

Article

Phosphorus Dynamics in Long-Term Flooded, Drained, and Reflooded Soils

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Abstract: In flooded areas, soils are often exposed to standing water and subsequent drainage, thus over fertilization can release excess phosphorus (P) into surface water and groundwater. To investigate P release and transformation processes in flooded alkaline soils, wheat-growing soil and vegetable-growing soil were selected. We flooded-drained-reflooded two soils for 35 d, then drained the soils, and 10 d later reflooded the soils for 17 d. Dissolved reactive phosphorus (DRP), soil inorganic P fractions, Olsen P, pH, and Eh in floodwater and pore water were analyzed. The wheat-growing soil had significantly higher floodwater DRP concentrations than vegetable-growing soil, and floodwater DRP in both soils decreased with the number of flooding days. During the reflooding period, DRP in overlying floodwater from both soils was less than 0.87 mg/L, which was 3–25 times less than that during the flooding period. Regardless of flooding or reflooding, pore water DRP decreased with flooding days. The highest concentration of pore water DRP observed at a 5-cm depth. Under the effect of fertilizing and flooding, the risk of vertical P movement in 10–50 cm was enhanced. P diffusion occurred from the top to the bottom of the soils. After flooding, Al-P increased in both soils, and Fe-P, O-P, Ca₂-P decreased, while Fe-P, Al-P, and O-P increased after reflooding. When Olsen P in the vegetable-growing soil exceeded 180.7 mg/kg and Olsen P in the wheat-growing soil exceeded 40.8 mg/kg, the concentration of DRP in pore water increased significantly. Our results showed that changes in floodwater and pore water DRP concentrations, soil inorganic P fractions, and Olsen P are significantly affected by fertilizing and flooding; therefore, careful fertilizer management should be employed on flooded soils to avoid excess P loss.

Keywords: phosphorus release; fertilizers; flooded soil; eutrophication; transformation

1. Introduction

The loss of phosphorus (P) from agricultural soils to surface water and groundwater has been a worldwide concern for many years, but losses of P from agriculture still contribute to nonpoint pollution [1–6]. P is a major contributor to eutrophication [7,8], and its loss from agricultural nonpoint sources can contribute to this process.

Many studies have examined soil P adsorption and release, especially under flooded conditions [9–18]. Flooding and draining causes chemical changes in soils, which leads to the dynamic

release or adsorption of soil P [19,20]. In flooding areas, soil P release mechanics and loss loads can be greatly affected by the flooding frequency and differences in water depth. During the rainy season, soils in some regions of China are often submerged under floodwaters. In these areas, the water–soil system experiences anaerobic conditions, and soil P can be readily released into surface and subsurface water or transported with the water deeper into the soil. After the floodwaters recede, P in the overlying water is carried into rivers and lakes along with runoff, thereby accelerating eutrophication. Meanwhile, the water–soil system becomes aerobic, and P availability decreases and P can be re-adsorbed by the soil [11].

Frequent flooding and drainage can alter pH and Eh in the water–soil system and thus affect soil P transformations and its availability in floodwater and pore water. Flooding can decrease Eh, which increases P release due to iron reduction [21,22]. However, a secondary reaction between Fe^{2+} (produced by the reduction of Fe^{3+}) and soluble P can decrease soluble P [23]. When there are higher concentrations of Fe^{3+} in pore water or floodwater, Fe^{3+} and Fe^{2+} form mixed Fe^{2+} - Fe^{3+} hydroxide with a larger specific surface area, which increases the adsorption of soluble P [24]. During flooding, the pH of acid soils increases, and the pH of alkaline soil decreases approaching neutral conditions [25]. Sah et al. reported that during flooding the Al-P fraction in soils decreased and the Fe-P fraction increased and that during draining Fe-P fraction decreased [9]. Olila et al. found that the amount of P released during flooding–draining periods was 2–4 times the amount released in continuously flooded conditions [26]. Twinch et al. reported that the biological availability of P decreased after draining [27]. During draining periods, some ferrous minerals were easily oxidized to amorphous iron oxide hydroxide, which has a higher adsorption capacity due to its larger specific surface area.

Previous research has reported transformations between inorganic and organic forms of P and changes in concentrations of soluble P in floodwater and subsurface water (0–20 cm) [10,15,18]. However, more studies need to focus on vertical P movement at depth in frequently flooded alkaline soils. The P transport in soil is closely related to the groundwater conditions. Phosphorus is readily accumulated deeper in the soil. Although its mobilization in soils is low due to high soil P adsorption capacity, more attention has been paid to the potential for P to pollute surface water and groundwater [28–30], especially in over-fertilized soils. Ding et al. used six different manure fertilizers to investigate P leaching risk and found that the risk of vertical P movement in the 20–40 cm soil depth increased when manure fertilization exceeded $7500 \text{ kg}\cdot\text{ha}^{-2}$ [30]. To address its contribution to eutrophication, agricultural non-point source P and its transport and transformation in rivers, lakes, wetlands, and agricultural soils have been studied [11,26]. However, little research has focused on P release and transformation in alkaline soils in flood zones. P release and transformations in flooded soils are considerably influenced by flood regimes. Therefore, we studied two types of fertilized soils, which were flooded, drained, and then reflooded, to investigate (i) the effects of long-term flooding, draining, and then reflooding on phosphorus release in different soil layers; (ii) the transformations of soil inorganic P fractions; and (iii) the relationships between Olsen P and DRP concentrations in pore water.

The objectives of our study were to determine how flood regimes affect transformations of P fractions and the potential relationships between pore water DRP and Olsen P in flooded alkaline soils. A second objective was to test the response of DRP concentration in floodwater and pore water to flood regimes.

2. Materials and Methods

2.1. Study Site

The soils used in this experiment were collected from Sanpu, in Xuzhou City, Jiangsu province, China ($34^{\circ}05' \text{ N}$, $117^{\circ}12' \text{ E}$, altitude 28.81 m) in the river floodplain and are subject to periodic flooding. The region is in the Huaihe River Basin, and has an average annual temperature of 14°C and precipitation of 860 mm. The soils are classified as Leptosols (fluvo-aquic soil) [31].

2.2. Soil Sampling and Preparation

Two types of soil were used in this experiment: a vegetable-growing soil and a wheat-growing soil. This experiment is for yearly soil fertilization when plants are not growing intensively. Soil samples were collected from six different depth intervals using core tubes: 0–5 cm, 5–15 cm, 15–25 cm, 25–35 cm, 35–45 cm, and 45–60 cm. Each sample consisted of six subsamples, which were mixed together and homogenized to obtain a single sample. A portion of each soil sample was air dried, passed through a 0.15-mm sieve. The remaining soil was used to fill the soil columns.

The soil columns were made of Perspex, with a height of 1 m and an internal diameter of 20 cm. They were filled with 45–60 cm, 35–45 cm, 25–35 cm, 15–25 cm, 5–15 cm, and 0–5 cm soils. To reduce the disturbance of the soil, the backfill soil was filled into the column according to the wet bulk density, which is 1.27–1.80 g/cm³. Below 45–60 cm, the soil was fine sandy, and its particle diameter was larger than that of the upper soils in the column. There was also a nylon wire netting between the 45–60 cm soil and fine sand. At the bottom of the sandy section, there was a water-tap to drain the column water.

2.3. Experimental Set-up

Two replicates of each soil were used and there were a total of four soil columns. Values are means of two replicates. Before flooding, the four columns were saturated with tap water from the bottom up to remove entrapped air. Next, fertilizer was added: 1.38 g KH₂PO₄ was dissolved in 4 L tap water, and this solution, in which the PO₄-P concentration was 34.5 mg/L, was put into the soil column. Three days later, we added tap water into the soil column until the water in the column was 20 cm deep. The soil columns were covered with a plastic cover to minimize evaporation and kept at room temperature (26 ± 2 °C).

Flooding, drying, and reflooding treatments were used to all soil columns: (i) long-term flooding-draining, which involved flooding the soil columns to a depth of approximately 20 cm for 35 days and then draining the floodwater and drying the soils for 13 days and (ii) reflooding, which involved reflooding the soil columns to the same depth of 20 cm for 16 days. Because of evaporation and water-sampling, 250 mL tap water was added into soil columns every 3 days during the flooding period.

During flooding and reflooding, pore water in each soil layer were collected with Rhizon samplers (Rhizosphere Research Products, Wageningen, The Netherlands) placed horizontally at 5, 10, 20, 30, 40, 50, and 60 cm depth in the soil profile. Rhizon samplers extract small volumes of pore water from soil, in an easy, non-destructive way. They are made of inert polymer with no ion exchange properties. Other advantages of Rhizons are their small diameter and low dead volume. The pore size of the porous part is 0.12–0.18 μm, hence filtering the samples before analyzing is unnecessary. Pore water samples were collected using these samplers every two or three days, and analyzed for pH, Eh, and DRP. Grab samples of standing flood water were collected manually during the flooded periods.

On the first day of draining and re-draining, soil samples were collected from each layer on one side of the soil column, opposite from the Rhizon samplers. Soil samples were air dried, sieved to 0.15 mm, and analyzed for TP, Olsen P, and inorganic phosphorus fractions.

2.4. Water and Soil Analysis

Soil samples were used to measure TP, Olsen P (soil available phosphorus), and inorganic P fractions. The analysis method of P forms in soil was given in Table 1. We used different extractant to analyze P forms and all extracted solutions were analyzed with molybdenum blue method [32]. The Olsen P was measured using the method described by Olsen [33]. The concentrations of inorganic P fractions were measured using methods described by Lu [34]. The soils were subjected to a sequential extraction: (i) Ca₂-P (CaHPO₄·2H₂O); (ii) Ca₈-P (Ca₈H₂(PO₄)₆·5H₂O); (iii) Al-P; (iv) Fe-P; (v) occluded P (O-P); and (vi) Ca₁₀-P (Ca₁₀(PO₄)₆(OH)₂).

Table 1. Analysis methods of P forms in soil.

P Forms in Soil		Extractant	Reference
TP		HNO ₃ , HClO ₄ , and H ₂ SO ₄ at a 3:1:1 ratio	[32]
Olsen P (soil available phosphorus)		0.5 M NaHCO ₃	[33]
inorganic P fractions	Ca ₂ -P (CaHPO ₄ ·2H ₂ O)	0.25 M NaHCO ₃ (pH 7.5)	[34]
	Ca ₈ -P (Ca ₈ H ₂ (PO ₄) ₆ ·5H ₂ O)	0.5 M H ₃ COONH ₄ (pH 4.2)	[34]
	Al-P	0.5 M NH ₄ F (pH 8.2)	[34]
	Fe-P	0.1 M NaOH-0.1 M Na ₂ CO ₃	[34]
	O-P (occluded P)	0.3 M Na ₂ S ₂ O ₄ -0.5 M NaOH	[34]
	Ca ₁₀ -P (Ca ₁₀ (PO ₄) ₆ (OH) ₂)	0.5 M H ₂ SO ₄	[34]

The contents of sand, silt, and clay were measured with a Laser particle size analyzer (LS-POP (6)); OMEC, Zhuhai, Guangdong, China). Soil samples were extracted by potassium dichromate and H₂SO₄ and then analyzed colorimetrically for organic matter [34]. Soil pH was determined in solution (1:1 soil/water) using a PHS-3C pH meter (Leici, Shanghai, China).

Floodwater was extracted with a 25-mL syringe, and pore water was extracted with Rhizon samplers. Then, water samples were filtered (0.45-µm membrane filters) and measured for pH, Eh, and DRP.

2.5. Statistical Analysis

SPSS 17.0 was applied for statistical analysis. Pearson correlations were used to discuss the relationship between floodwater P and pore water P.

3. Results and Discussion

3.1. General Soil Properties

Both soil types were alkaline, with pH values ranging from 7.31 to 7.96 (Table 2). According to the international classification of soil texture, both soils were silt loams at the 0–45 cm depth, whereas the 45–60 cm depth interval was a loam in the vegetable-growing soil (VS) and a sandy loam in the wheat-growing soil (WS). The clay content varied from 34.6% to 59.2% in VS and from 17.23% to 60.7% in WS and was higher in VS. Therefore, the specific surface area of VS was larger, and its P adsorption should be higher. TP, organic matter (OM), and Olsen P in both soils decreased progressively with soil depth. TP and Olsen P were higher in VS than WS. Furthermore, Olsen P in VS was 106.9–274.2 mg/kg at 0–35 cm. The content of Olsen P in surface soil was 79.87–210.32 mg/kg, which was higher than that in the research of Amarawansha et al. [18]. This will lead to increased soil P leaching into flood water and pore water and increased the risk of eutrophication of rivers and lakes from agricultural non-point source pollution.

Table 2. Properties of soils used in the study.

Soil Profile cm	pH	Total P g/kg	OM mg/kg	Olsen P mg/kg	Sand %	Silt %	Clay %
Vegetable-growing soil							
0–5	7.31	1.91	203.86	175.29	5.23	55.41	39.36
5–15	7.31	2.01	210.32	274.21	0.38	57.87	41.75
15–25	7.41	1.71	147.63	150.02	5.48	53.18	41.34
25–35	7.48	1.44	109.40	106.88	0.54	64.87	34.59
35–45	7.57	0.75	104.33	28.37	5.32	43.83	50.85
45–60	7.52	0.64	96.61	13.02	3.99	36.77	59.24
Wheat-growing soil							
0–5	7.62	1.13	188.11	92.50	9.77	73.00	17.23
5–15	7.64	1.06	82.12	79.87	9.60	72.85	17.55
15–25	7.83	0.62	34.60	48.19	12.00	75.05	12.95
25–35	7.90	0.55	26.17	35.95	6.82	73.62	19.56
35–45	7.96	0.54	58.78	15.93	4.65	54.46	40.89
45–60	7.96	0.58	24.48	10.88	5.35	33.98	60.67

3.2. Standing Floodwater P Following Long-Term Flooding, Draining, and Reflooding

Previous studies in flooded soils found that the P content of standing floodwater was low in unfertilized soils. Tian et al. found that in fertilized acid soils, the P content of floodwater was higher than in unamended soils [15]. Amarawansa et al. also found that the P content of floodwater and pore water in manured alkaline soil was significantly higher than in unamended alkaline soil [18]. The effects of long-term flooding, draining, and reflooding on pH, Eh, and DRP in floodwater are shown in Figures 1 and 2.

During the flooding period, floodwater pH increased significantly in both VS and WS, from 7.61 to 8.55 and from 7.48 to 8.35, respectively (Figure 1). Floodwater pH increased during the flooding and reflooding periods due to long-term exposure to the atmosphere [18]. After draining, the floodwater pH, which was initially higher than 8, decreased slightly during the reflooding period. Due to higher pH in floodwater, ion exchange occurred between OH⁻ and phosphate in soils, which released P into floodwater. Floodwater Eh of both soils decreased over time during flooding, which led to the release of P banded by iron [21,23,35].

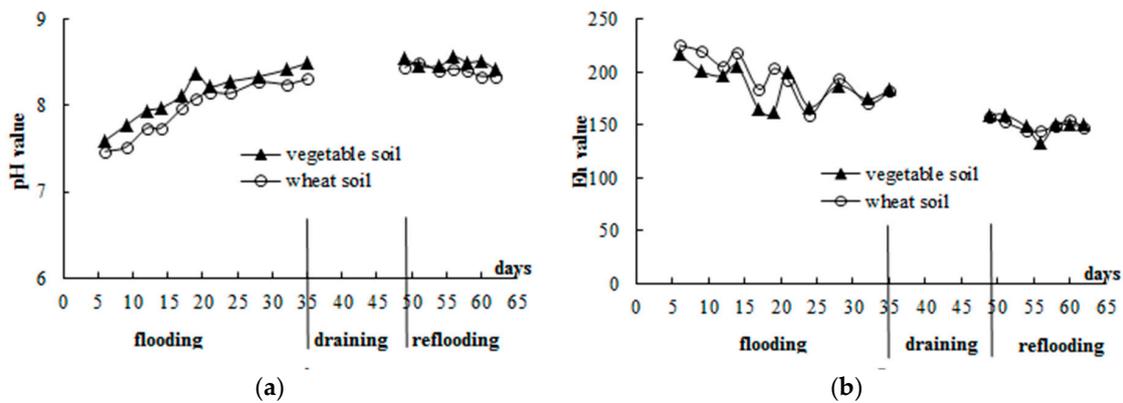


Figure 1. pH and Eh in floodwater ((a) pH changes; (b) Eh changes).

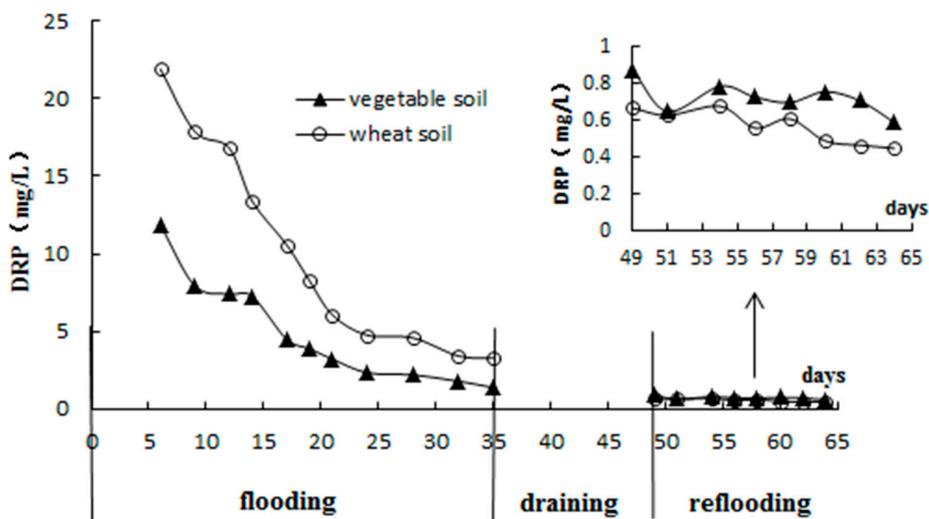


Figure 2. Changes of floodwater DRP in VS and WS over time (flooding period: days 0–35; draining period: days 36–48; reflooding period: days 49–64).

During the flooding period, the DRP concentrations in floodwater decreased significantly over time, likely due to the effect of soil adsorption. In the early period, the concentration of DRP was high: 11.88 mg/L and 21.92 mg/L in VS and WS, respectively. However, it was only 1.39 mg/L and 3.28

mg/L, respectively, on day 35. DRP decreased 88.3% in VS and 85.0% in WS. The result was consistent with those of Amarawansha et al. [18] but different from those of Tian [36]. Tian et al. found that DRP in floodwater decreased with time of flooding in amended acid soils. While, Amarawansha et al. found that DRP in surface floodwater increased within a few weeks of flooding, reached a peak, and then decreased slightly with time of flooding in most amended soils [18]. This could be a result of differences in fertilizing methods or maybe the soil texture and characteristics. In the experiment of Amarawansha, soils were amended first and then kept at room temperature for 4 weeks with field moisture before flooding. So, amended P was mostly adsorbed by soils in the early days and then released with the flooding days. In contrast, in our experiment the soils were amended by KH_2PO_4 solution for 3 days and then flooded to simulate the effect of flooding on soils. Within a few weeks of flooding, DRP in floodwater decreased. This could be the result of soil adsorption, and adsorption was likely the dominant process.

During the flooding period, DRP was higher in WS than in VS at the same fertilization rate. This meant that the P adsorption capacity was higher in VS than in WS, which could be due to the higher clay content of VS and thus larger specific surface area, or maybe because of metal ions, such as Fe, Al and Ca et al. [11,37]. During reflooding, DRP concentrations in standing floodwater on both soils were less than 0.87 mg/L, which was 3–25 times less than those during the flooding period (Figure 1). DRP increased slightly during reflooding. It was probably because of P being released into floodwater by soil. Furthermore, DRP concentrations were higher in VS than in WS during reflooding. That was to say that P content release from VS was more than that from WS. So, it could be noted that the ability of VS to release P was greater than that of WS.

3.3. Phosphorus Distribution in Pore Water

Regardless of WS or VS, DRP concentrations in floodwater and pore water were positively correlated ($r = 0.41\text{--}0.81$, $p = 0.01$) (Figure 3). During both flooding and reflooding periods in WS, floodwater DRP was higher than pore water DRP at 5 cm, which induced P diffusion from floodwater to pore water. In contrast, in VS, pore water DRP was higher than floodwater DRP after 28 d of flooding, including during reflooding. There was efficient P diffusion from pore water to floodwater as was also shown by Young et al. [10] and Amarawansha et al. [18]. Young and Ross found that pore water P increased with increasing Fe^{2+} concentration. This was because Fe-P in flooded soil dissolved under anaerobic conditions, which promoted P release into pore water [38–40].

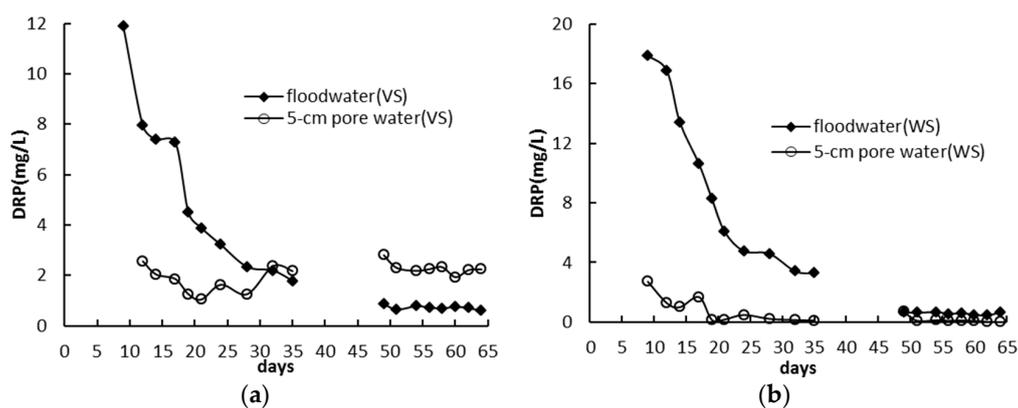


Figure 3. Changes of DRP in floodwater and surface pore water over time ((a) VS; (b) WS; flooding period: days 0–35; draining period: days 36–48; reflooding period: days 49–64).

During reflooding, DRP in pore water decreased over time. In both WS and VS, DRP in pore water decreased gradually along the soil profile. The effect of diffusion was less during the reflooding period than during the flooding period because of the lower DRP concentration in floodwater. Pore water DRP was lower during the reflooding period than during the flooding period. The observed pattern

was very different in VS. Furthermore, pore water DRP was higher in VS than in WS. Those differences were probably due to differences in soil adsorption and desorption.

On day 12 of flooding, a higher DRP concentration was observed in pore water at 5 cm and 30 cm, both of which decreased on day 19. In contrast, DRP at 10 cm and 40 cm increased on day 19. There was an opposite trend of DRP between days 12 and 19. There was a higher DRP concentration on day 28 in 20-cm pore water, which was greater than that on days 12 and 19. In contrast, DRP in pore water at the 30–60 cm soil depth was very low and was the same on day 35. Regardless of the flooding treatment, DRP in pore water decreased at the end of flooding.

In VS, after 19 d of flooding, pore water DRP was highest at 5 cm (greater than 1 mg/L), and relatively lower at 20 cm and 60 cm (less than 0.5 mg/L; Figure 4). DRP decreased over time during flooding except at 10, 40, and 50 cm. The slow diffusion of P was also observed. For example, DRP at 5 cm decreased over time during flooding, whereas DRP at 10 cm increased. There was diffusion of P from 5 cm to 10 cm due to a concentration gradient. Under fertilized and flooded conditions, the risk of vertical P movement was increased.

Floodwater DRP was higher in WS than in VS during the flooding period. Due to its larger surface area, P adsorption and release capacities were greater in VS than WS (Tables 1 and 2). During the reflooding period, pore water DRP in WS was relatively lower, which may be due to the effect of soil texture. Clay content was higher in VS than in WS. The porosity of VS was relatively uniform, which promoted P diffusion.

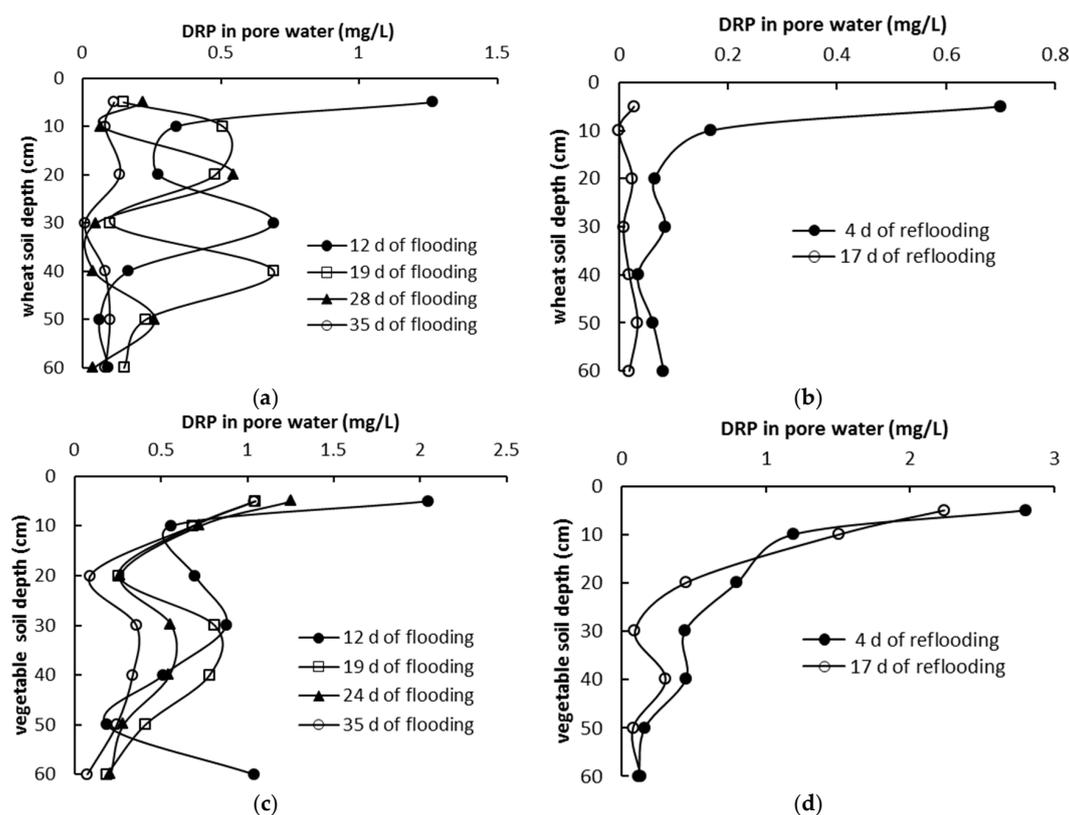


Figure 4. Pore water DRP in different soil layers ((a) WS, flooding; (b) WS, reflooding; (c) VS, flooding; (d) VS, reflooding).

3.4. Soil P Following Long-Term Flooding, Draining, and Reflooding

The soil O-P fraction was the smallest inorganic P fraction in both soils (less than 35 mg/kg), followed by Fe-P and Al-P, which accounted for 2.6–14.3% and 3.0–13.1% of total inorganic P, respectively (Figure 5). Total Ca-P ranged from 67.7% to 91.1%. Ca-P was the dominant fraction

in alkaline soils, and Ca compounds in alkaline soils played an important role in P retention and most of inorganic P was bound to Ca compounds [41,42]. The highest concentration of the Ca₁₀-P fraction (37.1–70.0% of total inorganic P) was observed in WS. The largest fraction in VS was Ca₈-P (14.2–51.0%), followed by Ca₂-P and Ca₁₀-P. As a result of long-term fertilization and irrigation, total inorganic P content was significantly higher in VS than in WS (0.37–1.71 g/L and 0.38–0.68 g/L, respectively). In both WS and VS, inorganic P fractions decreased along the soil profile. The highest concentrations of inorganic P were observed at 0–10 cm.

After the KH₂PO₄ solution was added, the Al-P and Ca₁₀-P fractions increased during the flooding period, but other soil P fractions decreased in WS (Figure 5). The Al-P content during the flooding and reflooding periods was 1.7–118.9% higher than before flooding. During both flooding and reflooding periods, Ca₈-P was 31.9–88.9% and 45.6–93.5%, respectively, lower than before flooding. Except at 30 cm and 40 cm, Ca₁₀-P was 14.6–61.9% and 10.8–56.5%, respectively, higher than before flooding.

A different pattern was observed in VS (Figure 5). The Al-P and Ca₈-P fractions increased, while other P fractions decreased. The Al-P content during the flooding and reflooding periods was 18–97% more than that before flooding. During both flooding and reflooding periods, Ca₈-P at 10–40 cm was 16–64% and 11–27% higher, respectively, than before flooding. Ca₁₀-P at 20–40 cm was 7–17% lower than before flooding but increased at 5, 10, 50, and 60 cm.

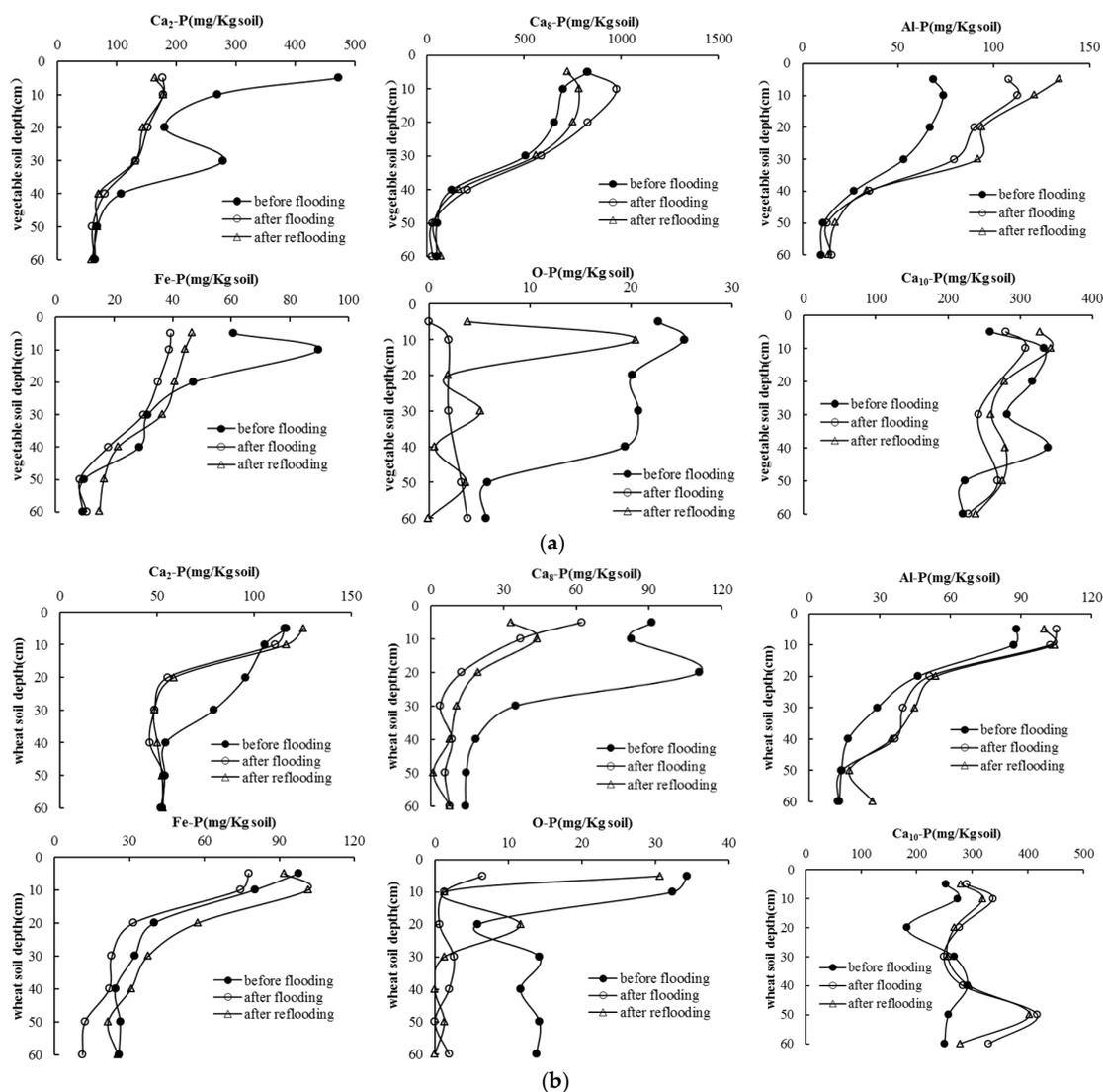


Figure 5. Inorganic phosphorus fractions in different soil layers ((a) VS; (b) WS).

The increased concentrations of Al-P, Ca₈-P, and Ca₁₀-P may be due to fertilizer inputs and transformations among these fractions. After fertilizing, DRP was tied up by Al and Ca, which increased the concentrations of Al-P and Ca-P. Flooding and draining changed conditions in the soil–water system, which greatly affected the transformations among inorganic phosphorus fractions, especially calcium phosphate. Ca₂-P and Ca₈-P were the effective P sources in alkaline soils and were readily soluble [43]. Leher et al. [44] and Lindsay et al. [45] reported that calcium phosphate occurred mainly as Ca₂-P, Ca₈-P, and Ca₁₀-P. Ca₂-P can transform into Ca₈-P, and Ca₈-P can transform into Ca₁₀-P. The increase in Ca₁₀-P in WS may be due to the transformation of Ca₂-P and Ca₈-P. However, total Ca-P at 0–30 cm in both soils decreased slightly after reflooding, compared to flooding.

In both soils, Fe-P decreased after flooding. When soil is subjected to reducing conditions, Fe³⁺ is reduced to Fe²⁺, and the associated phosphorus is released, so Fe-P decreases [21,23,36]. After 10 d of draining, the concentrations of Fe-P, Al-P, and O-P during the reflooding period were greater than those during the flooding period. Several studies have examined P transformations in flooded-drained soils [9,14,40,46,47]. Furthermore, Ca-P was different in the four soils and increased only in the soil with high initial Ca-P. The differences in these findings may be due to differences in soil management, fertilizer type, incubation length, and initial soil characteristics.

3.5. Relationships between Olsen P and Dissolved P in Pore Water

Olsen P is an important index for evaluating the capacity of a basic (high pH) soil to supply P, and it can predict P losses to surface water and groundwater [48,49]. Changes in Olsen P are shown in Figure 6. The initial Olsen P concentration was higher in VS than in WS: 12.0–274.2 mg/kg versus 10.1–92.5 mg/kg. In both soils, Olsen P was highest at 0–10 cm and decreased with depth. After flooding and reflooding, Olsen P increased in VS at all soil depths. Olsen P was lower after reflooding than after flooding, except at 0–20 cm. In WS, Olsen P increased after flooding and reflooding (relative to initial values) at 0–20 cm but decreased below 20 cm. Furthermore, Olsen P was higher after reflooding than after flooding.

Olsen P is also a good index for representing soil nutrient status of high pH soils [47]. According to the UK Agricultural Development and Advisory Service (ADAS), Olsen P concentrations greater than 46 mg/kg indicate a high nutrient status [50]. Figure 6 shows that Olsen P at 0–20 cm in WS and 0–40 cm in VS was greater than 46 mg/kg, which indicated a high P status. Relationships between Olsen P and DRP in pore water can be seen in Figure 7. When Olsen P in VS exceeded 180.7 mg/kg, and when Olsen P in WS exceeded 40.8 mg/kg, the concentration of P in pore water increased significantly, which increased the risk of P leaching. When Olsen P was accumulated to a certain degree, the release of soil P into floodwater and pore water would reach a threshold value. Edwards et al. proposed the concept of the break point of soil P [51], which has been studied by many researchers from North America and Europe [52]. When Olsen-P exceeds this break point, the release of P into floodwater and pore water would increase significantly.

The critical depth in VS for the risk of soil P release was 50 cm during flooding and 28 cm during reflooding. The critical depth in WS was 18 cm during flooding and 20 cm during reflooding (Figure 7). The ability of VS to release P was greater than that of WS during flooding. In VS, the risk of P release may increase during flooding, whereas it may decrease during reflooding after draining. Wright et al. also found that P availability was significantly higher in flooded soils and decreased after draining [53]. Olsen P at 20–60 cm decreased during flooding and reflooding. This was due to P re-adsorption by amorphous Fe and Al minerals [54]. Below this critical depth, the risk of P release may increase significantly. This could accelerate the transport of pore water P to deeper soils and increase the likelihood of groundwater P pollution.

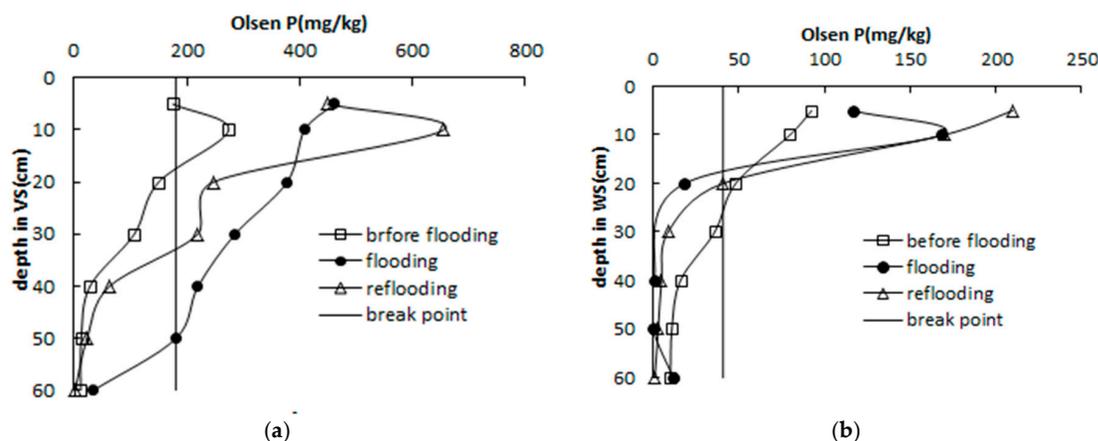


Figure 6. Changes in Olsen P before and after flooding and reflooding ((a) Olsen P in VS; (b) Olsen P in WS).

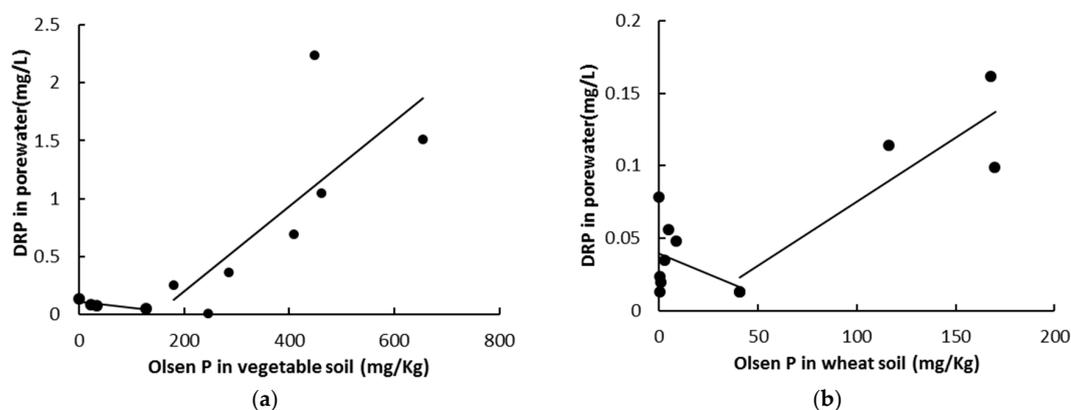


Figure 7. Relationships between Olsen P and DRP in pore water ((a) VS; (b) WS).

4. Conclusions

Based on the results of this study, we concluded that flood regimes strongly influence P release and transformations in flooded soils. Under flooded conditions, DRP in floodwater decreased significantly. During all periods, the concentration of DRP in pore water was highest at 5 cm soil depth. Under fertilized and flooded conditions, the risk of vertical P movement in 10–50 cm soil depth was increased. Flooding increased the concentration of Al-P and decreased the concentrations of Fe-P, O-P, and Ca₂-P. Reflooding increased the concentrations of Fe-P, Al-P, and O-P. Olsen P was closely related to DRP in pore water. When Olsen P exceeded 180.7 mg/kg in VS and 40.8 mg/kg in WS, the release of soil P into floodwater and pore water increased significantly.

These findings have substantial implications in understanding how flooding and draining affect soil P release and transformations in flood zones. After fertilizing and then flooding, vertical P movement increased at deeper soil depths, which increased the potential for groundwater pollution. Further research is needed to better estimate the P loss potential, P vertical diffusion, and its contributions to eutrophication.

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Abbreviations

P	phosphorus
TP	total phosphorus
DRP	dissolved reactive phosphorus
Al-P	aluminum-P, extracted with 0.5 M NH ₄ F
Fe-P	iron-P, extracted with 0.1 M NaOH-0.1 M Na ₂ CO ₃
Ca ₂ -P	CaHPO ₄ ·2H ₂ O, extracted with 0.25 M NaHCO ₃
Ca ₈ -P	Ca ₈ H ₂ (PO ₄) ₆ ·5H ₂ O, extracted with 0.5 M H ₃ COONH ₄
Ca ₁₀ -P	Ca ₁₀ (PO ₄) ₆ (OH) ₂ , extracted with 0.5 M H ₂ SO ₄
O-P	occluded P
Olsen-P	extracted with 0.5 M NaHCO ₃
VS	vegetable-growing soil
WS	wheat-growing soil
OM	organic matter

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