RESEARCH PAPER

Effects of Shallow Water Table Depth on Vegetative Filter Strips Retarding Transport of Nonpoint Source Pollution in Controlled Flume Experiments

Ran Li[1] · Yi-Ming Kuo[2]

Abstract

Vegetative filter strips (VFSs) have been recommended as the best management practice for reducing runoff nonpoint source (NPS) pollution. The efficiency of VFSs located adjacent to water bodies can vary with shallow water table depths (WTD). A vegetated soil tank containing silt loam soil and Shortleaf Lilyturf vegetation was designed to study the effects of VFSs under shallow WTD (0.08, 0.22, and 0.36 m) on retentions of surface runoff, sediment, phosphorus, and bromide. Experiments were conducted with a simulated rainfall intensity of 28 mm h^{-1} and inflow rates of 4.02–4.56 L min^{-1}. The results revealed that a deep WTD, low grass spacing, and low slope had high VFS retention efficiencies. The retention efficiencies varied greatly from 35%, 70%, 64%, and 55% at the 0.08-m WTD in the experimental group with high grass spacing (6.69 cm) and low slope (5%) to 96%, 98%, 96%, and 95% at the 0.36-m WTD in the experimental group with low grass spacing (4.18 cm) and low slope (5%) for surface runoff, sediment, phosphorus, and bromide, respectively. A steeper slope (at the same grass spacing) increased the effects of the WTD on VFS performance. For each experimental group, the average surface runoff outflow rate decreased with the WTD, whereas the average subsurface lateral flow rate increased. The transport of phosphorus in the surface runoff almost resembled that of bromide, and the average concentration ($C/C_{0\ \text{Ave}}$) of phosphorus and bromide decreased with the WTD. For the subsurface lateral flow, the transport of bromide and phosphorus exhibited typical breakthrough behaviors during each experiment, and both the normalized phosphorus and bromide concentrations in increasing limbs could be described by power equations. The high concentration of pollutants in the subsurface lateral flow may have affected the adjacent water bodies and groundwater. In quantification of the impact of WTD on effectiveness of VFS, we can effectively control the NPS pollutants in a watershed.

Article highlights

- **VFS with deep WTD, low grass spacing, and low slope was beneficial for reducing NPS.**
- **At the same grass spacing, a steeper slope increased the effects of the WTD on VFS performance.**
- **The solute concentrations in increasing limbs can be described by power equations.**

✉ Ran Li
r1028601357@163.com

✉ Yi-Ming Kuo
airkuo@ntu.edu.tw

1   School of Water Resources and Environmental Engineering, East China University of Science and Technology, Nanchang 330013, China

2   School of Environmental Studies, China University of Geosciences, Wuhan 430074, China

Introduction

Nonpoint source (NPS) pollutants (phosphorus, nitrates, pesticides, pathogens, organic matter, colloids, and metals) severely threaten ecological environments and water resources (Arora et al. 1996; Withers and Haygarth 2007; Rasmussen et al. 2011; Yu 2012; Wu et al. 2014; Muñoz-Carpena et al. 2018). Rivers and streams in China are deteriorating because of the extensive use of fertilizers and

pesticides, which is severely affecting human health. Thus, the Chinese government and researchers have focused on the management of water resources to control NPS pollutants.

Vegetative filter strips (VFSs), defined as vegetative areas situated downslope of agricultural lands, have been recommended as the best management practice for controlling NPS pollutants (Abu-Zreig et al. 2004; Dosskey et al. 2007; Kuo and Muñoz-Carpena 2009; Fox et al. 2018). VFSs are widely used in the United States and Europe, and they are relatively cost effective and require little maintenance other than biomass harvesting. VFSs reduce the transport of sediment and pollutant loading to nearby surface water bodies primarily through interception, infiltration, deposition, adsorption, and absorption (Muñoz-Carpena et al. 1999; USDA 2000; Dorioz et al. 2006; Blanco and Lal 2008; Kuo and Muñoz-Carpena 2009; Giri et al. 2010; Muñoz-Carpena et al. 2010; Yang et al. 2015).

The effectiveness of VFSs in reducing NPS pollutants transport depends on the characteristics of the VFSs (width, slope, vegetation, height, and density), inflow (runoff volume and velocity), rainfall intensity, and soil properties (pH, moisture, and particle size) (Reichenberger et al. 2007; Liu et al. 2008; Kuo and Muñoz-Carpena 2010; Lambrechts et al. 2014; Rahman et al. 2014). Sediment retention efficiency increases logarithmically with an increase in vegetation density (Abu-Zreig et al. 2004). A plant's morphology and growth dynamics also influence the sediment and total phosphorus (TP) retention efficiencies (Krutz et al. 2005; Xiao et al. 2011). A VFS with a slope between 3 and 12% was reported to reduce sediment by 79–56% (Wang et al. 2008), and a lower slope resulted in a higher retention effect of total nitrogen and TP (Pan and Deng 2003). Researchers have reported that the effect of rainfall intensity was considerably greater than that of the inflow rate on the sediment transport rate (Guy et al. 1987; Wen et al. 2015).

Riparian VFSs are located along river networks or streams, where shallow groundwater tables are frequently present (Reichenberger et al. 2007; Lacas et al. 2012; Carluer et al. 2017). A shallow groundwater table affects the surface hydrological response of a VFS by generating soil water saturation during rainfall, which limits the infiltration capacity of a VFS (Lauvernet and Muñoz-Carpena 2018). Without a shallow groundwater table in fine soils, the effectiveness of a VFS in reducing NPS pollutants is typically controlled by excess rainfall (Shin and Gil 2014). With a shallow groundwater table, the length of a VFS and the soil characteristics dominate the VFS' surface hydrological response (Carluer et al. 2017). Simpkins et al. (2002) reported that the position of the water table in thin-sand aquifers underlying a VFS was probably the most pertinent factor for determining VFS performance. Dosskey et al. (2001, 2006) also reported that runoff pollutants can interact with a VFS root zone in a shallow groundwater table

(< 1.8 m). Lauvernet and Muñoz-Carpena (2018) found that the runoff and pesticide retentions of a VFS were sensitive to a shallow water table depth (WTD) within a certain range (0–1.5 m from the surface based on the soil characteristics in their study). Moreover, variations in shallow WTD, which influence how the zones of aeration and saturation are distributed in subsurface soil, play a critical role in controlling nutrient cycling in soils and influencing the qualities of groundwater and adjacent streams (DeVito et al. 2000; Hill et al. 2004; Schilling and Jacobson 2014). Fox et al. (2018) called for further research on VFS effect on sediment and nutrient trapping efficiency under shallow water tables, indicating the relevance of quantifying the effect of shallow groundwater tables on the effectiveness of VFSs.

Infiltrated water in a VFS may accumulate and divert laterally downslope to rivers when it meets a shallow groundwater table (Newman et al. 1998; Zhang et al. 2011; Carluer et al. 2017). This lateral diversion of water flow is known as subsurface lateral flow. Numerous studies have confirmed that subsurface lateral flow is vital to hydrological response and chemical transport across the soil profile (van der Velde et al. 2010; Peyrard et al. 2016). Subsurface lateral flow may affect surface water quality when the adsorbed nutrients leach from the subsurface soil inducing by a rise of groundwater table. Thus, the pollution of subsurface lateral flow toward a stream should also be considered.

This study sought to quantify the effect of a shallow groundwater table on VFS efficiency for retarding the transport of runoff, sediment, phosphorus, and bromide in different grass spacings and slopes. A controlled vegetated soil tank with silt loam soil was placed under a laboratory rainfall simulator to (1) assess the retention efficiency of surface runoff, sediment, phosphorus, and bromide, (2) analyze both the similarities and differences in the transport behavior of phosphorus and bromide in the surface runoff and subsurface lateral flow, and (3) study the transport mechanisms of phosphorus and bromide in the subsurface lateral flow.

Materials and Methods

Laboratory Experimental System

A vegetated soil tank (2 m long, 1 m wide, and 0.6 m deep), placed on a metal shelf with an adjustable slope, was designed to evaluate the effect of a shallow groundwater table on VFS efficiency for retarding the transport of runoff, sediment, phosphorus, and bromide in different grass spacings and slopes (Fig. 1). The 2.0-m length fell within the range of VFS flow lengths reported in previous field and laboratory studies: 0.5 m to 29 m VFS lengths were reported by Sabbagh et al. (2009) and Poletika et al. (2009); 2.0 m length was used by Fox et al. (2018) in laboratory experiment. A
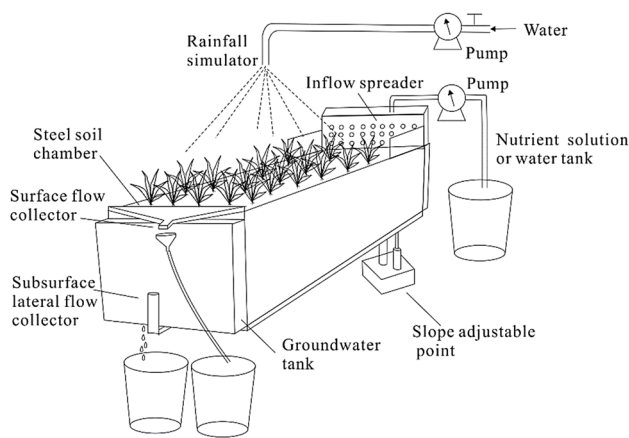
Fig. 1 Schematic of the laboratory runoff experimental system containing the collectors for the surface and subsurface lateral flow

water tank (0.2 m × 1 m × 0.5 m) on the lower side of the soil chamber was used to control the groundwater table. Silt loam soil (15.08% clay, 62.47% silt, and 22.45% sand based on the hydrometer method) was packed into the chamber to a bulk density of 1.28 g cm^{-3}. The tested soil was collected at a 0–20 cm depth from a field near the Hanbei River, Hubei Province, China. To represent a typical riparian vegetation in the Jianghan Plain, Shortleaf Lilyturf was established in the laboratory soil tank.

A peristaltic pump system and a polytetrafluoroethylene tube with uniformly distributed small holes were placed at the upper end of the soil tank to deliver runoff with given concentrations of sediment, phosphorus, and bromide. The VFS experienced a step inflow hydrograph with typical inflow rates of 4.02–4.56 L min^{-1}. Such step inflow hydrographs are commonly used to simplify the experimental procedures in VFS studies. For example, see Sabbagh et al. (2009) for a review of several such studies and Fox et al. (2018) for controlled laboratory experiments.

A rainfall simulator, set at 3.2 m above ground, used a peristaltic pump to supply a constant rainfall intensity of 28 mm h^{-1} for all the experiments, which represented the average rainfall on the Jianghan Plain, Hubei Province, China (Zhou 2009; Kuo et al. 2019). A rain gauge (TE525 tipping bucket rain gauge, Texas Electronics, Dallas, TX, USA) was installed between the rainfall simulator and the soil box to measure the rainfall intensity.

Experimental Design

The study contained nine experimental treatments (three experimental groups × three WTDs). The three experimental groups were performed with different grass spacings, which were obtained using Eq. (1) (Muñoz-Carpena 1993):

$$G_s = 100\sqrt{\frac{1}{D_s}}, \tag{1}$$

where G_s is the grass spacing (cm) and D_s is the grass density (stems m^{-2}),

and slopes (grass spacing and the slope for G7S05 were 6.69 cm and 5%, grass spacing and the slope for G4S05 were 4.18 cm and 5%, and grass spacing and the slope for G4S15 were 4.18 cm and 15%). Experiments with 0.08-m, 0.22-m, and 0.36-m WTDs were performed for each experimental group. For each treatment, the prepared nutrient solution (the concentrations of sediment, phosphorus, and bromide were 0.20 g s^{-1}, 0.70 mg L^{-1}, and 10.00 mg L^{-1}, respectively) was introduced to the inflow spreader (the running time depends on the results of the adsorption kinetic experiment), and then, the inflow was switched to tap water at the same inflow rate for another 30 min. Water samples from the surface runoff outflow and subsurface lateral flow were collected every 5 min. The volumes of the water samples were used to calculate the surface runoff and subsurface lateral flow rates, and the sediment concentration was measured using the evaporation method at 105 °C. The TP concentration (ppm) was analyzed using the potassium persulfate oxidation–molybdenum antimony colorimetric method (UV-1800 spectrophotometer, SHJH Company, Shanghai, China). Bromide (Br$^-$) was applied to all the runs as a conservative solute, and the bromide concentration (ppm) in the water samples was measured using an ion chromatograph (CIC100, SHINEHA, Qingdao, China). The retention efficiency is the ratio (%) between the trapped mass and the total mass in the inflow. Duplicated samples were collected and average breakthrough concentrations are reported.
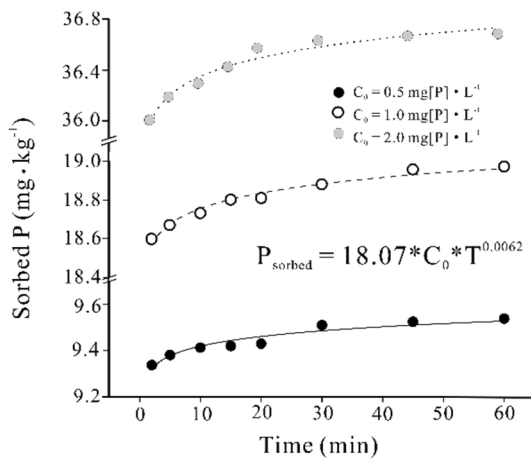
Adsorption Experiment

The soil samples were collected from soil chamber. All samples were air dried and then passed through a 0.15 mm sieve. Phosphorus adsorption kinetics analyses were conducted by mixing the dried soil samples (~ 1.0 g) and 20-mL 0.01 M KCl solutions containing 0.5, 1.0, and 2.0 mg[P] L^{-1}, which were added to a series of 50-mL acid-washed centrifuge tubes. The samples were taken at different time intervals (0, 2, 5, 10, 15, 20, 30, 45, and 60 min from the start of the experiment, respectively). After centrifugation at 5000 rpm for 20 min, the supernatants were filtered through a 0.45-μm membrane filter immediately to analyze the phosphorus concentration. The phosphorus adsorbed in the soil samples was calculated using the difference between the initial and final phosphorus concentrations in the solution.

Statistical Analysis

Spearman's rank correlation coefficient was used to evaluate the statistical dependence between the sediment yield, surface runoff volume, and peak flow rate, as well as between the bromide and phosphorus in the outflow. Regression analysis was used to study the relationships of normalized bromide and phosphorus concentrations with time in the subsurface lateral flow.

Results and Discussion

Figure 2 shows the phosphorus adsorption of the experimental soil included quick and slow adsorption steps (Zhang et al. 2011). The quick adsorption rate mainly occurred within 30 min, and it was then followed by a slow adsorption reaction. The adsorption and desorption of phosphorus between solid and liquid reached dynamic equilibrium within first 60 min. According to the results, the prepared

$$P_{sorbed} = 18.07 * C_0 * T^{0.0062}$$

Legend:
- ● $C_0 = 0.5 \, mg[P] \cdot L^{-1}$
- ○ $C_0 = 1.0 \, mg[P] \cdot L^{-1}$
- ● (gray) $C_0 = 2.0 \, mg[P] \cdot L^{-1}$

Fig. 2 The measured adsorption kinetics for different initial phosphorus concentrations

nutrient solution was introduced to the inflow spreader for 60 min, and then was switched to tap water.

Table 1 shows the effects of the different shallow WTDs on VFS retention efficiencies in surface outflow, sediment, phosphorus, and bromide for the nine experimental treatments. The retention efficiencies varied greatly from 35%, 70%, 64%, and 55% to 96%, 98%, 96%, and 95% for surface runoff, sediment, phosphorus, and bromide, respectively. The lowest retention occurred at a 0.08-m WTD in the group with high grass spacing (G7S05), whereas the highest retention occurred at a 0.36-m WTD in the group with low grass spacing and a low slope (G4S05). The deep WTD, low grass spacing, and low slope had high VFS retention efficiencies. For example, the surface runoff retentions were 35%, 44%, and 64% in G7S05 and 71%, 76%, and 96% in G4S05 for WTDs of 0.08 m, 0.22 m, and 0.36 m, respectively. The large variations in the VFS retention efficiencies among the different WTDs revealed the importance of the groundwater table on VFS performance. When compared with the experimental group (G4S05), the steeper slope in G4S15 (at the same grass spacing) increased the effects of the WTD on VFS performance.

We hypothesized that the phosphorus sorption is not inhibited by the saturation of the soil media and its adsorbed phosphorus would not accumulate in the VFS soil. The predictive equation for the TP and bromide retention efficiencies (TP_{ret}, Br^-_{ret}) was based on the runoff retention efficiencies (Q_{ret}, %) and sediment retention efficiencies (Sed_{ret}, %) (Eqs. 2 and 3) in the study treatments without high initial phosphorus and bromide concentrations in the VFS soil. Figure 3 shows the relationship between the predicted and observed retentions of TP and bromide:

$$TP_{ret} = 54.5 + 0.76 \times Q_{ret} - 0.32 \times Sed_{ret} \quad R^2 = 0.98, \quad (2)$$

$$Br^-_{ret} = -12.4 + 0.73 \times Q_{ret} + 0.40 \times Sed_{ret} \quad R^2 = 0.95, \quad (3)$$

Table 1 Measured (a) surface runoff (Q_{ret}), (b) sediment (Sed_{ret}), (c) phosphorus (TP_{ret}), and (d) bromide (Br^-_{ret}) retention efficiencies (%) in G7S05, G4S05, and G4S15 (grass spacing and the slope for G7S05 were 6.69 cm and 5%, grass spacing and the slope for G4S05 were 4.18 cm and 5%, and grass spacing and the slope for G4S15 were 4.18 cm and 15%)

Experimental group	WTD (m)	Initial soil water content ($m^3 \, m^{-3}$)	Q_{ret} (%)	Sed_{ret} (%)	TP_{ret} (%)	Br^-_{ret} (%)
G7S05	0.08	36.4	35	70	64	55
	0.22	34.6	44	72	68	62
	0.36	28.8	64	79	88	73
G4S05	0.08	37.4	71	91	83	75
	0.22	34.5	76	92	84	83
	0.36	28.3	96	98	96	95
G4S15	0.08	38.4	31	71	41	34
	0.22	36.7	66	80	82	53
	0.36	26.9	83	87	94	79
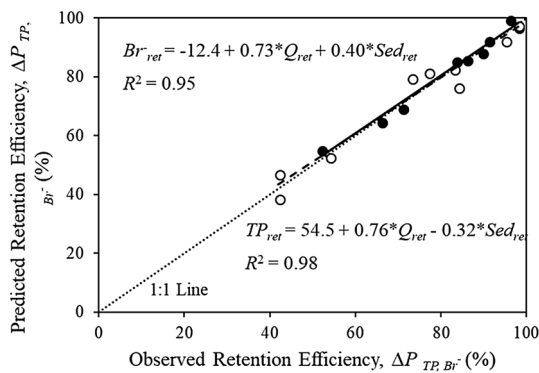
Fig. 3 Predicted versus observed retentions (%) of TP and bromide when using a multiple linear regression model based on the runoff retention efficiencies (Q_{ret}, %) and sediment retention efficiencies (Sed_{ret}, %) in the study treatments

where Q_{ret} (%) and Sed_{ret} (%) were defined as the total mass input to the VFS minus the mass in the runoff efflux from the VFS divided by the total mass input. A multiple linear regression model, similar to that proposed by Fox and Penn (2013), was developed for quantifying the TP trapping efficiency of the VFSs. The proposed equation provided an opportunity to evaluate the performance of a VFS installed in areas with shallow groundwater tables and to design a VFS for specific retention efficiency objectives.

Shallow WTDs Affected the Hydrologic and Sedimentological Responses

The 0.08-m, 0.22-m, and 0.36-m WTDs distinctly influenced the surface runoff flow and subsurface lateral flow (Fig. 4). The average surface runoff outflow rate was less than the inflow rate, and was typically between 37 and 69% of the inflow rate in the high grass spacing (G7S05) (Fig. 4a; Table 2). The reason why the normalized surface runoff outflow decreased with WTD might be related to the capillary action above the shallow WTD in the soil, which moved groundwater from wet areas to dry areas in the soil, filled the soil pore space, and decreased the runoff infiltration rate (Carluer et al. 2017). However, the relatively low capillary zone and unsaturated soil condition in the deep WTD (0.36 m) resulted in a high infiltration rate and low surface runoff outflow rate. Conversely, the moving average subsurface lateral flow rate increased from 0.27% to 0.53% of the inflow rate when the WTD decreased from 0.08 to 0.36 m (Fig. 4d; Table 2).

The surface runoff flows for the 0.08-m and 0.22-m WTDs occurred within 4 and 5 min, respectively, after the start of the nutrient solution application, which were much earlier than the occurrence time for the 0.36-m WTD, which took more than 15 min in G7S05 (Table 2). This phenomenon indicated that the WTDs influenced the occurrence

time of the surface runoff by affecting the infiltration capacity. The results may also be related to the initial soil water content. The initial soil water content at the WTD of 0.36 m was 28.8% in G7S05, which was lower than those of the 0.08-m and 0.22-m WTDs (36.4% and 34.6% in G7S05, respectively). At the early stages of the experiments under low initial soil water content conditions, the infiltration rates were equal to or exceeded the inflow rate. As the experiments progressed and the soil became wetter, the infiltration rates decreased and the surface runoff occurred (Cardoso et al. 2012).

In addition to WTD, the grass spacing and slope also influenced the hydrology responses and sediment retention efficiencies (Table 1). For the same WTD, the occurrence time of the surface runoff outflow in G4S05 was later than that in G7S05, and the surface runoff outflow rate in G4S05 was lower than that in G7S05, whereas the subsurface lateral flow rate in G4S05 was higher than that in G7S05 (Fig. 4b, e; Table 2). The plant roots in the VFSs increased the soil surface Manning's roughness and soil permeability, which enhanced the runoff infiltration rate, reduced the surface runoff velocity, and promoted sediment deposition (Schiettecatte et al. 2008; Zhang et al. 2011; Cardoso et al. 2012; Wang et al. 2014; Wu et al. 2014; Zhao et al. 2016). Compared with the hydrologic response in G4S05, for the same WTD, the surface runoff outflow in G4S15 occurred sooner and the average surface runoff outflow rate in G4S15 was higher, whereas the average subsurface lateral flow rate in G4S15 was lower (Fig. 4c, f; Table 2). A steep slope, which decreases runoff infiltrating time and sediment depositing time, causes a large transport capacity for overland flow and reduces residence time of surface runoff on soils (Gumiere et al. 2011). Therefore, at the same WTD, the low grass spacing and low slope had high surface runoff retentions (a low surface runoff outflow rate and high subsurface lateral flow rate).

Runoff sediment retention efficiencies in the VFSs increased with a deep WTD (e.g., 70%, 72%, and 79% at WTDs of 0.08 m, 0.22 m, and 0.36 m, respectively, in G7S05) for the relatively low flow conditions experienced, which resulted in a low flow transport capacity and a high sediment deposition. The low grass spacing and low slope had high sediment retention (Table 1). The sediment yields in the surface runoff can be estimated using Eq. (4), as shown in Fig. 5. The study was restricted to a VFS width of 1 m:

$$\text{Sed} = 7E + 06\left(Q \times Q_p\right)^{0.74} R^2 = 0.96, \tag{4}$$
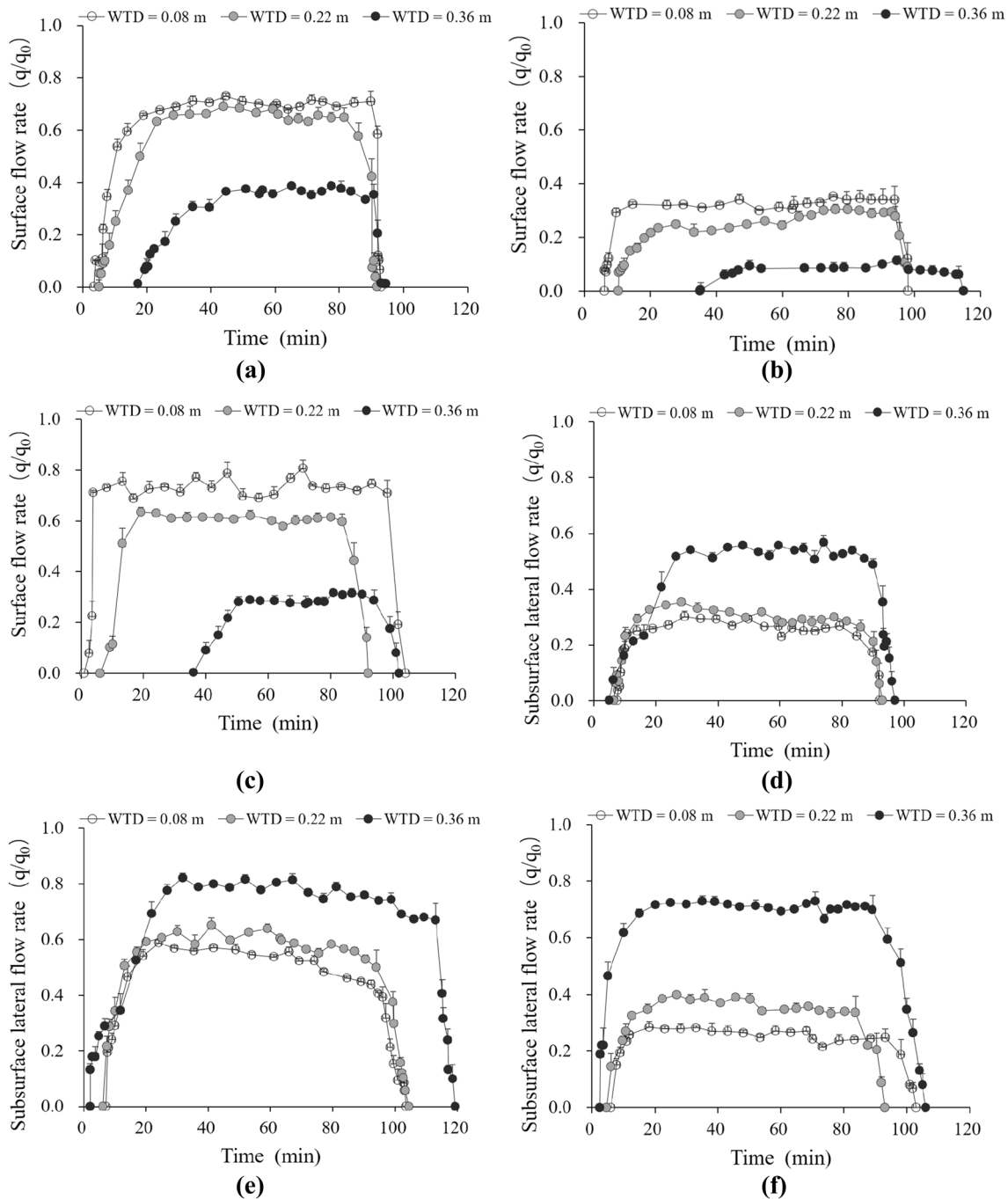
Fig. 4 Hydrological response of the VFS in the study treatments with the normalized surface runoff outflow rate (q/q_0) for (**a**) G7S05, (**b**) G4S05, and (**c**) G4S15, and the normalized subsurface lateral flow rate (q/q_0) for (**d**) G7S05, (**e**) G4S05, and (**f**) G4S15. Values are means, standard errors as error bars

where Sed is the sediment yield (kg/ha), Q is the surface runoff volume (m³), and Q_p is the peak flow rate (m³/s). A power equation, similar to the results proposed by Kuo (2007), was used to describe the relationship among the

Table 2 Start time and the average flow rate of the surface runoff and subsurface lateral flow for the experimental treatments

Experimental group	WTD (m)	Surface runoff outflow		Subsurface lateral flow	
		T_{start} (min)	$q/q_{0\,Ave}$	T_{start} (min)	$q/q_{0\,Ave}$
G7S05	0.08	4	0.69	8	0.27
	0.22	5	0.66	7	0.30
	0.36	17	0.37	5	0.53
G4S05	0.08	6	0.33	8	0.54
	0.22	10	0.27	7	0.59
	0.36	36	0.09	2	0.76
G4S15	0.08	1	0.75	7	0.21
	0.22	6	0.52	6	0.37
	0.36	35	0.27	3	0.71
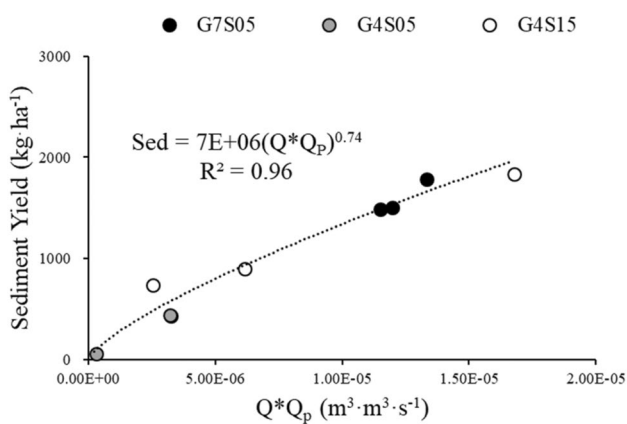
Fig. 5 Relationship between sediment yield, Q, and Q_p in the VFS

sediment yields, runoff volume, and peak flow rate for each runoff treatment.

Shallow WTDs Affected Bromide and Phosphorus Transport

After the inflow (prepared solution) application, the normalized bromide concentrations ($C/C_{0\,Br}-$) in the surface runoff increased rapidly and then were relatively stable in the first 60 min (Fig. 6b, d, f), whereas the normalized phosphorus concentrations ($C/C_{0\,TP}$) in the surface runoff fluctuated slightly (Fig. 6a, c, e), which may have been caused by the phosphorus in the surface runoff interacting with the soil. When the inflows were switched to tap water, the $C/C_{0\,Br}-$ dropped dramatically to 0, and the $C/C_{0\,TP}$ dropped but exhibited persistent concentration tailing, which suggested a slow release of phosphorus from the surface soil to runoff. For each experimental group, the average normalized concentrations of bromide and phosphorus increased with

the WTD (Table 3), and the average $C/C_{0\,Br}-$ was higher than the $C/C_{0\,TP}$ at the same WTD.

The transport of bromide and phosphorus in the subsurface lateral flow, however, exhibited typical breakthrough behaviors during each runoff experiment (Fig. 7). The maximum normalized concentrations ($C/C_{0\,max}$) for phosphorus were lower than those for bromide (Table 3; Fig. 7) because of the phosphorus adsorbed by the mediums (e.g., soil colloids).

For each experimental group, the $C/C_{0\,TP}$ and $C/C_{0\,Br}-$ in the increasing limbs can be described by power equations ($C/C_0 = W \times T^E$) (Table 4). The coefficient (W) in the power function indicates the infiltration rate of surface runoff, which was positively influenced by the decreased WTD. The coefficient (W) can be obtained from the empirical equations [Eqs. (5) and (6)] as follows:

$$W = a \times q/q_{0-Ave} + b, \tag{5}$$

$$q/q_{0-Ave} = c \times WTD + d, \tag{6}$$

where q/q_{0-Ave} is the average flow rate of the subsurface lateral flow; WTD is the shallow water table depth (m); and a, b, c, and d are the regression coefficients. Therefore, the decreased WTD increased the infiltration rate, which resulted in a more obviously increase rate of the normalized phosphorus and bromide concentrations.

The exponent (E) in the power function indicates that phosphorus and bromide are adsorbed or intercepted by clay or organic matter, and a relatively high E value represents a relatively low adsorption or interception ability of soil mediums. For all the aforementioned experiments, the bromide positively correlated with phosphorus ($R^2 = 0.85$, $p < 0.01$) in the subsurface lateral flow, and the slope of the equation presented in Fig. 8 was smaller than one (0.52), which showed a higher adsorption ability of phosphorus than that of bromide. The phenomenon was also reflected on the exponent (e.g., E was $0.943 \times a$ for phosphorus and 0.943 for bromide in G7S05, where a was $0.52^{1/2}$).

Different grass spacings and slopes also influenced the transport of phosphorus and bromide in the subsurface lateral flow. For example, compared with the experimental group G7S05, the low grass spacing in G4S05 (the same slope as G7S05) increased the infiltration of surface runoff, the adsorption of organic acids secreted by plant roots, and the interception by plant roots, resulting in high W and low E (e.g., for phosphorus, E was $0.943 \times a$ for G7S05 and $0.943 \times a \times b$ for G4S05, where a was $0.52^{1/2}$ and b was $(G4/G7)^{1/2}$) in the power function. Moreover, compared with the experimental group G4S05, the high slope of the experimental group G4S15 (the same grass spacing as G4S05) increased the surface runoff outflow and transport rate of infiltrated water in the subsurface soil, which resulted in a
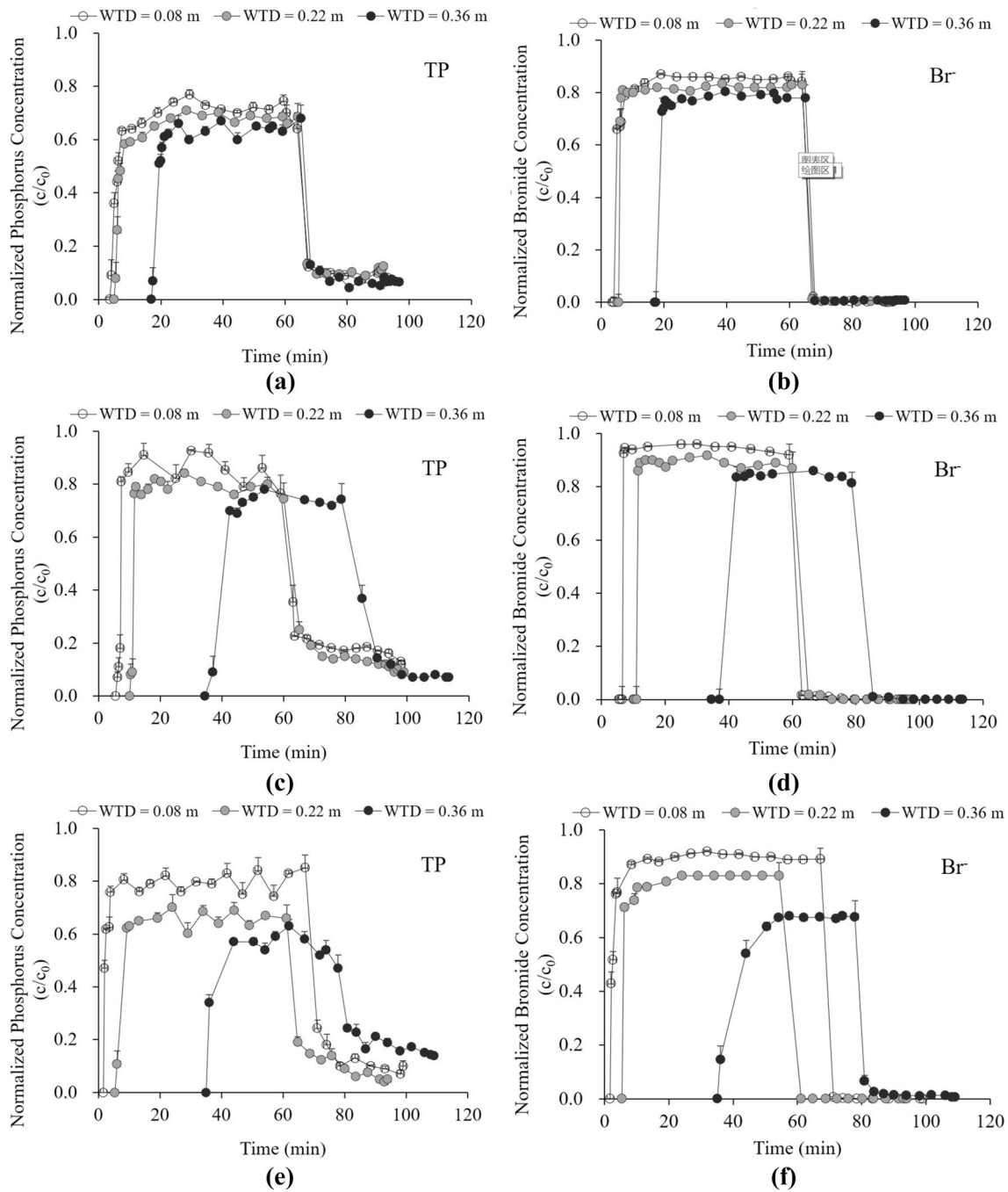
Fig. 6 Transport of (**a**) phosphorus and (**b**) bromide for G7S05, (**c**) phosphorus and (**d**) bromide for G4S05, and (**e**) phosphorus and (**f**) bromide for G4S15 in the surface runoff under different shallow water table depths. Values are means, standard errors as error bars

low W and high E (e.g., for phosphorus, E was $0.943 \times a \times b$ for G4S05 and $0.943 \times a \times c$ for G4S15, where a was $0.52^{1/2}$, b was $(G4/G7)^{1/2}$, and c was $(G4/G7)^{1/6}$) in the power function.

Mass balance calculations based on this study showed that the highest total recovery rate of bromide (both in the surface runoff outflow and subsurface lateral flow) was almost 75% in the aforementioned experimental conditions.

This incomplete recovery rate may be attributed to a certain amount of bromide remaining in the soil at the end of each runoff treatment. However, the highest total recovery rate of phosphorus was only approximately 61%. Such low recovery rates may be attributed to the phosphorus adsorption of the mediums, including soil colloids (Edzwald et al. 1976; Gérard 2016), organic acids secreted by the plant roots (Wang et al. 2012), and iron oxides in the soil (Tomer et al.

Table 3 Average normalized concentrations of bromide and phosphorus in the surface runoff and maximum normalized concentrations of bromide and phosphorus in the subsurface lateral flow

Experimental group	WTD (m)	Surface runoff outflow		Subsurface lateral flow	
		TP ($C/C_{0\,ave}$)	Br⁻ ($C/C_{0\,ave}$)	TP ($C/C_{0\,max}$)	Br⁻ ($C/C_{0\,max}$)
G7S05	0.08	0.70	0.85	0.32	0.57
	0.22	0.68	0.84	0.39	0.62
	0.36	0.64	0.79	0.42	0.69
G4S05	0.08	0.85	0.95	0.42	0.61
	0.22	0.79	0.90	0.46	0.62
	0.36	0.73	0.84	0.61	0.89
G4S15	0.08	0.79	0.91	0.41	0.48
	0.22	0.65	0.82	0.44	0.69
	0.36	0.56	0.67	0.47	0.79

2010; Fink et al. 2016). The weaker adsorption of bromide in the porous media resulted in $C/C_{0\,Br^-}$ decreasing quicker than $C/C_{0\,TP}$ when the inflows were switched to tap water (Fig. 7). Therefore, if we extended the experimental time, the slow release of phosphorus from the soil to the subsurface lateral flow would obviously decrease.

The effect of a seasonal shallow groundwater table on VFS retention efficiencies should be considered, because the high concentrations of pollutants in subsurface lateral flow may also affect adjacent water bodies or groundwater. When the groundwater level rises in the rainy season, phosphorus adsorbed in the soil is desorbed into groundwater, which then pollutes the groundwater.

Conclusions

Laboratory-scale VFS runoff experiments were conducted to study the effects of a shallow groundwater table on VFS efficiency for retarding the transport of runoff, sediment, phosphorus, and bromide in different grass spacings and slopes, and to examine the transport dynamics of phosphorus and bromide in the surface runoff outflow and subsurface lateral flow. We found that a deep WTD, low grass spacing, and low slope were beneficial for reducing NPS pollutants. The transport of phosphorus in the surface runoff almost resembled that of bromide, and the average concentration ($C/C_{0\,Ave}$) of phosphorus and bromide decreased with a deep WTD. The transport of phosphorus in the subsurface lateral flow was lower than that of bromide, which was due to the adsorption of phosphorus by the soil mediums. Both normalized phosphorus and bromide concentrations in the increasing limbs could be described by the adopted power equations, and the increased concentration rate was positively influenced by the decreased WTD. High concentrations of pollutants in the subsurface lateral flow may also affect adjacent water bodies and groundwater. Future research should further examine the transport dynamic of nitrogen in VFSs with a shallow groundwater table. Although this paper focuses on effects of shallow water table depth on vegetative filter strips retarding transport of nonpoint source pollution, only phosphorus is discussed in this paper. As an important part of nonpoint source pollution, nitrogen will also be studied in the further research. Moreover, controlled in-field VFS experiments should be conducted to explore the effects of a deep groundwater depth (more than 1.0 m) on VFS performance.
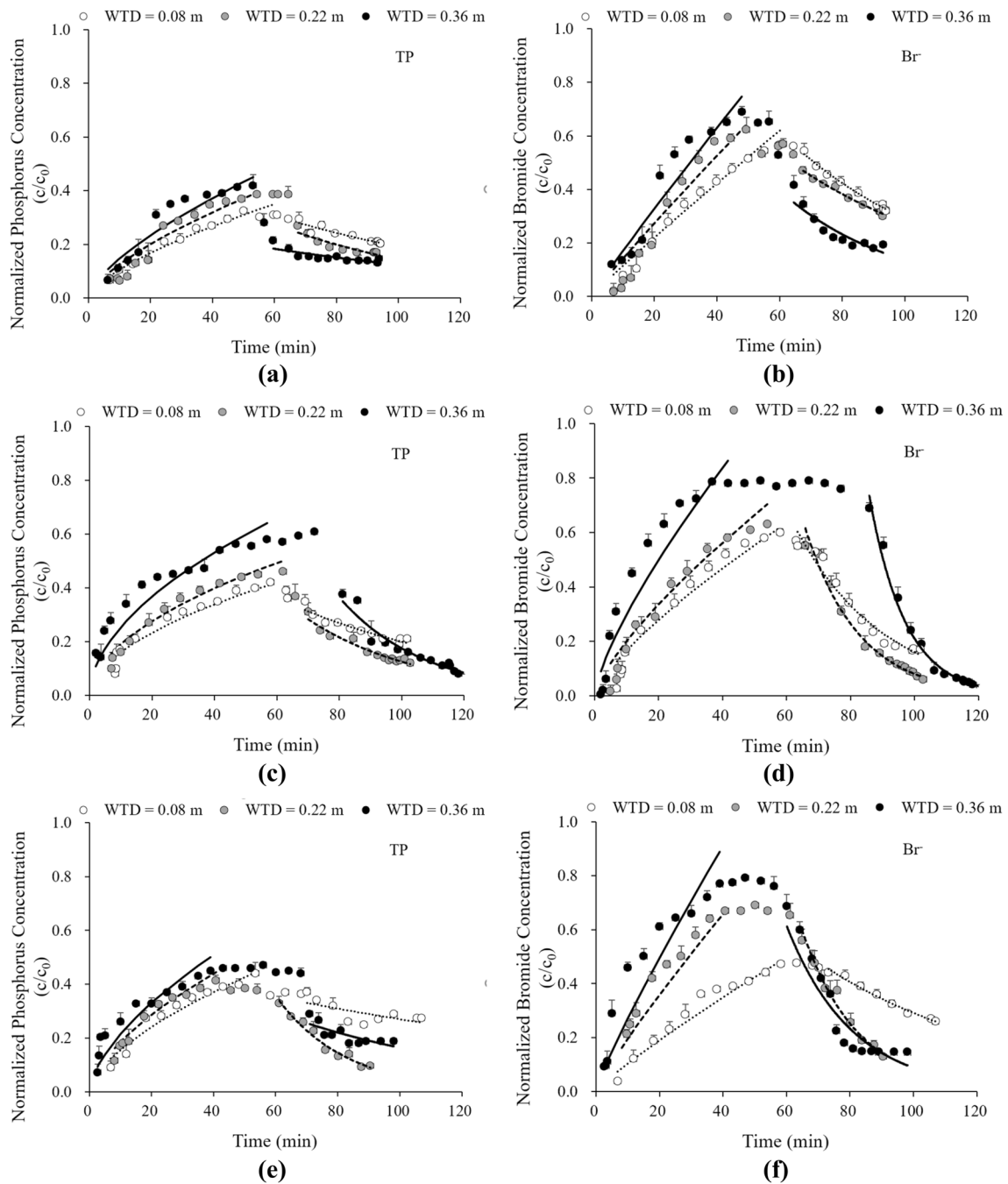
Fig. 7 Transport of (**a**) phosphorus and (**b**) bromide for G7S05, (**c**) phosphorus and (**d**) bromide for G4S05, and (**e**) phosphorus and (**f**) bromide for G4S15 in the subsurface lateral flow under different shallow water table depths. Values are means, standard errors as error bars

Table 4 Power equations of normalized phosphorus and bromide concentrations in the increasing limbs in the subsurface lateral flow

Experimental group	WTD (m)	TP		Br⁻	
		Equation	R^2	Equation	R^2
G7S05	0.08	$C/C_0 = (0.0314 \times WTD + 0.0198) \times t^{0.943a}$	0.94	$C/C_0 = (0.0228 \times WTD + 0.0112) \times t^{0.943}$	0.97
	0.22		0.90		0.95
	0.36		0.90		0.92
G4S05	0.08	$C/C_0 = (0.0966 \times WTD + 0.0398) \times t^{0.943ab}$	0.96	$C/C_0 = (0.0927 \times WTD + 0.0202) \times t^{0.943b}$	0.97
	0.22		0.97		0.96
	0.36		0.98		0.93
G4S15	0.08	$C/C_0 = (0.0497 \times WTD + 0.0334) \times t^{0.943ac}$	0.94	$C/C_0 = (0.0720 \times WTD + 0.0105) \times t^{0.943c}$	0.96
	0.22		0.94		0.95
	0.36		0.91		0.91

[a] Is $0.52^{1/2}$, relating to the different adsorption ability of P and Br⁻ (Fig. 8)

[b] Is $(G4/G7)^{1/2}$, which is related to the different grass spacings of G7S05 and G4S05

[c] Is $(G4/G7)^{1/6}$

References

Abu-Zreig M, Rudra RP, Lalonde MN, Whiteley HR, Kaushik NK (2004) Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. Hydrol Process 18(11):2029–2037

Arora K, Mickelson SK, Baker JL, Tierney DP, Peters CJ (1996) Herbicide retention by vegetative buffer strips from runoff under natural rainfall. Trans ASAE 39:2155–2162

Blanco H, Lal R (2008) Principles of soil conservation and management. Springer, Netherlands 9(1):199–200

Cardoso F, Shelton D, Sadeghi A, Shirmohammadi A, Pachepsky Y, Dulaney W (2012) Effectiveness of vegetated filter strips in retention of *Escherichia coli* and *Salmonella* from swine manure slurry. J Environ Manage 110(18):1–7

Carluer N, Lauvernet C, Noll D, Muñoz-Carpena R (2017) Defining context-specific scenarios to design vegetated buffer zones that limit pesticide transfer via surface runoff. Sci Total Environ 575:701–712

Devito KJ, Fitzgerald D, Hill AR, Aravena R (2000) Nitrate dynamics in relation to lithology and hydrologic flow path in a river riparian zone. J Environ Qual 29(4):1075–1084

Dorioz JM, Wang D, Poulenard J, Trevisan D (2006) The effect of grass buffer strips on phosphorus dynamics—a critical review and synthesis as a basis for application in agricultural landscapes in France. Agr Ecosyst Environ 117(1):4–21

Dosskey MG (2001) Toward quantifying water pollution abatement in response to installing buffers on crop land. Environ Manage 28(5):577–598

Dosskey MG, Helmers MJ, Eisenhauer DE (2006) An approach for using soil surveys to guide the placement of water quality buffers. J Soil Water Conserv 61:344–354
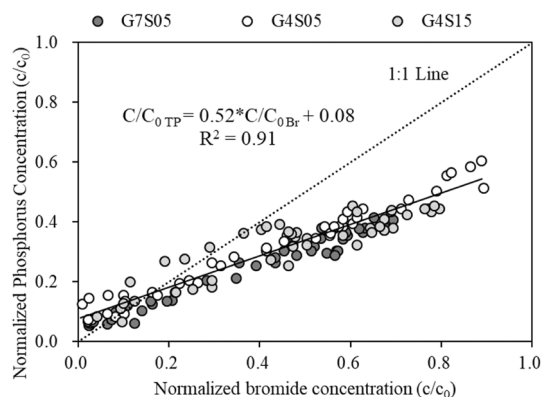
Fig. 8 Correlation between the bromide and phosphorus in subsurface lateral flow

Dosskey MG, Hoagland KD, Brandle JR (2007) Change in filter strip performance over ten years. J Soil Water Conserv 62:21–32

Edzwald JK, Toensing DC, Leung CY (1976) Phosphate adsorption reactions with clay minerals. Environ Sci Technol 10(5):485–490

Fink JR, Inda AV, Tiecher T, Barrón V (2016) Iron oxides and organic matter on soil phosphorus availability. Ciência E Agrotecnologia 40(4):369–379

Fox GA, Penn CJ (2013) Empirical model for quantifying total phosphorus reduction by vegetative filter strips. Trans ASABE 56(4):1461–1469

Fox GA, Muñoz-Carpena R, Purvis RA (2018) Controlled laboratory experiments and modeling of vegetative filter strips with shallow water tables. J Hydrol 556:1–9

Gérard F (2016) Clay minerals, iron/aluminum oxides, and their contribution to phosphate sorption in soils—a myth revisited. Geoderma 262:213–226

Giri S, Mukhtar S, Wittie R (2010) Vegetative covers for sediment control and phosphorus sequestration from dairy waste application fields. Trans ASABE 53(3):803–811

Gumiere SJ, Bissonnais YL, Raclot D, Cheviron B (2011) Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modelling: a review. Earth Surf Proc Land 36(1):3–19

Guy BT, Dickinson WT, Rudra RP (1987) The roles of rainfall and runoff in the sediment transport capacity of interrill flow. Trans ASAE 30(5):1378–1386

Hill AR, Vidon PGF, Langat J (2004) Denitrification potential in relation to lithology in five headwater riparian zones. J Environ Qual 33(3):911–919

Krutz LJ, Senseman SA, Zablotowicz RM, Matocha MA (2005) Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review. Weed Sci 53(3):353–367

Kuo YM (2007) Vegetative filter strips to control surface runoff phosphorus transport from mining sand tailings in the upper peace river basin of Central Florida. Ph.D. Dissertation, University of Florida

Kuo YM, Muñoz-Carpena R (2009) Simplified modeling of phosphorus removal by vegetative filter strips to control runoff pollution from phosphate mining areas. J Hydrol 378:343–354

Kuo YM, Liu WW, Zhao E, Li R, Yao L (2019) Water quality variability in the middle and down streams of Han River under the influences of the Middle Route of South-North Water Diversion Project, China. J Hydrol 569:218–229

Lacas JG, Carluer N, Voltz M (2012) Efficiency of a grass buffer strip for limiting diuron losses from an uphill vineyard towards surface and subsurface waters. Pedosphere 22(4):580–592

Lambrechts T, François S, Lutts S, Muñoz-Carpen R, Bielders CL (2014) Impact of plant growth and morphology and of sediment concentration on sediment retention efficiency of vegetative filter strips: flume experiments and VFSMOD modeling. J Hydrol 511(7):800–810

Lauvernet C, Muñoz-Carpena R (2018) Shallow water table effects on water, sediment and pesticide transport in vegetative filter strips: part B. model coupling, application, factor importance and uncertainty. Hydrol Earth Syst Sci Discuss 1–31

Liu X, Zhang X, Zhang M (2008) Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. J Environ Qual 37(5):1667–1674

Muñoz-Carpena R (1993) Modeling hydrology and sediment transport in vegetative filter strips Ph.D. Dissertation. Raleigh, NC, North Carolina State University. UMI 9404122

Muñoz-Carpena R, Parsons JE, Gilliam JW (1999) Modeling hydrology and sediment transport in vegetative filter strips. J Hydrol 214:111–129

Muñoz-Carpena R, Fox GA, Sabbagh GJ (2010) Parameter importance and uncertainty in predicting runoff pesticide reduction with filter strips. J Environ Qual 39(2):630–641

Muñoz-Carpena R, Lauvernet C, Carluer N (2018) Shallow water table effects on water, sediment, and pesticide transport in vegetative filter strips: part A. Nonuniform infiltration and soil water redistribution. Hydrol Earth Syst Sci 22(1):1–32

Newman BD, Campbell AR, Wilcox BP (1998) Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope. Water Resour Res 34(12):3485–3496

Pan XL, Deng W (2003) Advances in riparian buffers in agricultural catchments. J Agro Environ Sci 22(2):244–247

Peyrard X, Liger L, Guillemain C, Gouy V (2016) A trench study to assess transfer of pesticides in subsurface lateral flow for a soil with contrasting texture on a sloping vineyard in Beaujolais. Environ Sci Pollut Res 23(1):14–22

Rahman A, Rahman S, Cihacek L (2014) Influence of soil pH in vegetative filter strips for reducing soluble nutrient transport. Environ Technol 35(14):1744–1752

Rasmussen JJ, Baattrup-Pedersen A, Wiberg-Larsen P, Mcknight US, Kronvang B (2011) Buffer strip width and agricultural pesticide contamination in Danish lowland streams: implications for stream and riparian management. Ecol Eng 37(12):1990–1997

Reichenberger S, Bach M, Skitschak A, Frede HG (2007) Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review. Sci Total Environ 384(1–3):1–35

Schiettecatte W, Verbist K, Gabriels D (2008) Assessment of detachment and sediment transport capacity of runoff by field experiments on a silt loam soil. Earth Surf Proc Land 33(8):1302–1314

Schilling KE, Jacobson P (2014) Effectiveness of natural riparian buffers to reduce subsurface nutrient losses to incised streams. CATENA 114(2):140–148

Shin J, Gil K (2014) Effect of rainfall characteristics on removal efficiency evaluation in vegetative filter strips. Environ Earth Sci 72(2):601–607

Simpkins WW, Wineland TR, Andress RJ, Johnston DA, Caron GC, Isenhart TM, Schultz R (2002) Hydrogeological constraints on riparian buffers for reduction of diffuse pollution: examples from the bear creek watershed in Iowa, USA. Water Sci Technol 45(9):61–68

Tomer MD, Schilling KE, Cambardella CA, Jacobson P, Drobney P (2010) Groundwater nutrient concentrations during prairie reconstruction on an Iowa landscape. Agri Ecosyst Environ 139(1):206–213

USDA (2000) Conservation buffers to reduce pesticide losses. USDA Natural Resources Conservation Service

van Der Velde Y, De Rooij GH, Rozemeijer JC, van Geer FC, Broers HP (2010) Nitrate response of a lowland catchment: on the relation between stream concentration and travel time distribution dynamics. Water Resour Res 46(1):2387–2392

Wang M, Wu JQ, Huang SF (2008) Effects of slope and width of riparian buffer strips on runoff purification. Acta Ecol Sin 28(10):4951–4956 (in Chinese with English abstract)

Wang C, Wang Z, Lin L, Tian B, Pei J (2012) Effect of low molecular weight organic acids on phosphorus adsorption by ferric-alum water treatment residuals. J Hazard Mater 203–204(4):145–150

Wang B, Zhang GH, Shi YY, Zhang XC (2014) Soil detachment by overland flow under different vegetation restoration models in the Loess Plateau of China. CATENA 116(5):51–59

Wen L, Zheng F, Shen H, Bian F, Jiang Y (2015) Rainfall intensity and inflow rate effects on hillslope soil erosion in the Mollisol region of Northeast China. Nat Hazards 79(1):381–395

Withers PJA, Haygarth PM (2007) Agriculture, phosphorus and eutrophication: a European perspective. Soil Use Manag 23(s1):1–4

Wu L, Muñoz-Carpena R, Gao B, Yang W, Pachepsky YA (2014) Colloid filtration in surface dense vegetation: experimental results and theoretical predictions. Environ Sci Technol 48(7):3883–3890

Xiao B, Wang QH, Wang HF, Dai QH, Wu JY (2011) The effects of narrow grass hedges on soil and water loss on sloping lands with alfalfa (*Medicago sativa* L.) in Northern China. Geoderma 167:91–102

Yang F, Yang Y, Li H, Cao M (2015) Removal efficiencies of vegetation-specific filter strips on nonpoint source pollutants. Ecol Eng 82:145–158

Yu C, Gao B, Muñoz-Carpena R (2012) Effect of dense vegetation on colloid transport and removal in surface runoff. J Hydrol 434–435(3):1–6

Zhang GH, Liu GB, Wang GL, Wang YX (2011) Effects of vegetation cover and rainfall intensity on sediment-bound nutrient loss, size composition and volume fractal dimension of sediment particles. Pedosphere 21(5):676–684

Zhao CH, Gao J, Zhang M, Wang F, Zhang T (2016) Sediment deposition and overland flow hydraulics in simulated vegetative filter strips under varying vegetation covers. Hydrol Process 30(2):163–175

Zhou Y (2009) Pesticide transport and enrichment in water–soil environment: a case study of Jianghan Plain (in Chinese with English abstract)