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RESEARCH ARTICLE

Agricultural runoff pollution control by a grassed swales coupled with wetland detention ponds system: a case study in Taihu Basin, China

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Abstract The performance of a field grassed swales (GSs) coupled with wetland detention ponds (WDPs) system was monitored under four typical rainfall events to assess its effectiveness on agricultural runoff pollution control in Taihu Basin, China. The results indicated that suspended solids (SS) derived from the flush process has significant influence on pollution loads in agricultural runoff. Determination of first flush effect (FFE) indicated that total suspended solids (TSS) and total phosphorus (TP) exhibited moderate FFE, while chemical oxygen demand (COD) and total nitrogen (TN) showed weak FFE. Average removal efficiencies of 83.5 ±4.5, 65.3±6.8, 91.6±3.8, and 81.3±5.8 % for TSS, COD, TN, and TP were achieved, respectively. The GSs played an important role in removing TSS and TP and acted as a pretreatment process to prevent clogging of the subsequent WDPs. Particle size distributions (PSDs) analysis indicated that coarse particles larger than 75 μm accounted for 80 % by weight of the total particles in the runoff. GSs can effectively reduce coarse particles (≥75 μm) in runoff, while its removal efficiency for fine particles (<75 μm) was low, even minus results being recorded, especially for particles smaller than 25 μm. The length of GSs is a key factor in its performance. The WDPs can remove particles of all sizes by sedimentation. In addition, WDPs can improve water quality due to their buffering and dilution capacity during rainfall as well as their water purification ability during dry periods. Overall, the ecological system of GSs coupled with WDPs is an effective system for agricultural runoff pollution control.

Keywords Agricultural runoff · Grassed swale · Wetland detention pond · Removal efficiency · Particle size distributions · Nutrients

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Introduction

Nonpoint source (NPS) pollution includes agricultural runoff, urban road runoff, deposition of atmospheric pollutants and mine sites, etc. Among them, agricultural nonpoint source pollution (ANPS) and urban nonpoint source (UNPS) pollution are of particular concerns (Ockenden et al. 2012; Ongley et al. 2010). With the development of intensified agriculture, the increasing output satisfied human's increasing need for food. However, increasing inputs of fertilizer have led to ever-growing portion of these nutrients transport from agricultural farmland into receiving waters, thus threatening receiving waters quality. Rainfall runoff is the main power to form and carry ANPS pollution. Typically, about half of N-fertilizer is taken up by crops, with the remaining migrating via agricultural runoff into receiving waters, commonly in the form of nitrate (Lupwayi et al. 2012). P-fertilizer utilization ratio by crops is quite low, generally no more than 25 %. As a result, about 75–90 % P-fertilizer is retained in soil and easily be taken by farmland runoff (Veneklaas et al. 2012). In China, 2.7 million tons of total nitrogen (TN) and 0.28 million tons of total phosphorus (TP) were discharged by ANPS, which represented 57.19 % of the national TN discharge and 67.27 % of the national TP discharge, respectively (MEP et al. 2010).

Taihu Lake is the third largest freshwater lake in China, with a catchment area of 36,500 km^2 and a water surface area of 2340 km^3. More than 23 million people live in this region with the annual average runoff into the lake of 4100 million m^3. The area is also one of the most developed agricultural areas in China, with high fertilizer utilization and high agricultural output. The chemical fertilizer consumption in Taihu area accounts for 1.3 % of the whole nation's fertilizer consumption (Wang et al. 2004). During the last decades, rapid agricultural development without proper management has caused many serious environmental problems such as eutrophication, organic pollution, and aquatic ecosystem destruction. This resulted in the fact that the water quality cannot meet the required function. For example, Wuxi drinking water crisis happened in 2007 due to serve eutrophication of Taihu. Millions of people depending on the lake for drinking water were exposed to health risk. The relevance of agriculture as a major source of NPS pollution has been confirmed by many researchers (Emili and Greene 2013; Shortle et al. 2012). Therefore, research on ANPS pollution has direct and practical impact on water pollution control, especially in Taihu basin as it is an urgent task for water quality improvement in this area.

Grassed swales (GSs) and wetland detention ponds (WDPs) are all among the best management practices (BMPs) for ANPS pollution (Lam et al. 2011; Maringanti et al. 2011). GS is one of the simplest, efficient, cost-effective, and aesthetically pleasing ways of NPS control measures (Deletic and Fletcher 2006). Results of GSs studies showed that a removal efficiency of 68–93 % for total suspended solids (TSS), 28–83 % for TP, and 40–92 % for TN can be achieved (Davis et al. 2012; Pitt et al. 2007). This demonstrates that the GSs has a good effect in removing TSS in runoff while its performance in reducing TP and TN seems low due to the relatively low retention time in GSs. Nevertheless, it can be adopted as an ideal runoff pre-treatment process in ANPS pollution control system. Constructed wetlands (CWs) have a number of advantages of simple construction, large buffering capacity, simple operation and maintenance, little excess sludge production, and low operational and maintenance costs (Vyamazal 2011; Wu et al. 2014). These make the CWs popular in global level. WDPs have the characters of both surface flow CWs and detention ponds. It could act as buffers between pollution sources and receiving waters (Maltais-Landry et al. 2009). In particular, WDPs has ample buffering ability, it will prolong the detention time of agricultural runoff and allow it be treated in WDPs. Water quality in WDPs can be recovered during dry periods and can provide a dilution effect to the next rainfall runoff.

It has been well reported that the main practical problem in CWs is the clogging due to the particles in runoff (Kandra et al. 2014; Ye et al. 2014). This can be solved by application of GSs prior to CWs. Therefore, GSs can act as pre-treatment facility for WDPs due to its sound effect in removing SS and reducing runoff volume (Winston et al. 2013). As such, study on the combination of GSs coupled with WDPs ecological system in agricultural runoff pollution control seems a practical and economical way, which has significant application prospect. Actually, ANPS pollution has obvious geographical features and is affected by soil types, land use types, rainfall characteristics, and terrain conditions (Zhang et al. 2004). So far, agricultural runoff characteristics under different land use type in Taihu basin have not been fully studied. This forms the basic standpoint of this study.

The objectives of this study were as follows: (1) to make a probe into agricultural runoff characteristics and to analyze the correlationship among different water quality parameters in agricultural runoff; (2) to evaluate the pollutants removal performance of GSs as well as factors influencing the performance of GSs, for example, the length of GSs and particle size distributions (PSDs) in runoff; (3) to evaluate the performance of GSs coupled with WDPs system in reducing main pollution parameters such as TSS, chemical oxygen demand (COD), TP, and TN in agricultural runoff.

Materials and methods

Site description

The study site is a modern agricultural and technology park located at Xuebu Town in Jintan City, Jiangsu Province, China (31°40′53.38″N, 119°24′37.74″E). It belongs to subtropical monsoon zone with four distinct seasons. The average yearly rainfall is 1063.5 mm, focusing on May to September. A schematic layout of the study site is shown in Fig. 1. The agricultural park covers more than 13.3 ha while the study site is part of the agricultural park and is mainly orchards of 4.3 ha. In the study site, 2.13 ha is date trees with Chinese medicinal herbs planted between the trees; 1.67 ha is peach trees and some other fruit trees; 0.53 ha is breeding base. The main properties of the soil in the study site are pH 6.56–6.85, organic substance content 22–31 g/kg, TN 0.45–0.68 g/kg, and TP (P_2O_5) 0.62–0.98 g/kg. The study site itself is a small complete catchment area, agricultural runoff discharges into watercourses of Changdang lake and finally drains toward Taihu Lake. A separated wastewater treatment facility was built to treat the wastewater from breeding base and the effluent was not considered in the proposed GSs system.

GSs and WDPs system

The GSs coupled with WDPs system is mainly composed of six segments of GSs followed by a two-stage WDPs and some other facilities such as water retaining dams, grassed slope protection facilities, etc. (Fig. 1). As shown in Fig. 1, GS1, GS2, and GS3 connected with GS4 and formed a runoff conveyance system, which drained toward the WDP1, while GS5 and GS6 connected together and formed another runoff

Fig. 1 Schematic layout of GSs and WDPs (*GSs*—grassed swales; *WDPs*—wetland detention ponds)

conveyance system, which drained toward the WDP2. The two stages of WDP1 and WDP2 were operated in series. Water from WDP1 flows into WDP2 and finally drained into receiving water.

The study site has an average slope of about 3 % from the highest point in southwest to the lowest point in northeast. GSs were constructed in six segments according to the land slope to collect the runoff from farmland. The total length of the GSs was 470 m and covered about 760 m^2. The swales showed a trapezium shape cross-section (side slopes of about 2:1 to 3:1 on either side of the swales) with a top open width of 1.0–1.8 m and an average depth of 0.5 m. The average bottom longitudinal gradient of the swale was 2 %, which was close to the average slope of the study site. *Bermuda* grass were planted in the swales 1 year ago. The grass height was 12–15 cm during the testing period, while the average blade width was 0.28 cm by measuring 40 randomly selected grass blades. The grass density was 6.2 grass blades per cm^2 by counting the blades within five squares of 10 × 10 cm, no bare soil can be seen in the swales.

Initially, there was a gully in the north of the study site. The gully was lower than the farmland by 2.5 m. It was reconstructed as the two-stage WDPs by constructing two water-retaining dams. The two-stage WDPs had a total area of 960 m^2. The ordinary depth of water in the pond was 0.5–0.8 m, which was controlled by the drainage pipe in the dam, while the overflow water level (the top of the dam) was 1.2 m above the bottom of the WDPs. Common *reeds* and *pattails* were planted on the bank of the ponds. *Eichhornia crassipes* and *Myriophyllum spicatum* were planted on the floating treatment wetlands (FTWs) in water.

Methodology

The performance of the system was monitored under four rainfall events from May to August 2012. Sampling points were set at the entering point and the leaving point of each GS, the junction of GSs, the inflow point, outflow point, and both the two stages of WDPs (Sampling point are marked as ⊗ in Fig. 1). The samples were collected once the runoff began. Then, samples were collected every 5–10 min during the first 30 min and every 10–15 min after 30 min. The rainfall intensity and rainfall amount were determined by a JQ200 Rain Gauge with 0.5 mm sensitivity. The runoff volume was measured in situ using V-notch weirs installed at the two outlets of the GSs convenience systems. Automated water level recorders were set via the V-notches. The collected samples were sent to the lab for analysis of TSS, COD, TP, TN, and

PSDs immediately. The average rainfall interval in the study area is around 7 days in summer. Therefore, samples collected during rainfall and 1, 2, and 7 days after the rainfall in the WDP_S were analyzed to reflect general pollutants removal efficiency by WDPs system.

Water quality analysis

Mixed water samples were collected in GS_S and water samples from 0.2 m beneath the water surface in WDPs were collected at above-mentioned time intervals for analysis. Once the water samples were collected, the pH and temperature were measured in situ using a pH meter (PHS-3C, China) and a mercury thermometer, respectively. Then, the samples were sent to the laboratory and were stored in a refrigerator at 4 °C and analyzed within 24 h. TSS was quantified by filtering water samples through pre-weighed glass-fiber filters through a membrane with a pore size 0.45 μm and drying at 110 °C. COD was determined by the closed reflux titrimetric method. TN was determined using the Kjeldahl method, while TP was measured by ammonium molybdate spectrophotometry method. All the procedures were conducted according to the national standard methods (State Environmental Protection Administration of China 2002).

In this study, the method of mechanical sieving reported by Soupir and Mostaghimi (2010) for the weight distributions of various particle size fractions and the method of laser diffraction reported by Polakowski et al. (2014) for particle number distributions were employed to characterize PSDs and particle number in agricultural runoff. Stainless steel sieve with a mesh openings of 1000 μm (16# sieve) and 500 μm (32# sieve) and nylon sieve with a mesh openings of 150 μm (100# sieve), 75 μm (200# sieve), and 25 μm (500# sieve) as well as microfilter membrane with a pore size of 8 and 5 μm, respectively, were used to separate particles into the following size fractions: >1000, 500–1000, 150–500, 75–150, 25–75, 8–25, 5–8 μm. The SS retained on every sieve were washed off by particulate-free water. Analyzing SS in every rinsed water gave the PSDs in the samples. Since particles smaller than 75 μm is considered to be the main carrier contributing to the pollution load into receiving waters (Rushton et al. 2007), an IBR laser particle counter was employed to further study the number of fine particles ranging from 2 to 150 μm in runoff. Water samples were filtered through a sieve with an opening size of 150 μm (100# sieve). Thereafter, the filtrates were collected for particle number analysis for fractions of 2–5, 5–8, 8–25, 25–70, and 75–150 μm by the IBR laser particle counter. The filtrates may need to be diluted with particulate-free water to meet the measurable concentration range of IBR laser particle counter accordingly.

Calculation of event mean concentrations (EMCs)

EMCs, a commonly employed parameter to assess the overall pollutants removal efficiency in runoff (Lucke et al. 2014; Stagge et al. 2012), was used in this study and its concept may be presented mathematically via Eq. (1).

$$\mathrm{EMC} = \frac{\text{total constituent mass}}{\text{total runoff volume}} = \frac{\sum_{i=1}^{n} C_i \Delta V_I}{\sum_{i=1}^{n} \Delta V_i} \quad (1)$$

Water samples were collected during rainfall for pollutants concentration (C_i) analysis at a certain interval. The corresponding runoff flow volume (ΔV_i) was monitored simultaneously.

First flush effect (FFE) analysis

In this study, the FFE was determined in two ways. First, the approach (Geiger 1987) of using dimensionless curve of the cumulative pollutant mass vs. the cumulative discharged volume (*M(V)* curve) to determine the FFE was adopted. It has been proposed that the FFE occurs when the curve has an initial slope greater than 45°, while the maximum gap between the $M(V)$ curve and the bisector is greater than 0.2. Thus, FFE occurs when the data for a particular event falls above the 45° angle bisector. The second method is the $M(V)$ curve fitted to the power function (Saget et al. 1996; Bertrand et al. 1998), which may be presented mathematically via Eq. (2).

$$L = F^b \quad (2)$$

Where L is dimensionless cumulative pollutant mass; F is dimensionless cumulative runoff volume; b is first flush coefficient. The $M(V)$ curve can be divided into six zones according to b. Partitioning determination is as follows: zone 1 ($0<b\leq 0.185$), strong FFE; zone 2 ($0.185<b\leq 0.862$), moderate FFE; zone 3 ($0.862<b\leq 1$), weak FFE; zones 4 ($1<b\leq 1.159$), zones 5 ($1.159<b\leq 5.395$), and zones 6 ($1<b\leq +\infty$), no FFE.

Results and discussion

Characteristics of the four studied rainfall events

From May to September 2012, there were more than 15 rainfall events, representing about 70 % of the yearly rainfall in the study area and contributing most of the ANPS pollution load into receiving waters in a year. However, it was found that no apparent runoff could be formed under less than 10 mm rainfall amount in the study area. Therefore, this study mainly focused on the four typical rainfalls with higher than 10 mm rainfall during this period (Table 1). According to the

Table 1 Characteristics of the four studied rainfall events

Rainfall events	RA (mm)	RD (min)	ADP (d)	ARI (mm/10 min)
I (May 29)	23.6	105	8	2.24
II (June 19)	28.4	80	11	3.55
III (July 12)	42.2	85	15	4.96
IV (August 18)	38.8	120	7	3.23

RA rainfall amount, *RD* rainfall duration, *ADP* antecedent dry periods, *ARI* average rainfall intensity

rainfall standard in China, rainfall amount between 10 and 25 mm in 24 h belongs to moderate rain while rainfall amount of 25–50 mm belongs to heavy rain. Thus, rainfall I and II were moderate rain while III and IV were heavy rain.

Rainfall characteristics and correlation between pollutants concentrations

Samples collected at the same time form the three sampling points at the beginning of GS1, GS2, and GS3 were mixed to represent agricultural runoff characteristics. Pollutants concentrations in agricultural runoff under the four studied rainfall are shown in Fig. 2. ANPS pollution has obvious geographical features. In this study site, the ranges of TSS, COD, TN, and TP in the runoff were 82.0–241.2, 38.4–156.4, 19.6–81.0, and 0.6–4.7 mg/L, with the mean concentrations of 162.2 ± 17.4, 79.7 ± 29.4, 38.2 ± 12.5, and 2.1 ± 0.6 mg/L (mean ± SD, $n = 4$), respectively. These are relatively higher than the similar study in northern China (Liu et al. 2014). Many studies have indicated that low vegetation is a main cause to accelerate the runoff speed and runoff volume (Zhang et al. 2011; Zhang et al. 2012). In this study site, bare soil can be seen between fruit trees in the orchard, this made the soil was easily flushed away by runoff. The average 3 % slope of the land enhanced flush intensity and resulted in a high TSS in runoff. In addition, fertilization affects the N and P concentration in agricultural runoff (Wang et al. 2012). Liang et al. (2004) reported the loss of nitrogen and phosphorous from farmland was obviously influenced by fertilization in the following order: organic manure>chemical fertilizer>organic fertilizer. The orchard of this study site mainly takes organic manure from the breeding base as fertilizer. Therefore, the low vegetation and organic manure fertilizer resulted in high runoff pollutants concentration in this study.

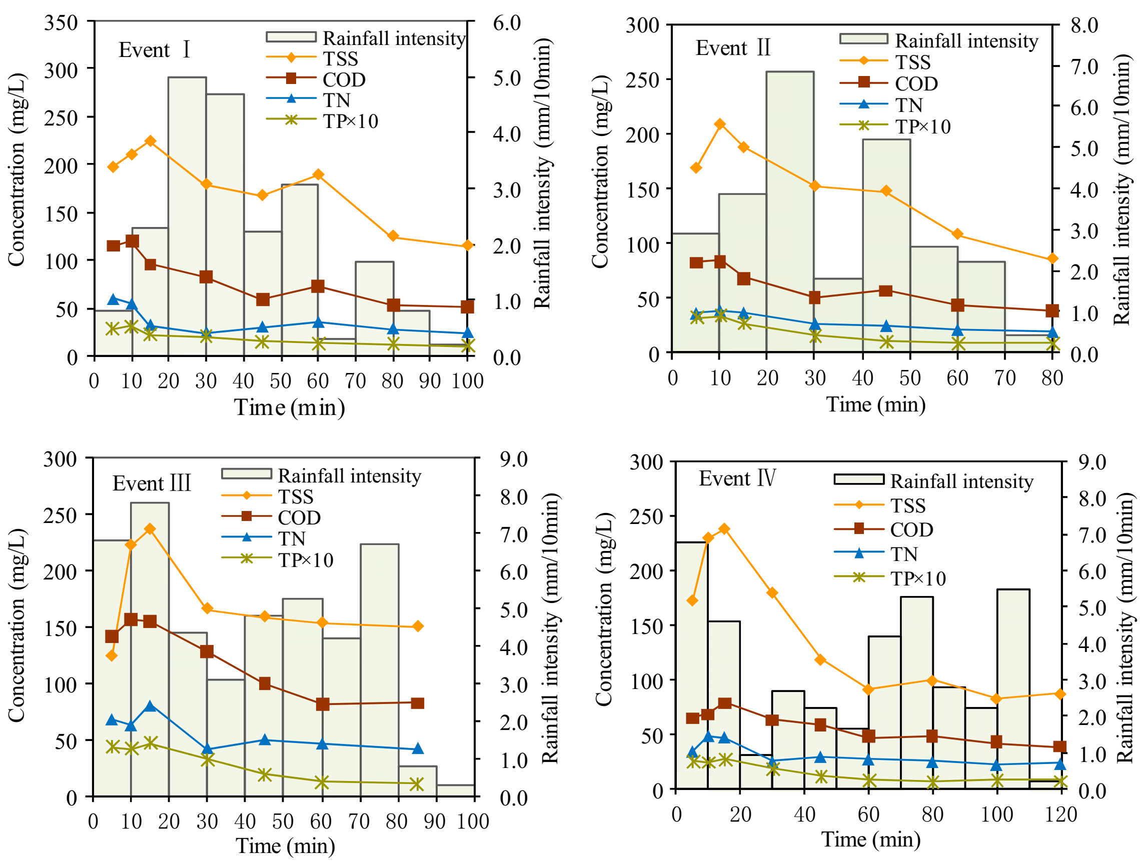

Fig. 2 Variation of runoff pollutants concentration under the four rainfall events (the pollutants concentrations in the mixed samples collected simultaneously form the three sampling points at the beginning of GS1, GS2, and GS3 were presented)

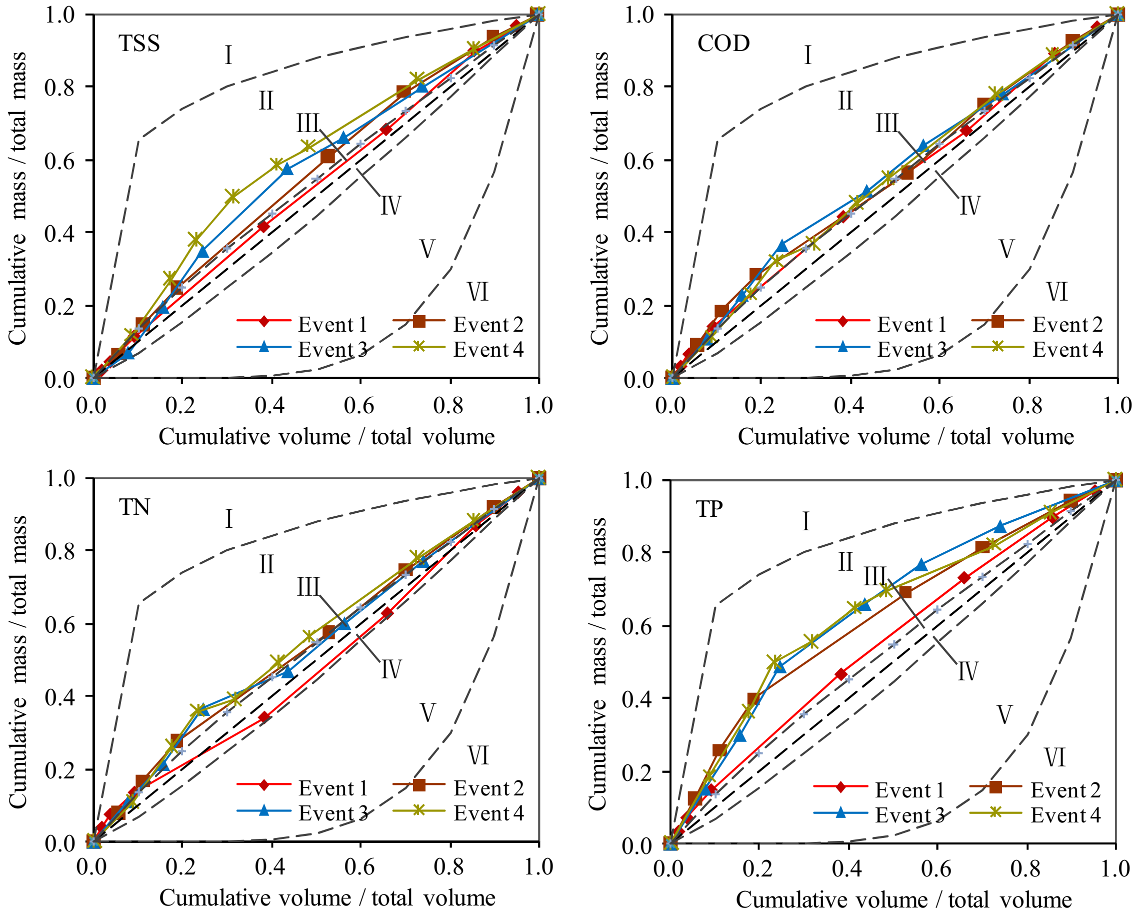

Fig. 3 *M*(*V*) curves of pollutants in agricultural runoff (zone I, strong FFE; zone II, moderate FFE; zone III ($0.862 < b \leq 1$), weak FFE; zones IV, zones V, and zones VI, no FFE)

Agricultural runoff pollutant concentrations under the four rainfall events are illustrated in Fig. 3. It shows a certain FFE with the exception of no FFE for TN being recorded under rainfall event I. According to the division standard based on the first flush coefficient b in Eq. (2), TSS and TP show moderate FFE, while COD and TN show weak FFE. This may be owing to the fact that most of the TSS and TP were transferred in particulate form, making them to be easily flushed away by the initial runoff. Generally, the strength of FFE is influenced by many factors such as underlying surface, rainfall intensity, impervious area, and antecedent dry weather period (Wang et al. , 2014b). In this study, the FFE characteristics of the agricultural runoff are mainly due to two reasons. Firstly, the impervious concrete road in the middle of the park is mainly used for carrying food from the outside and carrying animal wastes from the breeding base to the outside. Most of the deposited particles on the road will be flushed into runoff at the beginning of the rain. Secondly, fertilization has a

Table 2 The correlation between different parameters

Items	RD	TSS	COD	TN	TP
RD	1.00	−0.84 ± 0.12	−0.72 ± 0.03	−0.78 ± 0.12	−0.91 ± 0.03
TSS	−0.84 ± 0.12	1.00	0.79 ± 0.04	0.76 ± 0.09	0.86 ± 0.07
COD	−0.72 ± 0.03	0.79 ± 0.04	1.00	0.85 ± 0.07	0.92 ± 0.03
TN	−0.78 ± 0.12	0.76 ± 0.09	0.85 ± 0.07	1.00	0.86 ± 0.08
TP	−0.91 ± 0.03	0.86 ± 0.07	0.92 ± 0.03	0.86 ± 0.08	1.00

Mean ± standard deviation ($n = 4$) of the correlation coefficients between RD, TSS, COD, TN, and TP under the four rainfall events are presented

RD rainfall duration

Table 3 Removal efficiency of pollutants in agricultural runoff by the GSs coupled WDPs system

Items	AR[a] (EMC, mg/L)	GSs		WDPs[b]				TRE[c] (%)
		Outflow (EMC, mg/L)	RE[d] (%)	Rainfall period (mg/L)	1 day (mg/L)	2 days (mg/L)	7 days (mg/L)	
TSS	155.0 ± 24.5	50.4 ± 8.5	67.5 ± 9.6	38.5 ± 6.2	30.8 ± 1.3	28.2 ± 1.0	25.6 ± 0.8	83.5 ± 4.5
COD	75.0 ± 20.1	51.0 ± 13.3	32.0 ± 10.1	35.0 ± 5.5	30.4 ± 1.5	30.5 ± 1.3	26.0 ± 1.0	65.3 ± 6.8
TN	38.2 ± 11.4	18.6 ± 4.9	51.3 ± 6.2	6.2 ± 1.6	5.0 ± 0.5	4.0 ± 0.6	3.2 ± 0.3	91.6 ± 3.8
TP	3.2 ± 1.4	2.0 ± 1.0	37.5 ± 8.3	1.0 ± 0.4	0.8 ± 0.2	0.8 ± 0.2	0.6 ± 0.2	81.3 ± 5.8

AR agricultural runoff, *RE* removal efficiency, *TRE* total removal efficiency

[a] The mean concentration and the standard deviation of the four EMCs in agricultural runoff (means ± SD, $n = 4$)

[b] The mean concentration of water samples collected at four sampling points in WDPs during rainfall events (samples were collected at 0.2 m below water surface, at an interval of 30 min) and 1, 2, and 7 days after rainfall (samples were collected at 0.2 m below water surface, twice every day)

[c] Total removal efficiencies are calculated based on average concentrations of water samples collected 7 days after every rainfall and the EMCs of agricultural runoff under the same rainfall (mean ± SD, $n = 4$)

[d] The mean removal efficiency and the standard deviation of the four removal efficiency based on EMCs (mean ± SD, $n = 4$)

noticeable impact on pollutants fluxes in runoff, especially for nutrient concentrations (Delpla et al. 2011). The use of organic manure as fertilizer and the way of surface spreading in the study site allow the fertilizer to be easily flushed away by runoff. Lee et al. (2002) reported that the strength of the FFE was proportion to mean rainfall intensity. However, it can be seen from Fig. 3, the FFE strength under the rainfall events III and IV is stronger than that under the rainfall events I and II, especially for particulate-bounded pollutants, such as TSS and TP. By comparing the rainfall intensity presented in Fig. 2 and Table 1, it is reasonable to believe that the initial rainfall intensity instead of mean rainfall intensity is more closely related with FFE strength.

Relationships among rainfall duration, COD, TN, TP, and TSS under the four rainfall events were analyzed by linear correlation analysis and the results are listed in Table 2. Results show that all the water quality parameters of SS, COD, TN, and TP are negatively correlated with rainfall duration. However, COD, TN, and TP are all positively correlated with TSS, especially for TP. Many studies indicate that SS taken into runoff by the flush process had significant influence on pollutant load in runoff since SS is the main carrier of pollutants such as metals, phosphorus, and polycyclic aromatic hydrocarbons (Luo et al. 2012). P-fertilizer in soil mainly contains two forms of dissolved and particulate states; its utilization ratio by crops is not more than 25 % (Veneklaas et al. 2012). Most of the phosphorus is transferred in particulate form in agricultural runoff (Guo et al. 2014). Therefore, TP in runoff is closely related with flush intensity and TSS in agricultural runoff. Correlation between TN and TSS is the weakest because most nitrogen in soil exists as soluble ammonia and nitrate in runoff (Liu et al. 2014). Overall, results from this study indicate pollutants load in agricultural runoff is positively correlated with the loss of soil particles due to the flush process, suggesting that removal of particulate pollutants by interception, sedimentation, and filtration in GSs and WDPs are promising ways for agricultural runoff pollution control.

Pollutants removal efficiency of GSs coupled with WDPs system

As shown in Table 3, the average TSS, COD, TN, and TP removal rates of 67.5 ± 9.6, 32.0 ± 10.1, 51.3 ± 6.2, and 37.5 ± 8.3 % (based on EMCs, mean ± SD, $n = 4$) were achieved in GSs in terms of EMCs. Lucke et al. (2014) reviewed the performances of GSs in literature. It showed that TSS, TN, and TP removal rates of 61.3–86.4 % (mean = 67.9 %), −6.3 – 41.2 % (mean = 33.7 %), and 5.6–51.7 % (mean = 48 %) can be achieved, respectively. In general, GSs are effective in removing SS and particle-bounded pollutants. The main pollutant removal mechanisms in swale are sedimentation, filtration by grass blades, infiltration into the subsurface, and biochemical processes (Barrett 2005; Stagge et al. 2012). Among them, sedimentation and filtration within the grass layer are considered as the primary mechanism of pollutant treatment. Grasses in swale mainly play the role of filtration by their blades, while the uptake of nutrients by grass is minor during rainfall. That is why particles and particle-bound pollutants show the greatest removal in swales. Generally, removal efficiency of TN in GSs is lower than that of TP (Deletic and Fletcher 2006; Lucke et al. 2014) because approximately 70 % of the TP present in runoff is bound to particulates (Stagge et al. 2012), while 40–60 % of nitrogen in runoff is in soluble form (Lee and Bang 2000). Lucke et al. (2014) even reported that no reduction of TN was measured in swales by using KNO_3 solution as nitrogen source under simulated conditions in laboratory. This further approve that the removal of particle-bound nutrients by sedimentation and filtration are the main mechanisms for pollutants removal in swales. The findings

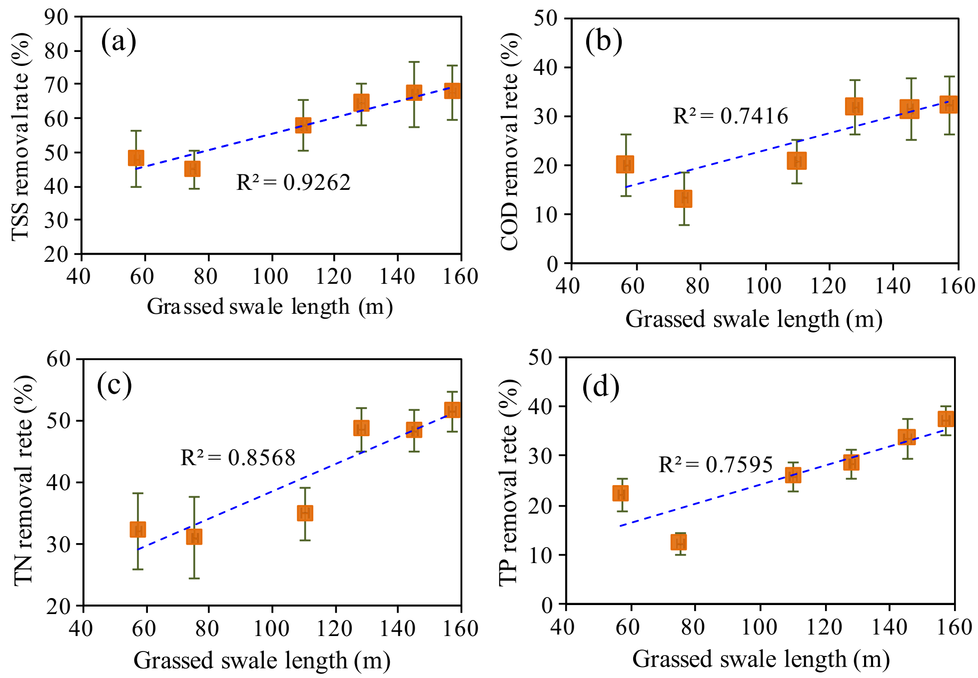

Fig. 4 Correlation between GS length and removal efficiency of TSS (**a**), COD (**b**), TN (**c**), and TP (**d**)

also indicate that GSs can act as a pre-treatment process to prevent clogging of subsequent WDPs.

WDPs can provide storage capacity between the ordinary water level during dry period and the highest overflow water level during rainfall. The roles of dilution, sedimentation, and ecological remediation in WDPs play an important role in runoff pollution control. Except for the removal rates in GSs, an extra 16.0 ± 3.7, 33.5 ± 6.5, 40.3 ± 6.9, and 43.5 ± 5.2 % (based on EMCs, mean ± SD, $n = 4$) removal rates for TSS, COD, TN, and TP, respectively, were achieved in WDPs after 7 days of the rainfall. However, 47.9 ± 9.6 % of the TSS removal, 64.0 ± 13.7 % of the COD removal, 80.5 ± 11.8 % of the TN removal, and 71.4 ± 9.9 % of the TP removal (based on EMCs, mean ± SD, $n = 4$) in WDPs were contributed by dilution during rainfall in this study (Table 3), while the remainder removal efficiencies were contributed by the sedimentation and ecological remediation process in WDPs during 7 days after the rainfall. Although ecological remediation and sedimentation are not the main pollutants reducing processes during rainfall, they are very important for improving water quality in WDPs during dry period and ensuring the dilution capacity for the next rainfall. FTWs have been proved to have water quality improvement effect across the world with different plant species (Chua et al. 2012; Headley and Tanner 2012). Biofilms developed within the root mass hanging below the mat provide a large treatment area (Tanner and Headley 2011). Wang et al. (2014a) reviewed N, P removal in FTWs and showed that nutrient removal efficiency ranges are 0.008–66.3 g/(m^2·day) for nitrogen and 0.00–1.8 g/(m^2·day) for phosphorus. In present study, an average nutrients removal efficiency of 0.3 g/(m^2·day) for TN and 0.057 g/(m^2·day) for TP, by FTWs, was achieved according to the 7-day monitoring data. The overall pollution control performances in the system indicate the system can effectively reduce pollution load taken by agricultural runoff to receiving waters.

Influence of GS length on pollutants removal efficiency

As shown in Fig. 4, the length of GS has significant positive influence on pollutants removal, correlation coefficient between TSS removal efficiency and GS length is the highest, while correlation coefficient between COD removal efficiency and GS length is the lowest. Although the processes which occur in swales are quite complex, involving hydraulic, physical and biochemical effects (Deletic and Fletcher 2006), sedimentation, and filtration within the grass layer are the main mechanisms of pollutant removal (Stagge et al. 2012). Increasing GS length tends to prolong hydraulic retention time and thus improve sedimentation and filtration efficiency. However, existing studies on the relationship between grass swale length and TSS removal efficiency showed wide variability. The average of 67.5 ± 9.6 % TSS removal efficiency in this study was within expected range when compared with previous studies, which showed a mean TSS reduction of 72 % by reviewing 18 swale study sources (Deletic and Fletcher 2006), a TSS removal range of 44.1–82.7 % in two field swales with an individual length of 198 and 138 m (Stagge et al. 2012). Lucke et al. (2014) reported that more than 80 % of the pollutants were removed in the first 60–75 m of the GS and suggested the length of GS should be no less than 30 m to ensure pollutant removal. In this study, an average removal rates of 67.5 ± 9.6, 32.0 ± 10.1, 51.3 ± 6.2, and 37.5 ± 8.3 % (based on EMCs, mean ± SD, $n = 4$) for TSS, COD, TN, and TP were achieved in a 157-m swale, respectively. The first 75 m swale contributed 66.5 ± 7.8, 41.2 ± 9.3, 60.3 ± 9.3, and 33.4 ± 6.5 % of the total removal rates in 157 m swale for TSS, COD, TN, and TP, respectively, suggesting that the pollutants removal efficiency still increase with the prolonging GS length after the first 75-m swale. In fact, the relation between GS length and pollutants removal efficiency is quite complicated, depending on many other factors such as the grass species, grass density, shape and slope of the swales, runoff volume, flow rate in swale and particle size distributions in runoff, etc. It is hard to simply say what is the best length. Some study had been conducted on the influencing factors of runoff volume, flow rate, and slope of the swales under simulated conditions (Deletic and Fletcher 2006), but further study is still needed. In general, length of GS is a key factor in its pollutant removal efficiency. Therefore, as for the application of this technology, GS should have enough length to ensure its pollutants removal efficiency.

PSDs in runoff and relation with removal by GS and WDP

Results of PSDs in GS are presented in Table 4. Several researchers divided PM in runoff into coarse fraction (≥75 μm) and fine fraction (<75 μm) (Rushton et al. 2007; Sansalone and Cristina 2004). Coarse particles larger than 75 μm can be easily separated from runoff while fine particles smaller than 5 μm can hardly be removed via natural process (Kim and Sansalone 2008). In this study, PSDs analysis indicates that larger than 75 μm particles account for an average of 79 % by weight in agricultural runoff. This result is higher than that in road runoff when compared with previous study, which showed a ratio of 25–80 % for fine particles smaller than 75 μm (Kim and Sansalone 2008). This difference is presumably due to the short duration and high intensity rainfall characteristics in the study site in summer. As shown in Table 4, GSs have a good and stable removal efficiency for coarse particles in runoff, while its removal efficiency for fine particles is relatively low and quite fluctuant. Particles smaller than 25 μm even increased in GSs, especially to particles smaller than 8 μm, suggesting that GSs cannot effectively intercept particles small than 25 μm. The increase in content of smaller than 25 μm particles are mainly due to the broken of large particles in transportation process as well as the additional particles flushed into runoff in GSs itself. These fine particles cannot be effectively removed in GSs and flow into subsequent treatment facility. Bäckström (2003) reported that the primary mechanism in swale is sedimentation, while filtration process plays a less important role. Sedimentation of small particles in swales follows "Stokes" Law, particle size is a key factor influencing its removal in swales (Clark and Pitt 2012). Andral et al. (1999) studied the sedimentation behavior of particles with different size in road runoff; the results showed that particles smaller than 50 μm fall at a speed of

Table 4 Particle concentrations for different particle size fractions and its removal efficiency in grassed swales

Size fraction (μm)	AR[a]		GS (75 m)			GS (157 m)		
	Min.–Max. conc. (mg/L)	Mean ± SD[b] (mg/L)	Min.–Max. conc. (mg/L)	Mean ± SD[b] (mg/L)	RR ± SD[c] (%)	Min.–Max. conc. (mg/L)	Mean ± SD[b] (mg/L)	RR ± SD[c] (%)
5–8	2.9–10.7	9.1 ± 0.9	3.1–16.8	11.2 ± 1.9	−23.4 ± 9.6	2.2–14.1	8.9 ± 2.7	1.9 ± 6.6
8–25	4.3–15.5	9.9 ± 3.2	3.5–17.6	10.3 ± 3.7	−3.2 ± 12.4	3.4–15.9	8.3 ± 3.3	15.9 ± 11.3
25–75	7.0–22.6	13.1 ± 5.4	4.9–19.8	11.9 ± 2.9	8.3 ± 20.6	4.1–16.9	9.7 ± 3.4	25.4 ± 13.9
75–150	11.1–38.1	26.6 ± 6.1	6.9–25.8	17.0 ± 4.5	36.3 ± 7.0	3.2–12.5	9.3 ± 2.6	65.5 ± 6.9
150–500	13.7–38.3	26.9 ± 7.2	5.3–19.7	11.8 ± 4.2	56.2 ± 13.7	2.9–8.4	4.7 ± 2.5	82.5 ± 8.4
500–1000	16.2–61.9	33.3 ± 14.3	3.2–19.8	11.8 ± 4.0	63.7 ± 11.0	2.2–8.1	4.2 ± 1.5	87.3 ± 6.2
>1000	20.1–59.3	38.3 ± 11.3	3.0–15.6	9.3 ± 4.3	76.1 ± 8.5	1.8–5.6	3.3 ± 0.9	91.2 ± 3.2

[a] AR = agricultural runoff; the minimum and maximum particle concentrations of different particle size fraction in runoff under of the four rainfall events

[b] The mean and the standard deviation of the particle concentrations of different particle size fraction in runoff under of the four rainfall events

[c] RR = removal rate; the mean and the standard deviation of the removal rate for different particle size fraction in 75 and 157 m GS under of the four rainfall events

2.98 m/h on average, while particles between 50 and 100 μm fall at a speed of 9.8 m/h on average. From the above studies, it is reasonable to believe the difference in sedimentation speed is the main cause leading to high removal rate for large particles with high sedimentation speed, and low or minus removal rate for fine particles with low sedimentation speed in GSs.

Results of further study on particle number distributions of particles smaller than 150 μm as well as its removal rate in the GSs and the WDPs are shown in Fig. 5. Although the content of particles smaller than 8 μm is not more than 5 % by weight in runoff, its number is predominately in runoff (Fig. 5a). The removal efficiency of these fine particles (<75 μm) in GSs is quite low and even shows an increasing trend, while coarse particles (≥75 μm) can be effectively removed in the system (Fig. 5b). WDPs can reduce particle number of all the size fractions by sedimentation in detention pond. Generally, the larger the particle is, the higher the removal efficiency is. WPDs act as a second barrier to particles in runoff in this system, especially, its average removal efficiency for particle size fraction of 5–8 and 8–25 μm reached 28 and 43 %, respectively, which is higher than the average removal efficiency of 1.9 % for 5–8 μm particle and 15.9 % for 8–25 μm particles in GSs. These differences are important for pollution control because small particles have a greater particle number per mass ratio, they are much more effective in light scattering which will influence the transparency of water and thus have influence on aquatic life (Grismer et al. 2008). In addition, fine particle has higher particle-bound pollutants due to it large specific surface area, they are also much more effective in transporting attached nutrients and microbial (Soupir and Mostaghimi 2010). Thus, GSs coupled with WDPs system forms a two-stage interception for particles in agricultural runoff, the system can effectively reduce pollution load to receiving waters.

Limitations and prospects

In this study, the agricultural runoff pollution control performance of a field GSs coupled with WDPs system was assessed, but there are still some limitations, which need further study. (1) The performance of the system was assessed under four typical rainfall during May to September 2012, which is the main season contributing to the agricultural pollution load to water bodies in the study site. Long-term performance of this system and the influence of maintenance measures on its efficiency are planned and highly desirable. (2) Owing to the limitations of field test, it is hard to assess the performance of this system under different influencing factors by changing its operating conditions, such as grass species, grass density, rainfall intensity, shape and slope of the swales, runoff volume, flow rate in swale, farming practice, etc. In addition, although the two detention ponds in this system worked in a series, they both received outflow from each of the two GS conveyance system. Therefore, it is impossible to make a study of individual role of the two-stage WDP in this system.

Overall, GSs coupled with WDPs system show good ANPS pollution control performance, it could have a better performance provided the mechanism and the corresponding influencing factors are fully investigated by further study. The system has a good prospect for wide field application in some regions, where suitable lands are available for the construction of this system.

Conclusions

A case study of the performance of a GSs system coupled with WDPs system was assessed for agricultural runoff pollution control under four typical rainfall events in Taihu basin, China. Results indicate that SS taken by flush process has significant influence on pollution loads in agricultural runoff; COD, TN, TP are all positively correlated with TSS, especially for TP. Agricultural runoff pollutant concentrations under the four rainfall events showed a certain FFE, TSS, and TP show moderate FFE, while COD and TN show weak FFE. The overall average removal efficiencies of 83.5 ± 4.5, 65.3 ± 6.8, 91.6 ± 3.8, and 81.3 ± 5.8 % for TSS, COD, TN, and TP,

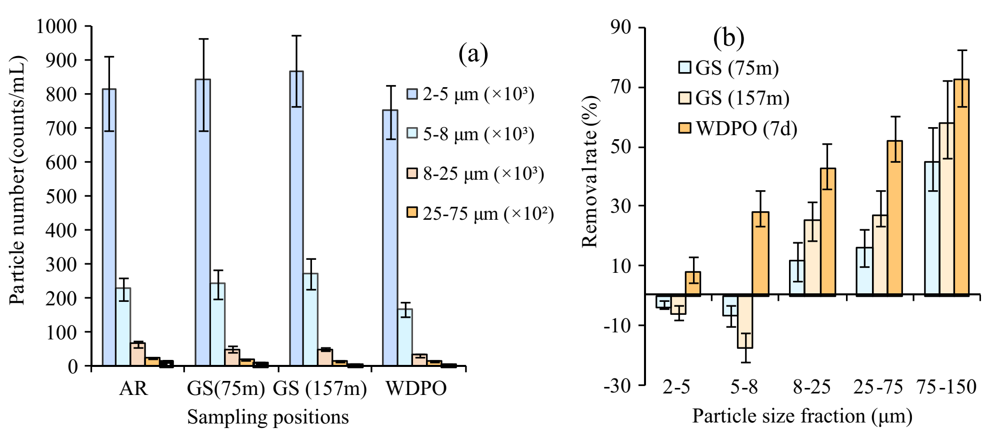

Fig. 5 Fine particle number distributions and corresponding removal efficiency in different parts of the GSs coupled with WDPs system (**a** particle number distributions; **b** removal efficiency; *AR*—agricultural runoff; *GS*—grassed swale; *WDPs*—wetland detention ponds; *WDPO*—wetland detention pond outflow)

respectively, were achieved in the system. The removal of particles and particulate bounded pollutants by sedimentation and filtration are the main mechanisms in GSs. The performance of GSs is dependent on PSDs in runoff, GSs can effectively reduce coarse particles larger than 75 μm in runoff, while its performance in reducing fine particles smaller than 25 μm is low, it can act as a good pre-treatment process for WDPs. The length of GS is a key factor in its performance. WDPs act as a second barrier to pollutants in runoff, it has a good removal efficiency for particles of all sizes by sedimentation. All the findings suggest that GSs coupled with WDPs system forms a two-stage interception for pollutants in agricultural runoff. It is a promising technology for agricultural runoff pollution control in some regions, which are facing agricultural runoff pollution and have convenient conditions for the construction of GSs coupled with WDPs system.

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