Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2012.748450

51 (2013) 3011–3017
March

Taylor & Francis
Taylor & Francis Group

Septage treatment using a combined waste stabilization ponds—vertical flow constructed wetland system

M. Tsalkatidou*, M. Gratziou, N. Kotsovinos

Department of Civil Engineering, Democritus University of Thrace, 67100 Xanthi, Greece
Tel. +30 2541079882; Fax: +30 2541079604; email: mtsalkat@civil.duth.gr

Received 4 December 2011; Accepted 20 August 2012

ABSTRACT

Eight vertical flow small-scale constructed wetlands were introduced in a pre-existing wastewater treatment pilot plant consisting of three interconnected waste stabilization ponds—a facultative pond followed by two maturation/aerobic ones. The wetlands were identical in couples but differed in substrate and plant presence (common reed) and were fed from the outflow of the first maturation pond. The system was monitored for two years in order to study its operation and efficiency for the treatment of septage in an open air experiment. Samples were collected twice a month and TSS, BOD_5, pH, EC, TP, $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ were monitored. BOD_5 removal was greater in the summer months. The unplanted wetlands were more efficient in TSS and BOD_5 concentrations removal. Still, when estimating the BOD_5 mass in the constructed wetlands effluents using Thornthwaite model to adjust the results, it was found that the BOD_5 mass of unplanted wetlands effluents is greater than that found in planted ones. The system did not remove TP successfully, possibly due to substrate origin and stratification. $N\text{-}NO_3^-$ concentrations in all wetlands' effluents were elevated due to nitrification. Nutrients removal was greater in the planted wetlands. Redesigning the constructed wetlands using a thicker sand layer could increase pollutants removal. The concentrations of the pollutants in the effluents from the constructed wetlands were lower than in the effluents from the waste stabilization pond that treated the same influent.

Keywords: Waste stabilization pond; Constructed wetland; Vertical flow; Septage treatment

---

1. Introduction

Wastewater treatment in small communities and remote agglomerations can be adequately addressed with the use of natural systems. Conventional wastewater treatment systems are more expensive to construct and maintain than natural systems, and the latter have been successfully used all over the world [1,2]. Scholz and Lee (2005) provide a critical review and evaluation of the processes within constructive wetlands, for systems with or without macrophytes and with different substrates [3]. Wetlands have been used to treat different types of wastewater (municipal, industrial, agricultural, stormwater runoff and landfill leachate); Vymazal (2009) reviewed the use of

---

*Corresponding author.

Third International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE 2011) & SECO-TOX Conference, 19–24 June 2011, Skiathos Island, Greece

horizontal subsurface flow constructed wetlands for the treatment of various types of wastewater [4]. The use of vertical flow constructed wetlands for upgrading the quality of waste stabilization ponds effluent has gained interest recently [5,6]. Septage is very typical of Greek small communities and agglomerations; therefore, its treatment is quite interesting from a practical point of view. In this paper, the focus is on the treatment of septage using a combined waste stabilization ponds (WSP)—vertical flow constructed wetland system (CW).

2. Materials and methods

The combined system was constructed with the introduction of eight vertical flow small-scale CWs in a pre-existing wastewater treatment pilot plant consisting of three interconnected WSPs—a facultative pond followed by two maturation/aerobic ones. All ponds are lined with geomembrane. The plant is located in Sindos, near Thessalonica and it was set up by the National Agriculture Research Foundation (NAGREF) in 1996 (see Fig. 1). From 2004, the first of the three interconnected ponds was fed with septage ($Q = 50\,\mathrm{m}^3\,\mathrm{d}^{-1}$; corresponding to a population equivalent of 350 PE) to study the performance of the WSPs system [7].

The CWs were identical in couples but differed in substrate and plant presence (common reed) and were fed from the outflow of the first maturation pond. The CWs were constructed in accordance with the International Water Association guidelines and were introduced in April 2005 [1]. Eight opaque polyethylene barrels (∅50 cm), placed on a special metal construction to accommodate containers for effluent collection, were filled with large stones around the perforated 30 cm long pipe to be found at the base of each barrel. The pipe acts as a draining outlet and the large round stones are used to prevent the materials from blocking the pipe. On top of this, in four out of the eight barrels, a 15 cm layer consisting of large round river gravel (30–60 mm) was put in place, while the respective 15 cm layer for the remaining four barrels (CW1–CW4) consisted of a 50–50% mixture of round river gravel and coarse gravel (30–60 mm). The next 10 cm wide layer was the same for all eight barrels consisting of coarse gravel (8–16 mm). The overlying 15 cm layer for the first four barrels (CW5–CW8) consisted of 2–8 mm washed pea-gravel, while for the remaining four (CW1–CW4) it consisted of a 50–50% mixture of 2–8 mm coarse gravel and washed pea-gravel. The upper 8 cm layer was the same for all eight barrels and consisted of black sharp sand (0–6 mm). On the barrel surface, large round stones were used for better sewage dispersion. Therefore, the first four barrels (CW5–CW8) have the same substrate (substrate A), which is different from that of the remaining four barrels (CW1–CW4) (substrate B). Four barrels (CW1–CW2, CW7–CW8) were planted with stems of common reed (*Phragmites australis*) and the other four barrels were left unplanted. This resulted in four different types of CWs. A cross-section of a

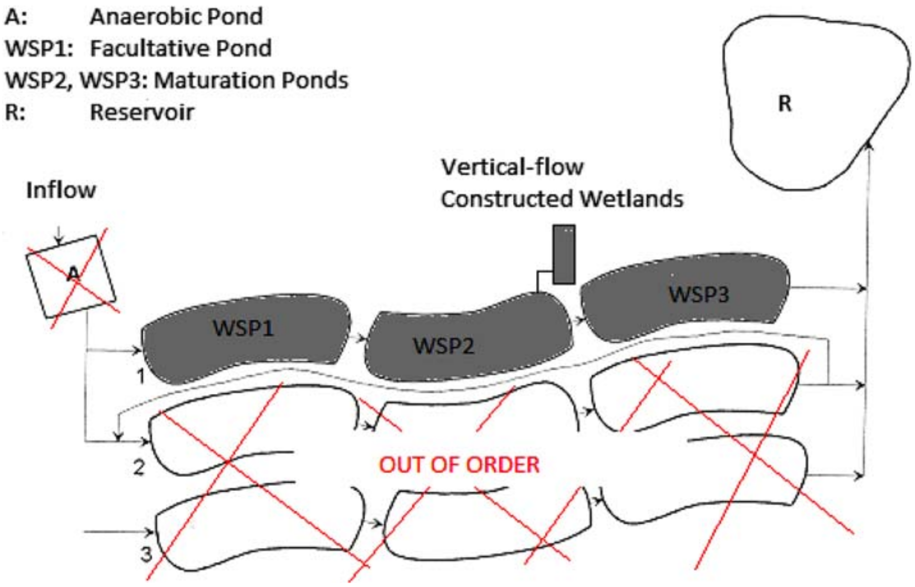

Fig. 1. Schematic plan of the NAGREF plant in Sindos (the parts of the plant that were used for the study are highlighted in grey).

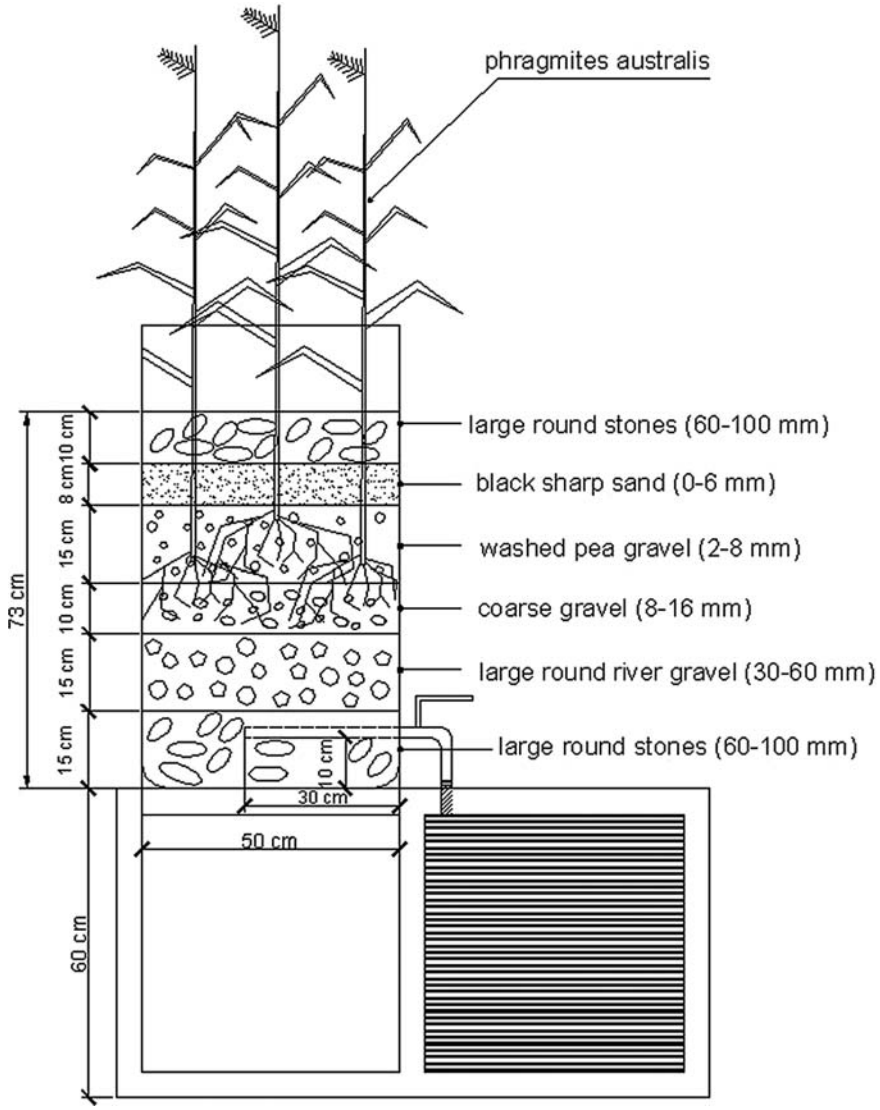

Fig. 2. Cross-section of a pilot vertical flow CW (CW7, CW8).

planted vertical flow constructed wetland with substrate A is shown in Fig. 2.

During the summer months, each CW was fed with 40 L of influent, whereas during the winter months only 20 L of influent were applied. The respective applied hydraulic rates for the warm and cold months were $q_w = 0.029\,\mathrm{m\,d^{-1}}$ and $q_c = 0.015\,\mathrm{m\,d^{-1}}$, respectively. To achieve good performance and prevent clogging, it is important that bed medium allows wastewater to pass through the bed before the next dose is applied but it is equally important for the bed media to hold the liquid back, long enough to allow contact with the bacteria growing on the media.

The combined system was monitored for two years in order to study its operation and efficiency for the treatment of septage in an open air experiment. Samples were collected twice a month and TSS, BOD_5, pH, EC, TP, N-NO_3^- and N-NH_4^+ were monitored. The analyses were carried out at the Soil Science Institute Laboratory of NAGREF using the American Public Health Association standard methods [8]. Meteorological data were collected from a station near the plant.

2.1. PET estimation with the Thornthwaite model

The concentrations of TSS and BOD_5 were higher in the effluents of the planted CWs, while the concentrations of N-NO_3^-, N-NH_4^+ and TP were higher in the effluents of the unplanted CWs. In order to find out whether the mass of the pollutants is following the trend of the concentrations, it is necessary to measure the volume of the effluents in each wetland, V_{out}, but since no measurements of the aforementioned effluents' volume were taken during the experiment, it was attempted to estimate it indirectly from the water balance:

$$V_{\text{out}} = V_{\text{in}} + V_{\text{rain}} - V_{\text{PET}} \tag{1}$$

where V_{out}: effluents' volume (L), V_{in}: influents' volume (L), V_{rain}: volume of water entering the wetlands through rainfall (L), V_{PET}: volume of water consumed in the wetlands due to evapotranspiration (L).

V_{in} was measured during the experiment and V_{rain} was calculated from the available meteorological data. In order to estimate the evapotranspiration volume, V_{PET}, and subsequently the effluents volume, V_{out}, the empirical Thornthwaite model was used. The Thornthwaite model has its limitations, but its simplicity and the little data required for its application make it more popular than the more reliable Penman–Monteith model [9].

$$\text{PET} = 1.6 \times \lambda \times \left(\frac{10T}{I}\right)^{a} \tag{2}$$

where PET: potential evapotranspiration for 30-day months with 12-hour daylight (cm month^{-1}), T: average daily temperature (℃), I: heat index which depends on the 12 monthly mean temperatures $I = (T_1/5)^{1.514} + (T_2/5)^{1.514} + \ldots + (T_{12}/5)^{1.514}$, T_n: monthly mean temperature (℃), λ: corrective index for 40.5° latitude and

$$a = 0.000000675I^3 - 0.000077I^2 + 0.01792I + 0.49239$$

For planted CWs, a correction factor equal to 1.5 times has been used due to increased PET, while in the unplanted CWs the correction factor is 0.5. Therefore, with the estimation of PET and of the wetland surface, V_{PET} and V_{out} can be calculated.

3. Results and discussion

The results of TSS, BOD$_5$, N-NH$_4^+$, N-NO$_3^-$ and TP are presented in Tables 1–4. The very nature of septage resulted in much higher TSS and BOD$_5$ standard deviation (SD) values compared to the respective values reported elsewhere for urban wastewater for the same system [5]. The effluents of planted CWs exhibited higher concentrations of TSS and BOD$_5$, while the different choice of filter media did not significantly affect the TSS and BOD$_5$ effluent concentrations. The effluent of the final WSP (i.e. WSP3), which similarly to the wetlands was fed from the WSP2 effluent, exhibited higher TSS concentration than the CWs, but the filtered WSP effluent exhibited lower BOD$_5$ concentration compared to the effluent of the planted CWs (Tables 1 and 2).

Conductivity and pH were higher in planted CWs. Conductivity was higher in the summer months. pH readings were always lower than 8 in the CWs, whereas, rarely, they read lower than 8 in the outflow of the second maturation pond.

The planted CWs exhibited lower N-NH$_4^+$, N-NO$_3^-$ concentrations than the unplanted CWs and the CWs with substrate B exhibited lower N-NH$_4^+$, N-NO$_3^-$ concentrations than the CWs with substrate A, although it needs to be mentioned that the CWs did not remove N-NO$_3^-$ at all. In fact, N-NO$_3^-$ concentrations in all

Table 1
TSS statistical data of the WSPs and CWs effluents

	TSS (mg L^{-1})				
	N	Min	Max	Mean	SD
CW1	37	19	352	90.22	61.38
CW2	38	13	244	81.58	43.15
CW3	39	11	175	56.38	32.68
CW4	39	8	168	50.31	29.54
CW5	39	13	287	64.82	53.09
CW6	39	18	255	63.74	48.71
CW7	38	3	231	85.13	56.77
CW8	39	29	222	86.79	43.90
WSP1	24	180	595	283.71	97.20
WSP2	36	44	432	134.61	77.40
WSP3	35	12	280	97.40	62.44

CW1, CW2: substrate A, common reed; CW3, CW4: substrate A, no plants; CW5, CW6: substrate B, no plants; CW7, CW8: substrate B, common reed; WSP1: facultative pond; WSP2: first maturation pond (wetlands' feeding); and WSP3: second maturation pond.

Table 2
BOD_5 statistical data of the WSPs and CWs effluents

	BOD_5 (mg L^{-1})					
	N	Min	Max	Mean	% conc. removal	SD
CW1	33	5.00	74.00	29.78	67.46	16.69
CW2	33	3.75	55.50	27.58	69.87	16.85
CW3	38	6.00	88.00	25.11	72.57	16.59
CW4	38	6.00	51.50	22.82	75.07	12.58
CW5	38	3.75	53.00	21.73	76.26	14.67
CW6	37	6.00	62.50	21.22	76.81	13.61
CW7	34	6.00	98.00	29.97	67.25	21.74
CW8	36	4.00	76.00	25.46	72.18	18.12
WSP1	19	25.50	288.00	147.24		71.32
$WSP1_{filt}$	19	12.00	177.00	68.84		52.64
WSP2	35	19.50	246.00	91.52		56.91
$WSP2_{filt}$	34	6.00	99.00	39.78		22.42
WSP3	34	12.75	114.75	54.95	39.96	29.03
$WSP3_{filt}$	32	4.50	67.50	26.50	71.05	14.27

Table 3
$N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ statistical data of the WSPs and CWs effluents

		$N\text{-}NH_4^+$ (mg N L^{-1})				$N\text{-}NO_3^-$ (mg N L^{-1})			
	N	Min	Max	Mean	SD	Min	Max	Mean	SD
CW1	8	14.5	21	18.88	2.37	8.1	11.7	9.98	1.17
CW2	8	14.7	21.2	18.56	2.14	7.5	11.2	9.49	1.30
CW3	8	16	25	20.94	2.64	9.5	12.1	10.85	0.99
CW4	8	16.4	24.5	21.44	2.67	8.5	12.5	10.98	1.38
CW5	8	16	23.8	20.90	2.96	8.5	11.1	9.71	0.95
CW6	8	15.1	22.6	19.80	2.70	8.5	10.2	9.28	0.58
CW7	8	14	20.9	17.38	2.22	7.2	9.5	7.96	0.74
CW8	8	13.5	20.5	17.20	2.80	7.3	9.1	8.16	0.57
WSP1	8	62.8	77.6	69.86	5.57	2	2.9	2.53	0.31
WSP2	8	32.3	46.3	40.45	4.32	1.7	2.4	2.03	0.26
WSP3	8	17.1	28.3	22.76	4.20	1	1.8	1.39	0.26

Table 4
TP statistical data of the WSPs and CWs effluents

	TP (mg L^{-1})				
	N	Min	Max	Mean	SD
CW1	8	3.8	5.8	4.79	0.74
CW2	8	3.7	5.5	4.63	0.66
CW3	8	4	5.8	4.96	0.67
CW4	8	3.9	5.9	4.98	0.68
CW5	8	3.8	5.7	4.90	0.68
CW6	8	3.9	5.9	4.89	0.67
CW7	8	3.5	5.4	4.66	0.72
CW8	8	3.7	5.4	4.73	0.65
WSP1	8	5.9	7.6	6.84	0.56
WSP2	8	4.2	6	5.21	0.66
WSP3	8	3.2	4.7	3.98	0.63

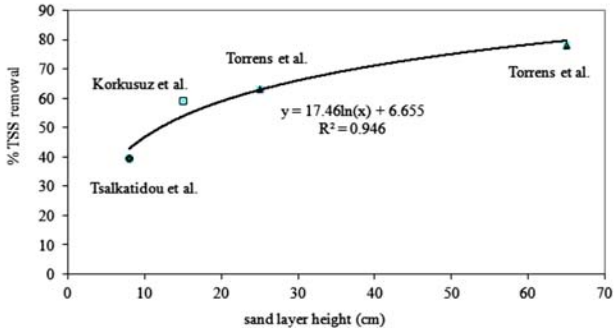

Fig. 3. % TSS removal in relation to sand layer height in vertical flow CWs with common reed.

CWs effluents were elevated due to nitrification. The effluent of WSP3 exhibited higher N-NH_4^+ concentrations than that of the CWs and the WSP—contrary to the CWs—also managed to remove N-NO_3^- (Table 3). TP concentrations were lower in the WSP3 effluent compared to the CWs effluents (Table 4). The combined WSP–CW system did not remove TP successfully, possibly due to substrate origin and stratification. In general, nutrients removal was greater in the planted wetlands, but still, very few measurements were made to read too much into these results.

Torrens et al. (2009), who studied vertical flow CWs, noticed that the CWs planted with common reed removed TSS, BOD_5 and N-NH_4^+ better than unplanted ones (i.e. sand filters) when the sand layer height was 65 cm, but they conducted experiments for different sand layer heights (i.e. 25 and 65 cm) and the removal of TSS and BOD_5 was exactly the same for a 25 cm sand layer. In this study, the sand layer height was only 8 cm, therefore, the comparison with the latter results seems more appropriate. Torrens et al. (2009) also found increased N-NO_3^- concentrations at the CWs effluents [6]. Korkusuz et al. also studied the performance of vertical flow CWs planted with common reed, but with two different types of substrate (substrate A—bottom to top: 15 cm of 15/30 mm gravel, 30 cm of 7/15 mm gravel and 15 cm of 0–3 mm of sand and substrate B—bottom to top: 15 cm of 15/30 mm gravel, 30 cm of 0–3 mm blast furnace granulated slag and 15 cm of 0–3 mm of sand) for a year. They reported TSS removal 63 and 59% for the slag and gravel, respectively, while TP removal was 45% for the slag and only 4% for the gravel [10]. The sand layer height seems to affect the performance of the vertical flow CWs and in the case of TSS removal; the correlation is shown in Fig. 3. In other correlations between the sand layer height and the removal efficiency of pollutants in vertical flow CW, it was found that a higher sand layer generally improves the performance of the CW, although aeration and clogging could become an issue after some point [11].

Stefanakis and Tsihrintzis (2009) studied the performance of 10 different pilot-scale vertical flow CWs fed with synthetic wastewater for a year and found that the CW designed according to the US standards (30 cm sand layer) removed BOD_5 more efficiently. The unplanted CW designed according to the European standards (10 cm sand layer) achieved 60.4% and 82.3% BOD_5 removal for temperatures below and above 15°C, respectively [12]. These figures are similar to those registered in this study for unplanted CWs, as during the cold months, the percentage of BOD_5 removal ranges between 67.9 and 70.7%, while during the warm months it increases to 72.7–78.8%. The unplanted CWs were more efficient in TSS and BOD_5

Table 5
BOD_5 mass in the vertical flow CWs effluents, planted or unplanted, each month, based on the Thornthwaite model

Month	Jun 2005	Jul 2005	Aug 2005	Sep 2005	Oct 2005	Nov 2005	Dec 2005	Jan 2006	Feb 2006	Mar 2006	May 2006	Jun 2006
With common reed	0.17	0.00	2.65	0.92	1.82	0.88	1.83	0.63	0.67	1.39	1.49	2.53
Unplanted	0.79	0.23	1.27	0.74	1.72	0.95	2.20	1.05	1.14	0.78	1.20	2.17
Month	Jul 2006	Aug 2006	Sep 2006	Oct 2006	Nov 2006	Dec 2006	Jan 2007	Feb 2007	Mar 2007	Apr 2007	May 2007	Jun 2007
With common reed	1.38	1.16	1.16	1.45	0.20	0.47	0.46	0.30		0.18	3.53	0.03
Unplanted	2.05	1.61	1.14	1.61	0.22	0.53	0.43	0.37		0.51	4.12	0.52

concentrations removal. Still, when estimating the BOD_5 mass in the constructed wetlands effluents using Thornthwaite model to adjust the results, it was found that the BOD_5 mass of unplanted wetlands effluents is greater than that found in planted ones (Table 5). The concentrations of the pollutants in the effluents from the CWs were lower than in the effluents from WSP3 that treated the same influent, although it needs to be noticed that the CWs were much smaller in scale than WSP3.

4. Conclusions

The results are encouraging, but the final effluents do not meet the standards for reuse. The unplanted wetlands were more efficient in TSS and BOD_5 concentrations removal than the planted ones. Still, when estimating the BOD_5 mass in the constructed wetlands effluents using Thornthwaite model to adjust the results, it was found that the BOD_5 mass of unplanted wetlands effluents is greater than that found in planted ones. The selected substrate did not significantly affect the removal of TSS and BOD_5. The percentage of TSS removal decreased in the second year of operation for the CWs—with the exception of CW2—while the opposite was the case for the WSP. Still, average TSS concentrations in the CWs effluents were above the USEPA suggested $30\,\mathrm{mg\,L^{-1}}$ for reuse. The average BOD_5 concentrations were below of the USEPA suggested $30\,\mathrm{mg\,L^{-1}}$ for reuse, although on occasions there were higher readings. The system did not remove TP successfully, possibly due to substrate origin and stratification. $N\text{-}NO_3^-$ concentrations in all wetlands' effluents were elevated due to nitrification. Nutrients removal was greater in the planted wetlands. The concentrations of the pollutants in the effluents from the CWs were lower than in the effluents from the WSP that treated the same influent, but the WSP was of a bigger scale. Redesigning the constructed wetlands using a thicker sand layer could increase pollutants removal.

References

[1] IWA Specialist Group on Use of Macrophytes in Water Pollution Control, Constructed Wetlands for Pollution Control-Processes, Performance, Design and Operation, first Reprint, IWA, Cornwall, 2001.

[2] R. Crites, G. Tchobanoglous, Small and Decentralized Wastewater Management Systems, McGraw-Hill, Singapore, 1998.

[3] M. Scholz, B. Lee, Constructed wetlands: a review, Int. J. Environ. Stud. 62(4) (2005) 421–447.

[4] J. Vymazal, The use of constructed wetlands with horizontal sub-surface flow for various types of wastewater, Ecol. Eng. 35(1) (2009) 1–17.

[5] P. Molle, A. Liénard, A. Grasmick, A. Iwema, Effect of reeds and feeding operations on hydraulic behaviour of vertical-flow constructed wetlands under hydraulic overloads, Water Res. 40(3) (2006) 606–612.

[6] A. Torrens, P. Molle, C. Boutin, M. Salgot, Impact of design and operation variables on the performance of vertical-flow constructed wetlands and intermittent sand filters treating pond effluent, Water Res. 43 (2009) 1851–1858.

[7] F. Papadopoulos, A. Papadopoulos, G. Parissopoulos, A. Zdragkas, I. Metaxa, The treatment of septage using stabilization ponds, Fresen. Environ. Bull. 16(4) (2007) 385–392.

[8] APHA, Standard Methods for the Examination of Water and Wastewater, 17th ed., American Public Health Association/ American Water Works Association/Water Environment Federation, Washington, DC, 1989.

[9] R.C. Ward, M. Robinson, Principles of Hydrology, fourth ed., Mc Graw-Hill, London, 2000.

[10] E.A. Korkusuz, M. Beklioglu, G.N. Demirer, Comparison of the treatment performances of blast furnace slag-based and gravel based vertical flow wetlands operated identically for wastewater treatment in Turkey, Ecol. Eng. 24 (2005) 187–200.

[11] M. Tsalkatidou, Design simulations study of waste stabilization ponds and combined wastewater treatment using waste stabilization ponds and constructed wetlands, PhD thesis, Department of Civil Engineering, Democritus University of Thrace, Xanthi, 2010 (in Greek).

[12] A.I. Stefanakis, V.A. Tsihrintzis, Performance of pilot-scale vertical flow constructed wetlands treating simulated municipal wastewater: effect of various design parameters, Desalination 248 (2009) 753–770.