Integrated framework for tracking phosphorus flows across human–terrestrial–aquatic interfaces in watersheds

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Phosphorus (P) is an essential element for sustaining ecosystem functions. However, its overuse has caused widespread eutrophication and biodiversity loss. Since the 1950s, global P consumption has increased more than sevenfold, causing 77% of lakes to experience eutrophication. In China, approximately 70% of the 277 surveyed lakes have reached or exceeded the eutrophication threshold.[1] Globally, external P inputs contribute 59% of total P loads in watershed water bodies, while the remaining 41% originate from internal P release from sediments. Therefore, managing P flows has become an urgent priority. However, due to the inherent complexity and cross-scale variability of P sources, flows, and sinks, the systematic tracking of P flows at the watershed scale remains insufficiently understood. To address this issue, the "Generate–Drive–Accumulate" framework conceptualizes P flows across human–terrestrial–aquatic interfaces (Figure 1), facilitating systematic analysis of their eco-environmental effects and providing the theoretical foundation for sustainable P management in watersheds.

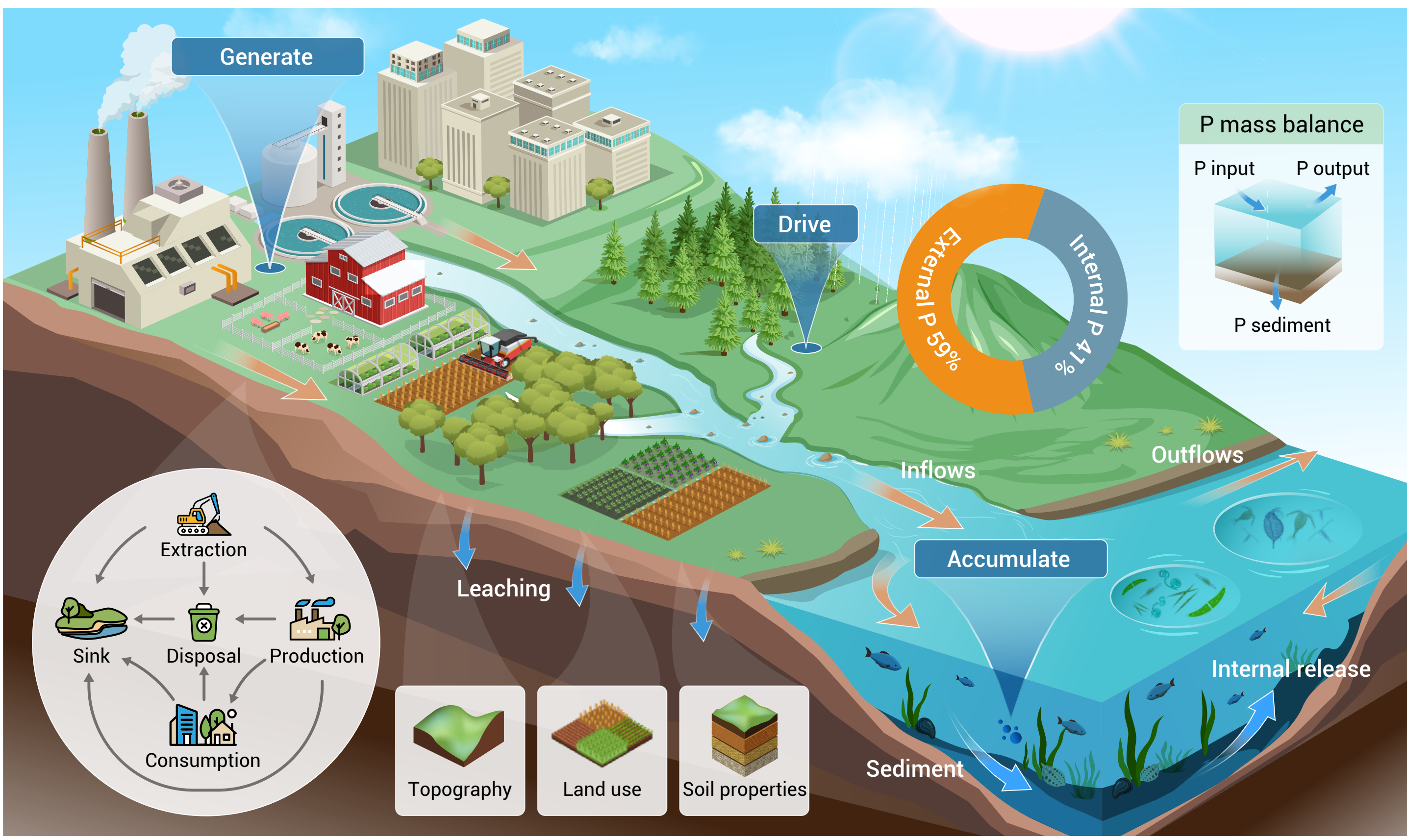

Figure 1. Conceptual diagram of the P flows "Generate–Drive–Accumulate" framework in the watershed.

ANTHROPOGENIC ACTIVITIES GENERATE P FLOWS

Anthropogenic activities play a vital role in watershed P output, particularly through agricultural, residential consumption, and industrial systems. In the Poyang Lake watershed, China, agricultural sources are the predominant contributor, accounting for approximately 85% of the total P load (58% from crop cultivation and 27% from livestock breeding). Residential consumption sources follow at 13%, while industrial sources contribute roughly 2%.[2] In agriculture, fertilizers constitute the main P input, yet limited crop uptake means that much of the applied P accumulates in soil and is subsequently mobilized through leaching and runoff. Over the past decade, the P fertilizer utilization rate in China has remained approximately 24%, substantially contributing to P flows and water quality degradation. Livestock and poultry manure P flows are second only to that of chemical fertilizers. In addition to fertilizers and manure, atmospheric deposition, seeds, and pesticides exert relatively minor impacts on the water environment.

Wastewater treatment plants and detergents mainly represent urbanization related P flows to watersheds. Globally, the annual average of P in food consumption was 0.86 kg P per capita, with roughly half ending up in municipal waste, becoming a non-point source P. As for P ingested daily by humans, approximately 98% is excreted, but only ~10% of this excreted P is recycled, with the residual ultimately entering water bodies or soils.[3] During the process of urbanization, increasing amounts of P are direct to sewage treatment plants through the pipeline and discharge into the surface water.

The industrial system, which converts phosphate ore into fertilizers, organophosphorus pesticides, and synthetic detergents, is closely related to P flows from other subsystems. In watersheds with the richest phosphate ore, such as the upper and middle reaches of the Yangtze River Basin (accounting for 60%–87% of the national total reserves). Consequently, waste generated by the P chemical industry poses a serious threat to freshwater systems within the watershed. Through P substance flow analysis (SFA), approximately 79% of mined P is used for fertilizers.

ENVIRONMENTAL FACTORS DRIVE P FLOWS

Hydrological, topographic factors, and soil properties jointly drive the movement of P flows within watersheds. Among these, hydrological drivers dominate the seasonal and annual variability of nutrient loads in watershed aquatic systems.[4] Under the background of global warming, extreme precipitation events have intensified erosion-driven P flows. During 1980–2018, the contribution of extreme precipitation to annual total phosphorus (TP) export in the Mississippi River Basin increased from approximately 21% to 36%. Additionally, under a warmer and wetter future climate, TP yields will vary from −24.0% to 199.0% across various regions. Topography further controls runoff patterns and P pathways. Slope gradient and curvature influence runoff generation and particle detachment. Steeper croplands (~20°) produce substantially more runoff and P loss. Slope affects not only erosion but also infiltration-related processes. Soil properties and land-use patterns jointly influence infiltration and runoff distribution. In mid-high-latitude regions, soil P concentration and P loss are more sensitive to temperature than to precipitation. A 14-year field experiment in Austria demonstrated that soil warming (+ 4°C) resulted in an 18% loss of TP in the surface layer (0–10 cm).[5]

However, the migration of P is not merely a function of land-use types but is fundamentally driven by the spatial configuration of landscape patches. At the sub-watershed scale, fragmentation indices such as Patch Density (PD) are positively correlated with P export and show slightly higher explanatory power for water quality than other scales. In contrast, at the watershed scale, the Large Patch Index (LPI) of water bodies exhibits a strong mitigating effect on P export.

AQUATIC ECOSYSTEMS ACCUMULATE P FLOWS

Aquatic ecosystems function as major sinks, accumulating P from both external inputs and internal recycling. Exogenous P not only directly triggers algal blooms but also forms "P sinks" through sediment-water interface dynamics, such as adsorption-desorption equilibrium. Upon entering aquatic systems, a significant fraction of particulate P undergoes sedimentation but remains geochemically active, while a portion of dissolved P is assimilated by primary producers. The lake P mass balance approach is widely applied across Europe, North America, with mechanistic models increasingly preferred over experimental methods. Among these models, the Water Ecosystem Tool (WET) provides an integrated platform for simulating hydrodynamic and biogeochemical processes within lakes, enabling the assessment of how aquatic ecosystems respond to external and internal P loads. Importantly, WET also supports direct integration with catchment data as model inputs. In particular, outputs from distributed hydrological models such as SWAT (Soil and Water Assessment Tool) can be used as boundary conditions or driving variables for WET, allowing the coupled system to simulate P transport, redistribution, and the responses of key functional groups. However, even with such coupling, these models still depend on upstream representations of human-driven P generation. This highlights the need for a more complete integration that links anthropogenic P sources, watershed transport processes, and lake ecological responses.

TOWARDS SUSTAINABLE P MANAGEMENT: CHALLENGES AND OUTLOOK

Sustainable P management in watersheds requires a systematic understanding of P flows from the "Generate–Drive–Accumulate" perspective, which requires cross-scale modeling approaches. Recent efforts, including coupling SFA with SWAT and coupling SWAT with WET, have validated the feasibility and practical value of coupled modeling frameworks for lake P flow analysis. However, we still face numerous challenges in developing a comprehensive model that captures sources, flows, and sinks. Concerning this issue, the substantial mismatch in spatiotemporal resolution is the first challenge. Ecohydrological models typically operate at high spatiotemporal resolutions (e.g., daily weather data and gridded hydrologic response units HRU) to simulate hydrological processes and P pollution. In contrast, SFA relies on administrative-based annual socio-economic data, which lacks spatial explicitness and prevents it from running effectively in gridded, process-based watershed models. Secondly, existing models are predominantly based on unidirectional coupling, lacking dynamic feedback mechanisms. Thirdly, data uncertainty propagates across the coupled model. As outputs from one model serve as inputs to the next, errors associated with model assumptions, missing data, and parameterization would accumulate and interact, ultimately amplifying overall uncertainty.

Looking forward, the "Generate–Drive–Accumulate" research framework requires further refinement to support watershed P management:

(1) Priority is given to theoretical approaches, with empirical relationships serving as a complement. High-resolution spatialization of P flows should be achieved by establishing explicit associations between each socio-economic system and specific land-use, and then leveraging high-resolution land-use and population datasets to map P flows at fine spatial scales.

(2) Introduce a system dynamics (SD) mode that couples socio-economic sectors, HRUs, and lake ecosystems to capture internal feedback dynamics. Furthermore, develop future scenario modules that enable managers to propose targeted mitigation measures based on simulation outcomes.

(3) It is necessary to develop evaluation indicators within the coupled model framework that capture P flow dynamics from source to sink. Key indicators should include P utilization efficiency, recycling rate, emission intensity, lake retention efficiency, uncertainty propagation metrics (such as the coefficient of variation derived from Monte Carlo simulations), and spatial hotspot contribution ratios.

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DECLARATION OF INTERESTS

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