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Design and assessment of stream–wetland systems for nutrient removal in an urban watershed of China

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Abstract Constructed wetlands are typical best management practices (BMPs) often used to reduce nutrient loads in streams. Evaluating the effectiveness of wetland design on nutrient removal is essential to assist watershed managers in optimal design of BMP dimensions and placement. In this study, we assess performance of two constructed wetland systems (comprising of nine wetlands) installed in downstream of Longhongjian Stream in Hangzhou City, China. These wetland systems are monitored and evaluated for their effects on nutrient removal, particularly TN, NO_3-N, TP, and PO_4-P. Based on wetland input–output metrics, removal efficiency (RE) is used to quantify wetland system. Results show that both wetland systems effectively removed nutrients, with RE as high as 45% of TN, 57% of NO_3-N, 78% of TP, and 86% of PO_4-P. In general, nutrient removal efficiency is seasonally dependent, with better removal efficiency occurring during warmer seasons than others. Macrophyte uptake is a primary removal process in these wetlands. We observe that more wetlands working concurrently can provide a greater level of control on nutrients in lotic environments. Wetland design parameters play an important role in removal of nutrients in streams. Increasing flow volume and surface area of wetland, designing curvilinear shoreline, and longer flow paths can be used as design criteria for wetland systems aimed at nutrient removal.

Keywords Constructed wetland · Nutrient pollution · Removal efficiency · Nitrogen · Phosphorus · Wetland design

1 Introduction

Nutrient pollution from agriculture, urban areas, point sources, precipitation, and soil loss (Chang et al. 2013; Wellen et al. 2014; Rosenquist et al. 2010) is a leading cause of impaired water quality (Davis et al. 2015; Shan et al. 2014; Kourakos and Harter 2014). This has adverse impacts on biological and aquatic life in watersheds, specifically excess algal growth, oxygen deficiency, toxicity to humans and animals, unpleasant odors, and reduction in freshwater biodiversity (Littlejohn et al. 2014; El-Sheikh et al. 2010). Thus, watershed management through effective best management practices (BMPs) is needed for mitigating nutrient pollution in surface waters. In design of constructed wetlands, there is a need for research into implications of design parameters on removal efficiency. In this study, we study two constructed wetland systems to link removal efficiencies to system characteristics for optimal design of such complex systems.

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BMPs are attractive options that are proposed to eliminate or minimize nutrient pollution in watersheds (Hogan and Walbridge 2007; McNett et al. 2011). Various BMPs (riparian buffers, bioretention and filtration systems, ponds, and constructed wetlands) can be used to manage nutrient loads from point source pollution, fertilizer runoff, manure runoff, and other contaminants along hydrological pathways (Di and Cameron 2002; Monaghan et al. 2007). Constructed wetlands and detention ponds are typical BMPs being widely implemented to reduce pollutant discharge from municipalities, rural communities, urban dwellings, agricultural and urban storm runoff, and discharges from rivers and streams (O'Geen et al. 2010). In addition to being an effective and economical way of improving water quality, these ecological treatment systems provide numerous secondary benefits, such as flood storage, groundwater recharge, biological diversity, and aesthetic value (Mitsch and Gosselink 2007; Zedler 2003; Díaz et al. 2012; Duffy and Kahara 2011). Wetlands contain a unique assemblage of water, vegetation, soils, and microbes related to physical, biological, and chemical processes (Yang and Best 2015; Dunne et al. 2013), which contributes to nutrient detention (Poach et al. 2007; Kayranli et al. 2010). In the USA, wetlands are popular as BMPs and have been widely used for stormwater management (Koch et al. 2012; Hogan and Walbridge 2007; Chang et al. 2013). In UK, the use of ponds and wetlands has been used for water quality improvements (Kay et al. 2005). China has the fourth largest wetland area in the world (10% of the world's wetland areas). In 2000, China implemented the National Wetland Conservation Program (NWCP) as a guideline for the conservation and wise use of wetlands. In the last decades, a large area of wetlands has been established and restored, and wetlands have provided a significant amount of ecosystem services, including freshwater supply, flood control, water purification, wildlife habitat, and aquatic life preserves. (Wang et al. 2012; Zhang et al. 2009).

Wetlands improve water quality through biochemical interactions, adsorption, filtration, sedimentation, and dissolution (Jia et al. 2014; Scholz and Hedmark 2010). The pollutant removal in wetlands can vary widely due to differences in ecological characteristics and functions (Richardson et al. 2011). For example, nitrate removal efficiency could range from being a nitrate source (negative removal efficiency) to as high as 98% removal (O'Geen et al. 2010; Díaz et al. 2012), and removal of total phosphorus can vary from zero net removal to 80% removal (Reinhardt et al. 2006). Pollutant removal thus depends upon environmental, design, and management factors such as wetland morphology, chemistry, hydrology, sediment, vegetation, climate, and age (Nas and Nas 2009; Fan et al. 2012). Several studies report that different practices can be combined to treat pollutants more effectively within a watershed, to suite hydrology, climate, system age, discharge, and operational scenarios (Scholes et al. 2008; McNett et al. 2010; Chen et al. 2013; Monaghan et al. 2007). However, a few attempts have been made to evaluate the effectiveness of wetland system design on nutrient removal (Filoso et al. 2015). There are as well fewer studies that compare stream–wetland systems comparatively for general conclusions on nutrient removal. Studies show that BMP efficiency is heavily influenced by changes in design parameters that influence composition, area, and retention time (McNett et al. 2010; Yang and Cui 2012). Thus, morphology and placement of BMPs in design of wetland systems can be an effective way to enhance nutrient removal in watersheds (Kröger et al. 2013).

In this study, we assess performances of two wetland systems, involving nine constructed wetlands, located in the downstream of Longhongjian Stream in Hangzhou City, China. The watershed is primarily agricultural and forest land use, with extensive agricultural and urban nonpoint sources. Intensive fertilization may result in adverse nutrient pollution effects on surface quality. Thus, wetland systems were constructed in 2012 in the stream system to improve the stream water quality of West Lake located downstream to the watershed. We analyzed and compared the performance of two wetland systems and evaluated wetland's efficacy to reduce nutrients and for identifying optimal criteria of BMPs for general wetland design. We hypothesize that nutrient removal varies with wetland features, such as size, shape, flow path, and volume, and these features can serve as sensitive indicators in evaluation of nutrient mitigation in these wetland systems. Specific objectives are to (1) quantify the effects of wetland restoration on the water quality and identify major removal mechanisms in nutrient removal; (2) evaluate the effect of wetland's quantity on nutrient removal; and (3) observe nutrient retention responding to wetland volume, area, flow path, and perimeter and provide recommendations for wetland design guideline. Results of this study can provide useful information in wetland design and in the management for improving stream water quality in similar suburban watersheds.

2 Materials and methods

2.1 Study area

This study area involves watersheds of Longhongjian Stream (Fig. 1) with two wetland systems comprised of nine constructed wetlands (M1–M5, T1–T4) installed in the stream. Longhongjian Stream drains into West Lake and is located southwest of lake located in Hangzhou City, China. It contains two streams: mainstream (MS) and tributary (TR). System 1 contains five-step wetlands located in the downstream of the mainstream (2.8 km), and system 2 contains four-step wetlands located in the downstream of the tributary (1.4 km) (Fig. 1). Longhongjian watershed has a subtropical humid climate and four distinct seasons. During the monitoring period (2013–2015), the annual mean temperature was 17 °C, ranging from −4.4 °C in December to 41.6 °C in August, and the total annual precipitation was 1520.9 mm in Hangzhou (CCRH 2014). It has two rainy seasons: the plum rain season from April to June and the typhoon season from July to September. In the watershed, approximately 70% of area is covered by forest, 20% by tea plantations, and the rest is residential, transportation, and water bodies. Fertilizers in large quantities are applied in the tea plantations, which include urea [$CO(NH_2)_2$], compound fertilizer (containing the elements: N, P), and manure (Jin et al. 2015). Though point source pollution is controlled in the watershed, the nitrate (NO_3-N) load from nonpoint sources discharged into rivers is still very high. To reduce the concentration of nutrients, Longhongjian pollution control project was initiated in 2012, and the stepping wetlands were constructed along the stream for ecological restoration. This study aims to study these wetland systems during 2013–2015 for design and efficiency observation.

Each wetland differs in parameters such as volume, shape, area, vegetation type, and flow paths (Table 1). Wetlands numbered M1–M5 (system 1) share the same water source originating from upstream of the mainstream. Wetlands T1–T4 (system 2) share the water source from upstream of tributary. The water flows sequentially from the first to the last wetlands by gravity and eventually discharges into the West Lake (Fig. 1). All wetlands have high coverage of various aquatic plants, including *Potamogeton crispus*, *Antirrhinum majus*, *eelgrass*, *Hydrilla*, *water lily*, *Typha orientalis*, *lotus*, *Nymphoides peltatum*, *Nuphar pumila*, *reed*, *wild rice*, *Thalia dealbata*, *Acorus calamus*, *Lythrum salicaria*, *Pontederia cordata*, and *Canna*. The plant is harvested in autumn, which prevents nutrients from being released into the water. In order to increase the retention time, baffles are set using wood fences in each wetland to force the water flow in a zigzag pattern. The HRT in system 1 and system 2 is estimated to be around 2.8 and 3 days, respectively.

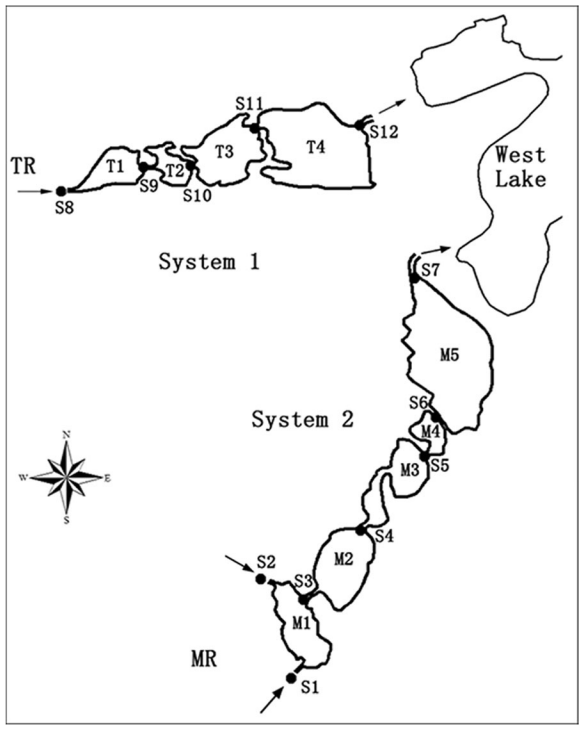


Fig. 1 Step wetland systems in Longhongjian Stream

2.2 Sampling and analysis

Figure 1 shows the location of each sampling site and reaches. Twelve water sampling sites (S1–S12) are established at the inlet or outlet of each wetland: seven in system 1 and five in system 2. S1 and S2 are set at the two inlets of system 1, and S3, S4, S5, S6, and S7 are set in the outlet of each wetlands, respectively. S8 is located in the inlet of system 2, and S9, S10, S11, and S12 are in the outlet of each wetland, respectively. Monthly water sampling and monitoring was conducted from November 2013 to October 2015 (except for February 2014 due to the Chinese New Year). Surface water samples were collected in 1-L acid-washed polyethylene bottles for the rest parameters. All samples were transported to the laboratory and conserved at 4 °C for further analysis (maximum storage time 1 week) (USEPA 2001).

Table 1 Physical parameters of wetland system

	Volume (m^3)	Area (m^2)	Depth (m)	Elevation drop (m)	Perimeter (m)	Flow path (m)
M1	3306.6	3674	0.9	0	305	182
M2	6894	5745	1.2	1.44	311	321
M3	4209.3	4677	0.9	2.45	390	235
M4	1837.8	2042	0.9	1.12	180	56
M5	12,286.8	13652	0.9	0.52	544	592
T1	3458.7	3843	0.9	0	268	139
T2	2794.4	1996	1.4	1.19	213	73
T3	6915.7	6287	1.1	0.76	328	301
T4	14,533.2	12111	1.2	0.64	496	453

In situ, pH of surface water was measured with a portable pH meter (HANNA, HI98128). Water temperature (WT, °C) and dissolved oxygen (DO, mg L^{-1}) were measured with a portable dissolved oxygen meter (HACH, HQ30D). In the laboratory, the water chemical parameters were determined following the officially recommended methods of analysis (SEPA 2002). The parameters analyzed in the water samples were total nitrogen (TN, mg L^{-1}), nitrate (NO_3-N, mg L^{-1}), nitrite (NO_2-N, mg L^{-1}), ammonium (NH_4-N, mg L^{-1}), total phosphorus (TP, mg L^{-1}), phosphate (PO_4-P, mg L^{-1}), chemical oxygen demand (COD_{Mn}, mg L^{-1}), and biochemical oxygen demand (BOD_5, mg L^{-1}).

2.3 Data analysis

The removal efficiency (RE, %) of each pollutant was calculated as

$$\mathrm{RE} = \frac{C_{\mathrm{in}} - C_{\mathrm{out}}}{C_{\mathrm{in}}} \times 100\%$$

where C_{in} and C_{out} are the inlet and outlet concentrations (mg L^{-1}). We calculate the seasonal RE using the mean value in each season (spring: March to May, summer: June to August, autumn: September to November, and winter: December to February). All water quality data were tested for normality using the Kolmogorov–Smirnov (K–S) test. According to the K–S test, water quality parameters showed non-normal distribution, so Spearman's correlation coefficient was used to assess the statistical significance of correlations between non-normal distributed parameters (Hayakawa et al. 2015). All statistical analyses were performed using SPSS 19.0 (IBM, USA) or Origin (OriginLab, USA).

3 Results and discussion

3.1 Performance assessment the wetland systems

3.1.1 Nitrogen

Water quality characterization of nitrogen in each system is presented in Fig. 2. The performance in system 1 (five wetlands) is better than system 2 (four wetlands). TN and NO_3-N concentrations in wetland varied by seasons but showed the same tendency as TN, which is dominated by NO_3-N (represented 82% of TN). In system 1, seasonal TN inflow levels varied from 4.72 to 9.87 mg L^{-1}, and NO_3-N varied from 3.8 to 8.76 mg L^{-1}. TN and NO_3-N concentrations decreased significantly after passing through the five-step wetland system (Table 2), with the outflow values lower than 3.59 and 2.51 mg L^{-1}, respectively. System 1 showed highest removal efficiencies in autumn (45.01% for TN and 56.74% for NO_3-N, respectively) and lowest in winter (30.87% for TN and 36.96% for NO_3-N, respectively). In system 2, inflow concentration of TN varied from 4.82 to 6.85 mg L^{-1}, and outflow concentration ranged from 3.2 to 5.71 mg L^{-1}. The lowest RE of TN was found in spring (16.70%). The RE tended to increase in other seasons and reached the highest value in summer (35.57%). Inflow level of NO_3-N ranged from 3.65 to 5.15 mg L^{-1}, and outflow level was from 2.32 to 4.37 mg L^{-1}. RE ranged from 7.63 to 40.47%, with the lowest value in spring and highest value in summer.

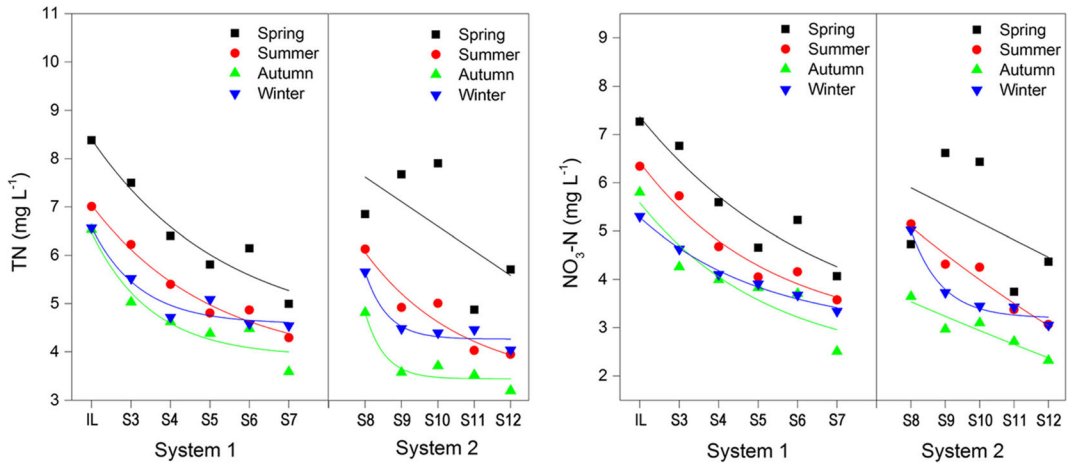


Fig. 2 Temporal and spatial variation of TN and NO_3-N

Several wetland sites showed a negative nitrogen removal (M4 and T2) (Fig. 2). There could be three reasons to explain this. Firstly, the sizes of the wetlands are too small to intercept nitrogen (Table 1). Secondly, the nitrogen cycling can take place in the wetland, and assimilated nitrogen can be subsequently released back into the wetland during death and decay of vegetation (Smith et al. 2006). Thus, plant harvesting is a wetland management option that can prevent nitrogen release from vegetation (Lu et al. 2009). Moreover, a wide variety of Actinomycetes and free-living heterotrophic bacteria plus blue-green algae can fix nitrogen in wetland (Johnson 1991). The rise of nitrogen in the wetland can be attributed to the biological nitrogen fixation and the nutrients trapped in plant parts dissolving in the water (Kanyiginya et al. 2010). High TN and NO_3-N concentrations were observed in spring, which is attributed to the fertilizer applied in the tea plantation in March and April. When the rainy season starts in spring, the high level of nutrients in tea plantation is flushed into the stream with runoff. The extremely high concentrations of TN and NO_3-N were observed at S9, S10, and S12 in April, 2014 (with NO_3-N 19.40, 18.81, and 7.61 mg L^{-1}, respectively), and the same rise occurs in phosphorus concentrations. The wetlands T2, T3, and T5 are close to the tea plantation where the runoff flows directly into the wetland without any buffers, and the sampling in April, 2014 was conducted after the rain event, which lead to the abrupt rise of nitrogen at S9, S10, and S12. That as well may result in the relatively low RE in spring in system 2. The high RE shown in warm seasons suggests that the biological nitrogen transformation rate increased since biological process is strongly affected by temperature. In autumn, the retention time increased as the flow rate became slow after the rainy season, which promoted transformation and assimilation in the wetlands. That is why the high RE was observed in autumn in system 1 (Fig. 3).

The main mechanism for NO_3-N removal in constructed wetlands is denitrification, sedimentation, and deposition of particulate N, ammonia volatilization, plant uptake, and algal assimilation (Díaz et al. 2012; Kadlec and Knight 1996). The primary mechanism for the loss of NO_3-N in wetlands is denitrification (Chen et al. 2015; Vymazal 2007). Wetlands in this study are low-carbon and high-oxygen systems. The carbon sources BOD_5 (0.75 ± 0.76 mg L^{-1}) and COD_{Mn} (3.55 ± 1.43 mg L^{-1}) were significantly low, which is a limiting factor for denitrification process in these systems (Mahmoud 2010). Moreover, denitrifying enzyme activity requires an O_2 concentration below 0.2 mg L^{-1} (Reinhardt et al. 2006), while the mean O_2 concentration was 10.22 mg L^{-1} with minimum value 1.71 mg L^{-1} in the wetland. Therefore, the denitrification was not the dominant NO_3-N removal process in the wetlands. Spieles and Mitsch (1999) reported that denitrification accounted for 60–95% of the NO_3-N removal in wetlands, which explains why the RE in our wetlands was not as high as some studies reported (Borin and Tocchetto 2007; McNett et al. 2011). Considering that our wetlands are characterized with high macrophyte coverage, we speculate that the major

Table 2 Wetland design: implementation

Design parameters	Direct influence	Design remarks
Area	Positive	Wetland area design requires balancing the area available for wetland systems and the costs estimated for long-term maintenance. High surface area increases sedimentation, adsorption, microbial activity, and plant uptake of pollutants. Maximizing surface area can be conducted by increasing the surface area of the wetland or by increasing the number of surfaces within the wetland.
Flow path	Positive	Flow paths play an important effect on nutrient removal. Providing long flow paths to maximize the contact of the water with the surfaces and vegetation within the wetland. The effective length of flow paths can be increased by creating both deep and shallow areas, complex flow paths, and a dense and diverse plant community. For example, adding baffles and berms to create serpentine flow patterns or building multiple cells can be an efficient way to increase the flow path (USEPA 1995).
Volume	Positive	The wetland volume design should consider the total volume of water entering the system, including streams, runoff, precipitation, and groundwater infiltration, and the total volume of water leaving the system, including outflow, evapotranspiration, and exfiltration. Adequate wetland volume is recommended to respond to the decrease in nutrient concentrations and sustainable water quality management. Building a large enough wetland could catch and retain the water long enough for treatment to occur.
Perimeter	Positive	Irregular perimeter plays a positive effect on decreasing the concentration of nutrients. Wetland could be designed with irregular and curvilinear shoreline in a variety of configurations. Trees and bushes can be planted along the shoreline to enhance nutrient uptake and increase habitat diversity for wildlife (USEPA 1995).

mechanisms for nitrogen removal are plant uptake (Spence and Jordan 2013; Tu et al. 2014).

3.1.2 Phosphorus

Temporal and spatial variations of TP and PO_4-P are shown in Fig. 4. The performance of system 1 on TP and PO_4-P removal was not as good as system 2. In system 1, TP decreased from around 0.05 mg L^{-1} in the inflow to below 0.04 mg L^{-1} in the outflow, with RE ranging from 27.65 to 45.16%; PO_4-P concentration decreased from around 0.035 mg L^{-1} to below 0.02 mg L^{-1}, with RE ranging from 44.61 to 55.14% (Fig. 5). In comparison with system 1, TP and PO_4-P were obviously retained in system 2. TP and PO_4-P had higher inflow level, especially in autumn (with TP 0.10 mg L^{-1} and PO_4-P 0.69 mg L^{-1}). The system was found by reducing TP and PO_4-P for as high as 77.92 and 85.50%, respectively, in autumn. The lowest RE was found in winter, with 23.33% for TP and 38.35% for PO_4-P (Fig. 5).

Wetlands in this study are relatively new (<3 years) and are therefore more effective at removing P since wetland has greater availability of soil adsorption and higher vegetation growth and associated P uptake during early stages (Smith et al. 2006). Efficiency in P removal over time may decrease and should be monitored. The higher RE in system 2 could be attributed to the higher inflow concentrations. Within a certain range, high inflow concentration results in high removal efficiency. Low levels of TP and PO_4-P are not sufficient for biological processes to achieve quantitative pollutant removal (Younger 2014). This reveals that water quality regulation is primarily based on pollutant concentrations. This was confirmed by much higher RE observed in autumn in system 2 due to high inflow P level. Given the same inflow concentration, we could speculate that system 1 have better performance in terms of the larger wetland. Low RE in winter is expected, as low temperature in winter reduces the chemical and biological processes. The reductions in some wetlands were not so outstanding, such as M1, M4, and T2. The outflow concentrations increased in these wetlands, and such rises tended to be obvious in the rainy season. There are three possible reasons to explain this. Firstly, phosphorus released from soil was flushed into wetland with runoff during storm events. Secondly, decomposition of biological materials in the wetlands could cause phosphorus concentration rises (Tu et al. 2014). Thirdly, sediment could act as sources contributing to phosphorus in the water (Mugisha et al. 2007).

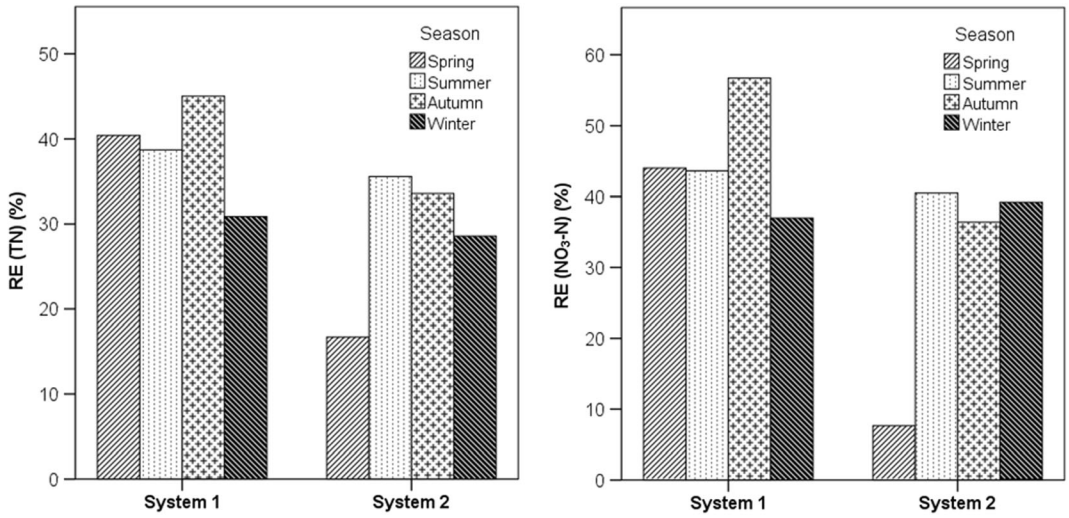


Fig. 3 Seasonal RE of TN and NO_3-N in two systems

Retention and removal of phosphorus in wetlands depend on inflow concentration and physical, chemical, and biological processes. Phosphorus transported to wetlands is present in organic and inorganic forms that are either dissolved or particulate (Maynard et al. 2009). The dissolved inorganic fraction of P is immediately available for biological uptake (Uusitalo and Elknom 2003), and insoluble precipitates under some circumstances may redissolve in some conditions (El-Sheikh et al. 2010). In this study, 60% of TP consists of dissolved P and the wetlands are covered 100% by macrophytes. Therefore, we speculate that plant uptake was the primal process causing the removal of phosphorus in the wetland system. Other processes such as sedimentation of particulate P (Díaz et al. 2012), P sorption in wetland soils (Maynard et al. 2009; Smith et al. 2006), and microorganism transformation (Reddy and DeLaune 2008) might be other mechanisms of P reduction.

3.2 Potential influence of the wetland design factors

Wetland design includes a series of parameters, such as shape, area, volume, and depth. N and P removal was various with design parameters changing, and NO_3-N removal was more affected, since nutrient RE is impacted by multiple factors, while nitrate is more sensitive to the wetland structure (Li et al. 2005). In the present research, we evaluate wetland's efficacy to reduce nutrients by analyzing the relationship between RE of nutrient and design parameters (wetland volume, flow path, area, and perimeter).

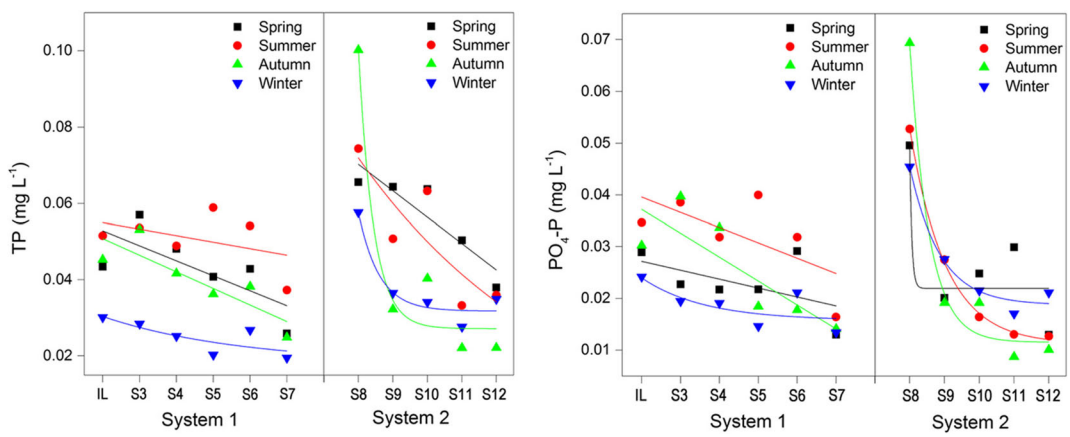


Fig. 4 Temporal and spatial variation of TN and NO_3-N

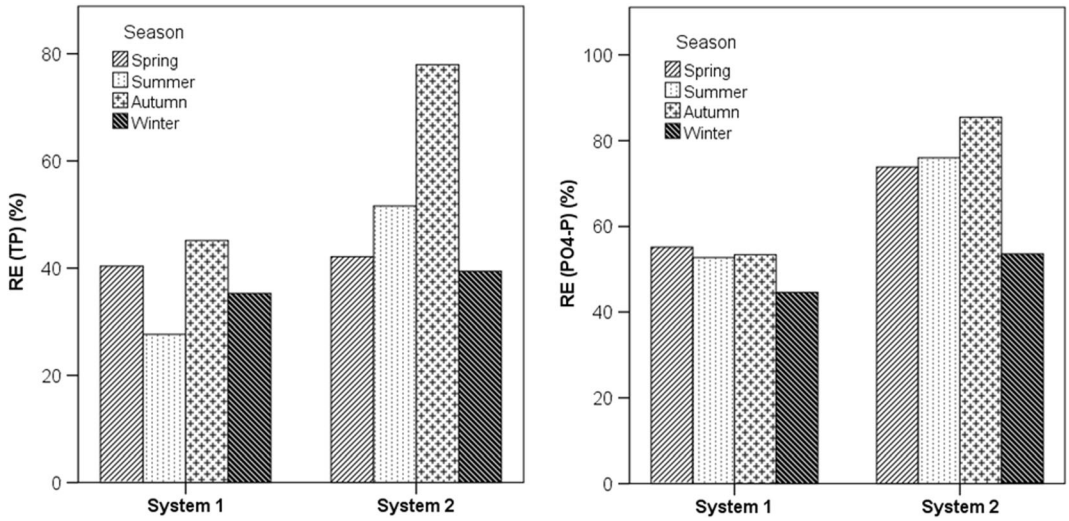


Fig. 5 Seasonal RE of TP and PO_4-P in two systems

We estimated wetland volume by multiplying the average depth by the area of the wetland. The capacity had a clear impact on nitrate concentrations. As seen from Fig. 6, there are positive relationships between wetland volume and nutrient RE. Taking NO_3-N as an example, with wetland volume increasing from 2000 to 15,000 m^3, the RE of NO_3-N increased from 14 to 30%. The decrease in nutrient concentration was correlated with an increase in water storage in the wetland. Large wetland volume gives chance for sustaining higher loadings and subsequently higher rates of nutrient removal. Large volume attenuates peak runoff rates and improves pollutant removal. Moreover, an increase in volume could compensate the concentrating effects of evapotranspiration due to transpiration from wetland vegetation and evaporation from the water surface.

The relationship of RE and flow path in wetland is shown in Fig. 7. The efficiency of surface water pollution removal in wetlands highly depends upon hydrology (Correll 1997). As seen in Fig. 7, three times of increase flow path resulted in 8, 20, 16, and 11% increase of RE in TN, NO_3-N, TP, and PO_4-P, respectively. Several researches reported that a number of pollutants generally decrease with distance at a range of wetlands (Kadlec and Knight 1996; Chen et al. 2015). Long flow path increases hydraulic retention time, which promotes removal processes, particularly denitrification and plant uptake (Haycock and Pinay 1993). Long retention time helps denitrification by maximizing contact with anoxic sediments, accumulating labile organic matter and providing anoxic condition to support the denitrifying microbial population (Birgand et al. 2007; Tournebize et al. 2015). Long flow path as well increases more chance for plant uptake by maximizing the contact of water with plant.

Figure 8 presents the wetland area and their impacts on nutrient removal efficiency. Nutrients are efficiently removed with increase in wetland area. With wetland area increasing from 2000 to 14,000 m^2, RE of TN, NO_3-N, TP, and PO_4-P increased by 8, 20, 15, and 13%, respectively. Large wetland area increases sedimentation, adsorption, microbial activity, and plant uptake of nutrients. Wetland area can play a critical role in reducing diffuse pollution by intercepting them. Moreover, if wetlands are too small, functions such as support of diversity storage of floodwater would no longer exist (Mitsch and Gosselink 2000). However, Schueler et al. (1992) found that treatment performance increased and variability in treatment performance decreased as the wetland area increased in relation to watershed area. The pollutant removal capability of a wetland generally becomes more consistent when the wetland to watershed area ratio is greater than 2%.

Increasing the perimeter of the wetland plays a positive effect on decreasing the concentration of nutrients (Fig. 9). Change of perimeter from 200 to 550 m resulted in a significant increase in N and P removal. NO_3-N showed the highest RE increase, from 13 to 32%. Using curvilinear shoreline could improve the water quality. Irregular shape of

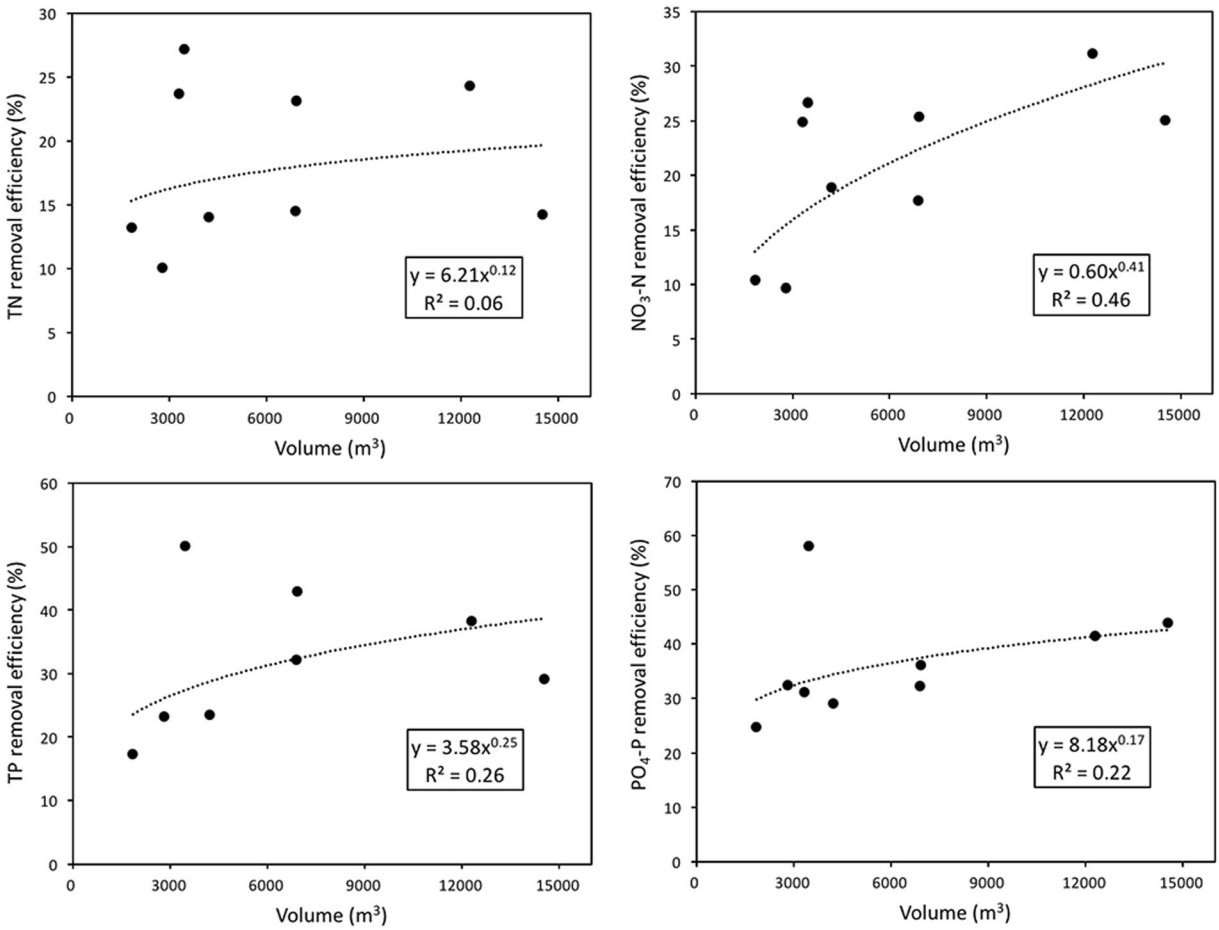


Fig. 6 The relationship between wetland volume and nutrient RE

wetland increases perimeter length and diversifies habitat. The curving shoreline can support more diverse and abundant plant growth which improve water quality. Trees and bushes along the shore can enhance nutrient uptake, increase habitat diversity for wildlife, provide shade, and moderate temperature.

3.3 Wetland design

BMPs encompass a wide variety of appropriate technologies to minimize the effect of nutrient pollutant. Observing the wetland performance and characteristics helps improve understanding of nutrient removal performance and system characteristics and provide context at the operational wetland scale. We managed two wetland systems and tracked the water quality over 2 years in order to assess wetland efficacy and identify the possible optimized design to develop the performance of wetland. Our study showed that the step wetland systems could achieve pollution nutrient retention and storm flow storage more effectively than single wetland. Several wetlands working together provide a greater level of control on nutrients than a one large system of similar total size. Water quality and quantity functions within a watershed are cumulative, and even very small systems provide important functions that benefit the system as a whole. Thus, choosing to construct several small wetlands is better than to construct one large wetland (USEPA 1995). The complex systems provide higher and more reliable levels of pollutant removal than simple systems (Schueler 1992).

Although the relationships between removal rates and wetland design parameters may not be accurate for wetland design to achieve a specific outflow concentration criterion, we do find them important for nutrient

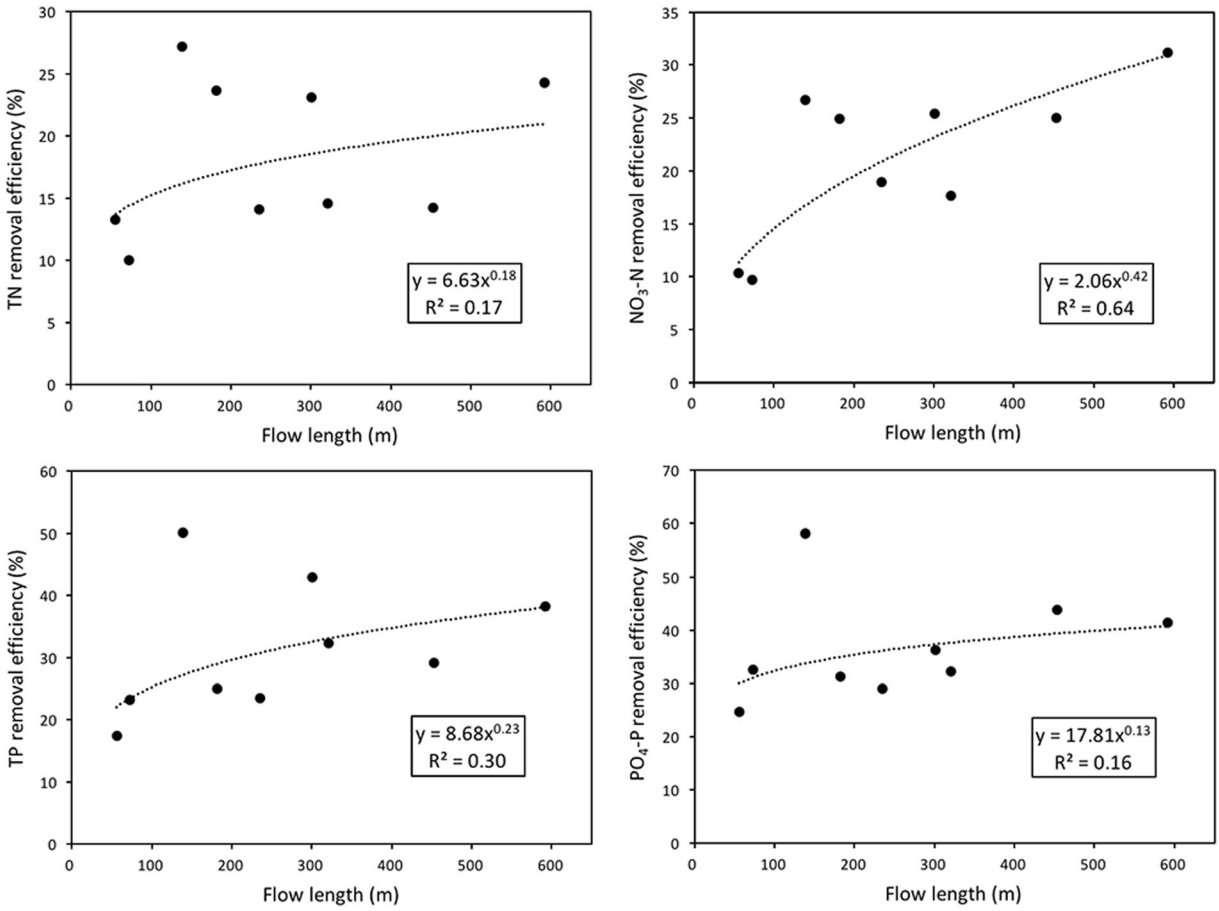


Fig. 7 The relationship between wetland flow path and nutrient RE

pollution retention and long-term watershed management. Nutrient removal was generally related to wetland area, volume, flow path, and perimeter. According to the relationship between RE and wetland parameters, our suggestion of the wetland design is elucidated in Table 2.

Pollution control functions of wetland change with the variation in wetland features, such as wetland shape, area, volume, and depth. Increasing wetland area and volume, flow path, and perimeter could contribute to increase in nutrient removal, so considering these features in the wetland design process could benefit to strengthen functions of wetland. However, it should be noted that the nutrient reduction and percent removal do not typically account for variations in wetland designs (D'Arcy et al. 2007). In addition to wetland design parameters, nutrient removal efficiency is impacted by a combination of various factors, including ecoregion, season, aquatic vegetation, dissolved oxygen level, hydrology, wetland age, and background contaminant levels (Chen et al. 2013; D'Arcy et al. 2007; Fan et al. 2012; Debusk et al. 2005). Possible changes such as choosing suitable aquatic plant, increasing vegetation density, and creating anaerobic environment could also contribute to improve the nutrient retention capacity in the wetland (Chen et al. 2013).

4 Conclusions

In order to reduce effects of nutrient pollution on downstream watershed, two systems with nine-step wetlands were constructed in the mainstream and tributary of Longhongjian Stream, respectively, to improve nutrient removal and ecosystem processing services. We studied the performances of two

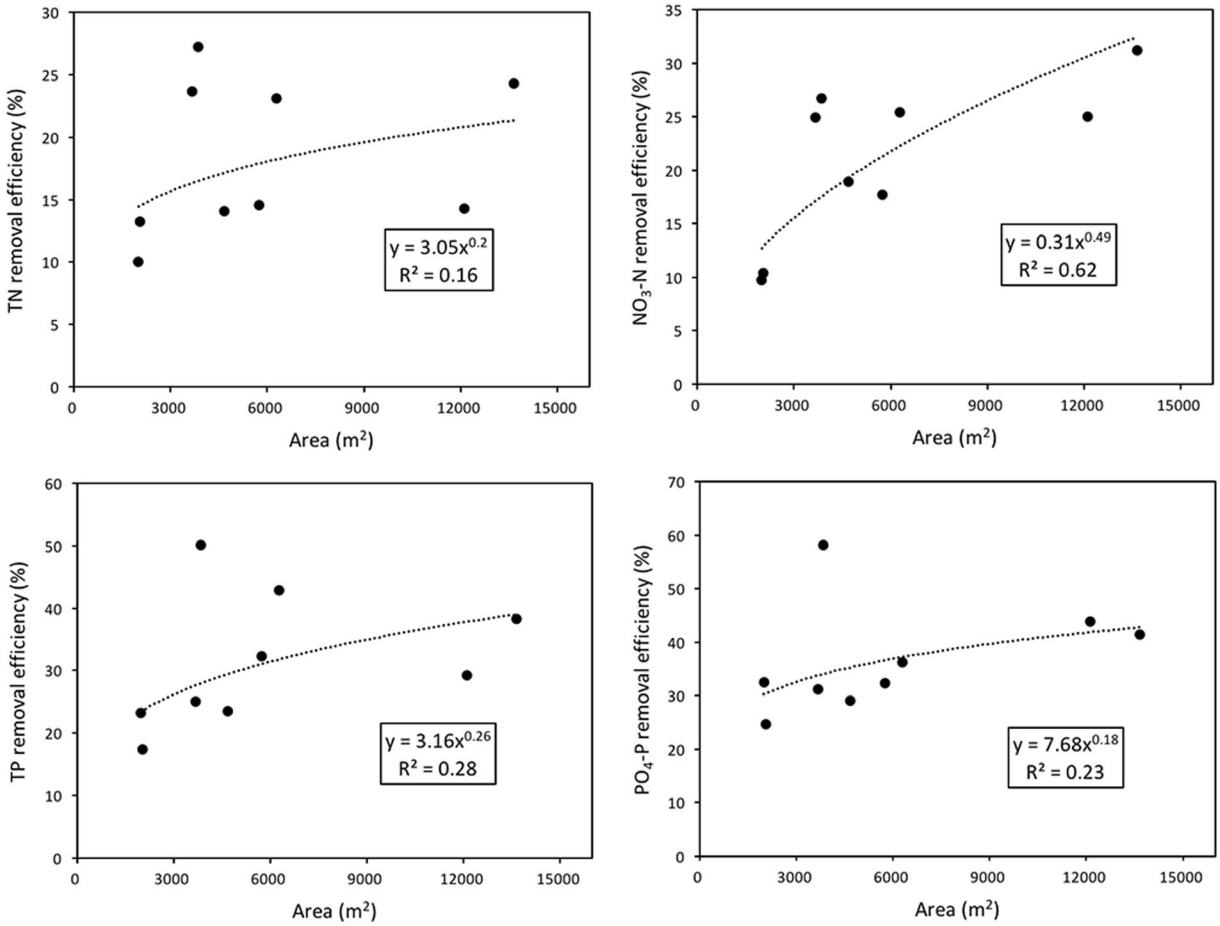


Fig. 8 The relationship between wetland area and nutrient RE

systems on nutrient removal. The results showed that both systems greatly improved water quality in the stream, with RE as high as 45% of TN, 57% of NO_3-N, 78% of TP, and 86% of PO_4-P. Nutrient removal rates were highly sensitive to temperature. The RE of nutrient showed a marked seasonal pattern with higher nutrient removal in warmer seasons in both systems. Wetlands are more effective at removing P than N due to the comparatively young wetlands. Since wetland removal efficiency could vary over time due to changes in soil adsorption capacity, the performance of the treatment should be evaluated during more stable period. Plant uptake was the primal process causing the removal of nutrients in the wetland systems. If the wetland was able to be developed to exert the function of denitrification, the efficiency of the system would be more satisfactory. In the two wetland systems, system 1 is more efficient in nutrient removal. Multiple wetlands appear to be more effective in nutrient removal compared to single wetlands. The more wetlands working concurrently, the better performance the wetland system achieve on nutrient removal.

We evaluated the relationship between the RE of nutrients and design parameters, including volume, flow path, area, and perimeter. Results generated from this study showed that the performance of wetlands for treating nutrients highly depends on the wetland characteristics, such as wetland volume, flow path, area, and perimeter. When wetland space and cost are available, designing larger area and volume of wetland would achieve better performance of nutrient removal. Moreover, irregular perimeter plays a positive effect on reducing nutrients. Trees and bushes can be planted along the shoreline to enhance nutrient uptake. Long flow paths, such as adding baffles and berms, are helpful to maximize

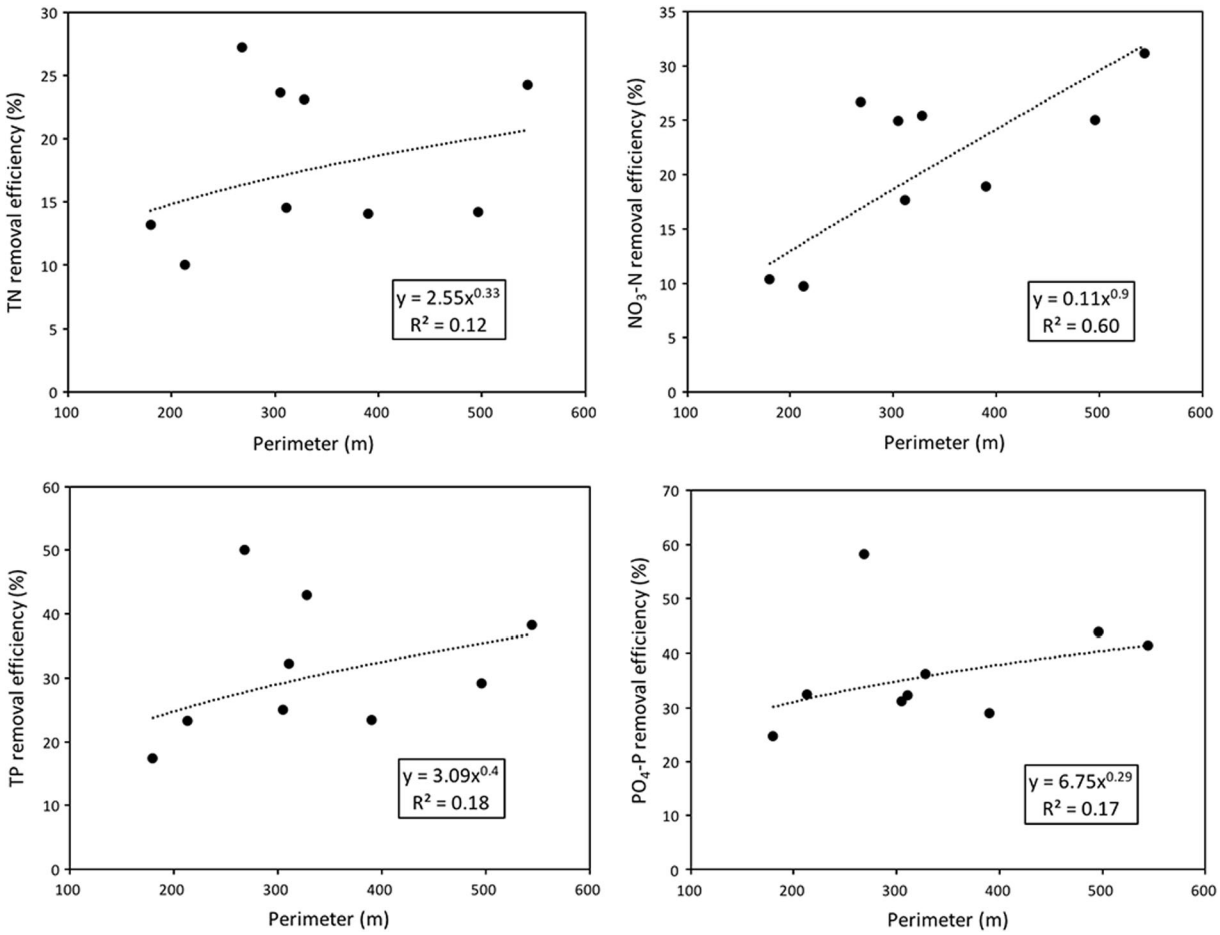


Fig. 9 The relationship between wetland perimeter and nutrient RE

the hydraulic retention time and increase the contact of water with the surfaces and vegetation within the wetland. However, the nutrient reduction and percent removal do not typically account for variations in wetland designs in this study. Further studies are required to verify the more accurate relationship between nutrient RE and design parameters.

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