Effect of HRT on nitrogen removal in a coupled HRP and unplanted subsurface flow gravel bed constructed wetland

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Abstract

This paper discusses the effect of hydraulic retention time (HRT) on nitrogen removal in a coupled high rate pond (HRP) and a gravel bed subsurface constructed wetland (SSCW) wastewater treatment plant. A pilot plant consisting of a high rate pond (HRT) coupled to an unplanted gravel bed subsurface constructed wetland (SSCW) was used to investigate nitrogen removal from domestic wastewater at the University of Dar es Salaam. The influent, which is predominantly of domestic origin, was drawn from the facultative pond unit of the university's waste stabilisation pond system. The pilot plant's HRP unit, which was 0.6 m deep, was designed to nitrify the influent while SSCW unit, which was filled to 10 cm above water level with 19-mm diameter aggregates, was predominantly anoxic and promoted denitrification. The study was conducted at two different operational settings. In Phase 1, both the HRP and the SSCW units had a retention time of 5 days. During Phase 2, the hydraulic retention time in HRP was increased to 8 days while the retention time of the SSCW unit was maintained at 5 days. Samples were collected daily for laboratory analysis of influent and effluent wastewater quality. All experiments were conducted in accordance with *Standard Methods*. The results showed that improved nitrogen removal occurred with increase in hydraulic time of the HRP unit. In Phase 1 an average nitrogen removal of 33% was achieved while removal efficiency improved to 43% in Phase 2. It was also revealed that the HRP can effectively be used to promote nitrification and the unplanted gravel bed subsurface constructed wetland can be used as a denitrifying unit.

Keywords: High rate pond; Sub-surface constructed wetland; Nitrification; Denitrification; Hydraulic retention time

1. Introduction

The release of nitrogen-rich wastewater effluents into receiving rivers result in environmental and human health problems such as fish poisoning by ammonia and eutrophication in water bodies. The presence of nitrogen compounds in fresh water is associated with methaemoglobinaemia in children (USEPA,1977), carcinogenicity (WHO, 1978) and *achlorohydria* in adults (Hill *et al*., 1973). Nitrogen removal from wastewater has mainly been done using expensive wastewater treatment systems such as activated sludge and the biological nutrient removal (BNR) technologies (Henze, 1991). These technologies are dependent on mechanical equipment, electrical energy and availability of skilled personnel. As such they are expensive and unsuitable for small and rural communities. Low-tech systems like constructed wetlands can effectively remove nitrogen from wastewater (Kadlec and

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Knight, 1996) at low cost and minimal maintenance. The microbial nitrification-denitrification processes are responsible for the bulk of nitrogen removal (Gersberg *et al*., 1984; Sikora *et al*., 1995). These mechanisms are dependent on aerobic and anoxic conditions, which are very difficult to regulate under natural conditions found in wetlands. The aim of this work is to investigate the potential of utilizing high rate ponds (HRP) and subsurface flow gravel bed constructed wetlands (SSCW) for removal of nitrogen. HRP and SSCW are biological treatment techniques, which require less financial input for construction and maintenance of the systems and can be managed by relatively low skilled personnel (Mashauri and Mayo, 2003; Senzia, 2003). They also do not mechanical equipment and energy input from external sources.

2. Methods and materials

A pilot plant (Fig 1) was used for the study. High Rate Pond (HRP) unit was sized using the traditional method (Hussein, 1976) and the Subsurface Flow gravel bed Constructed Wetland (SSCW) was designed in accordance with procedure outlined by Cooper (1990). The HRP unit base is of precast weld mesh reinforced concrete slab and is of 100-mm thickness. The walls are of concrete blocks 230 mm in thickness. These walls were plastered with 15-mm cement rich rendering to prevent wastewater leakage into surrounding ground. The floor slope is 1% and inclines towards the effluent. The influent is supplied using a 50-mm diameter HDPE interconnection, which discharges into an inlet box. Three control valves were installed to manage the flow: (1) one 20 mm diameter valve was fitted to the supply pipe to control inflow rate; (2) a second 20 mm diameter valve was fitted to the outlet pipe to control discharge to the gravel bed unit and finally one 50 mm diameter valve was fitted to the flush out pipe. To control maximum water level in the pond at 60 cm, a 20-mm diameter overflow pipe was fitted at 60 cm above floor level.

The sub-surface gravel bed constructed wetland unit was filled with clean water-washed 20-mm diameter aggregates up to 10 cm above maximum water level to ensure anoxic conditions within the unit. The porosity of the bed was 35% and the length to width ratio of 5 was adopted to maintain plug flow conditions. The dimensions of the gravel bed unit were 7.5 m x 1.5 m x 0.7 m.

During the sampling period of this study experiments were conducted under two distinct operational settings, viz.:

- Phase 1: In this setting both the HRP and the gravel bed units were each operating at 5 days retention time. The inflow rates in the HRP and wetland units were 1.2 m^3/d and 0.69 m^3/d, respectively.
- Phase 2: The retention time for the HRP was changed to 8 days in an attempt to improve the nitrification level. Flow rate was reduced to 0.75 m^3/d. Flow and operating conditions of the gravel bed unit were maintained at the settings described earlier.

Flow measurements were taken daily during sampling to monitor and ensure that constant flow rates were maintained. Flow rates were determined using a graduated cylinder, a stopwatch and a collecting can.

Wastewater samples for laboratory analyses were collected daily between 10.00 a.m. and 11.30 a.m. from the influent to HRP and effluents of HRP and SSFW. The collected samples were immediately taken to the University of Dar es Salaam (UDSM) water quality laboratory

for analysis. Temperature and pH were measured *in situ* using a pH meter with a temperature electrode (Metrohm pH meter, model 704). Dissolved oxygen concentrations were also measured *in situ* using a digital DO meter (YSI DO meter, model 50B). To determine nitrates and nitrites, cadmium reduction and diatomization method, respectively were used. A direct reading spectrophotometer (DR2000 model) was used to carry out the measurements. Ammonia nitrogen was extracted by distillation followed by titration with 0.02N sulphuric acid. TKN was determined using the semi-micro-Kjeldahl method (*Standard Methods*, 1992). TSS values were determined by the filtration method followed by oven-drying the filter residue solids at 105^0C for 2 hour before re-weighing.

3. Results and discussion

During Phase 1 operation the HRP received influent wastewater with an average of 5.82 mg/l ammonia nitrogen, 2.71-mg/l organic nitrogen and 0.35-mg/l nitrate nitrogen. Nitrite-nitrogen concentrations were low (average 0.012 mg/l) as observed elsewhere (Metcalf and Eddy, 1995). The average total nitrogen received by the unit was 9.11mg/l. Average inflow concentrations of NO_3-N, NH_3-N and organic nitrogen during Phase 2 studies were 0.51 mg/l, 3.90 mg/l and 2.36 mg/l, respectively. As was in Phase 1 study the nitrite nitrogen concentration was low as expected, averaging 0.02 mg/l. The average total nitrogen was 6.78 mg/l.

3.1 Performance of the HRP unit

Nitrate nitrogen

The average HRP effluent nitrate for Phase 1 study was 0.87 mg/l representing increase in NO_3-N concentration of 149%. This increase, which was attributed to nitrification process, was accompanied by a corresponding decrease in ammonia nitrogen concentration. The availability of oxygen in the HRP generated by photosynthetic activities of algae promoted the nitrification process. Nitrification in aquatic systems is normally estimated by the net increase in nitrate nitrogen concentration and the net difference in ammonium contents between sampling points (Hseih and Coultas, 1989; Azov and Tregubova, 1995).

A change of retention time from 5 days to 8 days in Phase 2 studies resulted in a significant increase in the HRP effluent nitrate concentration to 1.55 mg/l. This represented a 304% increase in nitrate concentration in the HRP system compared to the 149% increase in Phase 1 suggesting that the influent required more residence time in the HRP unit to complete nitrification process. Metcalf and Eddy (1995) recommended 8 days to be the minimum retention time for nitrification process in aquatic systems. Fig. 2 shows a comparison of influent and effluent nitrate nitrogen concentrations in the HRP during Phase 2.

Organic nitrogen

The average organic nitrogen for Phase 1 was 2.71, but decreases slightly to 2.19 mg/l in Phase 2. Organic nitrogen in HRP decreased by 22% in Phase 2 compared to 19% in Phase 1 because of mineralisation and sedimentation processes. A slight increase in reduction of organic nitrogen in Phase 2 was attributed to the increase in hydraulic retention time, which allowed more time for these transformation processes to take place. The quiescent conditions that existed in the HRP promoted sedimentation of organic nitrogen, which was also observed by Shin and Polprasert (1988) who reported that sedimentation of organic nitrogen contributes

significantly to nitrogen removal in aquatic systems. Reddy and Graetz (1981) also confirmed that even under facultative conditions obligate anaerobic mineralisation could take place.

Ammonia nitrogen
In Phases 1 and 2, the average NH_3-N concentrations were 5.82 mg/l and 3.90 mg/l, respectively. Ammonia removal in Phase 1 averaged 35%, whereas in Phase 2, the reduction was 21%. The removal was attributed to uptake by microorganisms (algae and bacteria) and nitrification processes. Ammonia uptake by microorganisms is more preferable to nitrate uptake (Neel *et al*., 1961; Fritz *et al.*, 1979). Nitrification was a more plausible cause for ammonia nitrogen reduction considering the high generation of nitrates observed in the system. Reduction of ammonia through volatilisation is very unlikely because of relatively low pH values in the system. Ammonia stripping occurs at pH values above 9.4 (Reddy and Graetz, 1981), but pH values in the system ranged from 7.6 to 8.1.

3.2 Nitrogen removal in the SSCW

Nitrate nitrogen
In Phase 1 studies, the average effluent nitrate concentration in SSCW unit was 1.33 mg/l, which was higher than the incoming influent nitrate concentration of 0.87mg/l. This is because of inadequate nitrification in HRT unit due to inadequate retention time (5 days) for growth of nitrifying bacteria. To test this hypothesis the retention time in the HRP unit was increased to 8 days in Phase 2 of studies. This change produced a shift in the levels of nitrate nitrogen concentrations in the SSCW. The average nitrate concentration in the effluent dropped from 1.55 mg/l to 0.93 mg/l (Fig. 3). This represented an average drop of 40% in the NO_3-N in the final SSCW effluent, which is comparable to results obtained by Kozub and Liehr (1998) at New Hanover County in U.S.A. The removal of nitrate is largely attributed to denitrification process in accordance with equation (1). Consumption of nitrate along the gravel bed unit is expected to be accompanied by increase in pH, which is clearly evident in Fig. 4.

$$0.65C_{18}H_{19}O_9N + 4.89NO^{-}_{3} + 4.89H^{+} \rightarrow C_5H_7NO_2 + 2.27N_2 + 6.7CO_2 + 5.12H_20 \quad \ldots\ldots\ldots\ldots(1)$$

Ammonia nitrogen
The average ammonia nitrogen in the SSCW unit increased by 2.7% during Phase 1 study, probably because of mineralisation of organic nitrogen as a result of incomplete mineralisation in HRP unit. When retention time in HRP unit was increased from 5 to 8 days in Phase 2, the removal of ammonia in the SSCW unit improved. During Phase 2 studies the concentration of ammonia nitrogen decreased by 28%. More efficient nitrification and mineralisation processes in HRP unit largely contributed to the reduction of ammonia in SSCW. As a result the retention time available in SSCW was more efficiently used for denitrification and ammonia uptake. The contribution of biofilm on gravel media is also noteworthy as they promote nitrification-denitrification and uptake of ammonia (Bigambo, 2003).

Organic nitrogen
The concentration of organic nitrogen decreased by 60% and 49% in the SSCW during Phases 1 and 2 studies, respectively. The main cause of decrease of organic nitrogen is sedimentation (Fig. 5) although mineralization is also partly responsible particularly in Phase 1 because of increase in ammonia.

Total nitrogen

The removal efficiency of total nitrogen in Phase 1 was 33.4%, and was largely in HRP unit, which removed 24.1%. Sedimentation and denitrification processes are the possible causes of the recorded nitrogen removal. In Phase 1, the contribution of denitrification in both HRP and SSCW is insignificant because of incomplete nitrification in HRP. The overall nitrogen removal during Phase 2 improved to 43.4% because of improved mineralisation and nitrification in HRP after hydraulic retention time was increased from 5 to 8 days. This change resulted in a significant increase in HRP nitrate production and a turn around of the final effluent nitrate nitrogen levels after significant denitrification in SSCW unit. Denitrification in SSCW unit was promoted by the availability of nitrates and anoxic or low oxygen concentrations in the unit. Helmer *et al.* (1999) suggested that autotrophi*c* ammonia oxidising bacteria, *Nitrosomonas europaea* and *Nitrosomonas eutropha*, can also denitrify aerobically under low oxygen concentrations.

4. Conclusions

The outcome of the research show that nitrification, denitrification, ammonia uptake and sedimentation all play a role in nitrogen removal in a coupled treatment system consisting of a high rate pond and a gravel bed subsurface constructed wetland. It is evident that the efficiency of the system depends on operating conditions such as hydraulic retention time. Inadequate hydraulic retention time in the HRP resulted in impeded mineralisation and nitrification and a corresponding reduced overall nitrogen removal due to poor denitrification in the SSCW unit. An increase of HRP retention time from 5 days to 8 days improved the total nitrogen removal from 33.4% to 43.4%. The research hence proved that provided the influent is fully nitrified, denitrification becomes the major contributor to the nitrogen removal process in subsurface constructed wetlands.

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Figures and figure captions

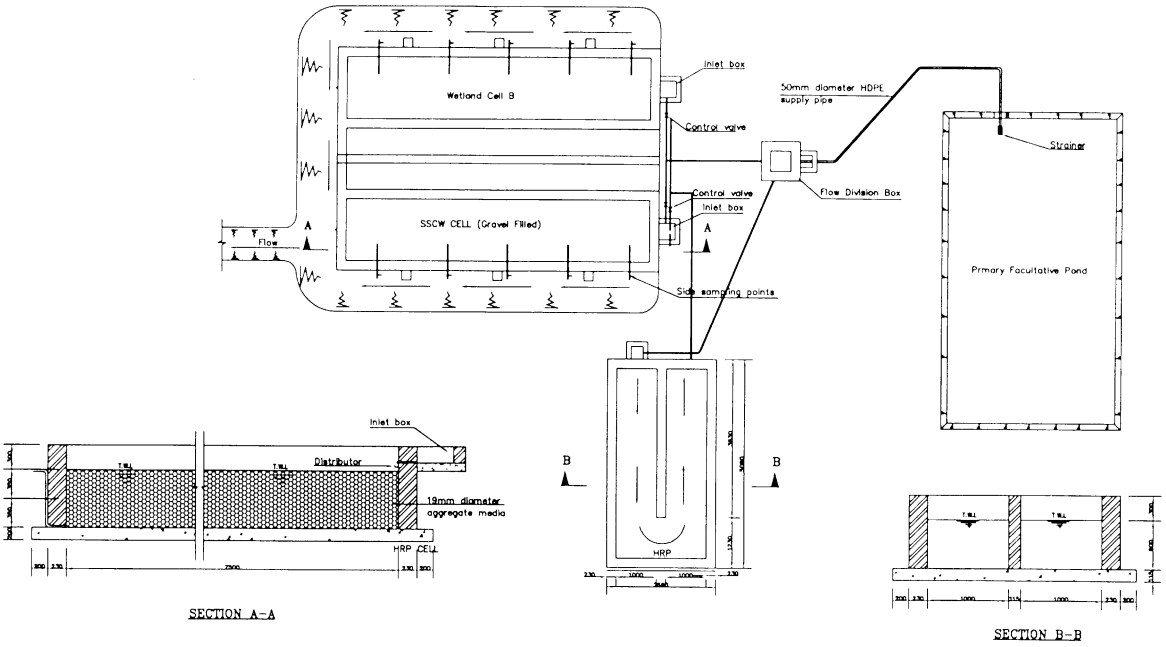


Fig. 1. Layout of constructed wetlands

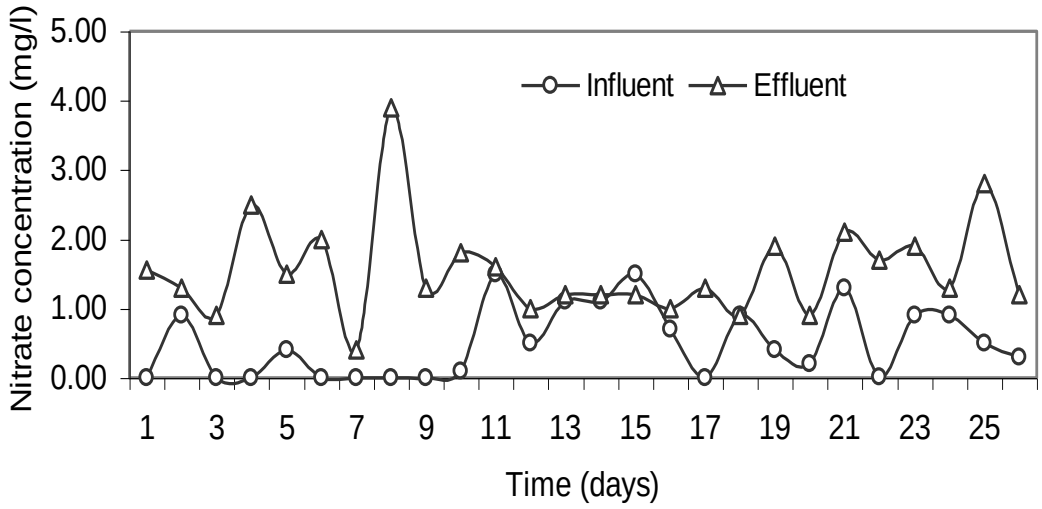


Fig. 2. HRP influent and effluent NO_3-N concentration in Phase 2 studies.

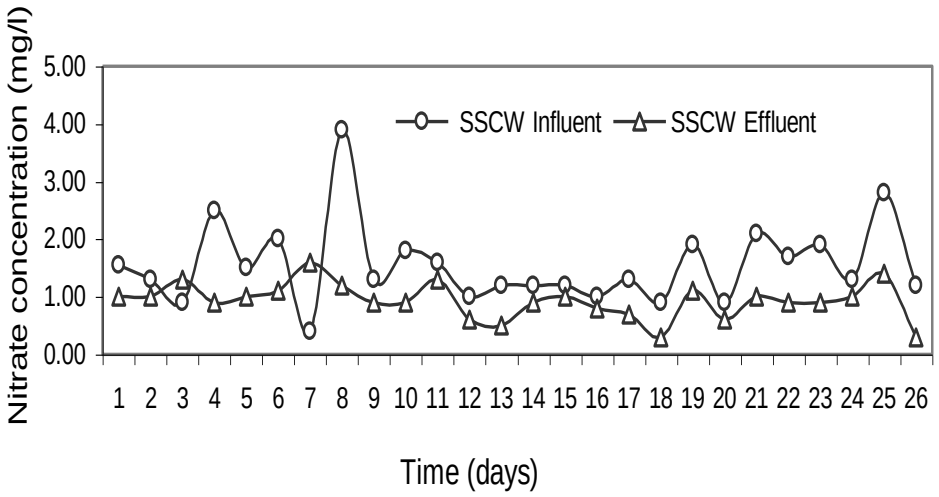

Nitrate concentration (mg/l)
5.00
4.00
3.00
2.00
1.00
0.00
SSCW Influent
SSCW Effluent
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Time (days)

Fig. 3. SSCW influent and effluent NO_3-N concentration in setting 2 studies

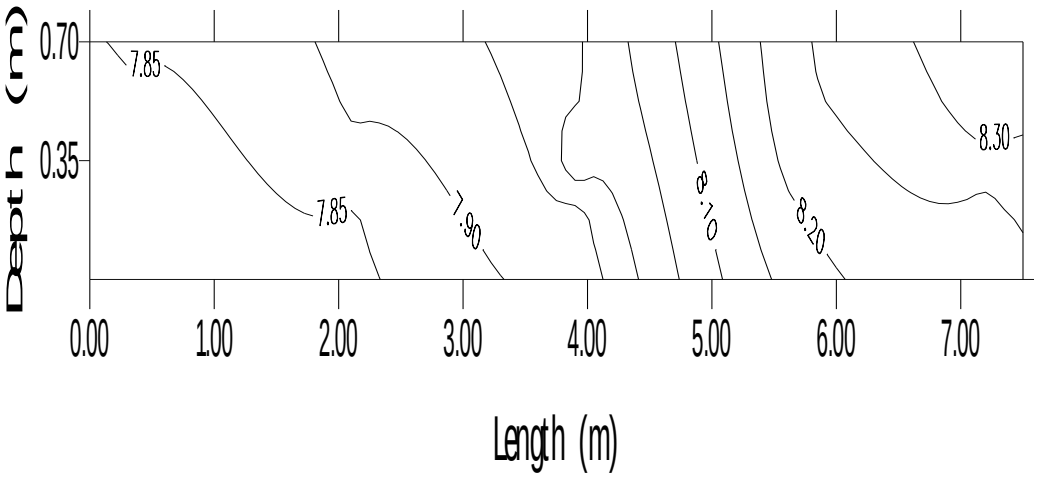


Fig. 4. Variation of pH with the depth and length of gravel bed.

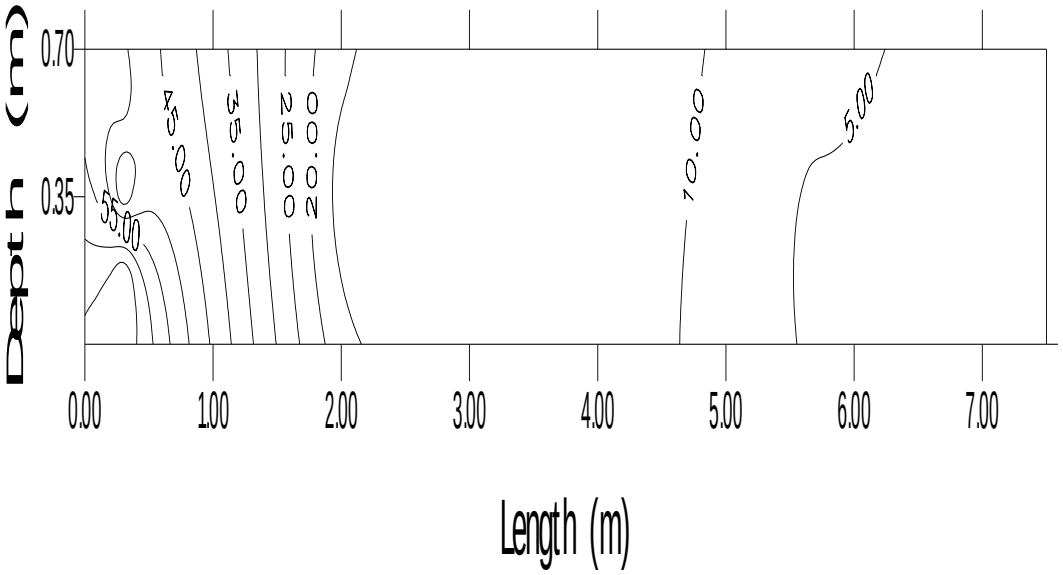


Fig. 5. Removal of suspended solids in a SSCW unit.