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A four-stage constructed wetland system for treating polluted water from an urban river

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ABSTRACT

A four-stage wetland was constructed to improve the water quality and flow pattern of a heavily polluted river in Luzhi Town, a water town in the Taihu Lake region of China. The four-stage constructed wetland system is composed of four interlinked units: a rapid filter, a down-flow subsurface constructed wetland, an up-flow subsurface constructed wetland, and a surface flow constructed wetland. The concentrations of chemical oxygen demand (COD), nitrogen and phosphorus, along the flow path of the constructed wetland, were measured and the pollutant removal efficiencies were calculated. The average removal rate over the whole wetland system was around 60% for COD and total phosphorus (TP), and around 70% for total nitrogen (TN) and ammonia nitrogen (NH_4^+-N). The total annual reduction in COD, TN, NH_4^+-N, and TP by the whole system was about 3.16 t/yr, 0.57 t/yr, 0.13 t/yr, and 0.03 t/yr, respectively. Following treatment of river water via the four-stage constructed wetland system, significant improvements resulted in the water quality and flow pattern of the polluted river.

1. Introduction

In most cities and towns located in the eastern and southern regions of China, there are complex urban river systems that intersect one another to create a river network that has lasted for centuries. However, because of rapid industrialization and/or urbanization, some urban rivers have become blocked, leading to very low or no water flow (Zhang et al., 2013; Du et al., 2012). Concurrently, these urban rivers receive large inputs of pollutants, including nutrients (nitrogen and phosphorus) that are difficult to remove (Jia et al., 2010; Loucks and Jia, 2012; Tang et al., 2013). In order to improve one of these urban rivers, a four-stage wetland was designed and constructed in Luzhi, a typical historical water town in the Taihu Lake region of China. The wetland system was designed to improve the water quality and flow pattern of a heavily polluted river in the upstream scenic areas of Luzhi. The stages of the wetland system were designed and constructed in the following sequence: rapid infiltration stage, down-flow subsurface constructed wetland stage, up-flow subsurface constructed wetland stage, and finally surface flow constructed wetland stage.

The rapid infiltration process has been widely used in many countries to improve water quality by removing suspended particulate pollutants efficiently (Stefanakis and Tsihrintzis, 2009; Li et al., 2012; Zhang, 2008). Constructed wetlands are artificial systems designed to simulate the function of natural wetlands for the purpose of improving water quality (Mitsch et al., 2012; Mungasavalli and Viraraghavan, 2006; Zhang et al., 2009; Scholz et al., 2002). There are various types of constructed wetlands (Ávila et al., 2013), such as surface and subsurface flow wetlands. For subsurface flow wetlands, there are subsurface vertical flow wetlands and subsurface horizontal flow wetlands, and so on. Various types of constructed wetlands have different technical characteristics (Mitsch, 2013; Van de Moortel et al., 2009; Jia et al., 2011; Ranieria et al., 2013; Vymazal, 2009). To realize the synergetic capabilities of different wetland types, a four-stage wetland system was designed and constructed in allocation adjacent to a heavily polluted river. The present study assessed the performance of the four-stage constructed wetland in terms of the improvement of water quality and the flow pattern in the river.

2. Materials and methods

2.1. Study site

Luzhi Town, located at 18 km east of Suzhou, is a historical water town in Taihu Lake region and is part of the national AAAA-class

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Table 1
Water quality monitoring data for the Zhijiashe River in 2010.

Item	Monitoring data		GB3838-2002 standard Grade V
	Average	Worst	
Transparence (m)	0.3	0.2	/
BOD_5 (mg/L)	45.5	81.44	10
COD (mg/L)	40.9	91.84	40
TP (mg/L)	0.4	1.27	0.4
NH_4^+-N (mg/L)	2.27	5.22	2.0

tourist scenic areas of China. Luzhi is not only a historical and cultural water town, but also a thriving industrial town. Industrial development and population growth have led to increased pollution and degradation of water quality. Water pollution has become a serious threat to tourism, and has become a key limiting factor in the sustainable development of Luzhi (Zhang et al., 2013). Improving the water environment is now one of the key tasks for the local government. The water quality aim of the urban river is set as Grade V according to Chinese National Environmental Quality Standards for Surface Water (GB3838-2002). (State Environmental Protection Administration, General Administration of Quality Supervision, Inspection and Quarantine, 2002).

The Zhijiashe River is a heavily polluted river upstream of the scenic tourist area in Luzhi (Fig. 1). The length of the river is around 1 km, and the average width and depth are 10 m and 1.5 m, respectively. The average flow rate varies from 0.01 to 0.02 m^3/s in winter to 0.07–0.14 m^3/s in summer. On the west side of the main reach of the Zhijiashe River, there is a branch of the river that was blocked by housing construction activities. The length of the river that was blocked is around 160 m, and the surface area is around 1950 m^2. The flow velocity in this branch of the river is nearly zero. In this area, crowded old houses exist and no wastewater conveyance system was built. All wastewater from the nearby houses and factories have been discharged directly into the river. Monitoring data in 2010 (Table 1) revealed that water quality in the river was worse than Grade V, which is the basic requirement for scenic waters.

To improve the water quality and flow pattern of the blocked branch of the Zhijiashe River, an area adjacent to the river was selected as the site for a four-stage constructed wetland system. The area is roughly rectangular in shape, with a length of 76 m and a width of 41 m. In addition, to cut off the wastewater that had been discharged to the Zhijiashe River, a parallel domestic wastewater collection and conveyance project was implemented during the same time period as the wetland system. The collected domestic wastewater is transported to a nearby wastewater treatment plant.

2.2. The four-stage constructed wetland system

2.2.1. Wetland location and design

The four-stage constructed wetland is located on the west side of the Zhijiashe River (Fig. 1). Polluted river water is pumped into the wetland system from the upstream section and flows through the wetland system in the following sequence: rapid filter unit, down-flow subsurface wetland, up-flow subsurface wetland, and surface flow wetland. The effluent from the wetland system then flows into the blocked branch of the Zhijiashe River. In addition, because there are many people living around the wetland site, the four-stage constructed wetland was also designed as an ecological park which can also act as a leisure place for them. The plan view of the wetland system is illustrated in Fig. 2.

The total land area of the project is 3116 m^2, of which the rapid filter area is 75 m^2, the down-flow subsurface wetland area is 160 m^2, the up-flow subsurface wetland area is 140 m^2, and the surface flow wetland area is 1020 m^2. The treatment capacity of the four-stage constructed wetland system is 500–750 m^3/d, and it operates at the scale of 550 m^3/d most of the time. For the case of a 550 m^3/d capacity, the hydraulic retention time (HRT) in the rapid filter unit, the down-flow subsurface flow wetland, the up-flow subsurface flow wetland, and the surface flow wetland is 0.14, 0.4, 0.4 and 1.85 days, respectively. The hydraulic loading for the four component units was 7.33 m^3/m^2 d, 3.44 m^3/m^2 d, 3.93 m^3/m^2 d, and 0.54 m^3/m^2 d, respectively.

2.2.2. Wetland stages and processes

A rapid filter was constructed and placed at the beginning of the wetland system to remove suspended solids (SS), and the particulate forms of chemical oxygen demand (COD), nitrogen, and phosphorus. The system was filled with various sizes of sand and gravel, as the filtration media, to a depth of 1 m. At the bottom, there was a supporting layer with a depth of 20 cm. The media was sand with diameter of 2–5 mm. The water harvesting pipe system was installed in this layer. The upper layers, from the bottom up, were 30 cm of sand with diameter of 1–3 mm, 30 cm of sand with diameter of 2–5 mm, and 20 cm of gravel with diameter of 5–10 mm, respectively. In the top layer, the water distribution system was installed.

The subsequent subsurface flow constructed wetland had two tandem units, a down-flow and an up-flow subsurface wetland. In the down-flow subsurface wetland there were five layers of media, made up of different sizes of gravel and ceramsite (an artificial foundry sand originating in China). The depth of the media was 1.4 m. The media along the flow path are 20 cm of pebble gravel with diameter of 5–20 mm, 30 cm of limestone with diameter of 5–20 mm, 20 cm of zeolite with diameter of 8–16 mm, 50 cm of ceramsite with diameter of 8–16 mm, and 20 cm of sand supporting layer with diameter of 2–5 mm. The water distribution pipe and water harvesting pipe systems were installed in the top layer and bottom layer, respectively. In the up-flow subsurface wetland, there were six layers of media, which was made up of different sizes of gravel, ceramsite, and quartz sand, the depth of the media was 1.6 m. The media along the flow path are 20 cm of sand supporting layer with diameter of 2–5 mm, 50 cm of zeolite with diameter of 8–16 mm, 20 cm of ceramsite with diameter of 8–16 mm, 30 cm of quartz sand with diameter of 1–2 mm, 20 cm of sand with diameter of 2–5 mm, and 20 cm of gravel with diameter of 5–20 mm. The water distribution pipe and water harvesting pipe system were installed in the bottom layer and top layer, respectively.

In the subsurface flow constructed wetlands, several wetland plant species were planted, including *Lythrum salicaria* (planting acreage: 50 m^2, planting density: 25 bundles/m^2), *Canna glauca* (planting acreage: 55 m^2, 16 bundles/m^2), *Thalia dealbata* (planting acreage: 40 m^2, 16 bundles/m^2), *Cyperus alternifolius* (planting acreage: 70 m^2, 25 bundles/m^2), *Iris sibirica* (planting acreage: 40 m^2, 25 bundles/m^2), *Schoenoplectus tabernaemontani* (planting acreage:15 m^2, 12 bundles/m^2), *Acorus gramineus* (planting acreage: 15 m^2, 20 bundles/m^2), *Acorus calamus* (planting acreage: 15 m^2, 20 bundles/m^2). After two months growth, plant height of *C. glauca*, *C. alternifolius*, and *I. sibirica* was about 1m, other plants could also reach a height of more than 50 cm.

The removal of pollutants in a wetland system is achieved by the interaction of physical, chemical, and biological processes as determined by the physicochemical conditions of the system (Bastian, 1993). As the wetland matures, a biological membrane develops in the media and plant roots, due to microbial growth, which further contributes to the degradation of pollutants (Van de Moortel