Evaluating performance of vertical flow constructed wetland under various hydraulic loading rates in effluent polishing

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ABSTRACT

The discharge of untreated wastewater or partially treated effluent and runoff from agricultural fields into water bodies is a major source of surface water pollution worldwide. To mitigate this problem, wastewater treatment using wastewater stabilization ponds and constructed wetlands have been promoted. The performance of such wastewater treatment systems is strongly dependent on their hydraulics, which if not properly considered during design or operation, may result in the partially treated effluent being discharged into water bodies. This paper presents results from a study that was carried out to evaluate the performance of a vertical flow constructed wetland system under varying hydraulic loading regimes. The influent and effluent samples from the constructed wetland were collected and analysed for physical, chemical and biological parameters of importance to water quality based on recommended standard laboratory methods. The data collected was useful in determining the treatment efficiency of the wetland. The hydraulic loading rate applied ranged between 0.014 and 0.174 m/day. Phosphorus reduction for the different hydraulic loading rates ranged between 92 and 47% for lowest and highest loading rates applied respectively. However, ammonium nitrogen reduction was not significantly affected by the different hydraulic loading rates, since the reduction ranged between 97 and 94%.

Key words | constructed wetland, hydraulic loading rates, hydraulics, treatment efficiency

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INTRODUCTION

Freshwater resources all over the world are threatened not only by over exploitation and poor management but also by ecological degradation (Crites *et al.* 2006). Wastewater is generally a major source of ground and surface water pollution, especially in developing countries as their treatment is never comprehensive enough to remove all pollutants. Given the rapid spread of water pollution and growing concern about water availability, the links between quality and quantity of water supplies have become more apparent (Smol 2002). When the quantity of pollutants is too high, it creates oxygen sag which leads to anaerobic conditions, an initial sign of primary pollution. According to UNEP (2005), conventional treatment plants have a primary aim of protecting freshwater from degradation. Wastewater stabilization ponds (WSPs) have been reported to have limited nutrient removal (USEPA 1988). There is a much greater challenge when WSPs are overloaded due to increased wastewater generation. The release of partially treated effluent with a high nutrient load in to water bodies robs them of naturally dissolved oxygen. This action leads to secondary pollution and is considerably more damaging to the oxygen level than primary pollution (Reed *et al.* 1995). Efficiency of WSPs in removal of nutrients and pathogens is influenced by their hydraulic performance, which in turn is affected by the loading of such facilities with wastewater. In this case therefore, the quality of the effluent rarely meets the standards required for its discharge into the receiving water bodies and requires further treatment.

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One of the technologies used in polishing the effluents from the WSPs is the use of constructed wetlands (CWs). The CWs involve the use of engineered systems that are designed and constructed to utilize natural processes associated with micro-organisms and soils to remove contaminants from wastewater effluents (USEPA 1993). The CWs enhance the removal of nutrients when proper design capacity and hydraulics performance are considered during construction.

MATERIALS AND METHODS

Study area

The study was conducted at Egerton University Njoro Campus and Municipal Council of Nakuru (MCN) in Kenya, where the focus was on Egerton University and Kaloleni WSPs. Egerton University is located at 35°55′46.8″ E, 0°22′19.48″ S and at an average elevation of 2,265 m, and MCN is located at 36°05′32″ E, 0°19′41.08″ S and at an average elevation of 1,755 m. The University has a population of about 15,000 persons (Egerton Water and Sewerage Department 2009), while that of MCN is about 800,000 persons (CBS 2009). The Kaloleni treatment plant in Nakuru receives wastewater from non-industrial sources, mainly domestic wastewater from residential areas in the municipality. The plant has a capacity of 16,200 m^3/day. It comprises two anaerobic, two facultative and six maturation ponds with rock and grass filters. The effluent flows directly into Lake Nakuru and acts as a major source of water and nutrients that promote the heavy growth of algae in the lake. The effluent from Kaloleni WSPs also supplies wild animals with drinking water, especially during the dry season. Egerton University has WSPs comprising two anaerobic ponds, with the old and new ponds receiving 37 m^3/day and 680 m^3/day of wastewater respectively. In addition there are two facultative ponds and two maturation ponds. The University generates about 717 m^3/day of wastewater, which is eventually released into Njoro River after treatment (Egerton Water and Sewerage Department 2009) (Figure 1).

Sizing of a pilot constructed wetland

A first order plug flow model was used in sizing the constructed wetland. The biochemical oxygen demand (BOD_5) of wastewater from the last maturation pond and the

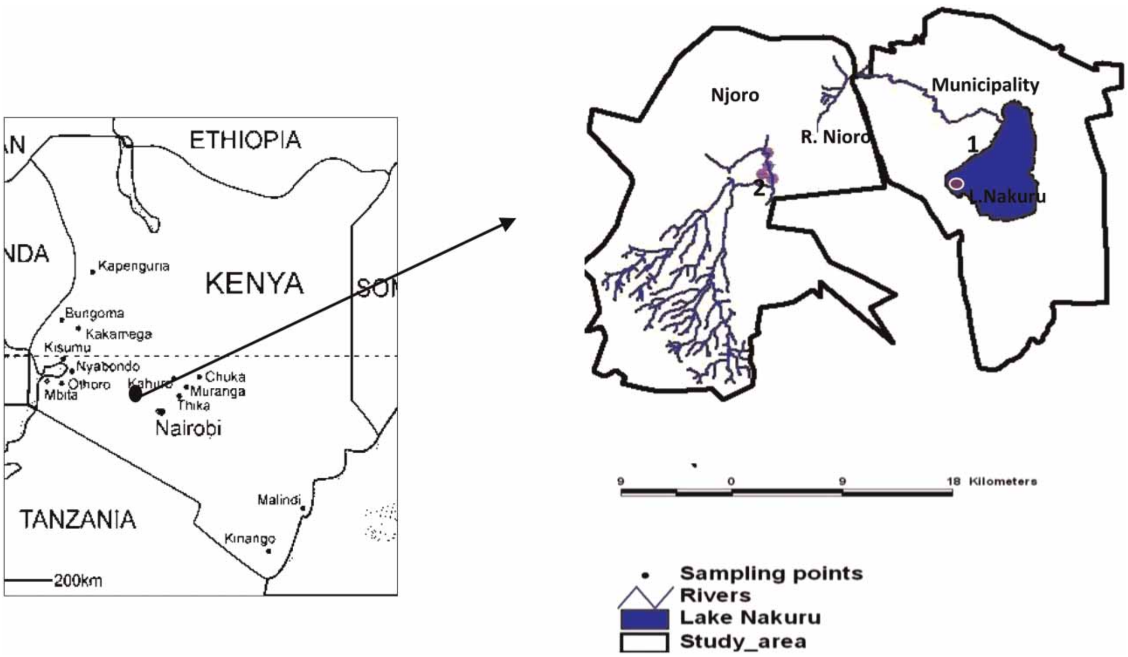

Figure 1 | Map showing the study area. 1: Nakuru, Kaloleni wastewater stabilization ponds; 2: Egerton wastewater stabilization ponds.

allowable discharge to the river were used as influent and effluent concentration respectively in the plug flow model to calculate the hydraulic retention time. The depth of water in the wetland was then calculated using Equation (1) given in Reed *et al.* (1995):

$$y = Q\frac{(\ln\ C_0 - \ln\ C_e)}{A_s K_T n} \tag{1}$$

where $y =$ depth of water in wetland; $A_s =$ surface area of the wetland; $n =$ porosity; $K_T =$ temperature dependent 1st order reaction rate.

The hydraulic loading rate (HLR) of the wetland was calculated using the equation given in Reed *et al.* (1995) as:

$$\mathrm{HLR} = \frac{100Q}{A_s} \tag{2}$$

Wetland water balance

The wetland water balance was established using meteorological data collected from Egerton weather station. Some of the important meteorological data collected included evaporation rate, precipitation and temperature. The evaporation data collected using a class A pan was converted to potential evapotranspiration, ET_0:

$$\mathrm{ET}_0 = k\mathrm{ET} \tag{3}$$

where $k =$ crop factor, in this case grass.

According to Reed *et al.* (1995), the k for sub-surface CWs is 0.8. The present study adopted this value in the conversion of evaporation data. The evaporation and precipitation data collected were then converted into volume per time using the area of the wetland. The inflow and outflow of the data from the wetland were taken throughout the study period. Plastic tanks were used and thus the infiltration and groundwater effect to the water balance were negligible.

Experimental set up of the pilot vertical flow constructed wetlands

Sub-surface vertical flow CWs in this study were composed of granular material with different grain sizes arranged in layers of varying configurations. The substrate used had three layers: sand, expanded clay and gravel. The cover layer was sand which facilitated water distribution over the entire wetland; the main layer was expanded clay and gravel was used in the drainage layer. Vetiver grass was planted in the wetland. In the experimental set-up, the continuous feeding method was applied with an overflow pipe connected such that a constant hydraulic head was maintained throughout. To ensure uniform wastewater distribution to the wetland units and out of the wetland, the flow was regulated. This regulation was achieved by use of ½ inch gate valves which were fitted to the flow distribution pipe and the outlet of the wetland as shown in Figure 2.

Evaluating the performance of the system

The wetland system was evaluated based on its treatment performance. Flows throughout the system were regulated to control the loading rate. The change of flow rate helped in establishing optimal HLR required for the treatment of all the pollutants. Samples were collected at the influent and effluent of the constructed wetland system and were then analysed for physico-chemical, nutrient and biological parameters. The results were compared with the standards set by National Environment Management Authority (NEMA) (Kenya Gazette Supplement No. 86 2006).

Sample collection and analysis

Sampling was carried out weekly for a period of 6 months. Plastic bottles of 500 ml were used for sample collection.

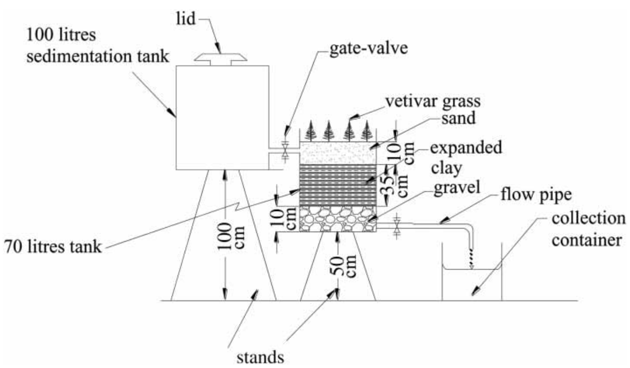

Figure 2 | The pilot vertical flow constructed wetlands system set-up (units of measurements in centimeters, cm).

The sampling bottles were pre-treated by washing them in dilute hydrochloric acid and then rinsing thoroughly with distilled water. The bottles were then autoclaved since samples were to be analysed for microbial contamination. The bottles were rinsed three times with the relevant samples of water and then filled with the samples and in-situ parameters analysed. In-situ parameters analysed during sample collection were: dissolved oxygen (DO; mg/L), pH, temperature °C, salinity g/L, total dissolved solids (TDS; mg/L), and electrical conductivity (EC; μs/cm). All these constituent parameters were measured using appropriate standard meters. The DO, pH and temperature were measured using a HQ40d dual input, multi parameter digital meter (Hach Company) with pHC101 and LDO101 probes, and TDS, EC and salinity were measured using a EC300 meter (VWR International).

Laboratory analysis

The laboratory nutrient analysis included: nitrate nitrogen (NO_3-N; mg/L), nitrite nitrogen (NO_2-N; mg/L), total phosphorus (TP; mg/L), soluble reactive phosphorus (SRP; mg/L) and ammonium nitrogen (NH_4-N; mg/L). In addition, BOD_5 (mg/L), and total suspended solids (TSS) mg/L were determined. The thermotolerant coliform was analysed using the most probable number (MPN) method within 2 hours after sampling.

The collected sample was divided in two: the portion used for SRP, NO_3-N, NO_2-N and NH_4-N was filtered using Whatmann GFC filters (diameter: 47 mm; pore opening: 0.45 μm). The filter was first pre-combusted and weighed. A known volume of water sample was filtered and the filter dried. After drying, the filter was weighed and the TSS calculated using Equation (4) given in APHA (1995). The filter was then combusted at 500 °C for 4 hours and weighed again in order to calculate the volatile and fixed content of TSS (APHA 1995).

$$TSS = \frac{(Wc - Wf) \cdot 10^6}{V} \tag{4}$$

where TSS = total suspended solids (mg/L); Wc = weight of empty filter and residue (g); Wf = weight of empty filter (g); V = volume of the sample filtered (ml).

Total phosphorus was analysed using the unfiltered sample. The sample was first digested and reduced to free ortho-phosphate form using the persulphate digestion for 90 minutes at 121 °C. After reduction, it was then analysed using the ascorbic acid method as recommended in APHA (1995). This method was also used in SRP analysis where the filtered sample was used. The NH_4-N was determined using the reaction between sodium salicylate and hypochloride solution while NO_3-N was determined using the sodium salicylate method (APHA 1995). Standard solutions of the nitrate were prepared and used for the standard calibration curve. The NO_2-N was determined using the reaction between sulfanilamide and N-naphthyl–ethylendiamin-dihydrochloride which gave an intense pink colour with the presence of nitrite. Nutrient concentrations were determined using a 4053 Ultrospec K Spectral Photometer (LKB) by reading the light absorbance at specified wavelengths for the given nutrient parameter.

The BOD_5 was determined using the Winkler method. The DO of the diluted sample was measured before and after incubation for a period of 5 days thus determining BOD_5 of the samples. The measurement of BOD was carried out in 'dark flasks' to prevent exposure of the sample to light thus inhibiting primary production by phytoplankton, which would have generated oxygen. The BOD_5 was then calculated using Equation (5) as given in Wetzel & Likens (1991):

$$BOD_5 = \frac{D_1 - D_2}{P} \tag{5}$$

where D_1 = DO of diluted sample immediately after preparation (mg/L); D_2 = DO of diluted sample after 5 days incubation (mg/L); P = decimal in volumetric fraction of sample used.

Microbial parameters

The presence of thermotolerant coliforms in samples was analysed within 2 hours after sampling using the MPN method. This regime aided in determining the sanitary quality of the water samples. The samples were diluted up to 0.01. Autoclaved multiple tubes that had 5 ml of medium A-1 were used and 1 ml sample was added and incubated at

44 °C for 24 hours. The numbers of positive tubes (with gas production) were then counted and MPN of thermotolerant coliforms per 100 ml of sample was determined (APHA 1995).

RESULTS AND DISCUSSION

Pilot system set-up

The means of BOD_5 concentration of influent and effluent used in plug flow model were 240.49 mg/L and 23.00 mg/L respectively. The hydraulic retention time calculated using the plug flow model was found to be 2 days for Egerton University and Nakuru (Kaloleni) wastewater polishing. The K_T value used in the calculation was 1.12/day, and mean temperature of the wastewater was found to be 20.22 °C. The HLRs applied were 1.4, 2.9, 4.3, 8.7 and 17.4 cm/day which corresponded with retention times of 6, 3, 2, 1 and 0.5 days. The calculated HLR was found to be within the two ranges for vertical sub-surface flow constructed wetland values given respectively by Kadlec & Knight (1996) and Wood (1995) as 8–30 cm/day and 0.2–3 cm/day. The calculated depth of water in the wetland had a range of 35–52 cm. This value was within the recommended depth of water in sub-surface flow CWs by Reed *et al*. (1995) of 30–60 cm. This depth of water facilitated flow within the wetland system by providing sufficient head.

Water balance

The results from water balance calculation indicated that hydraulic and pollutant overload was not recorded throughout the study period. The calculated average change of water volume with time in the CW was 0.0113 m^3/day and an average ET of 0.025 m/day. The low value of ET implies that the concentration of the pollutants was not highly influenced by evapotranspiration.

Performance of the system at different HLRs

The reduction of contaminants that is reported in the wetland systems relies on physical, chemical and biological processes. The efficiency of these processes is affected by the loading rate of wastewater through the wetland systems. The loading rate is affected by the retention time of wastewater within the system. This factor is a function of the porosity of the substrate used. The lower the HLR, the longer the wastewater remains in the wetland (Reed *et al.* 1995). This situation increases the chances of sedimentation, absorption, biotic processing and retention of the nutrients. In this study, the results showed that the physico-chemical parameters did not vary widely about the mean for the different HLRs operated (Table 1). Total suspended solids and BOD_5 decreased as the wastewater passed through the system (Table 1). This situation could be as a result of sedimentation and filtration processes taking place in constructed wetland. Biochemical oxygen demand could have decreased due to microbial uptake of organic matter. However, there was a remarkable decrease in pollutant concentration of TP, SRP and NH_4-N in all the HLRs applied (Table 2).

The NO_3-N concentration, within the CW was found to increase at all HLRs operated (Table 2). The concentration of this nutrient varied with the concentration of oxygen in the effluent from the system. The transfer of oxygen from the atmosphere to the root zone could be a factor causing the increase of NO_3-N tested in the effluent of the CW. This finding was an indication that vetiver grass used as a wetland plant in this system was active in oxygen transmission to the root zone and resulting in aerobic conditions existing. Increase of NO_3-N nutrient was proportional to the DO in the system.

The flow rates used included; 0.012, 0.024, 0.036, 0.072 and 0.144 m^3/day which corresponded with retention time

Table 1 | Means ± standard error of physico-chemical and microbial parameters for influent and effluent from the constructed wetland system

Parameters	Influent	Effluent
Electrical conductivity (μs/cm)	0.68 ± 0.01	0.57 ± 0.01
Total dissolved solids (mg/L)	480.21 ± 6.35	404.46 ± 5.85
pH	7.9 ± 0.06	7.17 ± 0.04
Salinity	0.37 ± 0.01	0.30 ± 0.01
Temperature (°C)	19.5 ± 0.2	19.7 ± 0.2
Total suspended solids (mg/L)	66.86 ± 4.17	15.97 ± 1.24
Dissolved oxygen (mg/L)	5.69 ± 0.4	5.78 ± 0.19
BOD_5 (mg/L)	158.39 ± 16.11	9.75 ± 1.28
Coliform (MPN/100 ml)	1,756 ± 60	109 ± 27

Table 2 | Removal efficiencies (%) in the constructed wetland system for different hydraulic loading rates

	Hydraulic loading rates (cm/day)				
Parameter (mg/L)	**1.4**	**2.9**	**4.3**	**8.7**	**17.4**
Total phosphorus	91.59	89.38	84.27	75.79	47.16
Soluble reactive phosphorus	92.63	91.73	86.14	78.42	52.79
NH_4-N	95.37	95.41	98.61	99.25	97.81
NO_3-N	−97.62	−98.23	−96.70	−10	−96.43
NO_2-N	12.85	21.40	47.68	53.90	−45.26

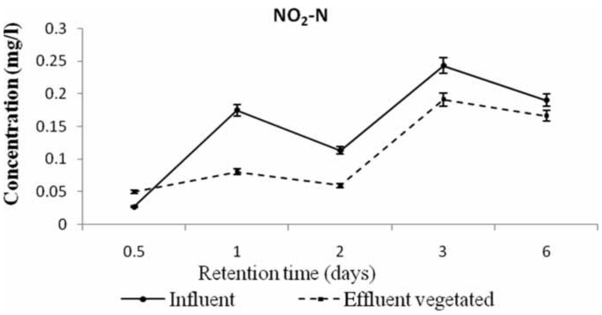

Figure 4 | NO_2-N concentration for the influent and effluent from the system at different retention times.

of 6, 3, 2, 1 and 0.5 days and HLRs of 1.4, 2.9, 4.3, 8.7 and 17.4 cm/day respectively. The NO_3-N in the influent increased as the wastewater passed through the wetland system (Figure 3).

For NO_3-N the highest percentage increase in the CW was at the flow rate of 0.024 m^3/day (retention time = 3 days) at a value of 98.23% and lowest percentage increase at flow rate of 0.072 m^3/day (retention time = 1 day) at a value of 10.0% (Table 2). Effluent from the CW showed a slight decrease in NO_2-N at retention time of 6, 3, 2 and 1 days, while an increase in NO_2-N was observed at retention time of 0.5 days (Figure 4). Dissolved oxygen at HLR of 17.4 cm/day (retention time of 0.5 days) was lower than the other HLRs; as a result the conversion of NO_2-N to NO_3-N did reach completion leading to an increase of NO_2-N (Table 2).

The decrease was at 12.85, 21.40, 47.68 and 53.90% respectively while the percentage increase for NO_2-N was 45.26% (Table 2). However, the effluent concentrations of NO_2-N and NO_3-N in all HLRs operated were below the NEMA discharge standards of 2 and 50 mg/L, respectively. The increase of NO_2-N and NO_3-N concentrations in relation to the influent concentrations indicate that NH_4-N was probably converted through nitrification to NO_2-N and NO_3-N after passing through the substrate layer. In this study, the rise in NO_2-N and NO_3-N loading in the effluent wastewater compared to the influent wastewater was a manifestation of an active system nitrification. This finding was in agreement with an increase of NO_2-N and NO_3-N in wetland effluent as reported by Kyambadde *et al.* (2005) for a study conducted in Uganda.

In the wetlands, nitrification occurs in aerobic regions of the water column, soil–water interface, and root zone (Atitaya *et al.* 2008). The oxygen required for the nitrification process is supplied by diffusion from the atmosphere and release by macrophyte roots. The results of this study showed a reduction of NH_4-N in effluent from the CW system (Figure 5).

With regard to nitrification, the results indicate that approximately 97% of NH_4-N concentration was reduced in the constructed wetland system (Table 2). As loading rate was increased, higher concentration of ammonium in the effluent was recorded. This situation could be attributed to reduced DO levels within the system which led to reduced nitrification processes taking place. The decrease in NH_4-N concentration in the effluent suggests that CW systems are effective in reduction of NH_4-N. It was noted that under all HLRs applied, NH_4-N concentration of the effluent was lower than the recommended discharge standard by NEMA of 1 mg/L.

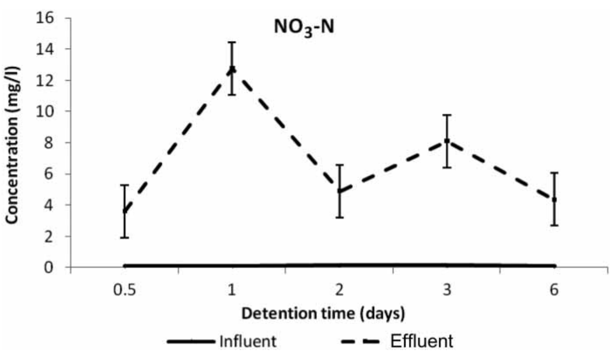

Figure 3 | Concentration of NO_3-N at different retention times (vertical bars: standard error).

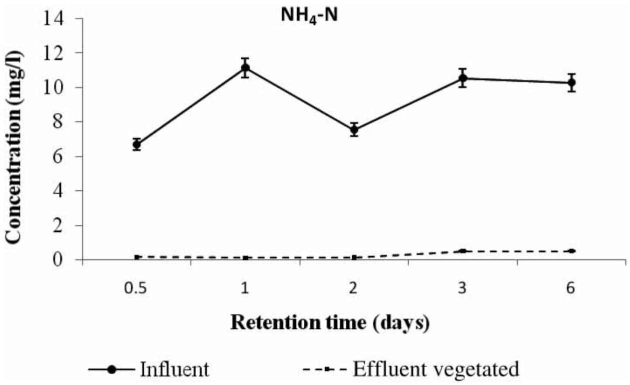

Figure 5 | Concentration of NH_4-N for the influent and effluent from the system at different retention times.

As retention time was reduced, the TP concentration increased. This finding could have been as a result of reduced contact time with the substrate and also time for plant uptake of the pollutants. Vetiver grass could have played a role in the reduction of the nutrients through filtration of nutrients and sediments by the plants. The TP and SRP effluent concentration did not meet the NEMA discharge standards of 2 and 1 mg/L respectively at higher HLRs of 17.4 and 8.7 cm/day (retention time of 0.5 and 1 days) (Figures 6 and 7).

As the loading rates decreased (i.e. increase of retention time) higher removal efficiencies were recorded. This finding could be attributed to increased contact time of the wastewater with the substrate. Generally, phosphate retention in the CWs depends upon the composition of the wastewater, loading rate, type of root medium and the type of substrate used (Brix *et al.* 1998). The most important removal mechanisms are chemical precipitation and physico-chemical sorption, processes that are not temperature

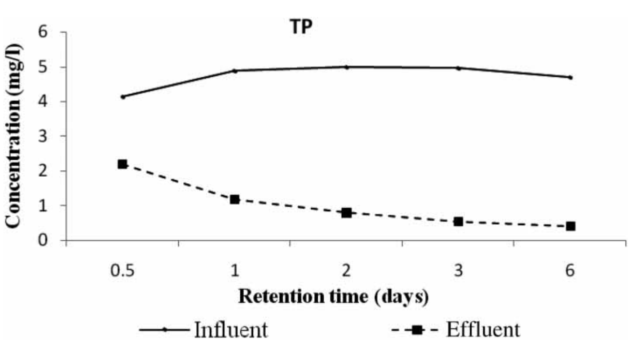

Figure 6 | Concentration of TP for the influent and effluent from the system at different retention times.

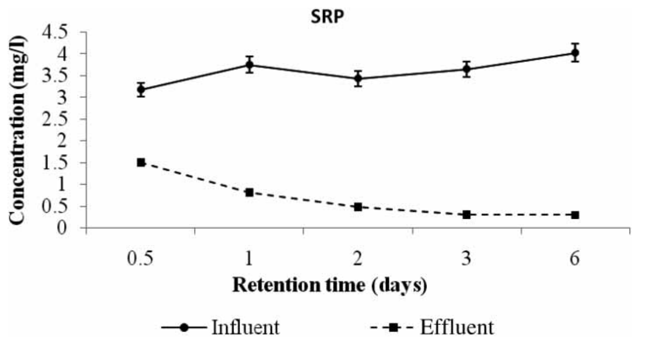

Figure 7 | SRP concentration in influent and effluent of the system at different retention times.

dependent. Phosphate removal could have been mainly due to retention by the filter bed material since expanded clay used as the main substrate layer could have encouraged redox conditions (Ulimaier *et al.* 2009). Also the periphyton, i.e. the biofilm formed of organisms and their remains onto the CW soil and macrophytes, could have enhanced phosphorus retention. According to Dodds (2003), periphyton plays several roles in reduction of phosphorus from the water column, including phosphorus uptake and deposition, filtering particulate phosphorus from the water and increasing oxygen concentrations near the sediment surface, thus encouraging the adsorption of dissolved phosphorus. A study by Mclatchey & Reddy (1998) showed that organic matter turn-over and nutrient cycling are strongly correlated with electron acceptor availability and redox conditions in wetland soils. The characteristics of the media type used in this study, i.e. expanded clay could have contained higher amounts of Ca, Al and Fe oxides, which were inferred to be a factor causing such high removal of phosphorus by adsorption. Therefore expanded clay can be used effectively as a media, alone or in combination with other materials in CWs.

The results further showed a significant reduction in thermotolerant coliforms concentration at all the HLRs applied. The effluent from the wetland system had thermotolerant coliform concentration of 109 ± 27 MPN/100 ml (Table 1). Wetlands are effective in pathogen removal, since they allow a variety of micro-organisms to grow which may be predatory on bacterial pathogens (Reed *et al.* 1995; Kadlec & Knight 1996). The processes that may contribute to the removal of coliform pathogens in wetlands include pH changes, natural die-off, sedimentation, filtration, ultra-violet light ionization, temperature effects and predation by other organisms (Kadlec & Knight 1996). The concentration of the pathogens in the effluent from the CWs system in this study was found to meet the NEMA discharge guidelines of 400 MPN/100 ml.

CONCLUSIONS

The constructed wetland reduced nutrients and microbial pollutants in the influent and the reduction was varying with different HLRs applied. At low loading rates, a higher removal efficiency of pollutants was recorded while the reduction deteriorated with an increase of HLR. The HLRs ranged between 0.014 and 0.174 m/day and the removal efficiency of TP, SRP and NH_4-N ranged between 97 and 47%. In all the HLRs applied, the effluent concentration of coliform in the CW was lower than the recommended effluent discharge standards of 400 MPN/100 ml by NEMA. NO_3-N was found to increase at all HLRs and the increase was proportional to the amount of DO available. Despite the increase of the nutrient the effluent concentration of NO_3-N at all HLRs met the NEMA discharge standard. NO_2-N increased at high HLRs while there was a decrease of the nutrient at low loading rate. In this study vetiver grass was found to be effective in transfer of oxygen to the root zone of the wetland, and as a result the nitrification process was encouraged leading to increase of NO_3-N and high removal efficiency of NH_4-N. A retention time of 2 days at HLR of 4.3 cm/day was found to be effective for polishing of effluent from Egerton and Nakuru Kaloleni WSPs.

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