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Performance of pilot-scale vertical flow constructed wetlands treating simulated municipal wastewater: effect of various design parameters

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Abstract

Ten pilot-scale, cylindrical, vertical flow constructed wetland units, of diameter 0.82 m and height 1.5 m, were designed, constructed, and operated treating a simulated municipal wastewater in parallel experiments. The operation scheme was 2 days feeding and 6 days resting. The 10 wetland units had various porous media materials (i.e., carbonate material, material from river bed, zeolite, and bauxite), two vegetation types (i.e., common reeds and cattails), and three total thicknesses of the porous media (i.e., 50, 80, and 90 cm). Water quality samples were collected at the inlet and the outlet of each unit, and were analyzed in the laboratory for BOD_5, COD, TKN, ammonia nitrogen, nitrate, nitrite, TP, and ortho-phosphate. This article presents the results obtained after operation of these systems for one full year. Organic matter removal proved to be very good in all 10 units, since it reached on the average 71.1% and 66.9% for BOD_5 and COD, respectively. Nitrogen removal was also satisfactory (47.1% for TKN and 42.2% for NH_4^+–N). TP and ortho-phosphate retention rates reached about 36.9% and 37.9%, respectively.

Keywords: Wastewater treatment; Constructed Wetlands; Vertical flow; Pilot-scale units.

1. Introduction and background

Constructed wetlands (CWs) are considered today as very promising technologies to treat wastewater. Their advantages include low construction and operation cost, simple operation and maintenance, exploitation of renewable energy sources (sun and wind), and favorable appearance [1,2]. Common systems in the United States are the free-water surface and horizontal subsurface flow (HSF), while vertical flow (VF) systems are more popular in Europe [1,3]. Growing interest over the VF systems took place at the beginning of the 1990s, in order to achieve more

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intensive oxidation of ammonia nitrogen, compared to HSF systems [4–7]. VF systems have proved very successful in wastewater treatment of small communities (<5.000 PE) [6–8]. They have been used to treat municipal and domestic wastewater [9–11], industrial wastewater [12], dairy wastewater [13], oil refinery wastewater [14], as well as sewage sludge [15–16]. Regarding municipal wastewater, mean removals in VF full-scale systems usually reach 95% for BOD_5 and suspended solids, 90% for TKN, and more than 50% for phosphorus [7,8].

Vertical flow constructed wetlands are characterized by the high oxygen transfer rate they can achieve [5]. The wastewater floods the wetland surface initially and then percolates through the wetland body by gravity [17,18]. As the wastewater percolates, air enters the substrate pores [3], enhancing the aeration and the microbial activity. VF systems perform well in organic matter (BOD_5 and COD) and suspended solids removal [6,19], while they can achieve a satisfactory level of nitrification [3,20–22].

Phosphorus removal in VF systems is limited [6,19], because of the inadequate contact time between the wastewater and the substrate. The proposed ways to enhance phosphorus removal include the use of special substrate materials with high adsorption capacity (i.e., rich in Ca, Al or Fe), the construction of an additional filter with an appropriate material for further treatment of the effluent [23], or the addition of a coagulant in a sedimentation tank before the wetland unit [19]. The proposed design principles differ among European countries. Guidelines in Denmark refer up to 3.2 m^2/PE [19], in Austria 5 m^2/PE [24], in the United Kingdom 1–2 m^2/PE, in Belgium 3.8 m^2/PE [25], and in Germany 2–3 m^2/PE [26].

A typical VF system usually comprises two or more stages with VF units, or stages which combine VF with HSF systems, the so-called hybrid systems [5,27,28]. The wastewater is introduced into one cell of the first stage (wet period), followed by a dry period, to allow for the re-establishment of aerobic conditions and the enhancement of BOD_5 and ammonia removals.

This article presents construction and operation details of 10 pilot-scale vertical flow constructed wetland units used for wastewater treatment, and evaluates treatment results, after operation for one full year, under a 2-day feeding/6-day resting operation scheme. The aim of the study is to test the effect of various design parameters on the removal of organic matter and nutrients. Metal removal was not tested, since metal concentrations in wastewater from small communities, where CWs are installed, are usually very low.

2. Materials and methods

2.1. Pilot-scale unit description

Ten pilot-scale, vertical flow constructed wetland units have been constructed and are in operation in an open-air laboratory.

The wetland units are cylindrical plastic tanks of diameter 0.82 m and height 1.5 m. In all the pilot-scale units, a drainage layer, 15 cm thick, made of cobbles (D_{50} = 90 mm) was placed at the bottom of each circular tank. This drainage layer also contains aeration tubes, which are PVC pipes (50 mm in diameter) perforated only within the drainage layer. Other porous media layers were placed on top, as described here. Three types of constructed wetland units were used: the European, the French, and the American type. The European type (units W1 to W8) includes from bottom to top, above the cobbles layer, a 10-cm thick layer of medium gravel (D_{50} = 24.4 mm), a 15 cm thick layer of fine gravel (D_{50} = 6 mm), and a 10-cm thick layer of sand (D_{50} = 0.5 mm), with a total thickness of 50.0 cm. The French type (unit W9) includes, above the cobbles layer, a 20 cm thick layer of medium gravel (D_{50} = 24.4 mm) and a 50-cm thick layer of fine gravel (D_{50} = 6 mm), with a total thickness of 90.0 cm. The American type (unit W10) has 80.0 cm in total thickness and includes, above the cobbles, a 25-cm thick layer of medium gravel (D_{50} = 24.4 mm), a 10 cm thick layer of fine gravel (D_{50} = 6 mm) and a 30-cm thick layer of sand (D_{50} = 0.5 mm).

Two porous media of different origins were used in the pilot-scale units. One was carbonate rock (main elements: Si 3.39%, Al 0.90%, Fe 0.82%, Ca 27.20, Mg 4.53%, P 0.03%) obtained from a quarry (units W1 to W6 and W8 to W10), and the other was obtained from a river bed (unit W7) in the area and is an igneous rock (Si 28.50%, Al 7.95%, Fe 4.22%, Ca 3.62%, Mg 1.76%, P 0.11%). In two pilot-scale units, the carbonate medium gravel was 50% mixed in one unit with zeolite (mixed D_{50} = 13.0 mm) and in the other unit with bauxite (mixed D_{50} = 17.5 mm) (units W5 and W6, respectively). In another unit, the carbonate medium gravel was totally replaced by zeolite (unit W4). The composition of the natural zeolite (D_{50} = 15 mm) is: calcic clinoptilolite 88% (chemical formula $Ca_{1.7}K_1Mg_{0.6}Si_{29.8}O_{72}\cdot 20.4H_2O$), aluminate minerals 4%, silica 3%, and microporous minerals 92% w/w. The chemical composition of the bauxite (D_{50} = 21 mm) is 50–55% Al_2O_3, 20–22% Fe_2O_3, >5% TiO_2, 5–8% SiO_2, and 0.5% CaO. The natural zeolite used in the study originated from natural deposits in the Evros area in northeastern Greece, and the bauxite from deposits in Parnassos mountain in Central Greece.

Two plant types were used: common reed (*Phragmites australis*) (units W1 and W4 to W10) and cattails (*Typha latifolia*) (unit W2), while one unit (W3) remained unplanted. The plants were collected from watercourses in the vicinity of the experimental facilities. Furthermore, one unit (W8) did not have aeration tubes. Table 1 contains the main design characteristics of each pilot-scale vertical flow constructed wetland. Various pictures from the experimental setup are presented in Fig. 1.

The units were constructed in June 2007 and planted immediately after their establishment. The 10 units were filled initially with water and left for the plants to grow and adjust to the new environment. From October 2008, synthetic wastewater was introduced into the units and experiments were started. Synthetic wastewater

Table 1
Pilot-scale vertical flow constructed wetland unit characteristics

Pilot-scale unit	Medium gravel	Fine gravel	Plant	Aeration tubes	Wetland Type
W1	Carbonate (quarry)		Reed	Yes	European
W2	Carbonate (quarry)		Cattail		
W3	Carbonate (quarry)		Unplanted		
W4	Zeolite	Carbonate (quarry)	Reed		
W5	50% Carbonate 50% Zeolite	Carbonate (quarry)			
W6	50% Carbonate 50% Bauxite	Carbonate (quarry)			
W7	River-bed				
W8	Carbonate (quarry)			No	
W9	Carbonate (quarry)			Yes	French
W10	Carbonate (quarry)				USA

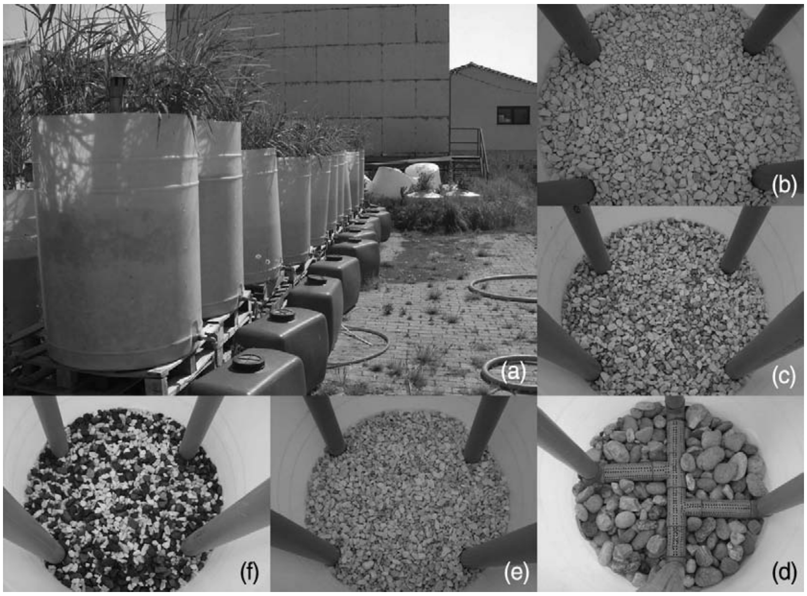

Fig. 1. Photos from the pilot-scale unit construction: (a) a general view of the 10 wetland units; (b) second layer with zeolite; (c) second layer with medium gravel and zeolite; (d) cobbles drainage layer and ventilation tubes; (e) medium gravel (carbonate); and (f) second layer with medium gravel and bauxite.

was designed and used to simulate to the best the characteristics of domestic wastewater [29]. The synthetic wastewater contained organic substances and a source of nitrogen, phosphorus, and other elements. The organic substances used were peptone (200 mg/L; which is the protein source), cane sugar (200 mg/L; which is the source of saccharose), and acetic acid (50 mg/L; which is the source of organic acids). Inflowing concentrations of BOD and COD were approximately 400 and 600 mg/L, respectively, which are typical values for wastewater from small communities. The source of phosphorus was hydrogen potassium phosphate (K_2HPO_4) with a typical inlet concentration of 10 mg/L PO_4^{-3}–P. The main source of nitrogen was urea with a typical inlet concentration of 60 mg/L TKN. For the other elements, a commercial agricultural fertilizer in powder was used. The typical inlet concentrations of other elements in the fertilizer were: Mg^{+2} 20 mg/L, Ca^{2+} 20 mg/L, Fe^{2+} <1 mg/L, and W^{2+} <0.1 mg/L. Although synthetic wastewater does not fully simulate the domestic wastewater, for these experiments the main purpose was to examine the comparative treatment performance of the 10 wetland units with different operational and constructional characteristics. In that sense, synthetic wastewater could be used. Furthermore, synthetic wastewater has the advantage of minimizing variations of influent characteristics and is also safe for people in the laboratory.

Wastewater was introduced to the units for 2 days (wet period) in three equal portions of 37 L/unit every 8 h (111 L/d). For these experiments, each unit was considered to operate in a series of four parallel cells in the first stage of a real system. Therefore, the dry period that follows each wet period was 6 days. The equivalent population for each unit can be calculated using the following approaches: First, using the inflowing rate and comparing it to an average inflow value of 150 L/PE/d (typical value for small settlements in Greece), one gets approximately

0.74 PE. A second computation would consider a typical surface area for the first stage of such systems of about 1.5 m^2/PE, which leads to about 0.38 m^2/PE when four parallel wetland cells are used in the first stage; considering that the area of the pilot-scale unit is approximately 0.53 m^2, one gets 0.72 PE. Both computations lead practically to the same value.

2.2. Water quality sampling and monitoring

The experiments lasted for one full year (from October 2007 until September 2008). Water samples were collected from the influent and from all pilot-scale effluent in the morning after the last wastewater introduction. The samples were analyzed in the laboratory following standard methods [30] for the determination of BOD_5, COD, TKN, ammonia nitrogen (NH_4^+–N), nitrite and nitrate, total phosphorus (TP), and ortho-phosphate (PO_4^{-3}–P). For BOD determination, respirometric bottles were used; for COD, the open reflux method; for TKN and ammonia, the titrimetric method; for phosphorus, the stannous chloride method; and for nitrite and nitrate, ion chromatography (IC-3000, Dionex) [30]. Meteorological data (air temperature, solar radiation, air humidity, wind velocity, and precipitation depth) were recorded on site, at a 5-min time interval, using an ELE MM900/950 meteorological station.

2.3. Statistical tests

In order to investigate statistically how different the mean removal efficiency values of the wetland units were, the *t*-student confidence interval for 95% probability was calculated. If the 0.0 value is contained within the 95% confidence interval where the difference of the mean values ranges, then the difference of the mean values is not statistically significant, otherwise it is.

3. Results and discussion

3.1. Meteorological and physicochemical parameter variation

Meteorological data (air temperature, solar radiation, air humidity, wind velocity, and precipitation depth) for the operation period of the wetland units are presented in Fig. 2a–d. Measured influent and effluent physicochemical parameter (pH, DO, conductivity, and wastewater and air temperature) statistics of each pilot-scale unit are presented in Table 2. Fig. 2e–h presents variations of these parameters during the operating period of the units.

The mean pH values were similar in all wetland units. During the first months of operation, mean pH values varied between 6.0 and 6.5, as Fig. 2e shows, and toward the end of the operation period showed the trend to be kept close to the neutral or slightly alkaline zone (7.0–7.5). The same was also observed for conductivity. After the first months of operation, conductivity values gradually increased (Fig. 2g). Possible interactions between the substrate and the formed biofilm might have caused release of water-soluble salts, thus increasing conductivity. Moreover, plant growth during the last months (especially after March) enhanced evaporation and transpiration, resulting in higher conductivity values. This has also been observed elsewhere [31].

As Fig. 2f shows, oxygen concentration was relatively low during the first months of unit operation, but increased with time, especially after March. This can be attributed to plant growth during the spring months. Mean dissolved oxygen concentrations were practically near zero in all pilot-scale units, mainly due to the presence of microorganisms, which consume the available oxygen to oxidize organic matter or to nitrify ammonia cations (e.g., *Nitrosomonas* and *Nitrobacter*). Fig, 2h presents air and wastewater temperature variations for each pilot-scale unit. It is obvious that the wetland units operated

Table 2
Statistical data of pollutant removal rates and physicochemical parameter statistics for each wetland unit

Parameter		Removal (%)										
		W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	Mean (W1-W10)
BOD_5	Mean	68.2	71.5	69.5	69.4	70.2	72.2	75.1	68.6	64.8	81.5	71.1
	SD	16.2	15.4	18.0	15.8	16.3	16.6	12.7	15.7	11.6	9.8	14.8
	Min	30.9	40.2	29.3	34.7	37.1	34.2	48.1	31.6	34.1	49.3	37.0
	Max	90.9	92.2	94.8	89.0	95.1	92.0	97.2	89.7	86.5	95.6	92.3
COD	Mean	65.7	68.0	66.6	64.3	66.3	66.4	67.6	64.9	61.3	77.6	66.9
	SD	15.2	15.9	17.9	16.2	16.7	18.3	16.0	15.7	13.1	11.8	15.7
	Min	33.4	34.7	21.3	30.1	26.9	24.8	36.4	32.7	23.1	46.7	31.0
	Max	91.4	91.2	89.1	86.4	91.3	92.1	92.0	89.6	86.4	93.6	90.3
TKN	Mean	46.0	49.0	41.0	50.2	52.2	46.5	48.0	40.1	38.4	59.3	47.1
	SD	9.8	12.2	14.0	11.2	12.7	12.4	15.8	11.7	13.7	12.5	12.6
	Min	26.1	6.0	10.9	22.3	29.5	23.0	3.7	9.0	10.3	31.9	17.3
	Max	69.2	71.8	72.6	74.6	74.5	75.9	71.4	59.1	65.4	80.4	71.5
NH_4^+–N	Mean	39.9	42.9	36.7	46.6	47.9	41.1	47.3	32.8	32.0	56.4	42.4
	SD	13.4	15.0	15.9	13.1	14.9	13.8	13.3	11.8	13.1	12.2	13.6
	Min	18.4	3.2	6.2	18.9	16.8	12.4	20.2	13.5	8.4	25.5	14.3
	Max	68.6	70.8	61.3	85.3	71.6	75.9	77.4	59.7	59.9	77.7	70.8
TP	Mean	34.2	36.5	33.7	34.5	35.2	40.1	39.3	35.2	36.6	43.6	36.9
	SD	15.9	12.2	11.0	10.6	12.7	15.0	14.4	14.9	16.1	14.4	13.7
	Min	9.6	8.5	16.3	13.3	12.7	12.2	8.9	4.0	12.2	15.1	11.3
	Max	67.5	61.5	63.2	59.5	57.3	67.3	65.4	70.8	81.1	82.4	67.6
PO_4^{-3}–P	Mean	36.7	39.9	33.9	38.1	39.4	39.6	38.9	33.0	34.9	44.4	37.9
	SD	16.5	15.5	14.6	15.1	15.5	16.7	16.0	14.2	15.1	15.2	15.4
	Min	7.7	4.1	7.0	14.4	7.1	11.4	9.5	2.6	8.1	19.7	9.2
	Max	80.9	79.7	77.2	81.0	79.7	82.3	83.5	86.1	78.5	81.5	81.0
		Physicochemical parameters statistics										
pH	Mean	7.2	7.3	7.3	7.1	7.1	7.1	7.1	7.1	7.0	7.4	7.2
	SD	0.6	0.7	0.6	0.5	0.6	0.6	0.6	0.6	0.7	0.5	0.6
	Min	6.1	5.8	6.2	6.2	5.9	6.0	6.0	5.9	4.8	6.2	5.9

(Continued)

Table 2 *(Continued)*

	Max	8.2	8.5	8.4	7.8	8.2	8.0	8.1	8.1	8.3	8.5	8.2
Conductivity (µS/cm)	Mean	722.9	710.2	729.5	719.4	710.1	729.5	702.4	742.2	741.2	734.0	724.1
	SD	63.7	56.8	46.0	63.1	70.9	71.0	66.5	86.7	96.0	68.3	68.9
	Min	600.0	605.0	646.0	598.0	601.0	595.0	555.0	587.0	511.0	601.0	589.9
	Max	890.0	830.0	826.0	815.0	883.0	897.0	823.0	926.0	890.0	888.0	866.8
DO(mg/L)	Mean	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.4	0.2
	SD	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.4	0.2
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
	Max	1.0	0.6	0.5	0.6	0.9	1.0	0.9	0.6	0.2	1.5	0.8
Temperature (°C)	Mean	16.2	16.3	16.3	16.4	16.4	16.4	16.5	16.5	16.3	16.4	16.4
	SD	8.5	8.4	8.5	8.5	8.5	8.5	8.4	8.5	8.5	8.6	8.4
	Min	2.3	2.8	2.4	3.6	3.2	2.2	3.4	2.8	3.0	2.1	2.8
	Max	28.5	28.5	28.7	28.5	28.9	29.4	28.9	29.5	28.4	28.4	28.8

Number of samples: 36

in a wide range of temperature, which included both low and high values.

3.2. Overall removal statistics

Table 2 presents respective mean removal rates for each pollutant, while Table 3 contains statistical data of influent and effluent concentrations of different pollutants for all pilot-scale wetland units. Figure 3 contains charts of the removal efficiency during the operation period of the 10 wetland units.

The 10 vertical flow constructed wetland units present a quite satisfactory performance in organic matter removal. Mean effluent concentrations are 132.6 mg/L for BOD_5 and 186.1 mg/L for COD (Table 3), with respective mean removal rates for all units 71.1% and 66.9% (Table 2). Mean removal rates for BOD_5 vary from 64.8% to 81.5% and for COD from 61.3% to 77.6% in the 10 wetland units (Table 2; Figs. 3a,b), indicating a rather satisfactorily operation. It has to be noted that the results simulate the first stage of full-scale systems, which include two or three stages of wetlands where additional removal takes place, usually exceeding 90.0% [18].

The performance in nitrogen removal is also positive. Mean TKN and NH_4^+–N removal rates for all wetland units are 47.1% and 42.4% (Table 2), respectively, as Fig. 3c and d also shows, with mean effluent concentrations 34.6 mg/L for TKN and 26.5 mg/L for ammonia nitrogen (Table 3). The rather high removal efficiencies of nitrogen, in addition to the relative low mean effluent concentration of nitrate and nitrite (3.9 mg/L for NO_3^-–N, 0.8 mg/L for NO_2^-–N; Table 3), indicate that nitrification and denitrification take place simultaneously in the wetland body. Organic matter and nitrogen removal rates confirm the sufficient level of substrate aeration achieved with vertical flow systems, resulting in significant BOD_5 reduction and adequate nitrification [6,19,21].

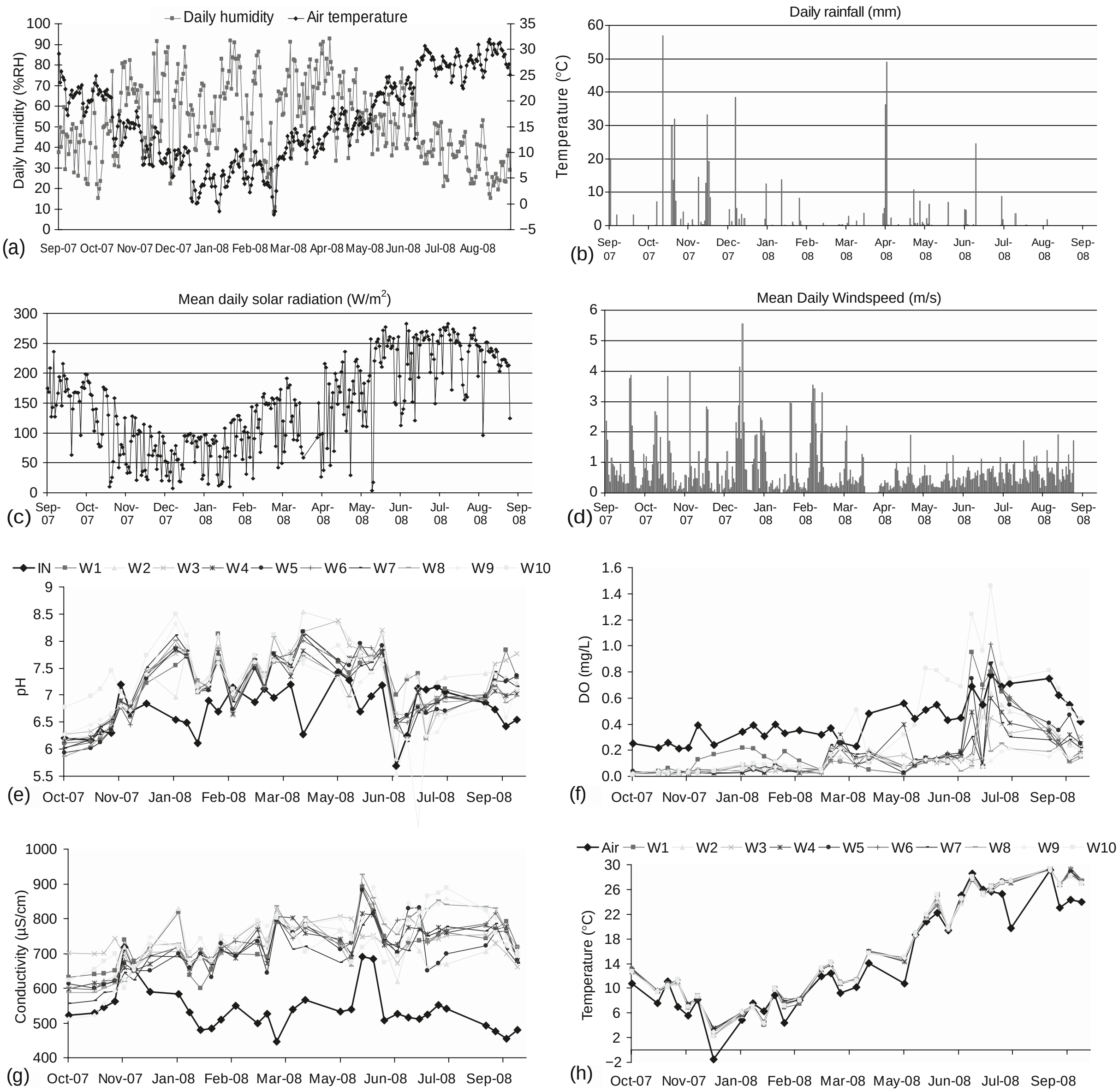

Fig. 2. Meteorological data variations during the unit operation period: (a) daily humidity and air temperature; (b) daily rainfall; (c) mean daily solar radiation; and (d) mean daily wind speed; and variation of various physicochemical parameters: (e) pH; (f) conductivity; (g) dissolved oxygen; and (h) temperature.

Phosphorus retention in all units has already exceeded the expected performance based on literature (20–30%) [19], as Figs. 3e and f present. Mean TP removal rate reached 36.9%, while the respective value for ortho-phosphate was 37.9% (Table 2). Mean effluent concentrations of TP and ortho-phosphate in all units were 6.7 and 4.5 mg/L (Table 3), respectively.

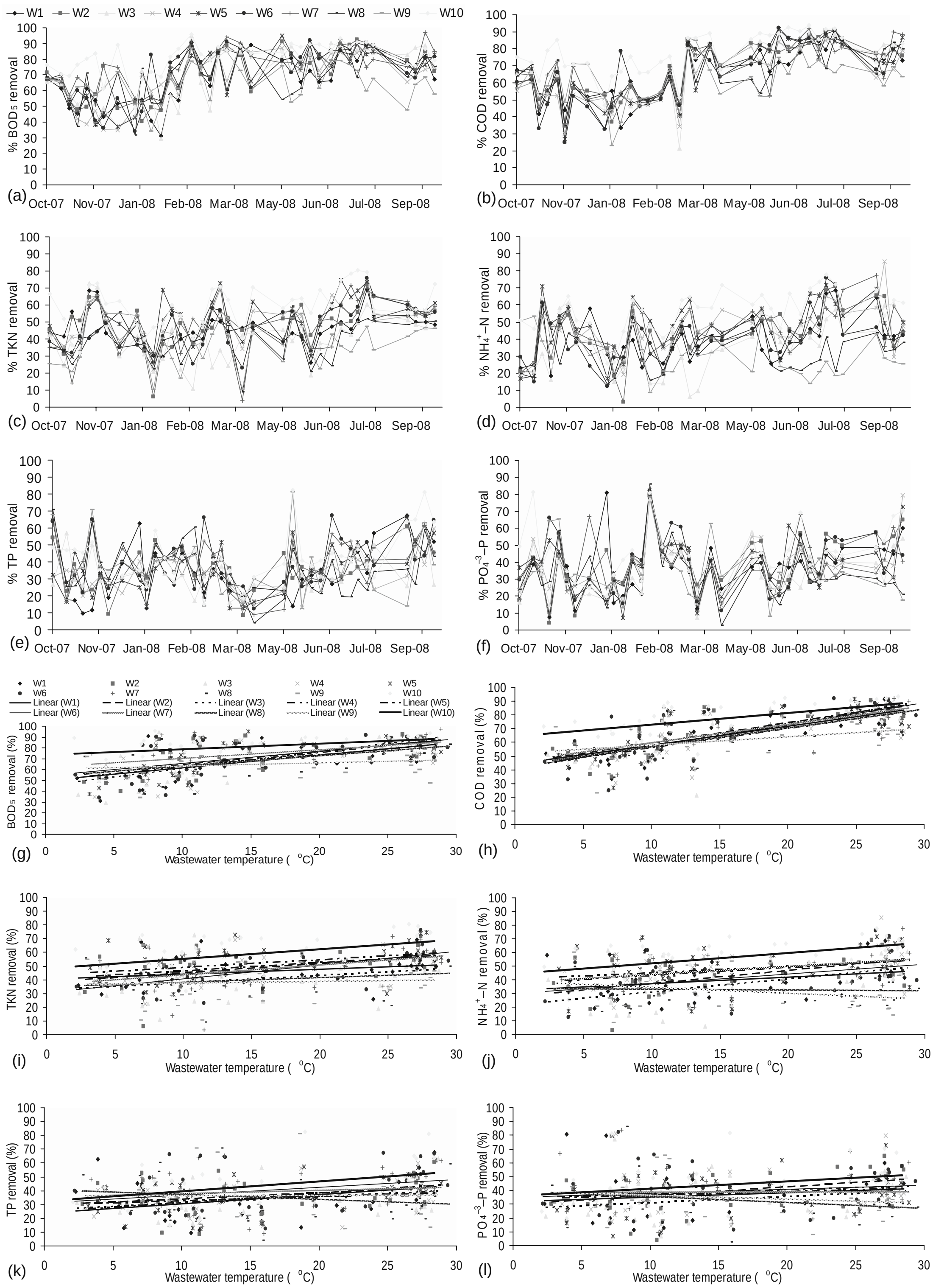

Fig. 3. Variation of pollutant removal rates during the unit operation period: (a) BOD_5; (b) COD; (c) TKN; (d) NH_4^+–N; (e) TP; and (f) PO_4^{-3}–P; and ccorrelation charts of: (g) BOD_5; (h) COD; (i) TKN; (j) NH_4^+–N; (k) TP; and (l) PO_4^{-3}–P removal with wastewater temperature.

Table 3
Statistical data of overall influent and effluent pollutant concentrations for each wetland unit

Parameter		Concentration (mg/L)											
		Influent	Effluent										
			W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	Mean (W1–W10)
BOD_5	Mean	469.6	147.2	132.1	140.2	139.8	136.5	126.0	114.3	143.7	161.9	84.2	132.6
	SD	77.7	76.6	71.5	82.8	67.1	72.0	71.9	58.8	69.6	52.8	40.6	66.4
	Min	303.0	45.1	33.8	33.8	49.3	21.1	39.4	14.4	49.3	67.5	28.5	38.2
	Max	727.0	346.0	287.0	354.0	277.8	307.0	295.0	260.0	312.0	332.0	200.2	297.1
COD	Mean	568.7	194.6	181.2	188.8	200.4	188.5	187.0	181.1	197.2	217.8	124.8	186.1
	SD	100.2	92.5	93.6	103.3	93.6	95.6	100.5	90.5	89.3	80.3	64.1	90.3
	Min	384.8	48.0	48.0	65.1	76.8	62.4	52.8	48.0	76.4	75.8	38.4	59.2
	Max	799.2	399.2	372.5	412.9	374.4	391.7	403.0	341.0	351.0	453.1	255.3	375.4
TKN	Mean	66.0	35.3	33.5	38.5	32.6	31.3	35.2	33.9	39.3	40.0	26.6	34.6
	SD	10.4	7.5	9.1	9.8	7.9	8.8	9.5	9.7	8.4	7.8	8.6	8.7
	Min	46.5	21.6	19.8	21.8	15.4	13.7	16.9	14.6	19.9	23.2	13.3	18.0
	Max	88.8	52.6	55.7	59.6	49.0	48.4	52.4	51.7	60.5	52.4	48.4	53.1
NH_4^+–N	Mean	45.7	27.5	26.4	29.0	24.7	23.9	27.1	24.4	30.9	31.2	20.1	26.5
	SD	8.6	7.9	9.4	9.3	8.1	8.3	9.0	8.1	8.5	8.9	7.9	8.5
	Min	28.3	10.1	9.8	12.3	4.5	8.7	11.2	6.4	14.0	16.2	8.9	10.2
	Max	69.0	49.0	50.7	51.5	42.3	43.1	45.4	38.9	50.4	48.2	44.5	46.4
TP	Mean	10.9	7.0	6.8	7.2	7.1	7.0	6.3	6.3	6.8	6.5	6.1	6.7
	SD	4.1	2.2	2.4	3.1	3.0	3.0	2.0	1.7	2.0	1.7	2.6	2.4
	Min	6.0	2.0	2.4	3.4	3.2	3.4	2.0	3.5	3.5	2.0	1.8	2.7
	Max	30.3	11.5	13.8	22.3	20.8	20.5	10.9	10.5	13.0	9.8	15.6	14.9
PO_4^{-3}–P	Mean	7.1	4.6	4.4	4.8	4.5	4.4	4.4	4.3	4.7	4.7	4.1	4.5
	SD	2.9	2.5	2.4	2.5	2.3	2.3	2.3	2.0	2.1	2.2	2.2	2.3
	Min	2.0	0.8	0.7	0.9	0.4	0.5	1.1	1.2	1.1	1.1	0.6	0.8
	Max	13.3	10.1	10.5	10.4	9.2	9.8	9.4	8.4	8.5	9.2	10.0	9.6

(Continued)

Table 3 (*Continued*)

NO_3^-–N	Mean	4.7	3.4	3.6	3.5	3.2	3.9	2.7	3.1	3.4	3.4	7.8	3.9
	SD	4.7	3.6	3.9	4.1	4.0	3.5	3.2	3.9	4.2	5.2	5.8	4.2
	Min	0.7	0.2	0.2	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.2	0.1
	Max	23.8	15.7	15.6	15.7	13.9	14.2	11.7	14.8	14.8	19.5	26.3	16.9
NO_2^-–N	Mean	0.6	0.9	1.0	0.4	0.7	1.3	0.5	0.9	0.6	0.3	1.8	0.8
	SD	1.6	1.3	1.9	0.4	1.5	1.7	0.6	1.3	0.9	0.7	2.0	1.3
	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	7.3	6.0	9.9	1.2	5.9	6.9	2.3	5.3	3.3	3.3	8.1	5.4

Number of samples: 36

3.3. Effect of temperature

Fig. 3g–l presents correlation charts of pollutant removal rates with wastewater temperature. A linear regression line in each chart is used to show the trend of pollutant removal variations with temperature. Tables 4 and 5 present pollutant removal statistics at temperatures below and above 15°C. This temperature value was selected because below it neither the bacteria responsible for nitrogen removal nor the vegetation functions properly [32,33]. Table 6 contains statistical analysis for pollutant removal rates at low and high temperatures.

With respect to organic matter (Fig. 3g and h), the dependence of removal efficiency on temperature seems to be significant. The same is also true for nitrogen removal (Fig. 3i and j). This has to do with the positive relation of higher temperatures with plant growth, which takes place in spring months (after March 2008). Organic matter removal rates were initially around 60.0%, and after March, they increased and reached 75.0 to 80.0%, which implies that initial removal must be attributed mainly to the microbial activity [24] and, secondarily, to the plant activity. Tables 4 and 5 confirm that removal rates are higher at high temperatures. Mean BOD_5 and COD removals at all units at temperatures below 15°C were 65.8% and 58.6%, respectively, while for temperatures above 15°C respective values increased and reached 78.6% and 78.5%. Furthermore, Table 6 shows that removal rates at high temperatures are statistically significantly higher for all units compared to removals at low temperatures, with the exception of the W9 unit, which also showed the lowest organic matter removal among all wetland units (Table 2).

In the case of nitrogen, the temperature dependence is also significant, because plant uptake plays a more important role in nitrogen removal [24,34,35] and microorganisms responsible for nitrogen removal function optimally at

Table 4
Statistical data of pollutant removal rates for each wetland unit for temperatures below 15°C

Parameter		Removal (%)										
		W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	Mean (W1–W10)
BOD_5	Mean	62.5	64.7	60.4	63.8	63.0	65.6	71.4	63.7	63.9	78.6	65.8
	SD	17.7	15.9	17.9	17.9	17.4	18.2	14.0	17.2	12.7	10.8	16.0
	Min	30.9	40.2	29.3	34.7	37.1	34.2	48.1	31.6	34.1	49.3	37.0
	Max	90.9	91.1	94.8	89.0	95.1	91.2	94.3	89.0	86.5	95.6	91.7
COD	Mean	57.5	58.9	56.0	55.3	56.1	56.2	59.7	56.3	58.1	72.0	58.6
	SD	13.9	14.2	15.9	14.4	13.7	16.1	13.8	13.2	15.1	11.3	14.2
	Min	33.4	34.7	21.3	30.1	26.9	24.8	36.4	32.7	23.1	46.7	31.0
	Max	84.2	85.8	81.1	82.5	82.1	82.1	84.4	83.9	86.4	89.1	84.2
TKN	Mean	44.7	45.6	38.6	47.1	49.6	40.9	43.8	38.0	37.4	55.3	44.1
	SD	10.4	13.0	15.2	11.3	12.4	10.0	16.5	12.0	16.2	12.8	13.0
	Min	29.4	6.0	10.9	22.3	29.5	23.0	3.7	9.0	10.3	31.9	17.6
	Max	68.3	65.1	72.6	69.3	72.7	57.9	70.9	58.4	65.4	72.5	67.3
NH_4^+–N	Mean	37.6	36.9	30.0	43.8	46.0	38.1	44.6	34.2	33.7	52.6	39.8
	SD	13.0	13.3	15.6	11.3	14.5	12.0	12.3	12.8	13.0	12.3	13.0
	Min	18.4	3.2	6.2	18.9	16.8	12.4	20.2	13.5	8.4	25.5	14.3
	Max	61.4	56.2	61.3	58.5	70.9	61.4	69.5	59.7	59.9	71.6	63.0
TP	Mean	30.2	34.2	29.7	31.5	30.4	36.9	37.9	37.3	36.3	38.1	34.2
	SD	15.1	12.3	7.8	8.9	11.8	15.0	15.5	16.9	14.3	10.5	12.8
	Min	9.6	8.5	16.3	14.4	12.7	12.2	8.9	4.0	14.0	15.1	11.6
	Max	64.6	54.4	49.9	44.3	51.7	66.3	65.4	70.8	70.7	58.6	59.7
PO_4^{-3}–P	Mean	34.1	35.7	31.3	35.4	37.5	38.6	38.3	35.3	37.5	40.0	36.4
	SD	19.7	16.2	16.7	15.8	17.0	19.2	18.2	17.2	17.4	14.1	17.1
	Min	7.7	4.1	7.0	14.4	7.1	11.4	9.5	2.6	12.9	19.7	9.6
	Max	80.9	79.7	77.2	81.0	79.7	82.3	83.5	86.1	78.5	81.0	81.0

Number of samples: 21

Table 5
Statistical data of pollutant removal rates for each wetland unit for temperatures above 15°C

Parameter		Removal (%)										
		W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	Mean (W1–W10)
BOD_5	Mean	76.1	80.9	82.3	77.1	80.4	81.4	80.3	75.4	66.1	85.5	78.6
	SD	9.8	8.5	7.6	7.6	6.6	7.9	8.7	10.4	10.3	6.7	8.4
	Min	61.3	63.6	64.2	65.2	66.0	68.0	68.4	57.6	47.6	70.5	63.2
	Max	89.9	92.2	90.4	87.4	90.7	92.0	97.2	89.7	81.4	93.4	90.4
COD	Mean	77.3	80.8	81.6	76.9	80.7	80.7	78.7	76.8	65.9	85.5	78.5
	SD	7.5	6.6	5.4	8.1	7.1	9.5	11.7	10.1	8.1	7.3	8.1
	Min	65.8	64.5	66.5	63.0	68.1	62.0	52.7	53.8	51.9	71.8	62.0
	Max	91.4	91.2	89.1	86.4	91.3	92.1	92.0	89.6	81.3	93.6	89.8
TKN	Mean	47.7	53.7	44.3	54.4	55.9	54.4	53.8	43.0	39.7	65.0	51.2
	SD	9.1	9.4	11.8	9.8	12.7	11.2	13.1	11.0	9.5	9.9	10.8
	Min	26.1	31.0	18.9	35.1	29.8	32.7	34.3	20.8	22.3	52.0	30.3
	Max	69.2	71.8	60.6	74.6	74.5	75.9	71.4	59.1	54.8	80.4	69.2
NH_4^+–N	Mean	43.1	51.2	46.1	50.5	50.5	45.4	51.0	30.9	29.6	61.9	46.0
	SD	13.7	13.5	11.1	14.7	15.7	15.4	14.1	10.3	13.3	9.9	13.2
	Min	25.0	20.6	21.1	25.0	18.6	14.9	26.8	17.4	13.8	46.1	22.9
	Max	68.6	70.8	60.7	85.3	71.6	75.9	77.4	53.7	53.4	77.7	69.5
TP	Mean	39.7	39.8	39.4	38.5	41.8	44.6	41.2	32.3	37.1	51.3	40.6
	SD	15.9	11.7	12.5	11.8	11.2	14.2	12.9	11.5	19.0	15.9	13.7
	Min	13.7	22.8	22.9	13.3	16.5	25.5	16.5	19.3	12.2	30.8	19.3
	Max	67.5	61.5	63.2	59.5	57.3	67.3	61.5	59.0	81.1	82.4	66.0
PO_4^{-3}–P	Mean	41.4	45.9	37.5	41.9	42.1	41.0	39.6	29.6	31.2	50.6	40.1
	SD	8.5	12.7	10.6	13.6	13.2	13.0	12.9	7.6	10.7	14.9	11.8
	Min	27.3	28.0	21.0	24.4	23.0	18.1	19.4	15.0	8.1	28.4	21.3
	Max	60.0	65.0	54.2	79.6	72.8	57.6	68.1	45.1	50.5	81.5	63.4

Number of samples: 15

Table 6
t-student confidence interval for the comparison of the mean removal values in the wetland units at low (<15°C) and high (>15°C) temperatures and for the different characteristics among the units

Comparison	Unit	BOD_5	COD	TKN	NH_4^+–N	TP	PO_4^{-3}–P
Removal rates for temperatures below and above 15°C	W1	(−25.0, −2.4)*	(−28.7, −11.1)*	(−11.0, 5.1)	(−16.7, 5.7)	(−22.4, 3.5)	(−19.1, 4.5)
	W2	(−26.2, −6.1)*	(−30.5, −13.2)*	(−17.3, 1.1)	(−25.5, −3.1)*	(−15.6, 4.3)	(−22.1, 1.6)
	W3	(−32.5, −11.2)*	(−34.7, −16.6)*	(−16.7, 5.4)	(−27.1, −5.2)*	(−18.7, −.08)*	(−17.4, 5.0)
	W4	(−24.0, −2.6)*	(−30.8, −12.3)*	(−16.0, 1.4)	(−17.9, 4.6)	(−15.9, 1.9)	(−18.6, 5.6)
	W5	(−27.6, −7.3)*	(−33.2, −16.0)*	(−16.9, 4.2)	(−17.2, 8.3)	(−20.9, −1.9)*	(−16.9, 7.8)
	W6	(−26.7, −4.9)*	(−35.0, −14.0)*	(−22.5, −4.5)*	(−19.2, 4.4)	(−19.8, 4.4)	(−15.6, 10.8)
	W7	(−18.2, 0.4)	(−29.5, −8.4)*	(−22.2, 2.1)	(−17.6, 4.8)	(−15.0, 8.4)	(−14.0, 11.5)
	W8	(−23.0, −0.4)*	(−30.1, −10.9)*	(−14.6, 4.5)	(−6.2, 12.9)	(−6.6, 16.7)	(−4.7, 16.1)
	W9	(−11.6, 7.3)	(−17.4. 1.7)	(−12.9, 8.3)	(−6.9, 15.1)	(−15.1, 13.4)	(−5.3, 17.8)
	W10	(−14.1, 0.2)	(−21.1, −5.9)*	(−18.9, −0.3)*	(−18.5, −0.2)*	(−24.8, −1.6)*	(−22.8, 1.4)
Wetland type	W1−W10	(−5.9, −20.7)*	(−4.4, −19.4)*	(−7.2, −19.6)*	(−23.6, −9.5)*	(−1.0, −17.8)*	(1.4, −15.9)
	W1–W9	(−4.5, 11.1)	(−3.4, 12.2)	(1.0, 14.2)*	(0.3, 15.6)*	(−11.8, 6.8)	(−6.9, 11.3)
	W9–W10	(−22.6, −10.7)*	(−23.2, −9.4)*	(−28.2, −13.8)*	(−31.4, −17.5)*	(−15.8, 1.9)	(−18.3, −0.8)*
Vegetation type	W1–W2	(5.4, −12.1)	(6.3, −10.9)	(3.1, −9.2)	(−10.8, 4.9)	(5.5, −10.2)	(5.9, −11.6)
	W1–W3	(−10.8, 8.1)	(−10.1, 8.3)	(−1.7, 11.6)	(−5.3, 11.8)	(−7.5, 8.4)	(−5.8, 12.1)
	W2–W3	(−7.3, 11.2)	(−7.9, 10.7)	(0.8, 15.2)*	(−2.3, 14.7)	(−3.9, 9.5)	(−2.7, 14.8)
Substrate material	W1–W7	(1.1, −14.9)	(6.8, −10.4)	(5.3, −9.3)	(−14.7, −0.1)*	(3.3, −13.5)	(7.2, −10.7)
	W1–W4	(−10.1, 7.6)	(−7.2, 10.1)	(−10.0, 1.6)	(−14.4, 1.0)	(−8.1, 7.6)	(−10.1, 8.1)
	W4–W7	(−13.6, 2.2)	(−12.1, 5.6)	(−5.3, 9.8)	(−7.9, 6.6)	(−12.2, 2.5)	(−9.8, 8.3)
	W4–W5	(−9.7, 8.0)	(−11.1, 7.1)	(−8.7, 4.5)	(−9.0, 6.5)	(−7.5, 6.1)	(−10.2, 7.5)
	W4–W6	(−11.8, 6.1)	(−11.6, 7.4)	(−2.8, 10.2)	(−1.9, 12.9)	(−13.2, 1.9)	(−10.7, 7.7)
	W5–W6	(−11.1, 7.1)	(−9.7, 9.6)	(−1.2, 12.7)	(−1.2, 14.7)	(−12.9, 3.1)	(−9.5, 9.1)
Substrate aeration	W1–W8	(8.4, −9.2)	(9.4, −7.6)	(11.8, −0.1)	(0.2, 14.1)*	(7.5, −9.6)	(12.5, −4.3)

* Implies statistically significantly different mean values.

higher temperatures [32,33]. The positive effect of temperature becomes clearer when the mean removal rates at temperatures below (44.1% for TKN and 39.8% for NH_4^+–N; Table 4) and above 15°C (51.2% for TKN and 46.0% for NH_4^+–N; Table 5) are compared. Statistical difference occurred for TKN removal in the W6 and W10 units (Table 6), which showed the highest difference in TKN removal rates at high temperatures (13.5% in the W6 and 9.7% in the W10 unit; Tables 4 and 5). In the case of ammonia nitrogen, removal rates in the W2, W3 and W10 units are statistically significantly higher at high temperatures. The W3 and W10 units showed the highest difference in ammonia nitrogen removal at high temperatures (16.1% in the W3 and 9.3% in the W10 unit; Tables 4 and 5). Enhanced nitrogen removal in the W2 unit at high temperatures implies that cattails intensify their activity through their extensive and vigorous root system, while increased removal in the unplanted W3 unit implies that microbial consumption and uptake is significantly affected by temperature. The W10 unit reached the highest removals among all units at both temperatures below and above 15°C.

Phosphorus removal also seems to be slightly favored by temperature increase, as Fig. 3k and l show. Plant activity after March can also be considered responsible for this behavior. Since adsorption is the main phosphorus removal mechanism [24,35,36], minimization of variations in phosphorus removal and a slight increase in removal rates after March should be attributed to plant growth and uptake at higher temperatures. Results obtained from Tables 4 and 5 confirm these remarks. Mean TP and PO_4^{-3}–P removal rates at temperatures below 15°C were 34.2% and 36.4%, respectively, and above 15°C, 40.6% and 40.1%. TP retention in the W3, W5, and W10 units is statistically significantly higher at high temperatures (Table 6). These units showed the highest increase in TP retention at high temperatures (9.7%, 11.4%, and 13.2% in W2, W5, and W10, respectively). An interesting observation is also that there is no statistical difference for ortho-phosphate removal for any unit between low and high temperatures, which implies that temperature variations do not affect phosphorus adsorption.

3.4. Effect of substrate thickness and size (wetland type)

Some interesting remarks can be drawn from the comparison of the different design parameters of the 10 units. As Table 1 shows, three different wetland types were examined: the European (W1), the French (W9), and the American (W10) type. The main difference among the units was the substrate thickness. The American type unit proved to be more efficient in all pollutant removals, compared to the other two wetland units. The W10 unit removed 81.5% of the influent BOD_5 and 77.6% of the COD, 59.3% of TKN and 56.4% of NH_4^+–N, and 43.6% of TP and 44.4% of ortho-phosphate (Table 2). The French unit (W9) showed the lowest removal rates among the three units. The high substrate thickness of the W10 unit and, mainly, the existence of the sand layer (30 cm), improved the wetland performance. The higher substrate thickness of the French unit (W9) compared to the W1 unit could not counterbalance the absence of the sand layer in this unit.

Statistical analysis showed that the removal rates of organic matter, nitrogen, and phosphorus in the W10 unit are statistically significantly higher compared to the other two units (W1 and W9), as Table 6 shows. Statistical difference also is observed in nitrogen removal between the W1 and W9 units, indicating that nitrogen removal in the W1 unit is significantly better compared to the W9 unit.

3.5. Effect of vegetation

Three of the 10 wetland units contained the same porous media and were planted with different plants: W1 was planted with reeds, W2 with cattails, while W3 was kept unplanted (Table 1). Regarding the removal efficiency of the organic matter, the W2 unit with the cattails performed better (71.5% and 68.0% for BOD_5 and COD, respectively; Table 2). The same was also observed for nitrogen (49.0% TKN and 42.9% NH_4^+–N) and phosphorus (36.5% TP and 39.9% PO_4^{-3}–P) removals. The first comparison shows that the vegetation type plays a role in pollutant removal. Cattails (unit W2) seem to perform better compared to reeds (unit W1), probably due to the fact that cattails have a more vigorous root system [37]. Furthermore, the presence of plants generally improves the wetland unit efficiency, especially in the case of nutrient removal. Similar results concerning the effect of vegetation type and species have also been found in HSF systems [29]. However, significant statistical difference occurred only for TKN removal between the W2 and W3 units (Table 6). This implies that the presence of cattails in the W2 unit plays an important role in nitrogen removal, while removal mechanisms—beyond microbial activity—like plant uptake are also important [24].

3.6. Effect of porous media type

Five wetland units were planted with reeds, but contained different porous media. The W1 unit contained carbonate material obtained from a quarry and the W7 unit material from river deposits. Moreover, three units contained special materials: the W4 unit contained zeolite, the W5 zeolite and carbonate material (50–50% mixture) and the W6 bauxite and carbonate (50–50% mixture).

Concerning the origin of the porous media (units W1 and W7), the W7 unit with the material from river bed performed better in all pollutant removals, compared to the W1 unit. For the W7 unit, BOD_5 and COD removal rates were 75.1% and 67.6%, respectively, TKN and ammonia nitrogen removal reached 48.0% and 47.3%, while TP retention was 39.3% (Table 2). However, statistically significant difference occurred only for ammonia nitrogen removal (Table 6), which indicates the better performance in the W7 unit, compared to the W1 unit for this constituent.

In the case of the two special porous media (zeolite and bauxite) in the W4, W5, and W6 units, the W6 unit with bauxite proved to be more efficient in organic matter removal (72.2% for BOD_5) and phosphorus retention (40.1% for TP), as Table 2 shows. Bauxite is rich in Al and Fe hydroxides, which favors phosphorus adsorption [38,39]. For nitrogen, the two units with zeolite reached higher removals—as expected—compared to the unit with bauxite, since zeolite has a high cation exchange capacity with NH_4^+ [40–41].

It is interesting that no significant statistical difference occurred among these units with alternative porous media, as Table 6 shows, probably because of the relative short contact time of wastewater with the substrate as it percolates. The main removal mechanism of ammonia nitrogen and phosphorus related to zeolite and bauxite, respectively, is adsorption onto the substrate surface [38–41], which is enhanced with increasing contact time between the wastewater and the material. In the vertical flow systems, where the wastewater percolates by gravity, the differences in contact time among the wetland units with different substrate material are not significant; thus, the respective removal rates do not differ statistically. Therefore, use of these materials would be justified in a HSF CW system.

3.7. Effect of ventilation tubes

In order to investigate the effect of the presence of ventilation tubes, two units were examined: W1 and W8 contained both carbonate material and were planted with common reeds, but W1 had ventilation tubes and W8 did not. In the case of organic matter and phosphorus, removal rates of both units were similar. The W8 unit removed 68.6% of BOD_5 (68.2% in W1), while COD removal in the W8 unit was 64.9% (65.7% in W1), as Table 4 shows. TP retention in the W8 unit was 35.2% (34.2% in W1), while ortho-phosphate removal in the W8 was 34.9% (36.7% in W1). However, concerning nitrogen removal, the W1 unit performed better (46.0% for TKN and 39.9% for ammonia nitrogen) compared to the W8 unit (40.1% and 32.8% for TKN and NH_4^+–N, respectively), indicating that the presence of ventilation tubes, and the respective increase in oxygen amount, affects positively the nitrification process [35]. The statistically significant difference that occurred in ammonia nitrogen removal between the two units (Table 6) confirms the fact that the absence of ventilation negatively affects nitrogen removal.

4. Conclusions

Ten pilot-scale vertical flow constructed wetland units with different settings (i.e., substrate thickness, vegetation, porous media and ventilation tubes) were constructed and operated continuously for one year. The units performed satisfactorily in pollutant removal (organic matter, nitrogen, and phosphorus). The American type unit, with the thickest substrate material and the existence of fine material (a sand layer), demonstrated the most satisfactory performance, with significant removal efficiency for all pollutants. The vegetation seems to improve the nutrient removal rates, while cattails contributed significantly to nitrogen removal. Material obtained from river bed performed better, especially in the case of nitrogen removal, while alternative media, like zeolite and bauxite, can only slightly improve nutrient removal due to short contact time. The presence of ventilation tubes affects significantly and positively the removal of ammonia nitrogen. Pollutant removal efficiencies in all units showed dependence on temperature and seasonal variations.

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