Turkish J. Eng. Env. Sci.
28 (2004) , 333 – 344.

Treatment Efficiencies of the Vertical Flow Pilot-Scale Constructed Wetlands for Domestic Wastewater Treatment

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Received 24.06.2004

Abstract

To foster the practical development of the constructed wetlands used for water quality enhancement in Turkey, 2 vertical subsurface flow pilot-scale constructed wetlands were implemented on the METU campus, Ankara, Turkey. Both of the wetlands were planted with *Phragmites australis* and operated identically at a flowrate of 3 $m^3.d^{-1}$ and a hydraulic loading rate (HLR) of 0.100 $m.d^{-1}$, intermittently. The main objective of the research was to quantify the effect of different substrates (gravel and blast furnace granulated slag) on the nutrient removal performance of the constructed wetlands in the prevailing climate of Ankara. According to the monitoring study (July 2002-January 2003), concentration based average removal efficiencies for the slag and gravel reed beds were as follows: TSS (64% and 62%), COD (49% and 40%), NH_4^+-N (88% and 58%), TN (41% and 44%), TP (63% and 9%) and PO_4^{3-}-P (60% and 4%). In general, the treatment performance of the slag system was better than that of the gravel system.

Key words: Vertical flow constructed wetland, Domestic wastewater treatment, Nutrient removal, Blast furnace granulated slag.

Introduction

Since the 1950s, constructed wetlands with different configurations, scales and designs have been used effectively worldwide for the treatment of municipal, industrial and agricultural wastewater, as well as storm water. This is due to their high nutrient capturing capacity; simplicity; low construction; operation and maintenance costs; low energy demand, process stability; low excess sludge production; effectiveness and potential for creating biodiversity. The most widespreadly used constructed wetland configurations are the free water surface wetlands (like pond systems) and subsurface flow wetlands (like filters), where the water does not have a free water surface. (Moshiri, 1993; Cooper *et al.*, 1996; Kadlec and Knight, 1996; Vymazal *et al.*, 1998; Haberl, 1999).

Nowadays, vertical flow subsurface constructed wetlands with intermittent feeding are state of the art in Europe due to their advantages over the other designs. Vertical flow constructed wetlands have more equal root distribution and water-root contact and fewer problems of bad odor and proliferation of insects since they do not have a free water surface (Haberl *et al.*, 1995; Cooper, 1999). Even though vertical flow constructed wetlands have been mainly used for the removal of carbonaceous oxygen demand, total suspended solids and coliform bacteria, there is growing interest in their use for nitrogen and phosphorus removal. In constructed wetlands, where aerobic and anaerobic environments are created, microbial degradation is the most important mechanism for nitrification and denitrification, whereas the adsorption of phosphorus to the substratum is an important mechanism for phosphorous removal (IWA, 2000). For such processes, substrates (fill media in constructed wetlands) have been also suggested as being very significant. In order to improve the P-retention of constructed wetlands, substrates with higher P-adsorption capacities; higher Ca, Fe and Al contents; larger particle surface areas and suitable hydraulic conductivity were commonly used (Vymazal *et al.*, 1998). Hence, wetland researchers have started to use industrial by-products like light weight aggregates (LWA, LECA, etc.) and waste materials from industries, as well as natural materials with higher adsorption capacities (Johanson, 1996; Brooks *et al.*, 2000; Zhu *et al.*, 2002).

Being low-cost and low-technology systems, constructed wetlands are potential alternative or supplementary systems for wastewater treatment in small communities. To date, however, there have been no full-scale constructed wetland applications for wastewater treatment in Turkey. In this context, to ascertain whether the constructed wetlands could be implemented in Ankara 2 parallel sets of the vertical subsurface flow pilot-scale constructed wetlands with identical design configuration were implemented on the campus of the Middle East Technical University (METU), Ankara. In these wetlands, the aim was secondary treatment of domestic wastewater (Korkusuz *et al.*, 2001). Each of the vertical flow wetland cell had an area of 30 m^2 and a filter medium depth of 60 cm. In one of the wetlands the filter medium was composed of different sizes of sand and gravel, whereas the other was composed of sand, gravel and blast furnace granulated iron slag provided by the Kardemir Iron and Steel Co. In order to quantify the effect of the filter media on the treatment performances of the constructed wetlands, a monitoring study has been conducted. In this paper, influent and effluent concentrations of the pollutants (organics and nutrients) monitored between July 2002 and January 2003, as well as the calculated removal efficiencies of the above-mentioned wetlands are presented and compared to each other and to the relavant literature.

Materials and Methods

Design of the constructed wetlands of METU and the operational scheme

In 2001, 2 vertical subsurface flow constructed wetlands with dimensions of 4.5 m x 6.5 m x 0.60 m (W x L x D) and a surface area of 30 m^2 each were implemented at the abandoned wastewater treatment plant at METU (Korkusuz *et al.*, 2001). The bottoms of the wetlands were sealed using a liner. A slope of 1% was created at the bottom of the wetlands to allow easier water collection. One of these wetlands was first filled with gravel (15 cm of 15-30 mm and 30 cm of 7-15 mm) from the bottom to the top and then with sand (15 cm of 0-3 mm); whereas the other one was first filled with gravel (15 cm of 15-30 mm) and then with sieved blast furnace granulated slag (30 cm of 0-3 mm), and finally with sand (15 cm of 0-3 mm) at the top layer.

Constructed wetlands were planted with the shoots of the *Phragmites australis*, which were transferred from the natural reed beds on the campus and transplanted at a density of 9 seedlings.m^{-2}, in May 2002. Using a submersible pump, the raw domestic wastewater was diverted from the nearest manhole to both of the primary sedimentation tanks (3 m^3 each) once a day. The wastewater that was kept in these tanks for 2-3 h for primary treatment was diverted to the wetland cells via perforated PVC pipes once a day yielding an HLR of 0.100 m.d^{-1} (Korkusuz *et al.*, 2002). Wetlands constructed at METU serve 60 persons if the wastewater produced per capita is assumed to be 100 l.d^{-1}. The treated wastewater was used for irrigation of the plants on the field.

Water quality monitoring studies and analysis methods

Influent and effluent water samples of the pilot-scale constructed wetlands have been taken periodically to evaluate the treatment performances of the wetlands since 2002 July. The characterization of the raw domestic wastewater and primarily treated wastewater was conducted 3 times before starting to operate the wetlands constructed at METU. Water samples were taken and brought to the Chemistry Laboratory of the Department of Environmental Engineering at METU in 15 min. The conductivity and temperature of the water samples were measured with a conductivity meter (ORION Model 115, precision ±1%) and the pH with a probe (EMAF EM78X).

On the same day, the analysis for chemical oxygen demand (COD) (using a HACH p/N 45600-02 spectrophotometer) (range: 0-1500 mgl^{-1}), total suspended solids (TSS), total phosphorus (TP), ortho-phosphate phosphorus (PO_4^{3-}-P), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), and total nitrogen (TN) were performed according to the

Standard Methods (AWWA, 1999). If the analyses could not be performed on the same day, the water samples were stored at +4 °C without adding chemicals for 1 day. For each of the parameters, samples were analyzed in duplicate. The meteorological daily average data (air temperature, precipitation and evaporation) were provided from the nearest meteorological station of the General Directorate of Rural Services, Ankara.

Statistical analysis

To determine whether the treatment performances of the slag system and gravel system were statistically different, one-way ANOVA at a significance level of 0.05 was applied to the removal efficiencies calculated from the data from a monitoring period from July 2002 to January 2003 for each of the water quality parameters. These analyses were conducted by using a sub-program of Microsoft Office Software EXCEL XP.

Results and Discussion

Characterization of the domestic wastewater applied to the wetlands constructed at METU

The characteristics of the domestic wastewater applied to the constructed wetlands in some countries have been summarized from the literature and are presented in Table 1. The raw domestic wastewater of METU (taken directly from the manhole) was also characterized and these data are also given in Table 1.

Since the raw domestic wastewater was kept in the sedimentation tanks for 2-3 h, the wastewater was applied to the wetland cells without creating any anaerobic conditions. As expected theoretically, TSS concentrations were reduced almost by half after primary treatment, and BOD_5 and COD concentrations were reduced about 15% and 30%, respectively. The PO_4^{3-}-P and TP concentration values of the primarily treated wastewater increased by small amounts. This increase may be explained by the conversion of the long-chained polyphosphates to short-chained phosphates during the sedimentation phase. Ammonium-nitrogen, nitrate-nitrogen and total nitrogen concentrations did not change significantly due to the prevailing aerobic conditions in the sedimentation tanks.

When the values in Table 1 were considered the average concentrations of the pollutants of the METU raw domestic wastewater were generally lower than those of the literature values given by Vymazal *et al.* (1998) but similar to the typical values for domestic wastewater given by Tchobanoglous

Table 1. Characteristics of the domestic wastewater applied to the Constructed Wetlands.

References	Parameters (mg.l^{-1})							
	BOD_5	COD	COD:BOD_5	TSS	TP	NH_4^+N	NO_3^--N	TN
Germany[1]	248	430	1.73	-	15.90	80.50	1.90	115.0
France[1]	215	495	2.30	225.0	8.50	25.00	2.85	46.0
Nepal[2]	110	325	2.95	83.0	-	33.00	-	-
Poland[3]	110	283	2.57	140.0	7.65	-	-	46.1
Slovenia[3]	107	200	1.87	-	-	28.70	-	-
Germany-Bavaria[3]	106	234	2.21	-	-	-	-	-
Denmark and UK[3]	97	264	2.72	98.6	8.60	21.00	-	36.6
Czech Republic[3]	87.2	211	2.42	64.8	6.57	28.10	-	46.4
North America[3]	27.5	-	-	48.2	4.41	5.98	-	18.9
Sweden[3]	80.5	-	-	-	5.03	-	-	25.3
Belgium[1]	54	168	3.11	60.0	4.60	-	-	16.9
Typical Domestic Wastewater Values[4]	220	250	1.14	100.0	8.00	25.00	0.00	40.0
This Study (Raw Wastewater)	65	280	4.30	102.0	6.14	24.00	0.60	34.7

References: [1]Vymazal *et al.*, 1998; [2]Shreshta *et al.*, 2000; [3]Vymazal *et al.*, 2000; [4] Tchobanoglous and Burton, 1991.

and Burton (1991). However, the BOD_5 value of the METU wastewater (65 ± 30 mg.l^{-1}) was comparably lower than the typical BOD_5 values for raw domestic wastewater. Moreover, the COD:BOD_5 ratio of the METU wastewater was about 4.3, which was very much higher than the literature value of 1.14 (Tchobanoglous and Burton, 1991). Thus it may be concluded that the METU domestic wastewater had low biodegradability. These differences could have arisen from the dilution of the wastewater by precipitation (METU has a combined sewer system) and the water and detergent usage habits of the METU residents.

The effect of the water budget on the pollutant concentrations of the wetlands constructed at METU

The inflow and outflow concentrations of the organics and nutrients to be treated in the constructed wetlands are affected by additional water inputs and outputs (precipitation, evapotranspiration, groundwater infiltration etc.) in addition to the fluctuations in the wastewater (IWA, 2000). Precipitation dilutes the pollutant concentrations within the wetland so that the measured effluent values are lower than the actual values. In contrast, evaporation and evapotranspiration concentrate the pollutant concentrations in the wetlands due to the decrease in the water levels so that the measured effluent values are higher than actual values. Thus, daily average outflow discharges were calculated by adding the difference of the evaporation and rain values multiplied by 30 m^2 to the daily measured inflow values of 3 m^3.d^{-1}. The correction factors were calculated by dividing the calculated outflow values by the measured daily inflow values. According to the correction factors of this study, the measured outflow concentrations can vary within a range of ±10%. However, as the treatment performances of most of the treatment wetlands have not been presented in the literature, considering these correction factors (IWA, 2000), the outflow concentrations of this study have also been presented without any corrections.

The treatment performances of the wetlands constructed at METU

The results of the monitoring study (July 2002-January 2003) are presented graphically in Figures 1-7 for both the gravel and slag systems. In these figures, sampling date versus influent and effluent concentrations (with their standard deviations) of TSS, COD, NH_4^+-N, NO_3^--N, TN, PO_4^{3-}-P and TP are illustrated. Throughout the monitoring period, the minimum and maximum concentrations of the water parameters of the primarily treated domestic wastewater (influent) were as follows: TSS 24-140 mg.l^{-1} (Figure 1); COD 108-398 mg.l^{-1} (Figure 2); NH_4^+-N 15-38 mg.l^{-1} (Figure 3); NO_3^--N 0-3 mg.l^{-1} (Figure 4); TN 20-50 mg.l^{-1} (Figure 5); PO_4^{3-}-P 3-8 mg.l^{-1} (Figure 6); and TP 4-9 mg.l^{-1} (Figure 7).

The fluctuations in the influent concentrations reflected the hourly, daily, seasonal and periodical variations of the raw wastewater received by the manhole, from where the wastewater to be treated was diverted. Since the sewerage system of METU also received the surface runoff, the concentrations of some of the wastewater parameters changed in rainy seasons. Especially during the heavy rainy days in autumn (2-17 September 2002 and 14-15 October 2002) and snow melt in winter, the influent concentrations of TSS (Figure 1), PO_4^{3-}-P (Figure 6) and TP (Figure 7) showed increases due to the additional inorganics carried by the surface runoff, whereas the nitrogen concentrations (Figures 3-5) of wastewater decreased because of dilution by the rain water.

As a result of the end of the summer holiday at METU, academics and students came back to their homes and dormitories in September-October 2002. They used detergents in large quantities for cleaning purposes, and produced more sanitary wastewater compared to in the summer season. This in turn resulted in steep increases, especially in NH_4^+-N, TN, PO_4^{3-}-P and TP concentration values (Figures 3-7). Moreover, COD influent concentrations (Figure 2) were affected by the increase in the amount of organic pollutants and carbons from detergents. Thus, COD influent values showed parallel changes to the changes in suspended solids and phosphorus concentrations.

Generally, effluent pollutant concentrations of both the slag and gravel systems fluctuated similarly to the influent concentrations (Figures 1-7). For the monitoring period of July 2002-July 2003, for each water quality parameter, the average concentrations (mg.l^{-1}) ±standard deviations (mg.l^{-1}) as well as the pH and conductivity values were summarized in Table 2. The average removal efficiencies (%) ± standard deviation (%) of the water quality parameters were calculated using the influent and effluent concentration values (mg.l^{-1}) of the slag and gravel systems and are presented in Table 3. Moreover, to differentiate statistically which wetland cell was more efficient, one-way ANOVA analysis was conducted and this is also summarized in Table 3. When the probability values (P) obtained in factor analysis were greater than 0.1, this indicated that the compared groups did not differ from each other statistically.

Total Suspended Solids (TSS) removal

Suspended solids effluent concentrations of the slag and gravel systems of METU (Figure 1) varied between 6 and 50 mg.l^{-1} and 4 and 81 mg.l^{-1}, respectively. During the start-up period of these wetlands, even though the effluent TSS concentrations were very low (<10 mg.l^{-1}); as time passed, the TSS effluent values increased. This could be explained by clogging of the voids in the wetland cells, seasonal variations and heavy rains (IWA, 2000). As stated by Börner *et al.*, 1998, the solids in the effluent of the wetlands are parts of the non-trapped influent solids, the surplus sludge and plant litter solids in the process of mineralization. A 3-year-old constructed wetland planted with emergent plants and having an extensive root system can enhance the TSS removal efficiency by providing a larger surface area, reducing the water velocity and reinforcing settling and filtration in the root network (Brix, 1997). Since the METU wetlands have been operated for 1 year, the

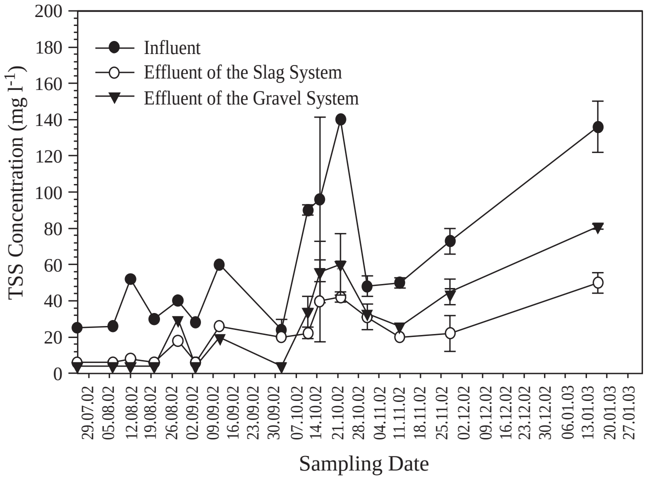

Figure 1. Influent and effluent TSS values (mg.l^{-1}) of the Constructed Wetlands of METU.

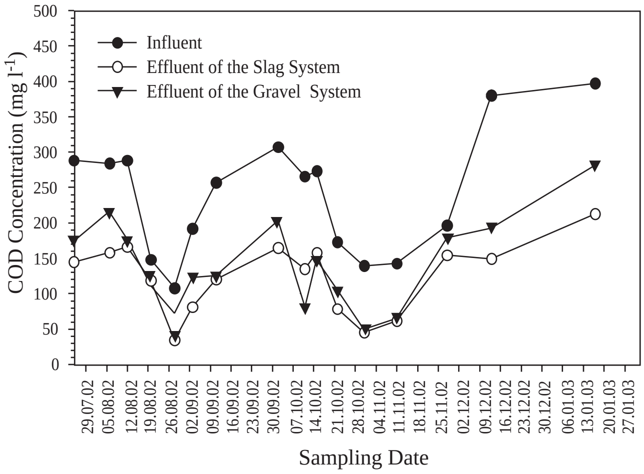

Figure 2. Influent and effluent COD values (mg.l^{-1}) of the Constructed Wetlands of METU.

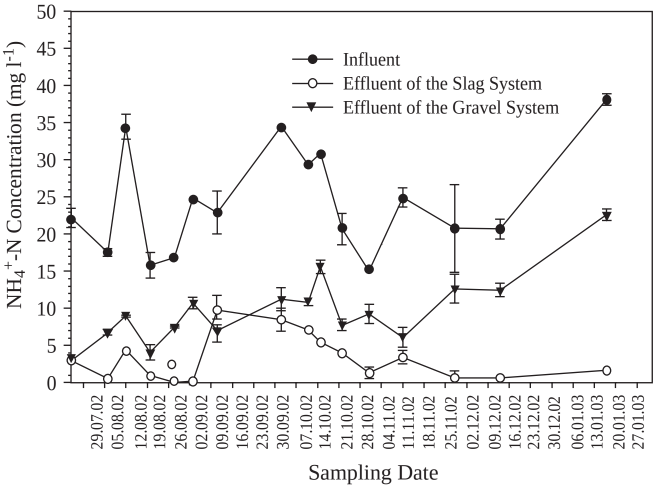

Figure 3. Influent and effluent NH_4^+-N values (mg.l^{-1}) of the Constructed Wetlands of METU.

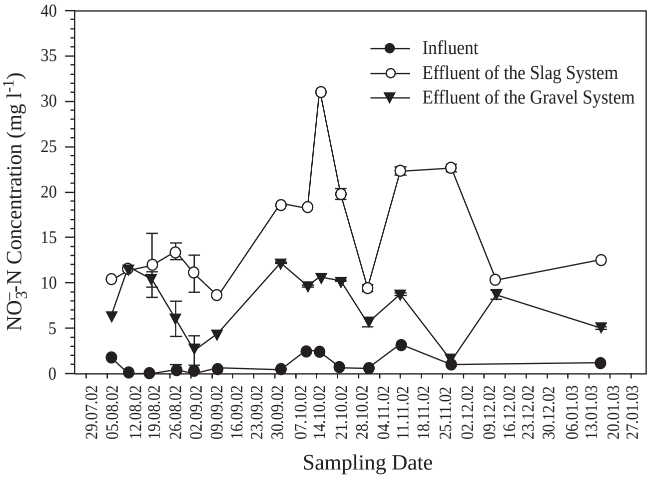

Figure 4. Influent and effluent NO_3^--N values (mg.l^{-1}) of the Constructed Wetlands of METU.

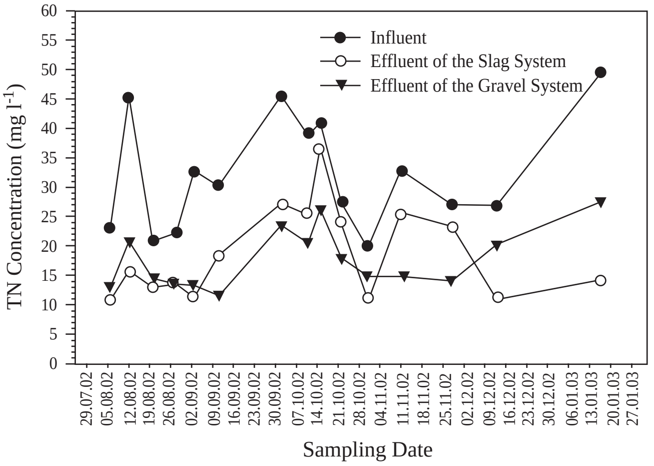

Figure 5. Influent and effluent TN values (mg.l^{-1}) of the Constructed Wetlands of METU.

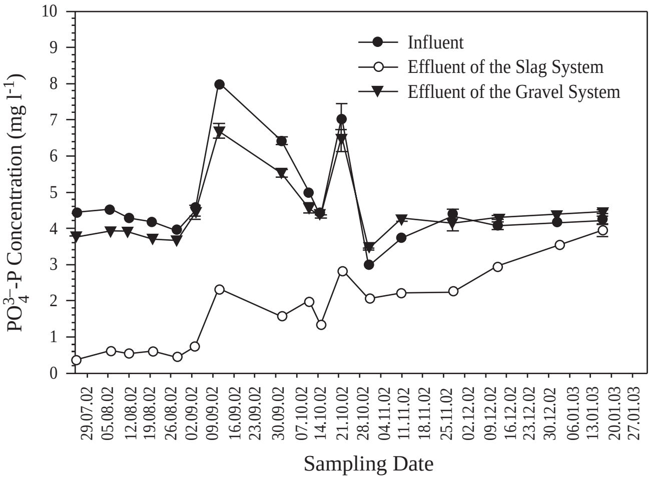

Figure 6. Influent and effluent PO_4^{-3}-P values (mg.l^{-1}) of the Constructed Wetlands of METU.

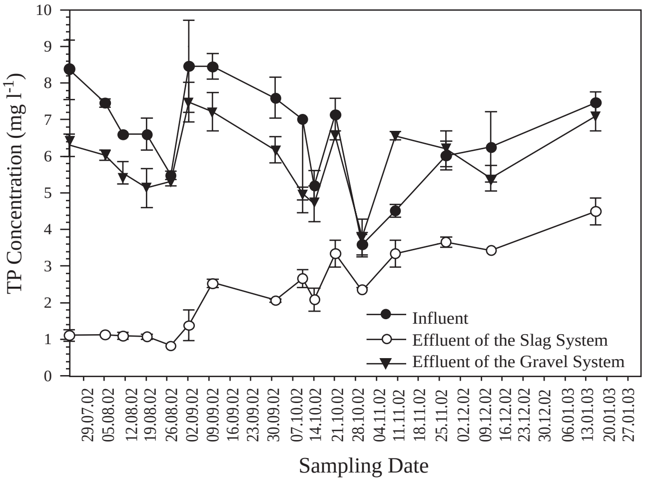

Figure 7. Influent and effluent TP values (mg.l^{-1}) of the Constructed Wetlands of METU.

Table 2. Influent and effluent concentrations of the wetlands constructed at METU.

Parameters	Presettled Domestic Wastewater	Effluent of Slag System	Effluent of Gravel System
TSS*	54.19 ± 36.83	19.71 ± 14.30	24.53 ± 24.29
COD*	243.15 ± 80.64	126.07 ± 49.38	144.06 ± 63.61
PO_4^{3-}-P*	4.56 ± 1.27	1.58 ± 1.12	4.48 ± 0.97
TP*	6.74 ± 1.43	2.16 ± 1.20	5.90 ± 1.00
NH_4^+-N*	24.87 ± 6.86	3.33 ± 3.03	9.79 ± 4.72
NO_3^--N*	1.20 ± 0.98	13.85 ± 7.59	7.20 ± 3.58
TN*	32.22 ± 9.72	18.71 ± 7.89	17.74 ± 5.12
pH	7.58 ± 0.28	7.78 ± 0.37	7.51 ± 0.38
Conductivity **	1074 ± 50.0	1110 ± 65	1061 ± 65

* Concentration values are given as averages (mg.l^{-1}) ± standard deviation (mg.l^{-1}).

** Unit: Microsiemens (μS).

Table 3. Removal efficiencies (%) of the wetlands constructed at METU.

Parameters	Slag System*	Gravel System*	1-factor ANOVA ($F_{0.95}$(dF;dN))**
TSS	63.80 ± 18.23	61.83 ± 23.20	$F_{0.95}(1;54) = 0.0328$; $P = 0.8568$
COD	48.78 ± 13.56	40.08 ± 15.49	$F_{0.95}(1;62) = 0.8219$; $P = 0.368$
PO_4^{3-}-P	59.87 ± 28.30	4.19 ± 10.15	$F_{0.95}(1;58) = 135.142$; $P < 0.0001$
TP	63.20 ± 21.01	8.82 ± 17.32	$F_{0.95}(1;58) = 119.46$; $P < 0.001$
NH_4^+-N	87.72 ± 11.80	57.86 ± 13.48	$F_{0.95}(1;58) = 69.24$; $P < 0.0001$
TN	40.72 ± 19.91	43.51 ± 11.69	$F_{0.95}(1;58) = 0.193$; $P = 0.661$

*Average removal efficiency (%) ± standard deviation (%);

** $F_{0.95}$ = 95% confidence limit; dF = degree of freedom; dN = sample size; $P > 0.1$ nonsignificant

observed average TSS removal efficiencies (60%) of the slag and gravel systems (Table 3) may mostly be related to the processes of sedimentation, filtration, bacterial decomposition and adsorption to the wetland media (Stowell *et al.*, 1981).

In the course of time, the accumulation of trapped suspended solids can clog the wetland filtrate and reduce the hydraulic conductivity of the media, and these may result in surface overflow (Reed and Brown, 1995). However, during the operation period, no surface overflow was observed in either of the wetlands of METU. According to ANOVA analysis (Table 3), TSS treatment performances of identically operated slag and gravel systems did not differ significantly statistically ($P > 0.1$). Therefore, it can be stated that the differences in the size, compositions and porosities of the substrates of the slag and gravel systems did not exhibit significant effects on the TSS removal performances of the wetlands in the first 6 months of the monitoring period. The treatment performances of both of the wetlands of METU showed similarities to the of TSS values of other constructed wetlands (Vymazal *et al.*, 1998). Generally, throughout the monitoring period, average effluent TSS concentrations of both the systems were below the discharge standard, which is 30 mg.l^{-1} for treated urban wastewater from agglomerations with a population from 1000 to over 10,000.

Chemical Oxygen Demand (COD) removal

COD effluent concentrations of the vertical flow constructed wetlands varied between 35 and 213 mg.l^{-1} for the slag system and between 50 and 281 mg.l^{-1} for the gravel system (Figure 2). Similarly to TSS effluent concentrations, COD effluent concentrations were also affected by the influent concentrations, precipitations, and seasonal changes. Identically operated slag and gravel wetland systems had average COD removal efficiencies of 49% and 40% (Table 3), respectively. The systems did not differ significantly statistically ($P > 0.1$) in terms of COD removal. In wetland systems, COD removal is supported by aerobically and anaerobically heterotrophic microorganisms (IWA, 2000). The COD load of the wastewater applied to the wetland cells, design of the wetland cells, operational conditions, and type of substrate affect the oxygen diffusion and convection (Vymazal *et al.*, 1998). Another important parameter that affects the COD removal is the oxygen leakage from the plant roots to the rhizosphere. Uptake of organic matter by the macrophytes is negligible compared to biological degradation (Watson *et al.*, 1989).

During the first 6 months of the monitoring period, it was thought that the COD removal was mostly due to biological degradation since the plant root zone was not well established in this period. Even though different COD removal performances were expected for each of the wetlands due to their different structures, the wetlands did not differ significantly statistically ($P > 0.1$). This may be explained by the low organic content of the wastewater applied to the wetlands, which probably did not clog the pores of the substrates with settled organics in 6 months. Moreover, the similar COD treatment trend in both wetlands could also be related to sufficient oxygen diffusion into both of the wetland cells, which was necessary for aerobic degradation. Vymazal *et al.* (1998) has stated that if the COD:BOD_5 ratio of the wastewater is very high, it is very difficult to have effluent COD values below 50 mg.l^{-1}. This was also the case for the wetlands of METU. Both of the average effluent COD concentrations (Table 2) were around 125 mg.l^{-1}, which is the limit of COD effluent discharge concentrations according to the Wastewater Treatment Plant Discharge Standards of Turkey (21.05.1991).

Nitrogen removal

The removal mechanisms for nitrogen in constructed wetlands include utilization, ammonification, nitrification/denitrification, plant uptake and matrix adsorption. Numerous studies have proved that the major removal mechanism in most constructed wetlands is microbial nitrification/denitrification (Vymazal *et al.*, 1998). Untreated ammonia can exert a significant oxygen demand through biological nitrification and it may cause eutrophication in receiving waters, and can be toxic to aquatic organisms. Therefore, the need for nitrogen control in wastewater effluents has generally been recognized and many treatment processes have been developed to remove nitrogen from the wastewater stream (Lee and Lin, 1999). In vertical flow wetland systems, intermittent–loading, particle type and the size of the filtrate increase oxygenation in the wetland matrix, which may result in efficient nitrification processes. Additionally, in order to have efficient nitrogen removal, most of the biodegradable carbon has first to be removed from the wastewater, enabling the nitrifying bacteria to convert ammonium to nitrate easily (Haberl *et al.*, 1995). The nitrate produced can subsequently be reduced to nitrogen gas by biological denitrification. At higher organic loads to the wetlands, only suspended solid and carbon removal can be obtained, whereas at lower loads nitrification and denitrification can take place (Vymazal *et al.*, 1998).

In METU, the NH_4^+-N effluent concentrations were affected by the influent NH_4^+-N values. The effluent NH_4^+-N values of the slag system and gravel system varied between 0 and 9.8 $mg.l^{-1}$ and between 3.2 and 22.6 $mg.l^{-1}$, respectively (Figure 3). The concentration based average NH_4^+-N removal efficiencies of the slag system and gravel system (Table 3) were 88% and 58%, respectively. The ammonium removal performance of the slag system was statistically better than that of the gravel system ($P < 0.1$) (Table 3). Both systems indicated better nitrification compared to other vertical flow wetland systems in other countries (Vymazal *et al.*, 1998; O'Hogain, 2002). Even though the discharge standards of Turkey do not yet include the ammonia, it appears that subsurface flow constructed wetlands can constitute an option for ammonia removal in Turkey.

The NO_3^--N effluent concentrations of the slag system and gravel system (Figure 4) were 1.2-31.3 $mg.l^{-1}$ and 1.4-12.2 $mg.l^{-1}$, respectively. It is known that the nitrification reaction is strongly temperature dependent, and temperatures below 15 °C can significantly reduce nitrification (Reddy and Patrick, 1984). As the temperature decreased in November, the production of nitrate also decreased in both systems. Due to the lower organic content of the wastewater treated in the constructed wetlands of METU, both beds had higher nitrate effluent concentrations compared to those in other wetland studies. The root system of both systems may have oxygenated the root zone and facilitated the establishment of a rich and productive community of attached nitrifiers by providing a higher surface area (IWA, 2000). Moreover, the average pH values of the effluents of both systems at METU were almost around 7.5 (Table 2), which indicated that the conditions were suitable for nitrification (IWA, 2000) within both wetland cells. The higher nitrification rate in the slag system compared to the gravel system could be related to the higher surface area of the slag particles as compared to the gravel, which might have encouraged more oxygen transfer to the biofilm.

As a result of the fluctuations in the influent ammonia concentrations, TN effluent concentrations (Figure 5) also varied between 11 and 37 $mg.l^{-1}$ and between 12 and 28 $mg.l^{-1}$ for the slag and gravel systems, respectively. The TN removal efficiencies (Table 3) of the slag system and gravel system were 41% and 44%, respectively. Comparing the 2 wetlands of METU in terms of TN removal performances, the systems did not differ statistically ($P > 0.1$). Average TN reductions in both systems were similar to those for wetlands operated in France and Austria. The average effluent TN concentrations of both wetland systems (Table 2) are higher than 15 $mg.l^{-1}$, which is the limit value set out in the Wastewater Treatment Plant Discharge Standards of Turkey (21.05.1991). Better nitrogen reductions could be obtained if horizontal flow constructed wetlands with a higher denitrification capacity were operated in series.

Phosphorus removal

Generally, phosphate retention in the constructed wetlands depends upon the composition of the wastewater, loading rate, type of root media and the calcium, aluminum and iron content of the substrate (Pant *et al.*, 2001). Since the materials used as a substrate (pea gravel, crushed stones, sand etc.) in subsurface constructed wetlands usually do not contain high concentrations of these elements, the removal of phosphate is generally low. Therefore, filter materials with higher phosphorus-adsorption capacities are preferred as substrates in wetland cells (Vymazal *et al.*, 1998). In order to obtain high phosphorus retention in the wetland cells of METU, an adequate substrate was sought to be used as filter medium in the wetlands constructed METU. In this regard, the blast furnace granulated slag (content of Ca: 34%; Al: 13% and Fe: 1%) from the Kardemir Iron and Steel. Co. was used in one of the wetland cells as a filtrate.

For the slag system, PO_4^{3-}-P and TP average effluent concentrations were 0.03-4 mg.l^{-1} and 0.26-4.5 mg.l^{-1} respectively. The PO_4^{3-}-P and TP average effluent concentrations of the gravel system were 3.43-6.7 mg.l^{-1} and 38-7.5 mg.l^{-1}, respectively (Figures 6 and 7). The concentration differences in the PO_4^{3-}-P and TP values may have resulted from the organic phosphorus bounded in the suspended solids and the phosphorus forms of the alcaline carbon chains of organic detergents. The effluent phosphorus concentrations of the slag system were almost constant and were very low during the first 2 months of the operation period. However, they rose with the increase in phosphorus loading rates, decrease in phosphorus-adsorption capacity and washout of the phosphorus captured in the wetland cell after heavy precipitation. The gravel system had a very low adsorption capacity and had an environment in which filtration and biological assimilation were dominant. Thus, the effluent phosphorus concentrations of the gravel system fluctuated depending on the influent fluctuations and the values were higher than the influent phosphorus values. The average PO_4^{3-}-P and TP removal efficiencies of the slag system and gravel system were 60% and 64%, and 4% and 9%, respectively (Table 3). As expected, the slag system showed higher phosphorus retention than the gravel system ($P < 0.1$). According to the Turkish Regulations (21.05.1991), for conventional treatment systems, which discharge their effluents into sensible waterbodies where eutrophication takes place, the permissible discharge limit for TP is 2 mg.l^{-1}. The average effluent TP concentration of the slag system of METU was compatible with the Turkish Regulations.

Conclusions

In order to foster the practical development of constructed wetlands for water quality enhancement in Turkey, 2 vertical subsurface flow constructed wetlands were implemented in 2001 on the campus of METU to treat primarily treated domestic wastewater. The main objective of the research was to quantify the effect of different fill media on the nutrient removal performance of the constructed wetlands operated identically in the prevailing climate of Ankara. In one of the wetland beds (gravel system), the filtration media chosen were sand and gravel, whereas in the other (slag system) blast furnace granulated iron slag was used in addition to sand and gravel. The domestic wastewater applied to the constructed wetlands of METU had lower biodegradability compared to the values in the literature. This resulted in removal of organic pollutants, as well as nitrogen and phosphorus removal.

According to the first - 6 month monitoring results and the statistical analysis, it can be concluded that the slag system was statistically more efficient than the gravel system in terms of NH_4^+-N, PO_4^{3-}-P and TP removal and NO_3^--N production. Both systems had similar organic removal (TSS, COD) and total nitrogen removal performances. Higher ammonification and nitrification capacities of the wetlands of METU were observed compared to other wetland applications in other countries. The differences in the removal performances may have resulted from the physical structures and the chemical compositions of the fill media, as well as from the differences between the aerobic and anaerobic environments within the wetland cells. These results indicate that properly designed and operated constructed wetlands could also be used for secondary and tertiary wastewater treatment in Turkey.

Acknowledgment

This work was partially funded by the METU Research Coordination and Industrial Liaison Office. The authors thank all the directors of the offices under the General Secretariat of the Middle East Technical University for their help during the study. We also thank all the wetland researchers who answered our questions related to the project, shared their experiences and opinions and encouraged us.

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