Review

A Review of Phosphorous in Fluvial Floodplains: Source or Sink?

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ABSTRACT: Fluvial floodplains are water-land transitional zones, playing an important role in hydrological and ecological systems. To date, the phosphorus migration and transformation in floodplain sediments remain elusive, which poses a large effect on river nutrient levels and primary productivity. This review summarized the sedimentary characteristics of floodplains and analyzed the spatial differences and temporal variations in phosphorus distribution. We further analyzed their potential change in floodplains under various conditions, determining the sedimentation and mineralization process of phosphorus. Meanwhile, phosphorus in the sediment will experience dynamic fluctuation as a source or sink of fluvial floodplains based on varying factors, including hydrological conditions, climate variations, biological activity, and pedological characteristics. In particular, the productivity and community population in floodplains, like vegetation and fishes, will be primarily associated with the periodic changes in phosphorus through food chain. Lastly, this review provided corresponding perspectives on improving the phosphorus administration in river floodplains based on existing problems. In total, it is anticipated that it will enhance the understanding of phosphorus resources or sink in the fluvial floodplains, contributing to the stability of aquatic ecosystems.

Keywords: Phosphorus; Fluvial floodplains; Release; Ecological effect; Periodic change

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1. Introduction

With the rapid economic development, water pollution caused by human activities (such as agriculture, industry, and animal husbandry) has become increasingly significant. Phosphorus (P) is an essential nutrient for living organisms [1] and plays a role in regulating primary productivity in aquatic ecosystems [2]. Approximately 2 million tons of P enter global water bodies yearly due to agricultural runoff and wastewater discharge [3]. Excessive P can enter the river ecosystems through various routes, including industrial discharges, agricultural runoff, and internal loading from sediment release, thereby compromising the health of these ecosystems [4]. For instance, the P concentration in the Ganges River in India had reached a high level of 0.5–1.1 mg/L due to the agricultural runoff [5], creating a high risk of water quality deterioration. Similarly, the Mississippi River Basin in the United States experienced an annual loss of approximately 15,000 tons of P due to surface runoff, which is a major contributor to the formation of hypoxic zone in the Gulf of Mexico, adversely affecting the local ecological balance [6]. Consequently, effectively monitoring and managing river P levels has become a core concern of watershed ecological management.

Fluvial floodplains are depositional surfaces located next to the active channel, formed by river processes and composed of alluvial sediments. While primarily considered a morpho-sedimentary unit shaped by contemporary dynamics, older alluvial units at comparable elevation levels may also experience frequent flooding [7]. The formation of floodplains results from the interaction of river lateral migration, flooding, and sediment deposition processes [8], leading to the sediments primarily consisting of fine silt or sand. These floodplains encompass numerous small geomorphic units, including sandbars, natural levees, sand ridges, abandoned channels, and oxbow lakes [9,10]. Additionally, many floodplains feature stable or semi-stable water bodies such as ponds, marshes, small lakes, wetlands, and various perennially moist depressions [11,12]. As a vital interface between land and water, floodplains facilitate the migration of aquatic species, thereby enhancing the cycling and exchange of water, sediments, nutrients, and organic matter [13]. The diversity of floodplain topography and the dynamic hydrological conditions support the habitats for aquatic organisms, promote the genetic exchange among species, and enhance the biodiversity [14]. Overall, fluvial floodplains are dynamic areas characterized by sediment deposition and erosion [15], playing a role in nutrient cycling within aquatic ecosystems.

Unlike gaseous elements such as carbon, nitrogen, and sulfur, P has a unique environmental cycle that makes it highly prone to adsorption and precipitation in sediments. During periods of high external nutrient input, P in the water column can be adsorbed or deposited into floodplain sediments [16]. Conversely, when external inputs decrease or are in response to external disturbances, P may be released from the sediments back into the overlying water column [17]. Unstable P forms in floodplain and riparian buffer sediments can cuase elevated P concentrations in adjacent waters [18–20]. For instance, inundation of riparian sediments at Strumpshaw Fen in the UK increased the dissolved P in pore water to over 3 mg/L within one month, and surface water concentrations exceeded 0.8 mg/L [21]. Similarly, in the Han River, South Korea, the P release rates of sediment could reach up to 90 mg/m² per week in summer, substantially influencing P cycling and posing a potential risk for P pollution in the water [22]. Thus, as both a P source and sink of riverine, floodplain sediments are important for regulating P concentrations in the overlying waters and maintaining biogeochemical P cycling.

Current research mainly focuses on the spatial and temporal distribution of P elements in floodplain sediments [23–25]. However, the migration of P in the floodplain remains elusive, determining whether the floodplain sediments act as a “source” or “sink” of P. Herein, we summarized the current research on the P distribution and deposition characteristics in the river-floodplain system and explored the affecting factors and the issue of floodplains as a source or sink of P. It is anticipated that this will reduce the gap in understanding the role of P in fluvial floodplains.

2. Phosphorus Characteristics in Fluvial Floodplains

2.1. Characteristics of Floodplain Sedimentation

Fluvial floodplains constitute an important part of river systems, exhibiting diverse forms and dynamic interactions with river channels. As illustrated in Figure 1, floodplains occur in diverse forms within natural environments. The formation of floodplain sediments involves the combined processes of lateral river migration, which creates point bars, and vertical overbank deposition, forming natural levees and floodplain depressions. On the one hand, lateral river migration results in the deposition of coarse-grained sediments on point bars along the convex bank while eroding the concave bank. As point bars accumulate and extend outward, discontinuous depressions may produce due to poor drainage conditions. On the other hand, floodwaters overflow and transport suspended fine-grained materials (e.g., silt and clay) onto the floodplain surface. As a result, proximal areas near the river channel often develop natural levees, while distal zones farther from the channel evolve into floodplain depressions [26–28]. The Cooper Creek floodplain in Australia, shaped by flow energy, sediment transport, and flood frequency factors, comprises 44% braided channels, 39% anastomosing channels, and 17% non-channelized areas [29]. As rivers flow through floodplain areas, decreased flow velocities promote sediment deposition on these surfaces. Moreover, due to different levels of erosion across upstream, midstream, and downstream floodplains, variations in sediment grain size, floodplain types, and other characteristics are observed [30]. Research indicated that in Nepal’s Karnali River, the average grain size of surface sediments decreased from 50 mm to 3 mm as they were transported downstream, with sediment layers transitioning from braided, jagged, and complex gravel formations to more sinuous and highly mobile sand beds [31–33]. The floodplains in the two regions exhibited distinct geomorphological and sedimentary characteristics. Compared with the Cooper Creek floodplain, the Karnali River floodplains underscored the significant role of river types and regional environmental factors, such as hydrological regimes and climatic conditions, in shaping floodplain sedimentary features. In total, the interplay between river-induced erosion and sediment deposition, along with the overbank sedimentation during flood events, drives the gradual expansion and morphological evolution of floodplains. This process gives rise to distinct floodplain types, such as planar, braided, and anastomosed floodplains, each characterized by unique geomorphic features and sedimentary processes [26].

Floodplain sedimentation patterns are intricately linked to the flood frequency, flow velocity, sediment supply, and river microtopography [29,34]. In addition, the grain size distribution of floodplain sediments varies considerably depending on channel morphology, hydrodynamic conditions, flood intensity, and sediment transport dynamics. Coarser materials like gravel undergo a preferential deposition process during high-flow periods, while finer sediments such as silt dominate under low-flow conditions [35,36]. Previous researches has indicated that floodplain sediments are enriched with nutrients and organic matter, supporting the aquatic plant growth and facilitating the water selfpurification processes [7,37]. Therefore, the variations in floodplain sedimentation contributed not only to the morphological changes in channels and banks but also played an important role in maintaining the diversity of river ecosystem [38]. For instance, the floodplains in the Mississippi River of North America were mianly controlled by periodic flood, providing the habitats for organism reproduction and the survival of numerous waterfowl and fish species [39,40]. In total, floodplain sedimentation was influenced by a series of driving factors, including climate, hydrology, and human activities, which is beneficial for the floodplains characterized by high nutrient storage and rich biodiversity [14,41]. Meanwhile, the habitat heterogeneity in floodplains provided favorable conditions for the survival of aquatic organisms.

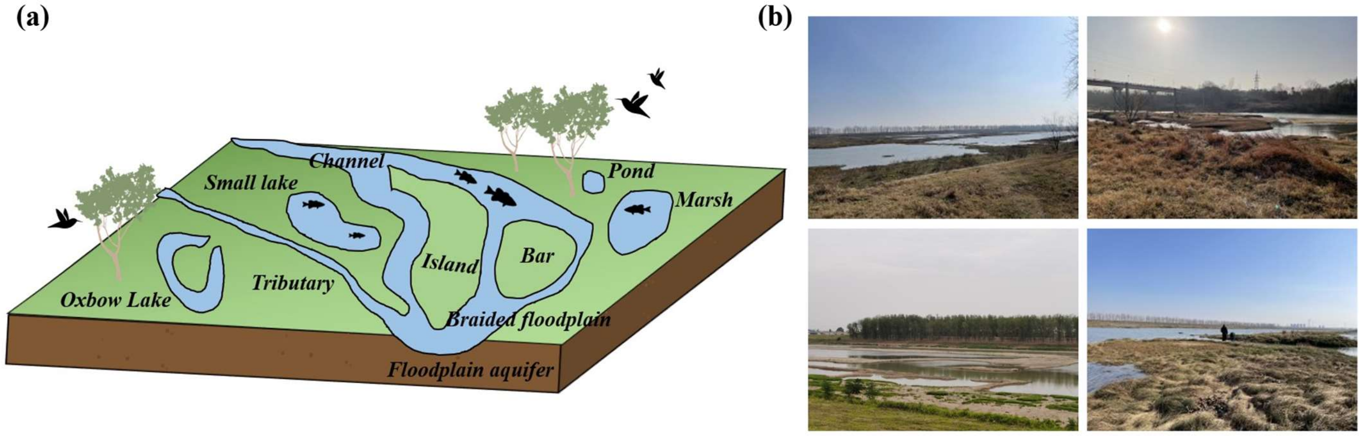

Figure 1. Several typical floodplain types. (**a**) Common types of floodplains. (**b**) Pictures of the floodplain in the Sheshui River, a tributary of the Yangtze River.

2.2. Phosphorus Distribution in Floodplains

P in floodplain sediments largely originate from external inputs and internal release. External inputs include the weathering of rocks and soils, biological activities, precipitation runoff, human activities, and others. P, as one of the most common mineral elements in nature, exists in rocks, soils, and minerals and can be released into the floodplain sediments through weathering and surface runoff. Additionally, P is released through the death and decomposition of organisms in the floodplain, potentially settling into the sediment. Human activities are also significant contributors to the P deposition. In the Yangtze River region, agricultural sources account for the largest proportion of emissions (68.1%), followed by domestic sources (29.52%) and industrial sources (2.40%). It is estimated that agricultural activities discharge tens of thousands of tons of P into rivers annually, significantly increasing the P concentrations in sediment [42–44]. Additionally, P in floodplains also comes from endogenous inputs, primarily from two sources: upstream sediments transported within the watershed and the release of P stored in floodplain deposits. Together, these exogenous and endogenous inputs contribute to the P supply in floodplains. The fate of P in floodplains involves several processes, such as accumulation, transformation, and cycling of P in fluvial floodplain. A portion of P in floodplain sediments is gradually accumulated through sedimentation, serving as a long-term P storage pool. Some of P may enter the food chain through plant uptake, eventually returning to the sediments in the form of biological remains. After decomposition, it re-enters the P cycle, or it may form organic P minerals or other precipitates through long-term geological processes. Lastly, P will transport along with the flow of the river downstream and settle in other river sections or estuaries, or contribute to the P cycle in marine ecosystems [43]. Overall, the P flux in floodplains is diverse and complex, influenced by both natural and human factors. Understanding these interwoven characteristics is necessary for studying the forms and distribution patterns of P in floodplain environments.

P in the river and floodplain sediments are typically categorized as either inorganic phosphorus (IP) or organic phosphorus (OP). The IP fraction includes exchangeable P, P bound to aluminum and iron oxides and hydroxides, and calcium-bound P (Ca-P) [45]. In Iran's Hamadan River sediments, Ca-P was regarded as a significant contributor to IP, constituting between 32.8% and 52.0%. Furthermore, the dominant P fraction shifts downstream from residual P (Res-P) to Ca-P [46]. Studies in the Tuojiang River in China have shown that Fe-bound P (Fe-P) was the primary form of sedimentary P at concentrations ranging from 87.9 to 619.0 mg/kg [23]. The study on the Hamadan River highlighted a shift in P forms, particularly Ca-P and Res-P, between the upstream and downstream sections. In contrast, the research on the Tuojiang River emphasized total pollution load assessment, with limited consideration of dynamic variations in

P forms across river sections. The observed differences in P forms and content between the two basins underscore the important role of sedimentary conditions in shaping the distribution and stability of sedimentary P, suggesting that P composition in river sediments varies with the sedimentary conditions across different river systems. Additionally, based on mobility, P can be classified into mobile and inert fractions. Labile forms of P—primarily loosely adsorbed P (Res-P), Fe-P, and OP—are considered potential mobile P and are readily released into pore water and overlying water [47]. The above indicates that the speciation of P in floodplain sediments is closely linked to its bioavailability and mobility, with each form exhibiting distinct depositional characteristics. Generally, while the forms of P in the main river channel and floodplains are similar, differences exist in the content and distribution of sediment P. The research by Fink et al. [48] on the Olentangy River floodplain in the U.S. found that oxbow lakes retained the nutrients during flood pulses, with an average TP retention of 0.08 g/m² per event, contributing to an annual reduction of 31.0% in TP. This highlights that floodplains, unlike the main river channel, often experience water stagnation or limited water exchange and easily trigger nutrient enrichment. In conclusion, the semi-enclosed nature of floodplains, including river deltas, oxbow lakes, and depressions, fosters the P accumulation and leads to the variability and instability in the spatial and temporal distribution of sediment P.

The spatiotemporal P distribution in floodplains is significantly shaped by human activities, periodic flooding, and seasonal variations [49–51]. Kronvang et al. [25] reported that during eight flooding events, the Gjer River floodplain in Denmark retained suspended sediments with an efficiency ranging from 17% to 62%, with retention influenced by factors such as flood magnitude, duration, and water exchange dynamics. Gonzalez-Sanchis et al. [52] demonstrated that the P deposition in the Ebro River floodplain, Spain, showed marked spatial variation through simulations, with 80% of sediments accumulating within 30% of the area nearest to the flood zone, compared to only 6% in more distant regions (1927–2010). These findings underscore the role of seasonal flooding in the spatial distribution and retention of P within floodplains. Typically, P deposition is lower in upstream segments with dense vegetation and minimal human disturbance, where mobile fractions such as Fe-P and OP are less prevalent. Conversely, downstream segments, subject to more pollution, display increased P content and higher concentrations, particularly in areas with intensive human activity [49,53]. This pattern illustrates the combined effects of hydrogeological processes, river transport, and human impacts on floodplain P distribution. Overall, the spatiotemporal distribution of P in floodplain sediments results from multiple factors, including water temperature, water level, dissolved oxygen, periodic flooding, and human activities [54], showing pronounced temporal fluctuations and spatial gradients and reflecting the complexity and dynamic nature of P distribution in floodplain sediments.

2.3. Transformations in Phosphorus Forms

The alteration of P forms within floodplain sediments is closely tied to river water quality and overall ecosystem health [54,55]. P forms within floodplain sediments, particularly labile fractions such as Fe-P and OP [56], are prone to transformation with shifts in hydrological conditions or when subjected to external disturbances. These transformations involve complex processes regulated by environmental and anthropogenic factors, such as biological, physical, and chemical mechanisms [54]. Understanding the shifts in sedimentary P fractions and their connection to P fluxes at the sediment-water interface is essential for effectively managing the riverine ecosystems. Transformations in the sedimentary phosphorus forms of floodplains are driven by a combination of environmental and anthropogenic factors. Firstly, environmental factors, like pH, water temperature, and dissolved oxygen (DO), significantly influenced the transformation of P species in sediments. The P solubility depends on water pH and redox conditions [57]. For instance, Fe-P and Al-P exhibit minimal solubility under neutral pH and adequate oxygen, allowing them to remain stably stored in sediments. When the sediment-water interface is aerobic, metals such as Fe and Mn are oxidized to Fe(III) and Mn(IV), immobilizing P through bonding with metal hydroxides. Conversely, Fe and Mn dissolve under reducing conditions, releasing P in the form of phosphate [58,59]. Secondly, the deposition and release of sedimentary P in floodplains are influenced by seasonal variations in temperature, DO, water level, and runoff inputs [54,60]. Lastly, external disturbances such as flood scouring, wet-dry cycles, and human activities affect sedimentary P. These disturbances alter hydrodynamic conditions, leading to shifts in P speciation. Overall, transformations in floodplain sedimentary P forms are shaped by a dynamic interplay of environmental and hydrodynamic factors, reflecting a complex and responsive system.

The dynamic distribution of sediment P in floodplains can be analyzed not only from the perspectives of biological, physical, and chemical mechanisms but also in terms of differences in its distribution after varying degrees of disturbance. Generally, under conditions of low flow velocity, the rates of P deposition and release in floodplain sediments remain relatively stable. Microbial processes and redox reactions play a large role in the fixation and release of sediment-bound P [61]. Once the P is deposited into floodplain sediments, its content might remain dynamic stabilization across seasonal changes. However, during periods of significant disturbance, such as rainy seasons or floods, frequent deposition and resuspension events lead to the highly dynamic behavior of P in the sediment (Figure 2). During flood periods, the P in sediment exhibits dynamic shifts via two main mechanisms. Firstly, hydrodynamic forces can directly erode the sediment, releasing adsorbed P into the water column and causing a rapid rise in water P levels [62]. Secondly, the influx of sediment and organic matter from floodwaters can alter sediment particle structure and redox conditions, increasing the P release rate [24]. For instance, Kinsman-Costello et al. [63] reported that following a secondary flood in wetlands in Michigan, USA, large amounts of P were released from sediments into the water column, with soluble reactive P (SRP) concentrations reaching up to 750 μg P/L in re-flooded zones, and SRP peaks in surface water reaching 20 times pre-flood levels. As floodwaters recede, suspended particles settle and form new sediment layers, indicating dynamic cycling. In conclusion, P dynamics in floodplains exhibit a "balance-imbalance" pattern: they tend toward equilibrium under low-flow conditions but display pronounced fluctuations during high-disturbance events.

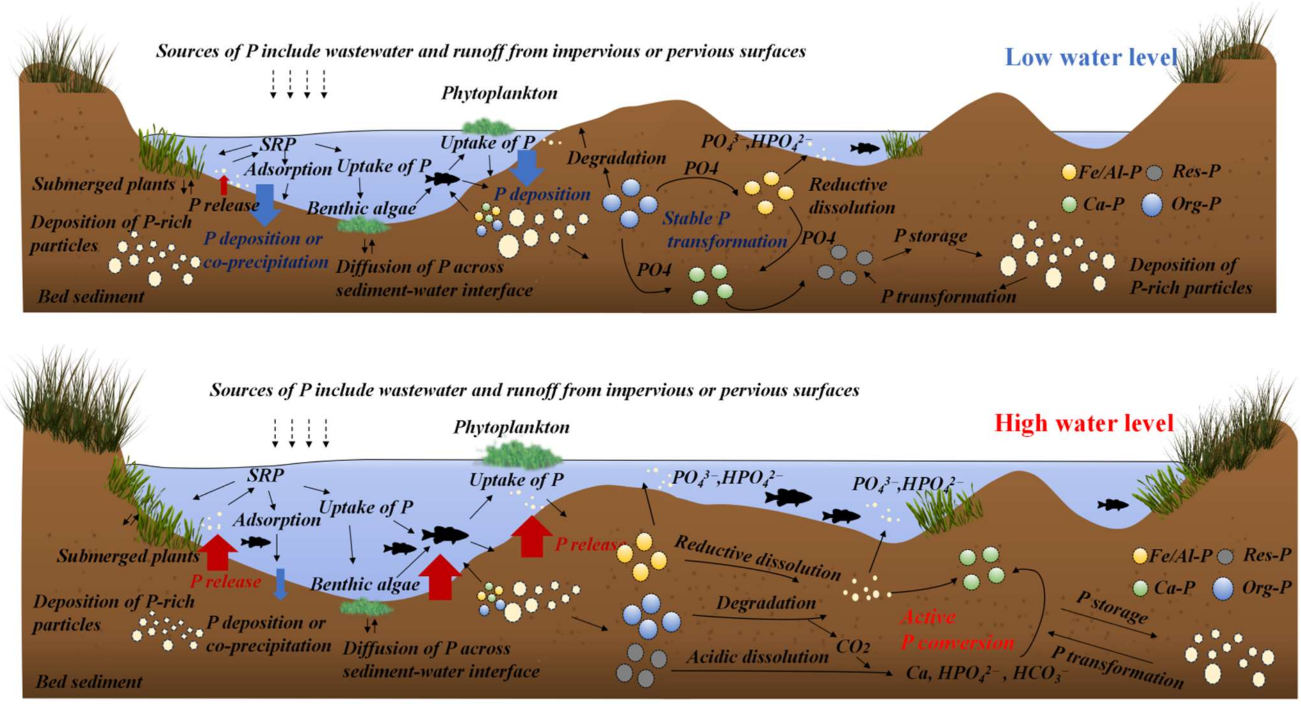

Figure 2. Phosphorus changes in the floodplain at different water levels.

3. Phosphorus Source or Sink in Fluvial Floodplains

Generally, floodplain sediments are considered a sink for P, fixing P through processes such as adsorption and immobilization, thereby reducing its bioavailability in the water. Under aerobic conditions, a solid layer of Fe and Mn oxides or sulfides may form on the sediment surface, effectively binding dissolved P and limiting mobility [64]. Microbial interactions with metal ions in sediments may further enhance P retention, particularly under low temperature and low disturbance conditions [65]. Jin et al. [66] simulated the adsorption of P by sediments in low-flow areas and found that the P concentration in overlying water decreased by about 25% after 35 h. The study indicated that sediments promoted the migration of pollutants to the riverbed, effectively reducing P pollution in overlying waters. Kim et al. [57] compared sedimentary P in two different tributary regions of the Han River and found that sediments with low non-apatite P (NAI-P) content were more likely to fix P, with P release rates of 25–40 mg/m² per week. Research comparing river sections with and without floodplain connectivity shows that floodplains typically enhanced the uptake and storage of nutrients [67]. Specifically, due to the influence of periodic flooding, the broader and wider areas of floodplains facilitate P retention within the floodplain. It means, as the floodwaters recede, becoming integrated into the floodplain sediments. These results suggest that sediments can effectively fix P in water, with varying stability across different P components. In conclusion, floodplain sediments play an important role in the sedimentary fixation of P, acting as a sink for river P.

However, floodplain sediments can also act as a P source for overlying water, particularly under hypoxic conditions or significant external disturbances. Hypoxic conditions promote the reductive dissolution of surface-associated oxides, releasing phosphates into the water column [65,68]. Studies have shown that when the redox potential drops below 300 mV or oxygen concentration falls below 0.1 mg/L, $Fe(OH)_3$ is reduced to ferrous iron by microorganism, leading to the phosphate release into overlying water, with phosphates trapped within the hydrated iron hydroxide coating [69,70]. In the upstream floodplain, sediments generally have high porosity and frequent water flow scouring hinders the retention and accumulation of P. In contrast, the middle and lower floodplain regions, such as river deltas and depressions, are more prone to formation of P accumulation. Sedimentary P is more likely to be released under anoxic conditions with a lower flow rate. Additionally, external disturbances during the rainy season and floods also trigger sedimentary P release. Research on the Danube River floodplain demonstrated that periodic wet-dry cycles enhanced sedimentary P release, particularly when drying periods reduced sediment moisture by 80%, resulting in the highest P release [24]. This release is mainly driven by the chemical changes under anoxic conditions in sediments, causing P to diffuse back into the water column, raising water P concentrations and increasing the risk of eutrophication. These findings highlight that the role of sediments as either a source or a sink of P involves the complex cycling of P through adsorption, release, and transformation processes between the water and sediment, influenced by various factors. Overall, floodplain sediments can release P under hypoxic and disturbed conditions, acting as a source of P and increasing water P concentrations. Meanwhile, the periodic floods resulted in more and more P sedimentation in the floodplains on both sides of the main river channel.

In recent years, more and more studies have focused on the role of P source and sink in the sediment (Table 1). Cai et al. [65] examined the seasonal dynamics of sediment P in the floodplains of the Yangtze River. They found that sediment P behaves as a sink during the winter when water temperatures are low, but as temperatures rise in summer, P becomes more mobile, resulting in an increasing of sediment P flux and pore water P concentrations, turning the sediment into a P source. When water temperatures drop below 10 °C, sediments again act as a sink. Jarvie et al. [71] studied that the river sediments of two catchment areas in the UK generally acted as a P sink, and the decreases in SRP during low-flow periods in spring and summer could lead to the shift of the system, turning sediments into a P source. Jin et al. [72] also found that during heavy rainfall, sediment particles became a significant source of TP pollution in rivers. Despite their differing emphases, previous studies consistently highlighted the dynamic nature of sediments as P sources or sinks, which were mainly driven by external factors, including temperature, hydrological regimes, and precipitation. In total, these findings enhance our understanding of intricate relationships between sediments and P cycling. Figure 2 illustrates the migration and transformation processes of P fractions in floodplains under low water levels (low disturbance) and high water levels (high disturbance). Under low water levels and minimal disruption, floodplain sediments predominantly act as a "P sink", sequestering phosphorus from the water column through adsorption and precipitation. Conversely, during flood events characterized by high disturbance, these sediments possibly transition to a "P source", releasing stored P into the overlying water via desorption and resuspension. The processes depicted here provide a generalized overview, which might vary depending on the floodplain style (e.g., braided, meandering, anabranching), temperature, precipitation, vegetation cover, and other environmental variables. It is not relevant to any particular style or category of the floodplain but rather serves as a simplified illustration of the P exchange.

In conclusion, floodplain serves as a P source through processes such as desorption, reductive dissolution, and resuspension. On the one hand, dissolved P forms complexes with iron and aluminum oxides under oxygen-rich conditions, while microbial activity and interactions with metal ions further promote P deposition. On the other hand, periodic flooding expands the floodplain's capacity to retain P, as receding waters allow P to integrate into sediments. Conversely, floodplains can act as P sources under specific conditions. In anoxic environments, the reductive dissolution of iron and aluminum oxides in sediments releases phosphate into the water column. Additionally, sediment erosion caused by high water flow during rainy seasons or floods can result in the loss of sediment-bound P, making it more likely to be released into overlying water. In total, phosphorus in the sediment will experience dynamic fluctation as a source or sink of fluvial floodplains based on varying factors, including hydrological conditions, climate variations, biological activity, and pedological characteristics. This dynamic shift between P source and sink states underscores the complex role of floodplains in regulating nutrient cycles and maintaining water quality.

Table 1. Research on the Forms, Distribution, and Transformation of Phosphorus in Sediments of Floodplains.

Study Area	Content	Floodplain Type	P Fractions in Sediments	Results			References
				Spatiotemporal Distribution	Migrate Conversions	Influencing Factors	
Swale Floodplain (UK)	The phosphorus content of floodplain sediment in rural and industrialized river basins	——	TP: 452–695 μg/g IP: 383–573 μg/g OP: 59–122 μg/g;	√	——	Human activities such as agriculture, industry	[73]
Aire Floodplain (UK)			TP: 1061–4657 μg/g IP: 800–4216 μg/g OP: 139–672 μg/g;				
Calder Floodplain (UK)			TP: 796–4708 μg/g IP: 701–4344 μg/g OP: 95–364 μg/g				
Han River (China)	Phosphorus fractions of floodplain sediments and phosphorus exchange on the sediment-water interface	——	TP: 643.86–985 mg/kg Exch-P: 6.94–9.35 mg/kg Fe/Al-P, Ca-P, IP, OP	√	√	point source pollution and non-point source pollution, immersion and emersion	[74]
Lower Lobau Floodplain (Austria)	Impact of drying and re-flooding of sediment on phosphorus dynamics of river-floodplain systems	in an abandoned channel	TP: 543.1–580.8 mg/kg IP: 385.6–391.5 mg/kg OP: 155.4–196.5 mg/kg Ca/Mg-P: 343.7–371.2 mg/kg Fe/Mn-P: 50.7–74.7 mg/kg	——	√	drying and re-flooding of sediment	[24]
River Yare Floodplain (UK)	Phosphorus mobilization and transport within a long-restored floodplain wetland	a wetland floodplain	TP: 1143–1461 mg/kg Fe-P: 121–130 mg/kg	√	√	a long-restored floodplain, sediment geochemistry, short-term hydrological events	[75]
Floodplain of Difficult Run (USA)	Hydrogeomorphology Influences Soil Nitrogen and Phosphorus Mineralization in Floodplain Wetlands	levee, back swamp, and toe-slope	TP: 403–600 mg/kg	√	√	hydrogeomorphology	[76]
Amazon floodplain (Brazil)	Nutrients and water-forest interactions in an Amazon floodplain lake: an ecological approach	semi-stable water bodies	TP: 19–52 mg/kg	√	——	water-forest	[77]
Iowa River Floodplain (USA)	Soil total phosphorus deposition and variability patterns	oxbow lakes, semi-stable water bodies	TP: 45.7–164.9 mg/kg	√	——	Flood characteristics: frequency, duration; Sediments: structure, particle size	[78]
Grand River (Canada)	Shifts in soil phosphorus fractions during seasonal transitions in a riparian floodplain wetland	a riparian floodplain	Total bioavailable P: 865.3–1497 mg/kg	——	√	freeze-thaw cycling, microorganisms, seasonal changes, metallic elements: Fe, Ca, Al	[79]
East-central Sweden floodplain (Sweden)	Phosphorus supply and floodplain design govern phosphorus reduction capacity in remediated agricultural streams.	——	H_2O-P, Fe-P, Al-P, Ca-P	√	√	Phosphorus supply and floodplain design	[80]

Note: "——" indicates that this content is not covered in the references, while "√" means that the references involve research in this aspect.

4. Ecological Effects of Phosphorus in Fluvial Floodplains

Fluvial Floodplains play a role in nutrient retention within rivers, and the retention of P in the sediments can significantly result in a lower P concentration in water, reducing the risk of P pollution [81,82]. However, releasing P from sediments leads to surface water pollution, excessive growth of aquatic plants, lower water transparency, and, ultimately, the health and stability of aquatic ecosystems. Research indicated that P release from floodplain sediments in the River Aire, UK, resulted in significant P pollution (above 0.8 mg/L) in the overlying water [21]. The concentration of dissolved P in the River Aire exceeded 0.8 mg/L, significantly higher than the Class V surface water standard (<0.4 mg/L). In conclusion, the adsorption and desorption processes of P in floodplain sediments are important in regulating river water quality, as they determine the mobility and bioavailability of phosphorus within the aquatic environment. When external pollution sources are controlled, the release of P from floodplain sediments may serve as a potentially internal source of P pollution.

Floodplains not only play a role in regulating water quality pollution in rivers but also provide vital habitats for supporting the primary productivity and biodiversity within river ecosystems [83]. Firstly, floodplain sedimentary P is a key nutrient driving primary productivity in rivers. The presence of sedimentary P in floodplains is linked to the growth cycle of aquatic plants, which affects the composition and distribution of aquatic macrophyte communities, thereby influencing the stability of the entire river ecosystem food web [84]. Kiedrzyńska et al. [85] quantified the P retention efficiency of floodplain vegetation. Their study on the Pilica River floodplain revealed that different plant communities posed varying influence on P accumulation. For instance, reed communities accumulated the most P in spring, with an efficiency of 34.7 kg/ha, while meadow communities exhibited relatively stable P content. The study also found that the P accumulation potential of Pilica River floodplain vegetation reached 255 kg per year in summer, and thus optimizing the floodplain area proportion can enhance P accumulation in willow patches [85]. Secondly, the abundant nutrient supply in floodplains creates diverse habitats for invertebrates, fish, and waterfowl, supporting species diversity within river ecosystems [83]. The active floodplain of the Paraná River in Brazil enabled intense active and passive exchanges between plant and animal species, like highland birds and some terrestrial mammals migrating to the floodplain during low water periods to take advantage of the abundant food resources [86]. Many fish species depend on the wetland environment of floodplains for spawning and juvenile development, significantly enhancing their reproductive success. Agostinho et al. [87] indicated that annual floods lasting over 75 d in the upper Paraná River floodplain benefited the migrating of fish population. Dole et al. [88] identified 112, 157, and 107 species in high, medium, and low disturbance areas, meaning that water-level fluctuation in floodplains poses a big effect on the community population. In total, fluvial floodplains provide habitats for aquatic and terrestrial flora and fauna, and the P in floodplain sediments plays an important role in nutrient cycling and energy flow within river ecosystems. On the one hand, there is a mutual feedback effect between the P transformation and the growth, reproduction, and distribution of organisms, offering essential nutrient support. The interaction between P in floodplains and organisms helps sustain the complexity of the river ecosystem's food web, interspecies relationships, and the stability of ecological processes.

5. Future Directions

Given the ecological and hydrological functions of floodplains in watershed systems, the research on sediment as both a P source and sink, as well as its ecological impacts, is rapidly expanding. Fluvial floodplains are not only a dispensable component of river watersheds but also play a vital role in maintaining the health of aquatic ecosystems. Recent studies have highlighted the significant role of sedimentary P in river environments, especially its dual function within the watershed as both a pollutant source and a nutrient supply, influencing aquatic communities and water quality changes [65,89]. While much research has explored the deposition and release processes of P in river and floodplain sediments, the source-sink dynamics of P in floodplains have become increasingly complex due to climate change, watershed development, and land-use changes. However, the challenges of quantifying the source-sink processes remain, predicting long-term trends, and understanding the interactions between multiple factors. As mentioned above, the P variation and transformation in floodplains is complicated and influenced by a couple of factors. Water level and water quality may be predicted through remote sensing-enabled machine learning technology based on the analysis of the giant database of river hydrologic information and historical remote sensing data [90,91]. Furthermore, it will be feasible to quantify the transformation and source-sink process of P in the floodplain. Meanwhile, intelligent models can help analyze the spatiotemporal changes in P distribution with greater precision [92,93]. Through high-frequency monitoring and model predictions, it will be possible to evaluate the effects of various climate conditions on the P deposition-release process in real-time and predict potential P migration and transformation patterns in floodplains.

6. Conclusions

Fluvial floodplains at the interface between terrestrial and aquatic ecosystems are integral to the biogeochemical cycling of P in river systems. Floodplain sedimentation is shaped by the combined effects of lateral river migration and vertical deposition, resulting in the diverse geomorphologies and unique sedimentary patterns. Influenced by climate, hydrology, and human activities, floodplains often exhibit semi-enclosed settings such as deltas, oxbow lakes, depressions, leading to distinct spatiotemporal distributions and dynamic variations in P forms. The temporal fluctuations and spatial gradients of P in floodplain sediments align with a "balance-imbalance" model: sediments tend to stabilize under low-disturbance conditions but experience significant fluxes during high-disturbance events. Specifically, under well-oxygenated or minimally disturbed conditions, floodplain sediments predominantly act as "P sinks" sequestering P from the water column through adsorption and precipitation. Conversely, during anoxic conditions or under external disturbances such as flooding or wet-dry cycles, these sediments function as "P sources" releasing stored P into the overlying water via desorption and resuspension. The dynamic interplay between the "P source" and "P sink" states in floodplain sediments was influenced by varying factors, including hydrological conditions, climate variations, biological activity, and pedological characteristics, which plays a big role in sustaining the primary productivity of aquatic vegetation and preserving the biodiversity of river ecosystems through food chain. However, the release of internally stored P from floodplain sediments poses a potential risk of water quality degradation. A comprehensive understanding of the mechanisms will be conductive to driving the "P source-sink" behavior of floodplain sediments and promoting the ecological health and long-term stability of riverine environments.

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Author Contributions

Conceptualization, J.L. and X.L.; Methodology, J.L. and Y.Y.; Software, J.L.; Validation, J.L. and Y.Y.; Formal Analysis, J.L.; Investigation, J.L.; Resources, J.L.; Data Curation, J.L.; Writing—Original Draft Preparation, J.L.; Writing—Review & Editing, X.L.; Visualization, M.L.; Supervision, X.L.; Project Administration, X.L.; Funding Acquisition, X.L.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data used in the study are available on public websites, and the links are provided in the data section of the manuscripts.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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