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Using aerated gravel-packed contact bed and constructed wetland system for polluted river water purification: A case study in Taiwan

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SUMMARY

The Ju-Liao Stream is one of the most contaminated streams in Kaohsiung City, Taiwan. A constructed wetland (CW) system was built in 2010 for polluted stream water purification and ecosystem improvement. An aerated gravel-packed contact bed (CB) system was built in 2011 and part of the stream water was treated by the CB before discharging to the CW. The influent rates of the CW and CB were approximately 5570 and 900 m^3/d, respectively. The CW contained one free-water surface basin planted with emergent wetland plants, followed by the plug-flow channel-shaped free-water surface basin planted with emergent and floating wetland plants. The mean measured hydraulic loading rate (HLR), hydraulic retention time (HRT), water depth, and total volume of wetland system were 1.7 m/d, 0.68 d, 0.7 m, and 4400 m^3, respectively. The aeration zone of the CB system had a dimension of 24 m (L) × 8 m (W) × 3 m (H), which was filled with gravels (average diameter = 5 cm) with a porosity of 0.4, and the aeration rate was 7.8 m^3/min. Results show that the CB system was able to remove 69% of suspended solid (SS), 86% of biochemical oxygen demand (BOD), and 58% of total nitrogen (TN). Up to 82% of BOD and 27% of TN could be removed in the CW system. Removal efficiency of SS was affected by the growth of chlorophyll a in the CW system due to the growth of algae. The observed first-order decay rates (k) for BOD and TN in CB were 9.3 and 4.2 1/d, and the k values for BOD and TN removal in CW were 2.5 and 0.45 1/d. The high pollutant removal efficiencies in the CB system indicate that the system could enhance the organic and nutrient removal through the biological processes effectively. Sediments contained high total organic matter (1.9–4.5%), sediment total nitrogen (6.4–10.1 g/kg), sediment total phosphorus (0.59–0.94 g/kg), and sediment oxygen demand (0.9–4.1 g O_2/m^2 d). The organic and nutrient-abundant sediments resulted in reduced conditions (oxidation–reduction potential measurements <158 mV). Increased evenness, richness, and biodiversity for birds and amphibious animals reveal that the CW had a positive impact on the ecosystem conservation and wildlife habitat rehabilitation.

1. Introduction

1.1. Application of constructed wetland and aerated gravel-packed contact bed on wastewater treatment

Constructed wetland (CW), one of natural treatment systems, has been recognized as an environmentally acceptable eco- and green-technology for wastewater control or treatment. It is increasingly used to replace the conventional treatment systems for the treatment of different wastewaters including domestic, industrial, agricultural wastewaters as well as polluted drainage (Babatunde et al., 2008; Saeed et al., 2012; Shao et al., 2013; Adrados et al., 2014; Ávila et al., 2014). The aerated gravel-packed contact bed (CB) system is a modified design of packed-bed reactor using gravels as the packed media for biofilm carriers. The biofilms in CB could grow on the surfaces of gravels and utilize the organic pollutants in the influent water. It might be classified as one type of natural and ecological treatment techniques for the improvement of river water or wastewater quality (Juang et al., 2008).

CWs have been used to remove different pollutants including suspended solids (SS), nutrients, organic chemicals, pesticides, trace elements, and heavy metals from the wastewater or surface water streams (Kao et al., 2001; Chen et al., 2006, 2008; Tu et al., 2014). Compared with the traditional secondary wastewater treatment facilities, CWs require lower construction and lower operational and maintenance costs (Saeed et al., 2012; Vymazal, 2013; Rahman et al., 2014; Sochacki et al., 2014a,b). CWs are especially

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beneficial to small communities or factors, which might not be able to afford more expensive conventional secondary wastewater treatment facilities with complicate operational and maintenance process (Musner et al., 2014; Sochacki et al., 2014a,b; Tu et al., 2014).

1.2. Types of CW and CB

Based on the designed flow patterns, CW has been classified into two different types including free water surface system (FWS) and subsurface flow system (SFS). The FWS wetlands typically have shallow water depths, with subsurface barriers filled with soil or suitable media to support the growth of wetland plants (Ülo and Mitsch, 2009; Shao et al., 2013; Vymazal, 2013; Beebe et al., 2014; Białowiec et al., 2014). As for the SFS wetlands, water flow laterally through the beds, which are filled with different media (Wang et al., 2012; Zheng et al., 2014). CW combined with CB system is a special design for river water purification. The organic and nutrient pollutants in the polluted river water can be efficiently and effectively degraded by the first-stage CB system and polished by the second-stage CW system. Depending on the site conditions, the CB can be classified into two different types: in-river system (installed in the flow course) and on-site system (installed on the river bank). For the on-site system, the river water is pumped or directed by gravity to the system located beside the river; for the in-river system, the river water normally flows by gravity through the system. Although the aeration is an option of the design, it can be applied for the highly polluted water to obtain effective pollutant removal efficiencies if relatively short hydraulic retention time is required (Carranza-Diaz et al., 2014; Ding et al., 2014). In this study, the first objective was to assess the feasibility and effectiveness of the combined CW and CB system on polluted stream water purification.

1.3. Case studies

CWs have been successfully applied for surface water purification and wastewater treatment containing different types of pollutants at many case studies worldwide (Kim et al., 2014; Lai, 2014; Li et al., 2014; Morató et al., 2014). Juang et al. (2008) reported that up to 70% of biochemical oxygen demand (BOD) removal efficiency could be obtained using the CB system. They indicated that aeration to CB system could reach a better or more stable treatment efficiency by increasing the dissolved oxygen (DO) in influent river water (Juang et al., 2008). Wang et al. (2012) applied the two-stage baffled surface-flow constructed wetland (BSFCW) for river water treatment. The CW had a total area of 7400 m^2 with a hydraulic loading rate (HLR) of 14 cm/d to maximize the wastewater loading. Emerging plants, submerged plants, and floating plants were planted in the wetland. Results show that the removal efficiencies for total nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH_3-N), chemical oxygen demand (COD), and SS were 75%, 78%, 85%, 40%, and 80%, respectively in summer and autumn seasons. While drops of the removal efficiencies were also observed in the winter season (Wang et al., 2012). Fountoulakis et al. (2009) constructed a pilot-scale SFS wetland system, planted with *Phragmites australis* and *Arundo donax*, to treat the effluent from a sewage treatment plant. With HLR of 130 mm/d, more than 40% of TP, 58.1% of TN, and 61% of COD could be removed (Fountoulakis et al., 2009). Harrington and McInnes (2009) applied an integrated CW to treat livestock wastewater. Results from their study indicated that approximately 95% of total and soluble phosphorus (molybdate reactive phosphorus) and 98% of NH_3-N were removed during the eight-year investigation period (Harrington and McInnes, 2009). El-Khateeb et al. (2009) used of a treatment train system consisting of an up-flow anaerobic sludge blanket (USAB) reactor followed by the FWS and SFS CWs for wastewater treatment. Results showed that significant reduction of COD, BOD, total suspended solids (TSS), total coliform (TC), fecal coliform, fecal *streptococci*, *Pseudomonas aeruginosa*, *Salmonellae*, total *Staphylococci*, and Listeria monocytogenes were observed (El-Khateeb et al., 2009). CWs have also been proved successful in treating municipal and industrial effluents in some case studies (Cameron et al., 2003; Vymazal, 2005; Morgan et al., 2008). Diza et al. (2012) reported that agricultural non-point source (NPS) pollutants impair water quality in the Sacramento–San Joaquin River system of California's Central Valley. CWs have been used to improve the water quality of irrigation return flows prior to discharge into surface waters in this region (Diza et al., 2012). Based on CW input–output measurements, load removal efficiencies (LRE) were used to determine the wetland performance. Field results show that CWs could obtain LRE of 22–99% for nitrate and 31–96% for TSS (Diza et al., 2012). Williams et al. (1995) used the gravel bed hydroponics (GBH) as a constructed wetland system for sewage treatment and approved GHB was effective for tertiary treatment in the UK and secondary treatment in Egypt. El-Serehy et al. (2014) reported that GBH was applied in several Egyptian villages and obtained effective sewage treatment efficiency.

1.4. Studied site description

The Ju-Liao Stream is one of the most contaminated rivers in Kaohsiung City, Taiwan. For the Ju-Liao Stream that has a long history of higher BOD, NH_3-N, and SS due to the inadequate disposal of agricultural wastewater, industrial effluents, and domestic wastewater, discharges of polluted stream water would cause the deterioration of the downstream water quality (TEPA, 2006; Lai et al., 2013). In the year of 2010, the Taiwan Environmental Protection Administration (TEPA) and Kaohsiung City Government jointly initiated a constructed wetland project by constructing a multi-function wetland to improve the water quality of Ju-Liao Stream and ecosystem of the surrounding environment. Furthermore, a CB facility was designed and installed at the upgradient of the wetland to lower the pollutant loading to the wetland. Thus, part of the polluted stream water is pumped into the CB system for treatment and the treated water is discharged into the stream to dilute the pollutant concentrations and improve the water quality. The influent of the CW is the diluted stream water, which would minimize the adverse impact on the wetland ecosystem.

1.5. Sediment characteristics

Pollutants in the water bodies are usually adsorbed onto the sediment particles in the bottom layer (Wu et al., 2010; Chen et al., 2013; Chen et al., 2014a,b; Gill et al., 2014). Researchers reported that significant anthropogenic heavy metals can be bound to articulate matters, deposited on the beds of water bodies, and sorbed onto the sediments (Amin et al., 2009). In the aquatic systems, transferring of heavy metals from the aqueous phases to sediment particles occurs through particles settlement and part of the pollutants are accumulated into the biota from the sediment sink (Zhang et al., 2012). If the sediment evaluation results indicate that the sediments become the sources of contamination and pollutants are released from the sediments to the ecosystem, the impact of sediment contamination on the ecosystem needs to be evaluated and sediment management measures are required. In this study, sediment samples were also collected and analyzed to evaluate the impact of polluted influent water on wetland sediment quality.