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A case study on gravel-contact-aeration-oxidation system to treat the combined sewage and rainwater flowing into Keelung River, Taiwan

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ABSTRACT

The combined sewage overflow (CSO) flowing into in Keelung River, Taipei impairs its water quality. Contact oxidation treatment system is an optimal choice available to reduce pollutants from the CSO. The pollutant removal efficiencies of CSO were assessed using contact oxidation treatment system. The system consisted of three treatment units, grit chamber, aeration zone and non-aeration zone. There was an average daily treatment capacity of 5,500 $m^3 d^{-1}$ with a total hydraulic retention time of 6 h and an average water depth of 3.5 m. The water samples were taken monthly from January 2011 to December 2013, for the analyses of total suspended solids, biochemical oxygen demand, chemical oxygen demand, ammonia and nitrate. The overall removal efficiencies were 70% for total suspended solids, 75% for biochemical oxygen demand, 99% for ammonia and 96% for organic N. This indicates that the contact oxidation treatment system is able to remove organic nitrogen, ammonia effectively. However, the outflow concentrations of nitrate were much higher than those of the inflow. The high ammonia and low nitrate removal efficiencies demonstrated that denitrification processes did not occur in the wetland system due to high concentrations of dissolved oxygen in non-aeration zone of the treatment system.

Keywords: Ammonia nitrogen; Gravel contact oxidation; Nitrate; Removal efficiency

1. Introduction

Nowadays, ecological treatment systems are widely used for the removal of pollutants from waste waters, for treatment of urban domestic sewage and storm water, industrial wastewater, mine wastewater, agricultural and dairy farmyard wastewater [1–10]. The gravel contact oxidation (GCO), as an ecological method, is a kind of common ecological purification systems. The wastewater flows through filter bed, which is filled with gravel and cinder. Wastewater is in contact with biofilm on the surface of gravel for microbial reaction. Gravel or pebble is usually selected by its porous surface suitable for biofilm attachment and growth. Juang et al. [11] have evaluated the treatment efficiency of a GCO treatment system at the Shin Chu city of Taiwan. The results showed that the GCO system could effectively remove biological oxygen demand (BOD_5), suspended solids (SS) and ammonia (NH_4^+) in river water at a relatively short hydraulic retention time. Harrington et al. [12] introduced the integrated GCO system working at the landscape scale. Tu et al. [13] has researched a GCO system for polluted stream remediation. Cui et al. [14] has evaluated of nutrient removal efficiency and microbial enzyme activity in a baffled GCO system. Fournel et al. [15] has modeled a GCO system with variably saturated vertical subsurface-flow for urban storm water treatment. There are three pollutant removal mechanisms of GCO system: (a) deposition: The suspended particles in the wastewater are deposited on the bottom of the sludge settling zone because of the interception by gravel and gravity sedimentation; (b) adsorption: It occurs mainly in biofilm on the surface of gravel. And; (c) decomposition: the contaminants (BOD_5, NH_3-N, SS, etc.) adsorbed on its surface are eventually decomposed by the microorganisms or algae growing on the surface of the medium [16–23]. The GCO system generally can be divided into two categories: (1) The purification

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facilities are built directly in the river, using water conduction facilities to control inflow and outflow water volume; and (2) The purification facilities are built in the land in coastal or offshore of rivers by diverting water to treatment units either by gravity or power. In order to enhance the purification efficiency of GCO system, aeration pipelines are laid in the bottom of the gravel tank and aerated periodically to provide oxygen for microbial decomposition.

The GCO system, located on the right bank of Keelung River, downstream of the Nanhu Bridge of Taipei, was selected to explore the removal efficiency of major pollutants in sewage (BOD_5, SS, ammonia, etc.). Nanhu gravel treatment facility has been running since 2008. The studied system is a non-toxic and environmentally friendly process, and the purified water can be reused as the urban landscape water. The aim of this paper was to explore the pollutants removal of the combined sewage and rainwater using gravel-contact-aeration-oxidation system.

2. Materials and methods

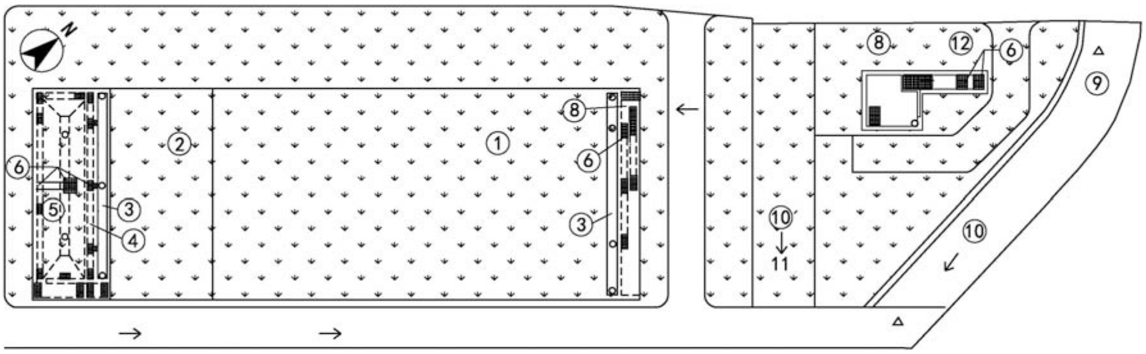
2.1. Site description and operation

The combined sewage for Nanhu gravel-contact-aeration-oxidation system process was domestic sewage of sunny days drained into Keelung River from Nanhu rainwater pumping station. The average daily treatment capacity of the gravel processing system was 5,500 $m^3\,d^{-1}$ with the maximum daily treatment capacity 8,000 $m^3\,d^{-1}$. The hydraulic loading rate was 5.73 $m\,d^{-1}$ with the organic loading rate 0.20 $kg\,d^{-1}\,m^{-2}$. The system included wastewater intake facilities, grit chamber, gravel contact oxidation facilities, wastewater discharge facilities, and sludge storage and transportation facilities (Fig. 1). To rid of undesirable objects (such as garbage, twigs, etc.) flowing into the pre-treatment facilities, the grille (grid distance of 10 cm) was set up at the wastewater intake with baffles to prevent floating debris entering the intake pipe to reduce subsequent loads. The grille is made up of a set of parallel metal paling, which is installed at the beginning of the sewage treatment plant. The main function of the grille is to block the large pollutants in the sewage. Otherwise, these large contaminants would block the pump or process pipeline of the subsequent units. The hydraulic rate of grit chamber was 1,800 $m^3\,m^{-2}\,d^{-1}$ (length × width × height was 4.5 × 1.5 × 3.3 m).

The GCO treatment facilities were divided into two sections in order to effectively remove high concentrations of ammonia in wastewater: the front was aeration zone; the latter was non-aeration zone. Aeration equipment was installed in the aeration zone. Blower aerator was mainly composed of a gas supply device, a micro-porous aerator and a connection tube, which provided adequate dissolved oxygen by forced aeration required for microbial decomposition of carbonaceous organic material and nitrification process. The non-aeration zone was mainly used for SS and solids settlement, organic matter and SS removal, further ammonia nitrification and denitrification processes. The bottom and the side of the tank used double impermeable structure. The permeable benthonic cloth was covered in the bottom of tank. Considering the uneven settlement brought by gravel and aeration tube, reinforced concrete and waterproof material were used to build a flexible foundation, and then the second layer of waterproof plastic cloth was paved. The designed parameters of gravel-contact-aeration-oxidation system are shown in Table 1.

2.2. Sampling collection and analyses

The inflow and outflow in GCO system flowed in one direction, both gravity flows. Sampling points of this study were located on the inlet channel and the outlet of system. From January 1, 2011 to December 1, 2013, inflows from pumping station and outflows of GCO system were sampled and analyzed monthly for such water quality index as T (temperature), pH, DO (dissolved oxygen), COD (chemical oxygen demand), BOD_5, SS, NH_4^+, NO_3^-, NO_2^-, Org-N (organic nitrogen), TP (total phosphorus). For sampling, paired water samples were collected as a means of verifying the accuracy and precision of the analysis. Only when no significant difference was found between replicated samples, then a mean was used in the subsequent data analysis. After field collection, all of the water samples were immediately taken to the laboratory and processed. All samples, which were unrefrigerated, were analyzed 24 h after the water samples were collected. The pH value, temperature,



(1) aeration zone; (2) non-aeration zone; (3) Rectification ditch of outflow; (4) Outflow ditch; (5) Sludge storage tank; (6) Grid cover plates; (7) Soil cover on the upper of gravel contact oxidation tank; (8) Entrance well; (9) Inflow; (10) Gravity drainage channel; (11) Outlet; (12) Grit chamber. "Δ "representing sampling locations.

Fig. 1. The gravel contact oxidation treatment system site.

Table 1
The design parameters of gravel-contact-aeration-oxidation system

	Each parameter of gravel contact aeration oxidation unit in Nanhu rainwater pumping station
Particle size of gravel	100–200 mm
Porosity of filled gravel	≥ 40%
Total system area	1,955 m^2
Volume of gravel contact oxidation tank	Total volume: 3,780 m^3, L × W × H: 45 m × 24 m × 3.5 m
	Aeration zone: 2,940 m^3, L × W × H: 35 × 24 × 3.5 m
	Non-aeration zone: 756 m^3, L × W × H: 10 × 9 × 3.5 m
HRT	Total 6 h (Aeration Zone: 5 h; Non-aeration zone: 1 h).
Treated wastewater	Combined sewage overflow
Capacity of sludge storage tank	300 m^3
Sludge discharge frequency	Three months

dissolved oxygen (DO) and SS were immediately measured using a portable Orion 5-Star meter, a pH electrode (9172BNWP, THERMO, USA), a DO electrode (086030MD, THERMO, 160 USA) and a portable detector (HACH sensION+EC7). BOD was measured using a portable biological oxygen demand detector (HACH BOD trak). COD was measured using the potassium dichromate method. Non-filtered samples were analyzed for total nitrogen (TN) and total phosphorus (TP). Filtrates were analyzed for ammonium (NH_4^+–N) and nitrate (NO_3^-–N). Nitrate and TN, measured as NO_3 on a persulfate-digested split, were quantified using a single reagent spectroscopic method. NH_4^+–N was determined spectroscopically with the Berthelot reaction, using a salicylate analog of indophenol blue. Total phosphorus (TP) was measured after Persulfate Digestion of unfiltered samples, followed by colorimetric analysis (or Ascorbic Acid Method). All methods were performed in accordance with "Standard Methods for Monitoring Water and Wastewater Quantity [24]".

3. Results and discussion

3.1. T, pH and DO

The pH values of inflow and outflow in GCO system are shown in Fig. 2a. During the experiment period, the range of temperature of inflow and outflow was from 15 to 30°C. The contaminant removal was affected by temperature. There was no change in pH value of inflow and outflow which was about 7. DO concentrations of most inflow were below 2 mg L^{-1} and the outflow was above 3 mg L^{-1}.

3.2. BOD_5, COD, SS, TP

The concentration of inflow and outflow for BOD_5, COD are shown in Fig. 2b. Clearly, COD removal performance is satisfactory. While BOD_5 pollutant loads were far less than COD, and it had been removed obviously by the gravel-contact-aeration treatment system. The average annual reduction rates of BOD_5 between 2011 and 2013 are shown in Table 2. During these operation periods, BOD_5 removal rate was more than 70%; the annual average removal rate between 2011 and 2013 was 75.1%. From the differences in BOD_5 and COD pollutant load reduction, it could concluded that the remove efficiency of gravel-contact-aeration-oxidation system not only just by microorganisms degradation of carbonaceous organic matter, but also by non-biological organic parts through adsorption, sedimentation and other processes. The gravel filled in the system not only provided microorganisms with a large number of surface areas as carrier, but also can be used as a good adsorption media to absorb pollutants in sewage effectively [25].

The relationship of SS pollution loads of inflow and outflow in the system is shown in Fig. 2c. SS pollution loads of inflow were 32.1–273.5 kg d^{-1}; SS pollution loads of outflow were 8.2–74.1 kg d^{-1}. From Fig. 2c it can be demonstrated that SS pollution loads of outflow were stable, but SS pollution loads of inflow changed dramatically. SS average removal rate in three years was 70.2% in Table 2. SS pollutant loads of inflow were high in rain day. High SS pollutant loads would clog the media filler in the gravel-contact-aeration-oxidation unit. With the operation of the GCO system, the gravel bed is gradually blocked and the removal rate of SS may decrease.

The variations of TP pollutant loads of inflow and outflow is shown in Fig. 2a. The TP pollution loads of inflow were 0.3–13.4 kg d^{-1}. The TP pollution loads of outflow were 0.2–9.1 kg d^{-1}. During the three-year experiment period, the gravel-contact-aeration-oxidation system had positive removal effect on phosphorus. However, the adsorption capacity of phosphorus was declined because of some blockage in gravel packing layer after years of operation.

3.3. The variation of nitrogen

The variations of ammonia nitrogen, nitrate nitrogen, nitrite nitrogen and organic nitrogen pollution loads of inflow and outflow are shown in Figs. 2d, 2e. Ammonia nitrogen pollution loads of inflow were 13.8–184.3 kg d^{-1}. The outflow was 0–7.9 kg d^{-1}. Like BOD_5, ammonia nitrogen pollution loads of inflow changed greatly, and the outflow was stable. The gravel contact aeration oxidation had good removal effect on ammonia nitrogen. The pollution loads of outflow were very low, basically below 0.5 kg d^{-1} (except for individual values). The annual average removal rate of

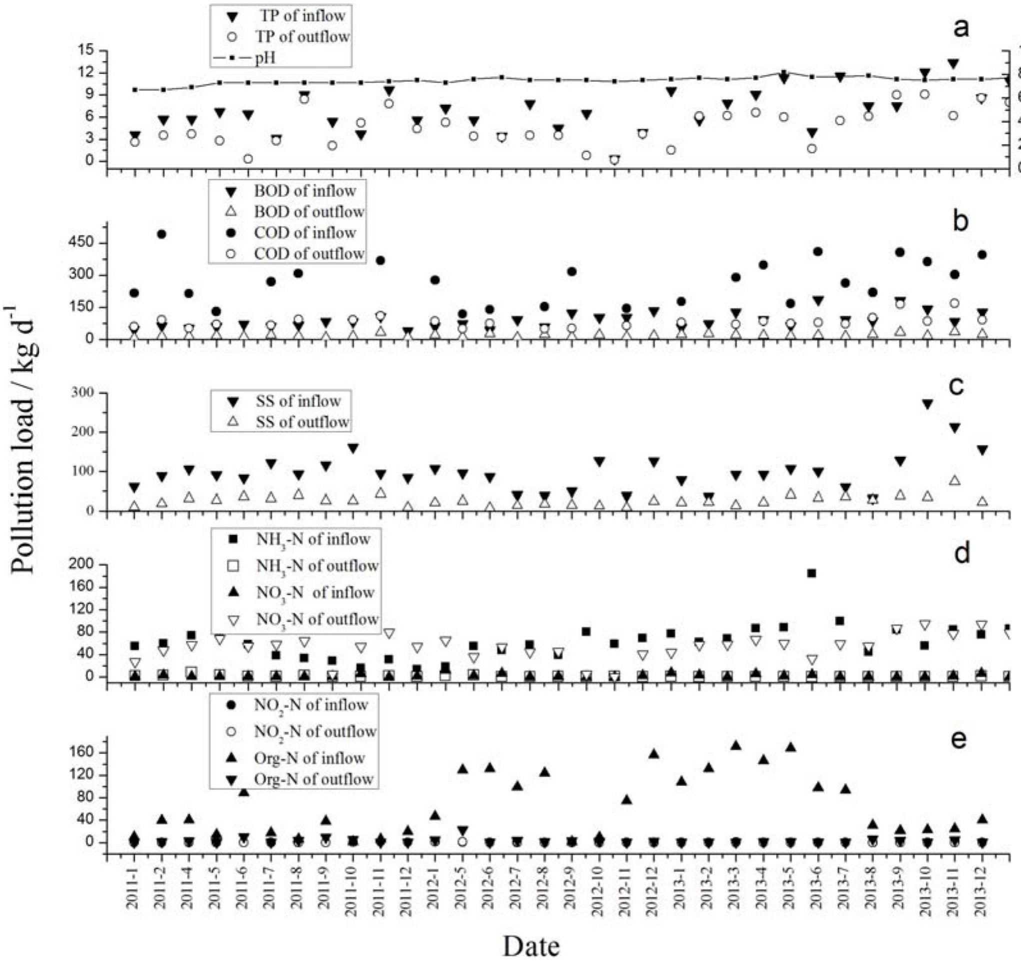


Fig. 2. Water quality parameters of inflow and outflow.

Table 2
The average annual water quality parameters (2011–2013) in Nanhu gravel contact aeration treatment system

Years	Total amount of water (106 m^3 d^{-1})	BOD_5 (mg L^{-1})		COD (mg L^{-1})		SS (mg L^{-1})		NH_3-N (mg L^{-1})		Removal efficiency (%)			
		Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	BOD_5	COD	SS	NH_3-N
2011	2.07	11 ± 2	3 ± 1	50 ± 17	18 ± 4	18 ± 4	6 ± 2	8.0 ± 4.3	0.6 ± 0.5	70	64	64	93
2012	1.41	16 ± 6	3 ± 1	35 ± 16	11 ± 2	14 ± 6	3 ± 1	10.3 ± 3.7	0.2 ± 0.2	78	68	76	98
2013	1.99	17 ± 8	4 ± 1	53 ± 18	15 ± 3	16 ± 10	5 ± 2	11.6 ± 5.8	0.1 ± 0.0	80	71	70	99
Average	1.82	16 ± 4	4 ± 0	46 ± 10	15 ± 3	16 ± 2	5 ± 1	10.0 ± 1.9	0.3 ± 0.2	76	68	70	97

ammonia nitrogen in the system is shown in Table 2. The average removal rate from 2011 to 2013 was 96.5%. The average annual removal rate reached 98.8% in 2013.

Nitrate nitrogen pollution loads of inflow were 0–12.0 kg d^{-1}. Those of outflow were 4.7–95.0 kg d^{-1}. Nitrate nitrogen pollution loads of inflow were far lower than that of outflow. Correspondingly, ammonia nitrogen pollution loads of outflow dropped significantly. In aeration zone of gravel-contact-aeration-oxidation treatment system, oxygen was excessive, and ammonia nitrogen, organic matter, organic nitrogen and other pollutants were fully oxidative degraded. Especially, ammonia nitrogen was oxidized to nitrate nitrogen or nitrite which was instable, and most ammonia nitrogen of inflow was converted to nitrate nitrogen through nitrification process. Meanwhile, DO concentration of outflow was much higher than inflow, illustrating that DO content was still too high in the non-aeration zone. It could be found that denitrification process of non-aeration zone did not proceed successfully, resulting in high nitrate nitrogen load of outflow. According to Fig. 2e, nitrite nitrogen loads were low of inflow and outflow, so it was not a major factor. Organic nitrogen load of inflow was high, and that of outflow was substantially reduced after gravel-contact-aeration-oxidation system treatment. As ammo-

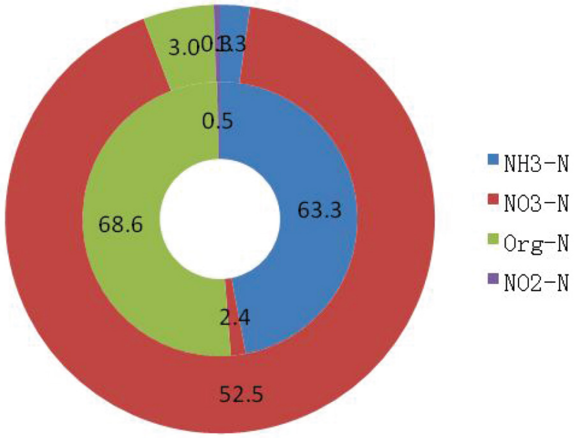


Fig. 3. The distribution ratio (%) of nitrogen of inflow and outflow. (The outer loop represents the influent data, and the inner loop represents the effluent data.)

nia nitrogen, the reason was that organic nitrogen was fully oxidized and mostly converted to nitrate nitrogen in the aeration zone.

Although organic nitrogen and ammonia nitrogen loads of outflow were reduced significantly, these two forms of nitrogen were not removed from the sewage, just changing form to nitrate nitrogen.

Fig. 3 was shown to represent respectively the proportion of different forms of nitrogen of inflow and outflow. NO_3-N, NH_3-N, NO_2-N and Organic nitrogen were all analyzed by standard methods. As seen from the figure, organic nitrogen and ammonia nitrogen accounted for a large proportion of nitrogen of inflow.

The rates were respectively 50.9% and 47%, totally accounting for 97.9% of nitrogen. The nitrate nitrogen ratio of outflow was much higher than other forms, accounting for 92.0% of nitrogen. And the other three forms of nitrogen took up less than 10%. Fig. 3 also verified the above findings that most ammonia nitrogen and organic nitrogen of inflow was converted into nitrate nitrogen. Although removal efficiencies of ammonia nitrogen and organic nitrogen load in the gravel-contact-aeration-oxidation system were high, most nitrogen was not removed from the sewage. The aeration rate of aeration zone should be controlled accurately to remove nitrogen pollutants more effectively by Nanhu gravel-contact-aeration-oxidation system, to complete organic pollutants (COD, ammonia nitrogen, organic nitrogen, etc.) degradation by aeration zone effectively, and meet the need of DO level in the non-aeration area to complete denitrification and other processes.

4. Conclusions

Nanhu gravel-contact-aeration-oxidation treatment system clearly can be an effective treatment facility for polluted water in Keelung River. The initial result of this research work, however, found that the ability of a wetlands system to treat such polluted water is dominated by the degradation of aerobic and anaerobic microorganisms. The microbiology of treatment systems is the most important factor influencing the removal of pollutants. Aerobic and anaerobic heterotrophic degradation often play a major role for organics removal, in gravel-contact-aeration-oxidation systems respectively. Special focus should be paid on detailed mechanisms of anaerobic biodegradation routes in systems, thereby allowing nitrogen and organics removal in a single reactor.

During the three-year experiment period, the gravel-contact-aeration-oxidation system had positive removal effect on phosphorus, ammonia nitrogen and nitrate nitrogen. The nitrate nitrogen ratio of outflow was much higher than other forms. The influent water quality in such a river was unstable and the range indicated was large. Together, spring and autumn overturns occurred in the river, resulting in the release of large amounts of toxic materials, such as metals, from the river sediment. Although this preliminary research suggests that gravel-contact-aeration-oxidation treatment systems are effective in removing pollutants, maintaining adequate treatment effectiveness continuously throughout the year is clearly the first goal to reach when applying this method to purify river water. To reach this goal, the next step of research work would be needed to understand in more detail the nature of the gravel-contact-aeration-oxidation system and its operating parameters.

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