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Flow conditions influence nutrient removal at an artificial lake and a drinking water reservoir with an algal floway

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ABSTRACT

To optimize flow condition of algal turf scrubber (ATS) system for nutrient (nitrogen and phosphorus) removal at eutrophic waterbodies, we constructed two experimental scale (2.5 m^2) algal floways to test nutrient removal rates under various flow conditions via regulating flow rate and intermittent frequency of pump on/off. Results showed that the largest algal productivity and nutrient removal rate were generally obtained under the hydraulic loadings of 120 $L\,min^{-1}\,m^{-1}$. Nutrient removal rate was high with an intermittent inflow 4 h^{-1}, followed by 12 h^{-1} and 60 h^{-1}. We estimated that a hectare-scale floway system under a flow rate of 120 $L\,min^{-1}\,m^{-1}$ and intermittent flow 4 h^{-1} which would have satisfactory performance with affordable investment. This option has the greatest potential for the application of such technology in nutrient pollution abatement while producing bioresources from harvested microalgae.

1. Introduction

Increased anthropogenic nutrient loading has caused water quality and eutrophication problems in both freshwater and coastal ecosystems worldwide [1–3]. There is an urgent need for a safe and efficient ecological water treatment technology to restore these eutrophic aquatic ecosystems. Numerous ecological approaches to remove excessive nitrogen (N) and phosphorus (P) have been proposed and tested, including constructed wetlands, ecological floating beds, and algal-based technologies [4–7]. Compared to other technologies, algae-based water treatment technology has received much attention for its high efficiency and economic advantages [8–11]. One algae-based technology, termed algal turf scrubber™ (ATS), utilizes algal photosynthesis and growth to remove nutrients and improve water quality [12,13]. Periodic harvesting of the algal turf removes metabolites from the ecosystem and stimulates continued production and nutrient removal [14–17]. In the past few decades, ATS has been applied in a variety of pollution sources, including aquaculture effluents [18–20], dairy manure effluents [21–25], industrial and municipal wastewater [26–28], agricultural drainage [29,30], and eutrophic waterbodies [14,31,32]. In addition to environmental benefits of nutrient removal, as the byproduct, algal biomass could be used as a slow-release organic fertilizer [33] and could potentially produce other value added products and biofuels [11]. Ilyas et al. (2017) reported that the N removal rate with constructed wetlands varied between 250 and 630 $g\,N\,m^{-2}\,yr^{-1}$ [34], while Ray et al. (2014) found that an ATS with area of 640 m^2 would produce 56.9 kg of algae (dry weight), which equaled to 4448 $g\,N\,m^{-2}\,yr^{-1}$ [19]. Therefore, such systems would have less than half the land requirements of a wetland treatment system for the same N removal rate as well as less capital costs and require only weeks to become fully established [35].

There are many critical environmental (light and temperature) and operational conditions (nutrient load, flow, CO_2) influencing ATS performance [15,21,29,36,37]. Among these conditions, flow condition is recognized to be important in engineering application. Kangas and Mulbry [29] found algal productivity using daytime-only flow was lower than that using continuous flow. Blersch, Kangas [36] observed a maximum algal productivity at a moderate wave surge frequency. Liu, Danneels [15] concluded that flow rate influence biomass production and N removal (but unlikely for P removal) from horticultural wastewater. Although flow condition is considered to be a vital application factor controlling nutrient removal efficiency, there is still a lack of systematic research on flow condition in ATS for nutrient removal from surface waters in subtropical regions.

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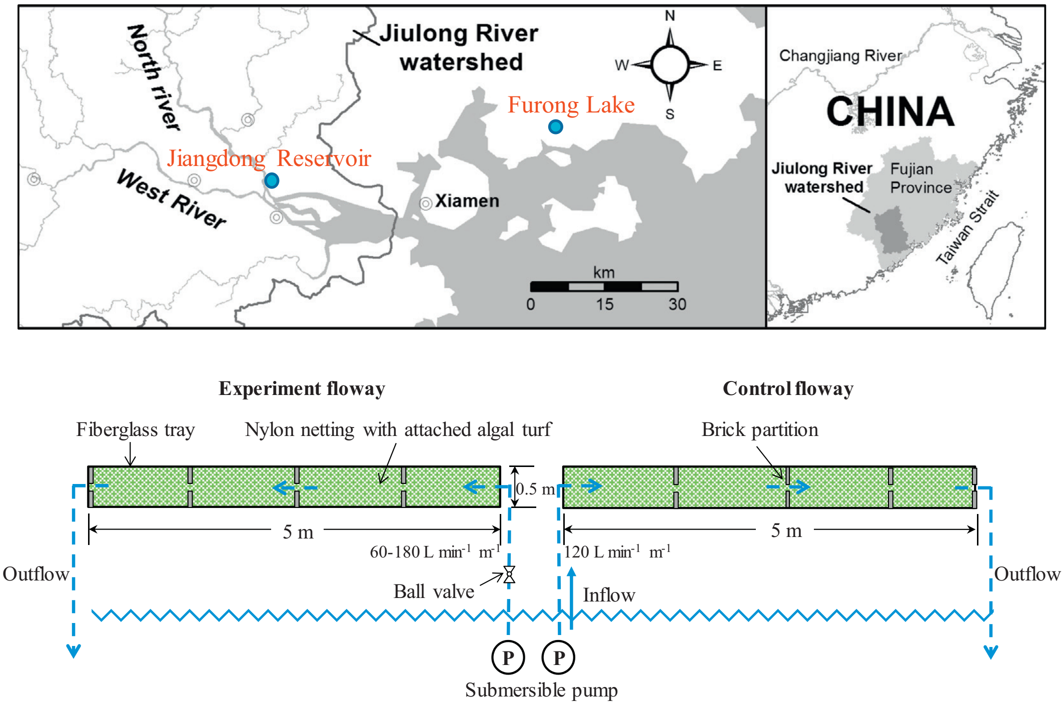

Fig. 1. Map of study sites Furong Lake and Jiangdong Reservoir (top), and schematic drawing of algal floways used in this study (bottom).

Based on a previous study on seasonal nutrient removal using a floway at a drinking water reservoir [32], this study aimed to optimize flow condition of the floway to increase nutrient removal from surface waters. Two experimental scale (2.5 m^2) algal floways were installed at two waterbodies (Furong Lake and Jiangdong Reservoir) under various flow conditions in terms of flow rate and intermittent on/off frequency of pumping. Based on experimental results, a hectare-scale algal floway system was designed for treating the eutrophic water. Cost-effectiveness of the floway system was further analyzed to highlight the potential application of such technology in future.

2. Materials and methods

2.1. Description of study site

Experiments were carried out at a campus artificial lake (Furong Lake) and a river reservoir (Jiangdong Reservoir). Furong Lake was built in 2012 within Xiang'an campus of Xiamen University. The lake water has a high turbidity due to bank erosion. Jiangdong Reservoir is located in the mouth of North Jiulong River, an important drinking water source for Xiamen City and other coastal urban areas (Fig. 1). The reservoir has experienced eutrophication and harmful algal bloom, largely due to increased nutrient loading in recent years [38]. Average nutrient concentration of the Jiangdong Reservoir (NH_4^+-N = 0.24 mg L^{-1}; SRP = 0.07 mg L^{-1}) during the experimental period was higher than Furong Lake (NH_4^+-N = 0.18 mg L^{-1}; SRP = 0.05 mg L^{-1}) (Table 1).

2.2. Experimental design and operation

Two pilot-scale algal floways with the length of 5 m and the width of 0.5 m were made by fiberglass. They were constructed at a 1% slope along the bank of the waterbodies to test the effect of flow condition on nutrient removal (Fig. 1). One floway was operated as a control (floway C) while another one as an experiment (floway E). Two submersible pumps delivered water to the inlet of algal floways and the water drained back to the lake or reservoir by gravity. Flow rates were carefully calibrated using a ball valve and T-Cock pipe. For floway C, the flow rate was fixed at 120 L min^{-1} m^{-1} (liters of water flow per minute per meter width of the floway). For floway E, five flow rates increasing from 60 L min^{-1} m^{-1} to 180 L min^{-1} m^{-1} with an interval of 30 L min^{-1} m^{-1} were set at the Furong Lake site while seven flow rates with an interval of 20 L min^{-1} m^{-1} were set at the Jiangdong reservoir site. Algae, as periphyton, grew attached to a plastic mesh screen that is placed on the bottom of the floway. Bricks were placed on the screen to distribute the water flow which had a water depth of approximately 50 mm. Experiments were operated from July to November 2015 at Furong Lake and from April to August 2016 at Jiangdong Reservoir. The floway operation stopped and restarted for each sampling event.

Table 1
Summary of water quality in Furong Lake and Jiangdong Reservoir.

Parameter	Furong Lake	Jiangdong Reservoir
Temperature (°C)	31.8 ± 1.6	27.8 ± 3.1
pH	9.10 ± 0.32	6.84 ± 0.19
DO (mg L^{-1})	9.36 ± 2.41	6.74 ± 0.67
NH_4-N (mg L^{-1})	0.18 ± 0.07	0.24 ± 0.05
NO_3-N (mg L^{-1})	0.06 ± 0.03	1.82 ± 0.11
TDN (mg L^{-1})	N.D	2.53 ± 0.33
SRP (mg L^{-1})	0.05 ± 0.01	0.07 ± 0.02
TP (mg L^{-1})	N.D	0.15 ± 0.02

N.D, not detected. Data shown is the mean ± SD, $n = 5$ for Furong Lake and $n = 7$ for Jiangdong Reservoir.

To further evaluate the cost-effectiveness of intermittent flow on floway performance (in this case power cost reduce by half), the two algal floways were operated at Jiangdong Reservoir from October 2016 to January 2017. Floway C was operated under continuous flow (120 L min^{-1} m^{-1}); Floway E was also set at a flow rate of 120 L min^{-1} m^{-1} but intermittent (pump off/on) in three ways (4 h^{-1}, 12 h^{-1} and 60 h^{-1}). We developed a microcomputer time controller to auto-control the submersible pump to achieve intermittent flow. For example, 4 h^{-1} intermittent means 15-min power on and 15-min power off. Three groups of repetitive experiments were carried out. The