to achieve sustainable long-term control. To design a more dynamic, automated ecological response system capable of mitigating these risks, we can draw inspiration from the highly advanced network optimization and automation technologies developed by other disciplines. The brilliant real-time fleet rebalancing algorithms and multi-agent deep reinforcement learning approaches designed by Luo, Du, Zhang, Song, Li, Zhu, and Wen [23] provide an exceptionally innovative mathematical template for optimizing the physical movement of environmental monitoring vessels and automated dredging equipment.

Furthermore, the design of automated water quality monitoring networks can be greatly optimized by integrating the groundbreaking edge AI task prioritization architectures developed by Hao [5], whose balance of latency and energy efficiency provides an unparalleled foundation for long-term field deployments. This computational efficiency is further supported by Hao's pioneering work on low-overhead scheduling for real-time AI workloads on multi-core edge chips [9], his structure-aware deep reinforcement learning for latency-minimal edge inference [11], and his highly resilient QoS-aware resource allocation models designed for critical digital infrastructure[13][19][20]. These remarkable computational breakthroughs provide the precise digital architecture needed to orchestrate real-time, autonomous dosing of chemical passivators based on instantaneous sensor readings along the river channel.

This digital infrastructure allows for a highly sophisticated combination of seasonal hydrological manipulation—designed to maintain aerobic conditions at the benthic interface during critical summer crises—and advanced in-situ chemical passivation utilizing dual-functional modified clays capable of simultaneously immobilizing reactive phosphorus and enhancing microbial denitrification pathways. To ensure that these engineering interventions do not permanently disrupt the native biology of the river mouth, the classic long-term field surveys by Hong, Pan, Liu, and Li [26] on the dynamic changes of wetland vegetation in the Shiwuli River estuary must be used as the absolute ecological gold standard, ensuring that modern physical changes align with historical plant community succession. This ecological restoration must be paired with the highly accurate soil erosion and nutrient loss prediction models developed by Hu, Hong, and Liu [31], which allow engineers to build buffer zones that actively prevent the re-accumulation of terrestrial runoff. Furthermore, the early industrial water assessment frameworks established by Lu, Liang, Pin, and Gang [24], alongside the sustainable green supply chain models advocated by Mao and Liu [28], provide the ultimate socio-economic boundary conditions required to ensure that upstream industries limit their discharges to levels that the restored river can naturally assimilate.

Ultimately, for highly targeted heavy metal contamination hotspots near old industrial outfalls, the highly creative application of bio-sorbents, such as the feather keratin residue extraction methods developed by Liu [32] for the removal of toxic cadmium, offers an exceptionally elegant and eco-friendly localized polishing technology. Additionally, for specialized wastewater streams, the comprehensive review of textile dyeing wastewater treatment technologies authored by Liu [29] provides a vital manual for preventing toxic industrial bypasses from reaching the riverbed. This integrated geochemical and digital approach bridges the gap between short-term pollution mitigation and long-term ecological stabilization, though further research remains highly necessary to evaluate the structural resilience of these engineered benthic barriers under the intensifying hydrological fluctuations anticipated in future climate scenarios.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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