© IWA Publishing 2019 Journal of Water Supply: Research and Technology—AQUA | 68.2 | 2019

Application and performance of eco-bag revetment for water purification in lake environments: a case study from rural China

Van Tai Tang, Eldon R. Rene and Qiuhong Li

ABSTRACT

Intense agricultural activities and pollutants from different man-made sources directly pollute rural lake water. The main aim of this study is to ascertain the water purification effect of a revetment constructed of eco-bags on a rural lake located in Jidong village, Jiangsu province, China. During the test period of 22 weeks, the microbial biomass increased from $0.089 \pm 0.055 \times 10^9$ to $3.83 \pm 1.02 \times 10^9$ cell.cm^{-2}. In terms of the composition ratio, P*roteobacteria*, *Nitrospirae* and *Firmicutes* in the eco-bags accounted for 68.7, 9.5 and 10.1%, respectively. The growth of microbial population in the eco-bags and the growth of plants in the grass belt played a major role in the removal of pollutants. The chemical oxygen demand (COD), NH_3-N, total nitogen (TN), total phosphorus (TP) and total suspended solids (TSS) removal efficiencies in the lake water were 43.9, 17.9, 43, 25.9 and 74.5%, respectively, while the dissolved oxygen (DO) concentration increased from 1.85 ± 0.42 to 2.93 ± 0.46 mg.L^{-1} during the 22 week test period.

Key words | COD removal, eco-bag, lake water purification, microbial community analysis, plant growth

Van Tai Tang (corresponding author)
Green Processing, Bioremediation and Alternative Energies Research Group, Faculty of Environment and Labour Safety,
Ton Duc Thang University,
Ho Chi Minh City, Vietnam
E-mail: *tangvantai@tdtu.edu.vn*

Van Tai Tang
Qiuhong Li
School of Civil Engineering,
Southeast University,
Nanjing 210096, China

Eldon R. Rene
Department of Environmental Engineering and Water Technology,
IHE – Delft Institute for Water Education,
2601 DA Delft, The Netherlands

Qiuhong Li
NARI Technology Development Co., Ltd,
Nanjing, Jiangsu, China

INTRODUCTION

Since the economic reformation in the year 1979, China's economy has rapidly increased in the past 15 years, leading to large-scale investment in rural Chinese villages (Chen 2002). As a result of this development, the agricultural and industrial production processes generate a great deal of wastewater and solid wastes. The inability of the existing waste management facilities to handle such pollutant loads and the lack of awareness among villagers for environmental protection causes large volumes of wastewater and garbage to be directly discharged into rural rivers and lake water (Pistocchi 2010; Reddy *et al.* 2014). In Jidong village, located in Jiangsu province of China, the drinking water source is polluted with high concentrations of coliform bacteria, organic matter and nutrients. The lakes in many rural areas have used concrete materials to construct hard revetments in order to make the bank structure stable and offer good resistance against flooding conditions.

One of the advantages of using a hard concrete revetment is that it offers structural strength to the bank and prevents the collapse of soil into the lake. On the other hand, the hard revetment can separate the water and soil relation and negatively affect the natural ecology that reduces the water purification effects. In order to restore the natural conditions and enhance the water purification effects, revetments can be constructed with eco-bags that serve the dual purpose of slope stabilization and bank protection. Zhou *et al.* (2012) used eco-bags for soil slope protection and studied the long-term impact of the project by testing the degree of compressibility of the filled eco-bags fillers. Zheng *et al.* (2012) showed that the use of eco-bag bank slope can achieve good anti-erosion and

doi: 10.2166/aqua.2019.110

anti-frost performance, and its application in seasonally frozen soil zones can be vegetation-friendly for ecological restoration projects. Cheng & Li (2015) conducted uni-axial cyclic compression tests on geotextile bags filled with 80% sand and 20% soil to study the effect of stress history on the bags' deformation. Most previous studies have focused only on evaluating the performance of the eco-bag as a revetment construction material for river bank protection and increasing the soil slope stability. Very few studies have discussed the microbial community dynamics in eco-bags and studies related to the ecological restoration ability of eco-bags are scarce. In addition, previous researchers have used soil and sand as the filling material and which have low water purification effect. Eco-bags with high nutrient adsorption ability and porosity could reduce the nutrient concentration and also provide a good habitat for the growth of microorganisms (Feng *et al.* 2014; Xia *et al.* 2015). Hence, from a practical perspective, it is important to understand the mechanism of pollutant removal, i.e., chemical oxygen demand (COD), NH_3N, total nitogen (TN), total phosphorus (TP) and total suspended solids (TSS) removal, by understanding the microbial community distribution and relate it to the properties of filling material used in eco-bags.

In this study, eco-bags filled with a mixture of activated zeolite and sand were used to construct the 'eco-bag revetment' in a rural lake and the performance was monitored for a duration of 22 weeks. The microbial diversity, composition and lake water quality was determined to evaluate the water purification ability of the tested eco-bags.

MATERIALS AND METHODS

Experimental site

The project was demonstrated at a small lake located in Jidong village (119.02°E, 31.65°N), Lishui District, Nanjing City, Jiangsu province, China. The area of the lake is 327 m^2 and its depth varied between 0.85 and 1.43 m. A hard vertical concrete wall was used to provide structural stability around the periphery, i.e., the bank of the lake (Figure 1). There are also residential areas and farm lands near the lake that produce a large amount of domestic garbage and sewage. During heavy rainfall seasons, most of the storm water in Jidong village was collected in the drain system; however, a part of the flow was directed to the lake. As observed in other reports, the storm water runoff carries the pollutants from landfills into the lake, thereby causing severe water pollution and health-related issues (Hathaway & Hunt 2011).

Figure 1 | Experimental lake site located in Jidong village, Jiangsu province, China.

Construction of the eco-bag revetment

The eco-bag revetment was constructed between March 11th 2017 and April 6th 2017. In order to construct the eco-bag based revetment, first, the lake water was pumped out and a portion of the mud near the vertical wall structure was dredged. Then, the original hard concrete wall was broken to construct the eco-bag revetment. At the foot of the bank slope, a pit of 100 cm width and 50 cm depth was dug out. Wooden pipes of 15–18 cm diameter were placed in rows at the bottom in order to maintain the stability of the eco-bag and prevent it from moving. Geotextile (Puyang Yongxing Craft Products Co., Ltd, Jiangsu, China) material was used to cover the pit. After that, broken stones of 8–12 cm dimeter were used to form a stone layered base of depth 20 cm.

Concerning the size of the polypropylene geotextile (Puyang Yongxing Craft Products) eco-bag, each bag had a dimension of $80 \times 60 \times 20$ cm. Two geotextiles were interlocked to form two-layered bags that provided enhanced durability and longevity of the eco-bags. To decrease the cost of the eco-bag and ensure its nutrient adsorption and small particle filtration ability, the sand material was added to activated zeolite. The filling material comprised activated zeolite (diameter 10–20 mm) and sand (0.09–2.80 mm) mixed in a ratio of 1:1 (Qingdao Pengrun Zeolite Minerals Co., Ltd, Shandong, China). The eco-bags were stacked vertically to construct the revetment. Behind the eco-bags, *Secale cereale L.* grass was planted to form a 40 cm green belt around the lake (Figure 2(a) and 2(b)). The mixed microbial consortium was manually added over the eco-bags and this served as the inoculum for the development of microorganisms on the zeolite material.

Determination of microbial populations

The sampling for water quality analysis and microbial community analysis were started after 1 week of the construction of the eco-bag revetment. To analyse the growth of microorganisms on the eco-bags, mud samples were collected from the core of the eco-bags at a sampling frequency of once every 2 weeks. The mud samples were also collected once every 2 weeks from five eco-bags that were located in different parts of the lake. The total microorganism population was estimated after straining the cells according to the protocol described by Zimmermann *et al.* (1978). At the end of the 22 weeks of experiments (April 12th to September 4th), one sample of lake water and two mud samples from the geotextile and the internal zeolite–sand mixture were taken to determine the microbial community diversity. The high throughput DNA sequencing technology was used to explore the microbial community profiles in the mud samples (He *et al.* 2016; Schmautz *et al.* 2017). All the mud samples were immediately transferred to Jiangsu Zhongyi Jinda Analytical Testing Co., Ltd, Yixing, Jiangsu, China to determine the microbial population and diversity index.

Determination of lake water quality

The lake water quality was investigated in the period of high rainfall in summer and autumn (April 12th to September 4th) when the lake water was affected by the pollutants contained in storm runoff. To determine the water quality improvement as a result of the eco-bag structure, five water samples were collected from five representative points located near the bank of the lake, once every 2 weeks. The five sample collection points form a pentagon-like shape on the lake, and the distance from the sampling location to the bank was 1.5 m. The COD, NH_3-N, TN, TP, TSS, dissolved oxygen (DO) concentrations and the pH values were used to assess the water quality. The samples were analysed externally at Yixing Yongxin Biological Co., Ltd, China.

Plant growth determination

The plant samples were collected from five selected sampling points situated on the grass belt located at the periphery of the lake. At each individual sampling site, an area of 20 cm × 20 cm was marked and during the sampling time, five plant samples were collected from each sampling site and the average and standard deviation (SD) values reported. The height of the plant samples was determined by a plastic ruler (Shuda, Zhejiang, China) and the plant biomass weight was monitored during the 22 week experimental phase.

Figure 2 | Eco-bag based revetment: (a) before construction and (b) after construction.

RESULTS AND DISCUSSION

Microbial growth on the eco-bags

The growth of microbial biomass on the eco-bags as a function of the experimental time and the sample location is shown in Figure 3. After adding the inoculum over the eco-bags, the microorganism population proliferated in the eco-bags. During the period of 22 weeks, the microbial biomass increased from 0.089 ± 0.055 to $3.83 \pm 1.02 \times 10^9$ cell.cm^{-2}. The increase of microbial biomass in the eco-bags was strongly correlated to an enhancement of nutrients contained in the eco-bags (Wu *et al.* 2013). The increasing nutrient levels accumulated in the eco-bags were affected by the pollutants present in the storm runoff that provided good conditions for the growth and reproduction of the microorganisms in the eco-bags (Hathaway & Hunt 2011; Wu *et al.* 2013). Wu *et al.* (2013) revealed that the microbial biomass carbon increased from 686 to 1,324 μg C/g soil with an increase in the soil moisture content, organic matter, ammonia nitrogen and nitric nitrogen index. Activated zeolite has high nutrient adsorption capacity that can provide a rich source of nutrient for the microbes attached on the zeolite particles (Feng *et al.* 2014; Xia *et al.* 2015). In addition, the zeolite–sand mixture in the eco-bags has a great deal of void spaces that provide a good habitat for the growth and reproduction of microorganisms.

The microorganisms in the eco-bags decomposed the organic matter and absorbed the nutrients from the lake water before converting them into other end-products. However, the efficiency of pollutant removal depends on the type of microorganism, the environmental conditions, pH, temperature, DO, and the presence of other competing ions or toxic pollutants present in the lake water (Chang *et al.* 2009; Feng *et al.* 2014; Vera *et al.* 2014). Feng *et al.* (2014) reported that the number of heterotrophic and nitrobacteria bacteria in biological aerated filters packed with zeolite mixture was 1.9×10^9 and 4.6×10^9 CFU mL^{-1}, respectively.

Microbial community distribution in the lake

The microbial community distribution in the activated zeolite–sand mixture, geotextile and the lake water is shown in Figure 4 and Table 1, respectively. As seen from this figure, the *Proteobacteria*, *Actinobacteria*, *Armatimonade*, *Acidobacteria*, *Cyanobacteria*, *Nitrospirae*, *Gemmatimonadetes*, *Euryarchaeota* and *Firmicutes* were detected in the biofilm and the lake water samples. The *Proteobacteria* (α, β, γ) in the samples M1 (mixture zeolite–sand) and M2 (geotextile surface) were 68.7 and 44.1%, respectively. The *Nitrospirae* composition in the samples M1 and M2 were 9.5 and 4.2%, respectively. The *Firmicutes* composition in the samples M1 and M2 were 10.1 and 6.9%, respectively.

The *Proteobacteria*, *Nitrospirae* and *Firmicutes* composition in the zeolite–sand mixture and on the geotextile surface of the eco-bags were significantly high and their dominance played an important role in removing the pollutants from the lake water. He *et al.* (2016) revealed that the microorganisms belonging to *Proteobacteria* and *Firmicutes* play an important role in the biodegradation and

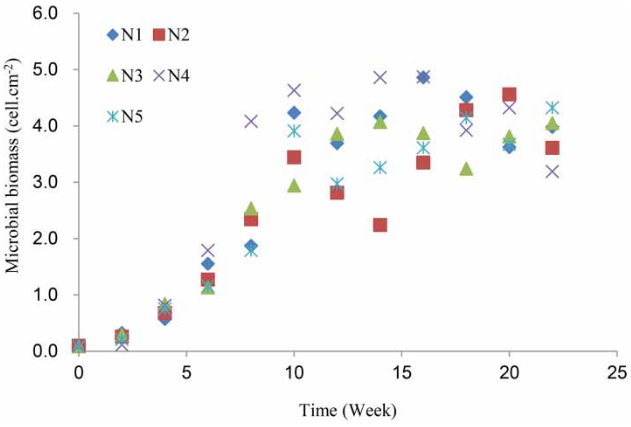

Figure 3 | Variation of microbial biomass as a function of the experimental time and sample location in the lake.

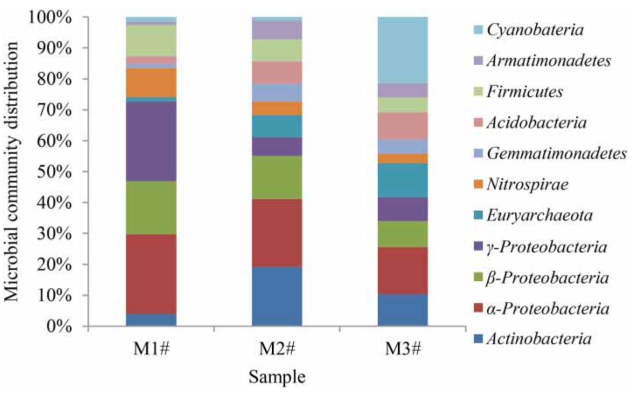

Figure 4 | Microbial community distribution in the zeolite–sand mixture (M1), geotextile (M2) and lake samples (M3).

Table 1 | Lake water characteristics during the 22 weeks of experiments

Time (week)	Microbial biomass (10^9 cell.cm^{-2})	Temperature (°C)	pH	COD (mg.L^{-1})	NH_3-N (mg.L^{-1})	TN (mg.L^{-1})	TP (mg.L^{-1})	DO (mg.L^{-1})	TSS (mg.L^{-1})	Grass height (mm)
0	0.089 ± 0.055	25.5	7.0	40.5 ± 12.7	1.06 ± 0.27	4.53 ± 1.28	0.413 ± 0.125	1.85 ± 0.42	132.1 ± 33.4	1.8 ± 1.2
2	0.237 ± 0.157	24.5	6.9	34.8 ± 9.3	1.25 ± 0.43	4.27 ± 0.97	0.439 ± 0.138	1.82 ± 0.40	117.6 ± 27.8	6.2 ± 2.3
4	0.723 ± 0.273	26.6	7.1	37.7 ± 13.6	0.87 ± 0.19	4.35 ± 0.10	0.395 ± 0.102	2.03 ± 0.46	102.3 ± 23.6	9.1 ± 4.5
6	1.38 ± 0.57	24.7	6.8	32.5 ± 10.3	1.06 ± 0.23	3.71 ± 0.93	0.357 ± 0.095	2.47 ± 0.35	92.5 ± 19.5	10.3 ± 3.6
8	2.52 ± 1.03	30.5	7.0	30.6 ± 8.8	1.12 ± 0.17	3.59 ± 0.82	0.362 ± 0.082	2.52 ± 0.43	73.8 ± 15.3	11.5 ± 2.9
10	3.83 ± 1.38	33.8	7.2	28.4 ± 12.6	0.87 ± 0.12	3.32 ± 0.78	0.376 ± 0.087	2.48 ± 0.48	79.2 ± 17.8	12.2 ± 1.8
12	3.51 ± 1.12	34.2	7.1	26.8 ± 9.5	0.92 ± 0.14	3.18 ± 0.74	0.327 ± 0.073	2.73 ± 0.57	52.6 ± 12.7	12.0 ± 1.9
14	3.72 ± 1.54	32.8	7.3	24.3 ± 8.6	0.73 ± 0.15	2.67 ± 0.63	0.345 ± 0.081	2.79 ± 0.42	37.8 ± 5.6	12.3 ± 1.1
16	4.11 ± 1.86	33.6	7.1	25.7 ± 8.3	1.08 ± 0.11	2.53 ± 0.65	0.301 ± 0.065	2.95 ± 0.45	30.3 ± 4.5	12.4 ± 1.2
18	4.02 ± 1.27	28.5	6.9	23.5 ± 7.8	0.81 ± 0.16	2.46 ± 0.51	0.319 ± 0.056	2.87 ± 0.52	31.7 ± 5.7	12.2 ± 1.5
20	3.97 ± 1.18	30.7	7.2	20.4 ± 9.2	0.83 ± 0.18	2.64 ± 0.47	0.328 ± 0.061	2.81 ± 0.48	36.1 ± 6.3	12.3 ± 1.2
22	3.83 ± 1.02	27.6	7.0	22.7 ± 7.3	0.87 ± 0.14	2.58 ± 0.45	0.306 ± 0.063	2.93 ± 0.46	33.7 ± 5.8	12.1 ± 1.5

biotransformation of various organic compounds and also micropollutants. Schmautz *et al.* (2017) reported that *Nitrospirae* is important for the nitrification step and it plays a major role in reducing the total nitrogen content of water.

The *Proteobacteria*, *Nitrospirae* and *Firmicutes* distribution in the lake water sample (M3) was 37.0, 3.6 and 5.8%, respectively, which was lower than that observed in the eco-bags. The suspended microorganisms have the tendency to attach and grow on the eco-bags which contained large void spaces and nutrients to form the biofilm (Davis *et al.* 2015). Hence, the microbial biomass concentration in the eco-bag is higher than that of lake water, leading to enhanced pollutant removal rates and natural treatment of the lake water.

COD removal

The correlation of microbial biomass with the COD concentration in the lake water is shown in Figure 5. The results showed that the growth of microorganisms had an immediate effect in decreasing the COD concentration in lake water ($r^2 = 0.823$). With an increase in the microorganism population, the COD concentration in lake water decreased from 40.5 ± 12.7 to 22.7 ± 7.3 mg.L^{-1} (removal efficiency 43.9%). In addition, the high population and ratio of heterotrophic bacteria such as *Actinobacteria*, *Firmicutes*, *Acidobacteria* and *Proteobacteria* growing in the zeolite–sand mixture also played a major role in removing the COD of lake water.

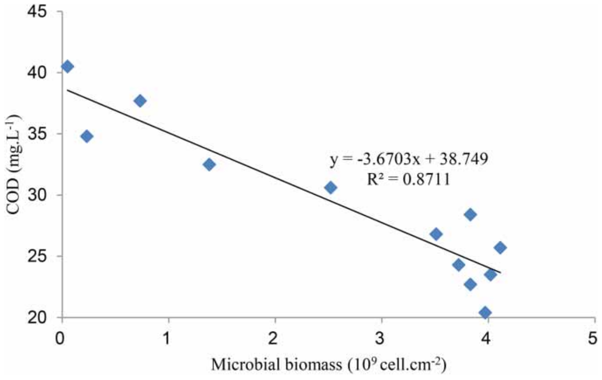

Figure 5 | Correlation of microbial biomass and COD concentration.

He *et al.* (2016) revealed that microorganisms belonging to *Proteobacteria* and *Firmicute* might play important roles in the biodegradation or biotransformation of various organic compounds in constructed wetland systems or biofilters. Under aerobic condition, the heterotrophic bacteria utilizes the organic matter present in the lake water as a food source and converts it into new biomass and carbon dioxide (Chang *et al.* 2009; Feng *et al.* 2014). Chang *et al.* (2002) reported that for organic loads varying between 1.2 and 3.3 kg COD/m^3.d, the COD removal efficiency in a biofilter packed with natural zeolite and sand was ~88 and 75%, respectively.

With high porosity, the zeolite–sand mixture inside the eco-bags will not just filter the water, but it will also detoxify the pollutants as well as remove a certain amount of micropollutants present in lake water. Stefanakis *et al.* (2009) showed that zeolite filters, when used as a post-treatment step, could remove 60.6–63.2% 5-day biochemical oxygen demand (BOD_5) and 52.5–62.0% COD during the treatment of effluent from a horizontal sub-surface flow constructed wetland.

Nitrogen and phosphorus removal

The correlation of microbial biomass with the concentrations of NH_3^-N, TN and TP in the lake water is shown in Figure 6(a)–6(c), respectively. Although the removal efficiencies were not the same, an increase in the biomass concentration in the eco-bags led to a decrease in the NH_3^-N, TN and TP concentrations in lake water. The microbial biomass did not correlate ($r^2 = 0.358$) with the NH_3^-N removal. The NH_3^-N concentration decreased from 1.06 ± 0.27 to 0.77 ± 0.14 mg.L^{-1}, corresponding to a removal of ~18%. One possible reason for the lower NH_3^-N removal could be the influence of temperature in the lake. The variation of temperature (24.5–34.2 °C) during the experimental study could have possibly affected the activity of *Cyanobacteria* that plays a nitrogen fixing role in natural ecosystems (O'Neil *et al.* 2012). Reyes *et al.* (1997) reported that the removal efficiency of NH_4^+-N in sand and natural zeolite based filter media ranged from 20 to 30% and 50 to 95%, respectively.

Concerning TN removal, the microbial biomass concentration correlated well with the removal of TN ($r^2 = 0.903$). The TN concentration decreased from 4.53 ± 1.28 to 2.58 ± 0.45 mg.L^{-1}. The removal of TN in the lake water was 43%. Xia *et al.* (2015) performed experiments using zeolite and observed that particle sizes of 0.18–0.30 mm and a dosage of 0.4 g/mL of zeolite yielded the highest TN adsorption efficiency of 55%. The ammonification and nitrification–denitrification processes by microorganisms present in the biofilm grown inside the eco-bags are important for efficient TN removal in the lake water (Chang *et al.* 2002, 2009; Feng *et al.* 2014). Chang *et al.* (2002) reported that the number of nitrifying bacteria within the biofilm was higher on natural zeolite than on sand. Therefore, the biofilm grown on the surface of zeolites plays a more important role to remove nitrogen from lake water as well as urban storm waters (Reddy *et al.* 2014).

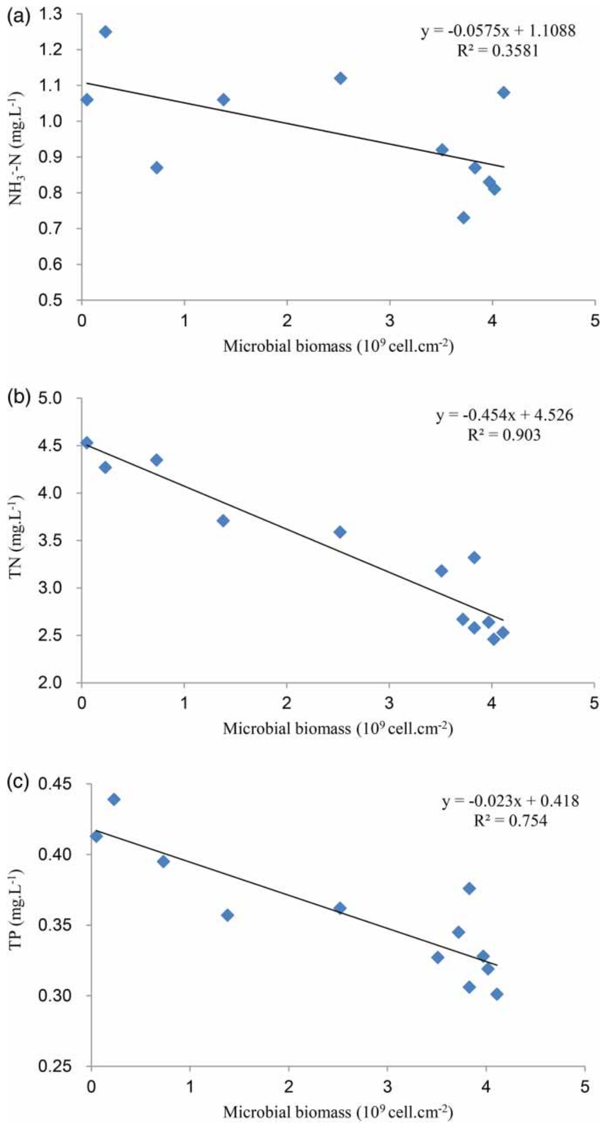

Figure 6 | Correlation of microbial biomass with: (a) NH_3^-N removal, (b) TN removal and (c) TP removal.

The TP concentration decreased from 0.413 ± 0.125 to 0.306 ± 0.063 mg.L^{-1}, corresponding to a removal efficiency of 26%. The increase of microbial biomass correlated moderately with the TP concentration ($r^2 = 0.754$) in lake water. In such environments, the soluble phosphorus will be absorbed by the microorganisms growing in the eco-bags (Chang *et al.* 2002; Feng *et al.* 2014). In previous studies, phosphate removal by a stand-alone zeolite filter was shown to vary from 59 to 100% (Reddy *et al.* 2014), while in a constructed wetland having zeolite as the medium, the phosphate removal was ~70% (Vera *et al.* 2014).

TSS, DO and pH variations in the lake

The correlation of microbial biomass with the TSS concentration and plant biomass is shown in Figure 7(a) and 7(b). The decrease of TSS concentration correlated with the increase of microbial biomass in the eco-bags ($r^2 = 0.881$) and grass biomass around the lake ($r^2 = 0.681$). During the period of 22 weeks, the TSS concentration decreased from 132.1 ± 33.4 to 33.7 ± 5.8 mg.L^{-1}, corresponding to a TSS removal of ~74%. Bank erosion and storm runoff are the main causes for an increase in the TSS content of lake water (Pistocchi 2010). As explained previously, the eco-bags, wood piles and broken stones were used to construct the ecological revetment. After the construction of the eco-bags' based revetment, falling soil was avoided and the eco-bags also acted as a filter for removing the suspended fine particles present in water. As well, the green grass belt around the periphery of the lake also helped in reducing the velocity of storm water flow, retaining the nutrients and removing a part of the suspended solids. With increasing plant height, the TSS concentration significantly decreased ($r^2 = 0.731$).

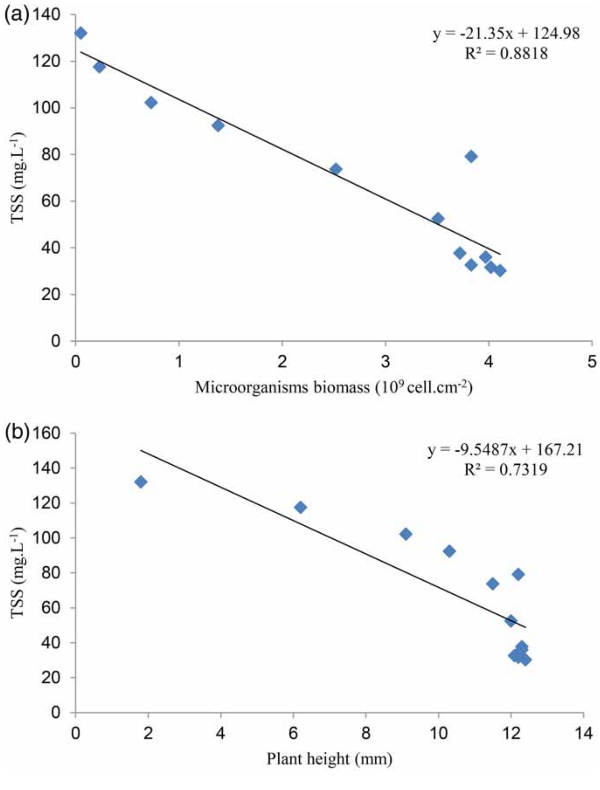

Figure 7 | Correlation of TSS with (a) microbial biomass and (b) plant height.

Syversen (2005) reported that the vegetated buffer zones adjacent to a stream can effectively remove 60–89%, 37–81% and 81–91% of phosphorus, nitrogen and particles from water runoff, respectively. In another study, Kim *et al.* (2010) showed that zeolite filters can handle highway storm water runoffs, achieving TSS, Cu, Pb and Zn removal efficiencies of 62.5%, 73.7%, 61.8% and 67.3%, respectively. Besides the role of physical-adsorption, the extracellular polymeric substances produced by the microorganisms also has high adhesion ability towards removing suspended solids in the eco-bags (Tsuneda *et al.* 2003).

During the period of 22 weeks, the pH did not change significantly (6.8–7.3), while the DO concentration increased from 1.85 ± 0.42 to 2.93 ± 0.46 mg.L^{-1}. The DO concentration correlated well with the decreasing TSS concentrations ($r^2 = 0.9412$). Bank erosion, storm runoff, leachate from solid waste dumps were the main reasons for an increase in the TSS content of lake water, which also includes substantial amounts of organic and inorganic matters (Pistocchi 2010; Hathaway & Hunt 2011). At high organic loading rates, the decomposition of organic matter by microorganisms requires the consumption of DO, leading to a decline in the DO levels in lakes (Chang *et al.* 2009; Feng *et al.* 2014). As is evident from the results obtained from this 22 week study, the application of an eco-bag revetment not only helped to reduce the organic matter into the lake, but it also avoided the invasion of nutrients, TSS and other particulates to the lake.

CONCLUSIONS

The eco-bags provided a suitable habitat for the growth and reproduction of microorganisms that increased the removal efficiency of COD, NH_3N, TN, TP and TSS in the lake water. The removal of COD, NH_3N, TN, TP and TSS depended on the increase in microbial biomass in the eco-bags. The eco-bag revetment did not cause any major fluctuations in the pH of the lake water; however, it increased the DO concentration in the lake water. The results from this 22 week study clearly proved that the eco-bag based revetment is advantageous in terms of preventing the intrusion of pollutants in the lake as well as restoring the water quality in a rural lake.

ACKNOWLEDGEMENTS

The authors would like to thank the School of Civil Engineering, Southeast University (Nanjing, China) for support for the experiment. We thank IHE-Delft and TDU for providing infrastructural and staff time support to collaborate with Southeast University.

REFERENCES

Chang, W. S., Hong, S. W. & Park, J. 2002 Effect of zeolite media for the treatment of textile wastewater in a biological aerated filter. *Process Biochemistry* **37**, 693–698.

Chang, W. S., Tran, H. T., Park, D. H., Zhang, R. H. & Ahn, D. H. 2009 Ammonium nitrogen removal characteristics of zeolite media in a biological aerated filter (BAF) for the treatment of textile wastewater. *Journal of Industrial & Engineering Chemistry* **15**, 524–528.

Chen, C. H. 2002 Property rights and rural development in China's transitional economy. *Economics of Planning* **35**, 349–363.

Cheng, L. & Li, L. 2015 Surface settlement calculation of eco-bags revetment. *Electronic Journal of Geotechnical Engineering* **20**, 625–632.

Davis, C. A., Pyrak-Nolte, L. J., Atekwana, E. A., Werkema, D. D. & Haugen, M. E. 2015 Acoustic and electrical property changes due to microbial growth and biofilm formation in porous media. *Journal of Geophysical Research Biogeosciences* **115**, 1–14.

Feng, Y., Yu, Y., Qiu, L., Feng, S. & Zhang, J. 2014 Domestic wastewater treatment using biological aerated filtration system with modified zeolite as biofilm support. *Desalination & Water Treatment* **52**, 5021–5030.

Hathaway, J. M. & Hunt, W. F. 2011 Evaluation of first flush for indicator bacteria and total suspended solids in urban storm water runoff. *Water Air & Soil Pollution* **217**, 135–147.

He, T., Guan, W., Luan, Z. & Xie, S. 2016 Spatiotemporal variation of bacterial and archaeal communities in a pilot-scale constructed wetland for surface water treatment. *Applied Microbiology & Biotechnology* **100**, 1479–1488.

Kim, L., Kang, H. & Bae, W. 2010 Treatment of particulates and metals from highway stormwater runoff using zeolite filtration. *Desalination & Water Treatment* **19**, 97–104.

O'Neil, J. M., Davis, T. W., Burford, M. A. & Gobler, C. J. 2012 The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. *Harmful Algae* **14**, 313–334.

Pistocchi, A. 2010 An assessment of soil erosion and freshwater suspended solid estimates for continental-scale environmental modeling. *Hydrological Processes* **22**, 2292–2314.

Reddy, K. R., Xie, T. & Dastgheibi, S. 2014 Nutrients removal from urban storm water by different filter materials. *Water Air & Soil Pollution* **225**, 1778–1792.

Reyes, O., Sánchez, E., Pellón, A., Borja, R., Colmenarejo, M. F., Milán, Z. & División, M. C. A. 1997 Comparative study of sand and natural zeolite as filtering media in tertiary treatment of wastewaters from tourist areas. *Journal of Environmental Science and Health* **32**, 2483–2496.

Schmautz, Z., Graber, A., Jaenicke, S., Goesmann, A., Junge, R. & Smits, T. H. M. 2017 Microbial diversity in different compartments of an aquaponics system. *Archives of Microbiology* **199**, 1–8.

Stefanakis, A. I., Akratos, C. S., Gikas, G. D. & Tsihrintzis, V. A. 2009 Effluent quality improvement of two pilot-scale, horizontal subsurface flow constructed wetlands using natural zeolite (clinoptilolite). *Microporous & Mesoporous Materials* **124**, 131–143.

Syversen, N. 2005 Effect and design of buffer zones in the Nordic climate: the influence of width, amount of surface runoff, seasonal variation and vegetation type on retention efficiency for nutrient and particle runoff. *Ecological Engineering* **24**, 483–490.

Tsuneda, S., Aikawa, H., Hayashi, H., Yuasa, A. & Hirata, A. 2003 Extracellular polymeric substances responsible for bacterial adhesion onto solid surface. *FEMS Microbiology Letters* **223**, 287–292.

Vera, I., Araya, F., Andrés, E., Sáez, K. & Vidal, G. 2014 Enhanced phosphorus removal from sewage in mesocosm-scale constructed wetland using zeolite as medium and artificial aeration. *Environmental Technology* **35**, 1639–1649.

Wu, H., Zeng, G., Liang, J., Zhang, J., Cai, Q., Huang, L., Li, X., Zhu, H., Hu, C. & Shen, S. 2013 Changes of soil microbial biomass and bacterial community structure in Dongting Lake: impacts of 50,000 dams of Yangtze River. *Ecological Engineering* **57**, 72–78.

Xia, R., Duan, N., Zhang, Y. H., Li, B. M., Liu, Z. D. & Lu, H. 2015 Nitrogen and phosphorous adsorption from post-hydrothermal liquefaction wastewater using three types of zeolites. *International Journal of Agricultural & Biological Engineering* **8**, 86–95.

Zheng, D., Zhou, J., Yang, J. & Zhu, Z. 2012 Applied research on the eco-bags structure for the riverside collapse slope in seasonal frozen soil zone. *Procedia Engineering* **28**, 855–859.

Zhou, J., Yang, J., Zheng, D. & Liu, J. 2012 Simple tests for the design parameters and sinkage algorithm for eco-bags slope. *Procedia Engineering* **28**, 844–849.

Zimmermann, R., Iturriaga, R. & Beckerbirck, J. 1978 Simultaneous determination of the total number of aquatic bacteria and the number there of involved in respiration. *Applied and Environmental Microbiology* **36**, 926–935.

First received 10 August 2018; accepted in revised form 20 September 2018. Available online 29 January 2019