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PERFORMANCE MONITORING OF A VERTICAL FLOW CONSTRUCTED WETLAND TREATING MUNICIPAL WASTEWATER

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ABSTRACT
A two-year monitoring program was undertaken in a vertical flow constructed wetland treating wastewater from Gomati, a village in Chalkidiki, North Greece. This constructed wetland operates since 2003. The monitoring campaigns were organized every 15 days. Water quality samples were collected at the inlet, at intermediate points (i.e., at the end of each treatment stage) and at the outlet of the system. Measured mean removal efficiencies were as follows: 92.3% for BOD, 91.7% for COD, 80.3% for TKN, 87.5% for NH_4^+, 61.3% for TP, 45.7% for ortho-phosphates, 93.2% for TSS and 99.9% for total coliforms, which suggests a satisfactory and reliable performance of such systems in Greece. The paper presents facility description, study details and monitoring results.

KEYWORDS: vertical flow constructed wetlands, reed beds, nutrients, removal, performance.

INTRODUCTION

The need for treatment of municipal wastewater, even for small towns, is now imperative based on EU directive 1991/271/EEC. A good alternative for small settlements is the use of constructed wetlands (CW). The use of these systems is becoming very popular in many countries, and several studies have shown the overall effectiveness of constructed wetlands in treating municipal wastewater (e.g., Hammer, 1989; Reed *et al.*, 1995; Kadlec & Knight, 1996; He & Mankin, 2002; Akratos and Tsihrintzis, 2007).

Even though the ability of CW in removing BOD and total suspended solids (TSS) is relatively high, nitrogen removal in most of the systems, especially in horizontal subsurface flow (HSF) CWs, requires the use of large areas, due to limited oxygen supply. Nitrogen removal is mainly achieved by microbial activity through nitrification and denitrification, while other mechanisms, such as volatilization, plant uptake and absorption, play secondary roles. Increased nitrification ability is observed in vertical flow (VF) CWs (Greenway and Woolley, 1999). Results from several studies show that the removal efficiency in VF CWs for BOD and COD are above 90%, while nitrogen and phosphorus removal efficiencies can also rise to 90%, depending on the system (Lantzke *et al.*, 1999; Luederitz *et al.*, 2001).

MATERIALS AND METHODS

Facility description

The CW facility in Gomati is designed for 1000 p.e., is a VF system and comprises the following stages (Tsihrintzis *et al.*, 2004) (Figure 1): (1) screen, (2) primary settling tank, (3) sludge tank, (4) siphon tank, (5) 1st stage VF CWs, (5) 2nd stage VF CWs, (6) 3rd stage HSF CW, (7) VF CWs for sludge treatment.

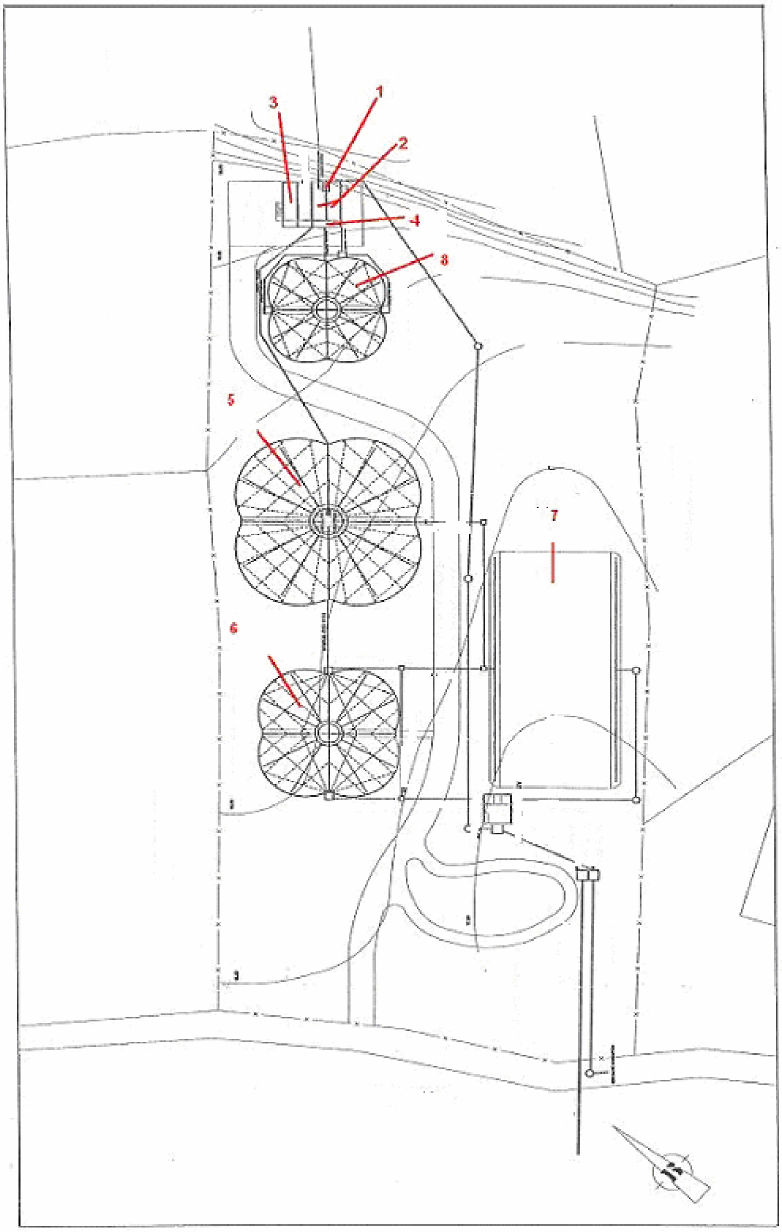

Figure 1. Facility layout: (1) screen, (2) primary settling tank, (3) sludge tank, (4) siphon tank, (5) 1st stage VF CWs, (6) 2nd stage VF CWs, (7) 3rd stage HSF CW, (8) VF CWs for sludge treatment

Screening comprises a self-cleaning drum with 1 mm openings. Then, the wastewater is guided into the settling tank. The total volume of this tank is 48 m^3, of dimensions 4.0 m long, 6.0 m wide and 2.5 m deep, and consists of two equal compartments. The primary sludge from this tank is collected in the sludge tanks, which also have a total volume of 48 m^3 and the same dimensions with the settling tank. The sludge remains in the tank for three months and then is guided to the VF CWs for sludge treatment. These are circular in plan view and consist of 4 cells with an area 60 m^2 each. They are planted with *Phragmites australis.*

The sludge dries in the units, the leachate is collected at the bottom and is guided to a tank equipped with a siphon. The wastewater, after passing through the settling tank, is also collected in the siphon tank. The volume of the siphon tank is 3.2 m^3 and its dimensions 1.0 m long, 4.2 m wide and 0.8 m deep. The purpose of this tank is to feed periodically (in batches) the 1st stage VF CW. The 1st stage VF CW is circular in plan view and it consists of 4 cells with an area of 160 m^2 each. Each cell is periodically flooded every 2 days. The effluent of the 1st stage CW is the influent for the 2nd stage VF CW. The 2nd stage VF CW is similar to the 1st

stage. The difference is that every cell is smaller and has an area of 90 m^2. Finally, the wastewater is introduced to the HSF CW. This is a unit with a total area of 800 m^2, filled with 50 cm of gravel (diameter 2-5 cm). The wastewater is introduced in this unit through a perforated PVC pipe (160 mm inner diameter), which has been placed across the CW. The treated wastewater is finally discharged to an adjacent creek.

Water quality monitoring

Water samples were collected almost every two weeks from the influent and the effluent of each treatment stage. In-situ temperature, conductivity, pH and dissolved oxygen (DO) were measured using proper equipment (WTW 197-series). The water samples were analyzed immediately in the laboratory for BOD, COD, TKN, ammonia, ortho-phosphates, total phosphorus (TP), nitrite and nitrate. For BOD determination respirometric bottles were used, for COD the open reflux method was employed, for TKN and ammonia the titrimetric method, for phosphorus the stannous chloride method, for nitrite the colorimetric method and for nitrate the cadmium reduction method (APHA, 1998).

RESULTS AND DISCUSSION

In order to assess the function and pollutant removal efficiency of the facility, 37 field campaigns were undertaken from July 2003 until September 2005 (approximately one field campaign every 15 days). Measured physicochemical parameters and pollutant concentration statistics are presented in Tables 1 and 2, respectively.

The temperature did not show any significant spatial variations along the unit, and generally ranged between 8.6 to 27.9^{o}C, depending on the season. The small differences between temperature values in the various sampling points depend on the way the sampling points are exposed to the sun or the air. Practically, temperature variation along the facility was only minor. The mean conductivity showed a decreasing trend along the facility, which was expected due to the removal of dissolved salts. Mean pH values throughout the wetland were neutral and relatively constant along the facility. There was, however, a seasonal variation of pH value in the influent, also reflected along the facility. Dissolved oxygen concentrations were increasing along the facility as expected, but there were also seasonal variations related to wastewater temperature. Specifically, lower concentrations were observed during the winter (0.0 mg l^{-1}) and higher during the summer (7.8 mg l^{-1}). This is in part due to the lack of oxygen transfer from the plants during winter.

Table 1. Physicochemical parameter statistics

Parameter		Influent	Effluent from					
			Settling tank	Sludge digestion	Siphon tank	1st stage VF CW	2nd stage VF CW	3rd stage HSF CW
Temperature (^{o}C)	Mean	18.4	18.3	18.1	18.1	18.0	17.5	18.5
	SD	4.9	5.0	5.1	4.6	4.6	4.5	5.2
	Min	8.7	8.6	8.8	10.2	10.9	9.3	8.8
	Max	27.4	27.4	27.9	27.9	27.7	24.5	25.3
Conductivity (μS cm^{-1})	Mean	1064	970	963	950	790	747	955
	SD	655	556	542	540	460	425	261
	Min	141	195	204	181	183	163	214
	Max	2610	1782	1642	1730	1606	1437	1200
pH	Mean	7.4	7.1	7.4	7.4	7.5	7.5	7.3
	SD	0.6	0.8	0.5	0.5	0.5	0.5	0.5
	Min	5.7	5.2	5.7	5.8	5.8	6.3	6.4
	Max	8.7	8.3	8.2	8.3	8.5	8.8	8.6
DO (mg l^{-1})	Mean	1.1	1.3	1.2	1.9	2.7	2.0	1.2
	SD	1.0	0.9	0.9	1.4	1.4	0.9	0.9
	Min	0.0	0.0	0.3	0.2	0.0	0.1	0.2
	Max	4.1	3.6	4.2	7.0	7.8	4.1	3.4

BOD and COD concentrations decreased along the facility indicating that organic matter removal is achieved in all the stages of the facility. There were, however, significant seasonal variations, mainly caused by the variations of influent concentrations (Figure 2). Specifically in the summer, mainly due to the increase of the population and reduction of rainfall, higher BOD and COD concentrations were observed (e.g., max values of 819.0 mg l^{-1} and 1354.0 mg l^{-1}, respectively). Seasonal variations were observed at the effluent of the facility as well. Lower concentrations of effluent BOD and COD (6.0 mg l^{-1} and nearly 0.0 mg l^{-1}, respectively) were observed during the summer, when the plant function was optimal, but the facility removed organic matter sufficiently even during the winter (max effluent BOD 92.0 mg l^{-1} and COD 148.8 mg l^{-1}).

TKN and ammonia concentrations also decreased along the facility. Seasonal variations of the influent concentrations (Figure 2) were also observed, caused by the increase of the population during the summer (TKN 187.0 mg l^{-1} and N-NH_4^+ 136.4 mg l^{-1}). The minimum effluent concentrations of TKN and ammonia (both nearly 0.0 mg l^{-1}) were also observed during the summer. On the contrary during the winter the effluent concentrations of TKN and ammonia (72.5 mg l^{-1} and 15.9 mg N l^{-1}, respectively) were significantly higher, indicating that nitrification was insufficient, mainly due to the low temperatures and low oxygen transfer from the plants to the roots and the porous media.

Phosphorus concentrations also decreased along the facility. The variations in the influent concentrations were also due to the increase of the population in the summer. The variations in the effluent concentrations at the various stages of the facility are not caused by season variations but are related to the age of the facility. Specifically, the lower concentrations of TP and ortho-phosphates (both nearly 0.0 mg P l^{-1}) were observed at the beginning of the facility operation and the higher (11.6 mg P l^{-1} and 12.2 mg P l^{-1}, respectively) during the more recent field campaigns after two years of facility operation.

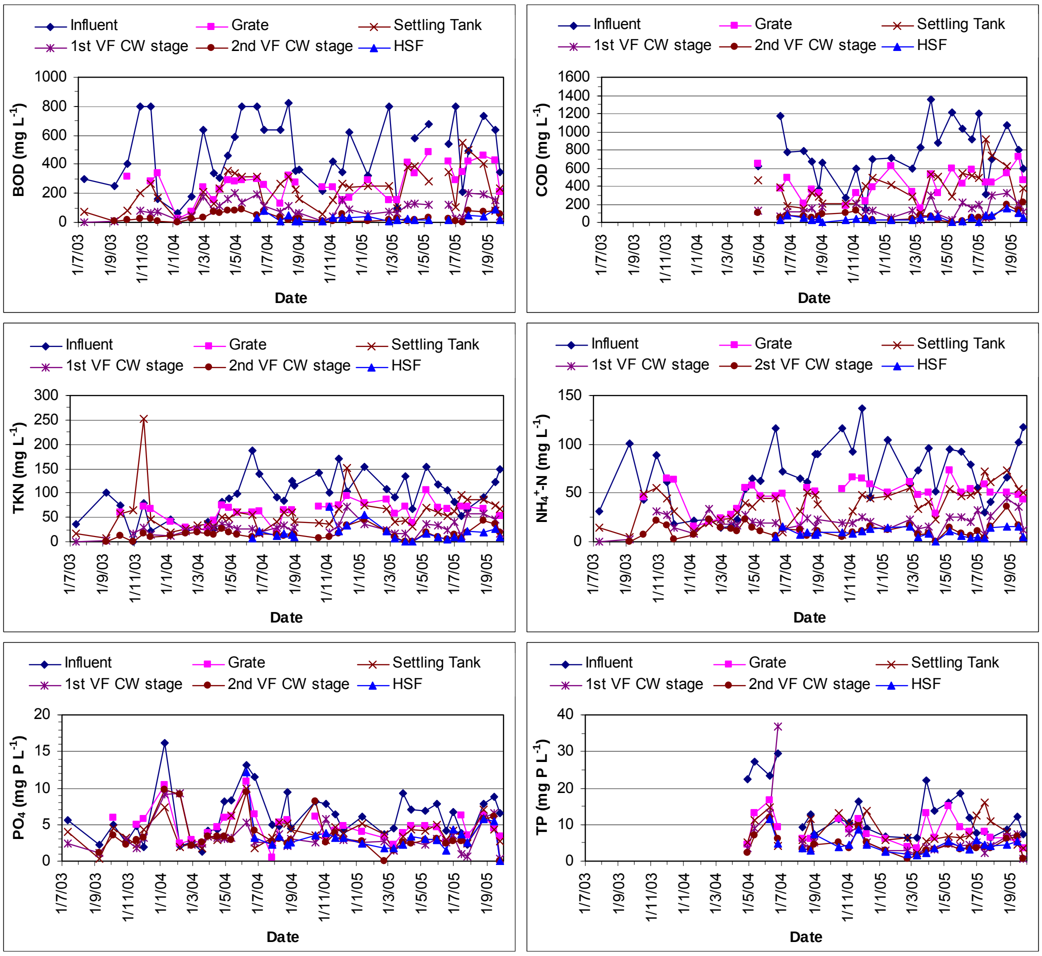

Figure 2. Temporal variation charts of pollutant influent and effluent concentrations

Table 2. Pollutant concentration and removal statistics

Parameter		Influent	Effluent from settling tank	Effluent from sludge digestion	Siphon tank	Effluent from 1st stage VF CW	Effluent from 2nd stage VF CW	Effluent from 3rd stage HSF CW	Overall Removal (%)**
BOD ($mg\ l^{-1}$)	Mean	487.2	272.5	266.1	228.0	93.5	34.9	30.4	92.3
	SD	231.0	110.0	100.1	131.3	59.0	28.5	23.3	5.8
	Min	62.0	25.3	73.2	9.8	1.4	BDL*	6.0	78.5
	Max	819.0	480.0	440.0	546.0	200.0	91.6	92.0	98.5
COD ($mg\ l^{-1}$)	Mean	758.2	421.6	477.3	390.1	143.5	72.8	47.2	91.7
	SD	306.6	153.4	171.9	197.9	83.9	51.2	33.9	8.6
	Min	144.0	153.6	211.2	105.6	24.0	4.8	BDL	60.0
	Max	1354.0	720.0	806.4	921.6	316.8	220.8	148.8	100.0
TKN ($mg\ l^{-1}$)	Mean	93.8	77.0	69.8	58.8	27.1	15.5	18.2	80.3
	SD	44.2	87.4	54.9	41.4	15.3	10.9	17.0	16.7
	Min	BDL	16.2	BDL	8.4	BDL	BDL	BDL	31.0
	Max	187.0	552.0	371.6	251.1	71.7	46.5	72.5	100.0
$N\text{-}NH_4^+$ ($mg\ l^{-1}$)	Mean	67.7	48.0	50.7	39.1	19.7	11.3	9.1	87.5
	SD	32.7	15.0	14.3	17.0	9.6	7.2	4.5	8.5
	Min	14.0	11.8	16.0	4.3	BDL	BDL	BDL	65.5
	Max	136.4	73.1	72.6	73.4	44.8	36.4	15.9	100.0
$P\text{-}PO_4$ ($mg\ l^{-1}$)	Mean	6.0	4.7	5.0	3.9	3.2	3.5	3.3	45.7
	SD	3.2	2.1	2.2	1.8	2.0	2.3	2.3	25.2
	Min	1.3	0.5	1.8	0.4	0.3	BDL	BDL	-8.7
	Max	16.1	10.9	11.3	9.9	9.3	9.8	12.2	100.0
TP ($mg\ l^{-1}$)	Mean	13.0	8.3	8.3	8.2	6.3	4.4	4.4	61.3
	SD	6.8	3.6	4.5	3.8	6.9	2.5	2.4	16.6
	Min	6.3	3.4	2.5	2.3	0.5	0.5	BDL	24.1
	Max	29.3	16.7	22.0	16.1	36.8	11.9	11.6	89.3
$N\text{-}NO_3$ ($\mu g\ l^{-1}$)	Mean	144.2	325.7	156.9	350.3	987.4	1446.5	987.9	
	SD	301.4	697.5	420.6	745.5	1180.5	1641.6	894.0	
	Min	BDL	BDL	BDL	BDL	BDL	BDL	BDL	
	Max	1122.8	2899.3	1530.6	2852.8	4636.0	8132.8	3681.4	
$N\text{-}NO_2$ ($\mu g\ l^{-1}$)	Mean	23.6	62.4	24.1	218.3	655.0	337.5	111.8	
	SD	21.4	169.0	28.4	363.3	270.4	176.5	190.6	
	Min	BDL	BDL	BDL	BDL	BDL	BDL	8.3	
	Max	68.6	829.0	118.6	995.2	936.2	677.6	795.9	
TSS ($mg\ l^{-1}$)	Mean	713.7	135.9	135.3	116.2	55.5	35.5	13.6	93.2
	SD	1384.6	81.7	96.2	73.0	71.4	141.5	27.4	13.4
	Min	11.3	31.0	10.0	6.5	BDL	BDL	BDL	50.9
	Max	7060.0	338.4	358.5	354.0	284.0	726.0	91.5	100.0
TC (10^6 N/100 ml)	Mean	47.9	32.5	30.3	30.2	2.4	0.2	0.05	99.9
	SD	45.3	43.0	27.3	32.9	9.8	0.4	0.06	0.2
	Min	1.0	0.6	BDL	0.5	BDL	BDL	BDL	99.2
	Max	200.0	200.0	100.0	130.0	50.0	2.0	0.2	100.0

**BDL: Below Detection Limit*
***Statistics based on removals computed for each sampling*

Nitrate and nitrite concentrations increased along the facility stages, indicating that nitrification takes place. A decrease of nitrate and nitrite concentrations was observed at the last stage (HSF), indicating that in this stage of the facility denitrification takes place. Nitrate and nitrite concentrations were always lower than the effluent permitted values. TSS concentrations also decreased along the facility and the effluent concentrations were relatively low (13.6 mg l^{-1}). Total coliform (TC) concentrations also decreased along the unit but the effluent concentration was relatively high (mean: 53208 N/ 100ml) to permit water use for irrigation.

Figure 3 presents the variations of mean removal efficiency along the various facility stages for all the pollutants. BOD and COD were removed only by 40% at the primary treatment stages (screening and primary settlement). The stage with the higher removal of organic matter was the 1st stage VF CW where additional 40% removal of BOD and COD was achieved. At the 2nd stage VF CW and at the HSF CW the removal of the organic matter was significantly lower. The total additional removal in these two stages for BOD and COD was about 10%.

TKN and ammonia removal at the pre-treatment stages was lower than those of BOD and COD (below 30%). Nitrogen at the 1st stage VF CW was additionally removed by 40%. The high removal efficiency in organic matter and nitrogen achieved at the 1st VF CW stage was due to the fact that this unit is larger in surface area. At the 2nd VF CW and HSF stages nitrogen removal was also significant (20% for both stages).

TP showed the same trend along the facility as nitrogen. Specifically, only a small part of TP was removed (around 20%) in the pre-treatment stages. The larger part of TP was removed at the 1st VF CW stage where the removal efficiency was above 50%. The last two stages of the facility (2nd VF and HSF stages) had an only small contribution to TP removal (around 10%), rising the total TP removal to about 60%. Ortho-phosphates showed a different behavior than TP. At the pre-treatment stages of the facility the same percent with TP was removed (around 20%). The difference with TP occurred in the 1st and 2nd VF CW stages, where only 10% of ortho-phosphates were removed. This may be due to the fact that other forms of phosphorus are transformed to ortho-phosphates due to low DO (Lantzke *et al.*, 1999). The HSF CW was the stage of the facility, which contributed the most in ortho-phosphate removal (around 20%), rising the total removal of ortho-phosphate to about 50%.

The facility showed an important TSS removal (93%). Although the pre-treatment stage should have shown a significant contribution in TSS removal, TSS removal there was below 30%. Particularly the settling tank contributed less in TSS removal, probably due to insufficient design. It seems that the 1st VF CW stage removed the larger portion of TSS (more than 40%) and the last two stages (2nd VF and HSF stages) removed an additional 20%, rising the overall removal above 90%. Total coliform removal was low in the pretreatment stages (around 20%). The CW stages of the facility removed around 70%, rising the overall removal to almost 99.9%. The stage with the maximum removal was the 1st VF CW stage (70 %).

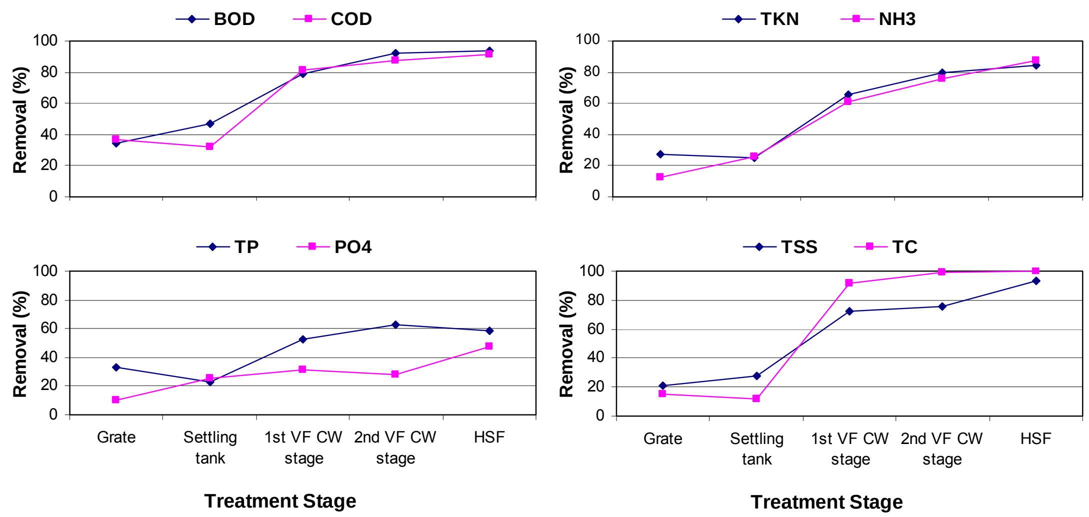

Figure 3. Pollutant mean removal charts along the facility stages

The influence of temperature on pollutant removal in this constructed wetland was also investigated. Figure 4 presents, BOD, COD, TKN, NH_4^+, PO_4^{-3} and TP removal in relation to temperature. Table 3 presents statistics of these pollutant removals separately for temperatures above and below 15°C. The temperature of 15°C was selected because below this temperature value the bacteria that are responsible for nitrogen removal do not work efficiently, and also plant growth is halted (Kuschk *et al.*, 2003).

With regards to BOD and COD removals, the influence of temperature was not so important, something also observed by Steinmann *et al.* (2003). The mean BOD removals were 89% and 93.5% for temperatures below and above 15^oC, respectively (Table 3). The respective mean COD removals were 95.1% and 91.2%. This fact supports the view that organic matter is removed mainly by the activity of aerobic and non-aerobic bacteria, which work efficiently also in low temperatures down to 5^oC (Greenway & Woolley, 1999; Steer *et al.*, 2002; Vymazal, 2002).

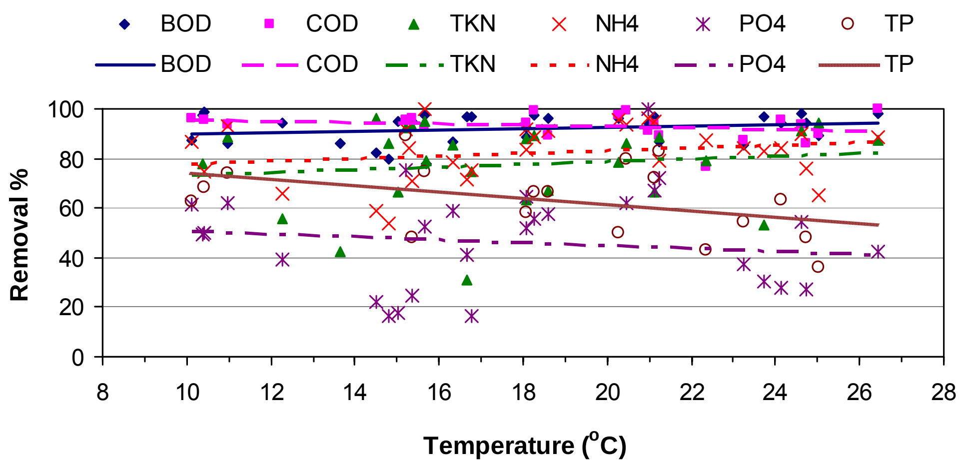

Figure 4. Pollutant removals as function of temperature

With regards to TKN and ammonia removals, the trend line in Figure 4 has a positive slope with wastewater temperature, which shows that the influence of temperature on pollutant removal is significant. For temperatures below 15^oC, mean TKN and NH_4^+ removals were 64.6% and 84.8%, respectively (Table 3). For temperatures above 15^oC the respective removals were 83.6% and 87.8%. The higher nitrogen removals for high temperatures are due to: (a) plants, that are growing in spring and summer and block nitrogen as nitrates and ammonia; and (b) bacteria responsible for nitrogen removal, that work better in temperatures above 15^oC (Reed *et al.*, 1995; Yang *et al.*, 2001; Vymazal, 2002; Kuschk *et al.*, 2003).

Finally, the trendline of TP removal has a negative slope with temperature, while that of ortho-phosphate removal a slightly positive slope (Figure 4; Table 3), indicating that the main mechanism of phosphorus removal in subsurface flow constructed wetlands is adsorption and precipitation, while the blocking by plants has a significant role only in the case of ortho-phosphates (Brooks *et al.*, 2000; Vymazal, 2004). The negative correlation of TP and temperature may be due to plant decomposition and water recharge with organic phosphorus, and/or phosphorus release from the porous media (Kadlec and Knight, 1996).

Table 3. Pollutant removal statistics for temperatures below and above 15^oC

Temperature	Statistical Parameter	Removal (%)					
		BOD	COD	TKN	$N\text{-}NH_4^+$	TP	$P\text{-}PO_4$
Below 15^oC	Mean	89.0	95.1	64.6	84.8	68.4	42.9
	SD	6.5	1.1	19.9	7.5	4.4	16.6
	Min	79.7	93.6	31.0	74.9	63.0	16.7
	Max	98.5	95.9	92.9	93.1	73.9	61.9
Above 15^oC	Mean	93.5	91.2	83.6	87.8	60.1	46.4
	SD	5.0	8.9	12.0	8.4	17.1	26.4
	Min	78.0	60.0	53.1	65.5	24.1	-8.7
	Max	98.3	100.0	100.0	100.0	89.3	100.0

CONCLUSIONS

From the first two years of operation, it seems that the Gomati CW facility operates successfully and removes pollutants satisfactorily. With regards to organic matter, BOD and COD mean removals were above 92.3% and 91.7%, respectively, and their effluent concentrations were low during most of the operation period, with the exception of cases of extremely low temperature. TKN and ammonia were removed satisfactorily with mean removals of 80.3% and 87.5%, respectively. Although the mean removal of nitrogen was high, there was significant removal variation during the year, as it strongly depends on temperature. Phosphorus showed also a satisfactory removal (around 60%), due to the fact that the facility is new (two years of operation) and the porous media of the CW cells are not saturated yet. TSS removal efficiency was 93.2%, even though the primary settlement did not function properly as it removed only a small percentage. This is probably due to insufficient design of the settling tank. Although TC removal efficiency was quite high (99.9%), the TC effluent number (mean: 53208 N/100ml) was still high for effluent use in irrigation, indicating the need for additional disinfection.

Results show that organic matter removal is not significantly affected by temperature, something not observed for TKN and ammonia, which showed dependence on temperature. Indeed, for temperature values above 15^{o}C, with plants growing and bacteria function promoted, nitrogen removal was significantly higher than that for temperature values below 15^{o}C. Ortho-phosphate removal also increased with temperature, while the opposite was observed for TP removal. This was expected, as the main mechanism of phosphorus removal is the adsorption to the porous medium.

The study shows that the use of constructed wetlands in wastewater treatment is a promising solution for small towns and villages in Greece.

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