Potential of Horizontal Subsurface-Flow Constructed Wetlands for Polishing of Treated Sewages

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Abstract: Constructed wetlands (CWs) are increasingly being applied for wastewater treatment and as pretreatment before artificial recharge of the effluents. Three horizontal subsurface-flow CWs were operated in parallel for almost 7 months and fed with three types of treated effluents to analyze enhancement of water quality at an average hydraulic retention time (HRT) of 1.3 days. The wastewater effluents analyzed in this study were an on-site anaerobically pretreated sewage at an Al-Mazra'a house, tertiary effluent at Al-Bireh City, and secondary effluent at the Birzeit University campus in Palestine. The average dissolved organic carbon (DOC) removal of 48, 50, and 47%, chemical oxygen demand (COD) removal of 55, 45, and 50%, biochemical oxygen demand (BOD) removal of 57, 38, and 60%, ammonia-nitrogen (NH_4^+-N) removal of 96, 90, and 97%, nitrate-nitrogen (NO_3^--N) removal of 88, 94, and 93%, total nitrogen (TN) removal of 72, 70, and 71%, phosphate (PO_4^{3-}) removal of 63, 61, and 57%, total suspended solids (TSS) removal of 37, 41, and 42%, and fecal coliform (FC) removal of 90, 85, and 95% were achieved with the CWs of the Al-Mazra'a, Al-Bireh and Birzeit effluents, respectively. The dissolved solids in the effluent of the three investigated CWs were increased. The total dissolved solids (TDS) and electrical conductivity (EC) of the (influent; effluent) of Al-Mazra'a, Albireh, and Birzeit were (337, 366 mg/L; 680, 737 μs/cm), (327, 351 mg/L; 658, 695 μs/cm), and (299, 326 mg/L; 603, 653 μs/cm), respectively. The CW was efficient in terms of NH_4^+, NO_3^-, and BOD removal, and achieved the Palestinian standards for treated effluent reuse and discharge to wadis for recharge, despite the high evapotranspiration of approximately 24%. The maximum achieved specific removal rates of phosphorous (P), nitrogen (N), and BOD were 2,211, 15,329, and 5,980 kg/ha/year, respectively. The study clearly showed that CWs have a high potential for further polishing treated effluents in both urban and rural arid areas of Palestine, such as Al-Bireh and Ramallah Cities and the adjacent villages, while achieving the double goal of environmental protection and environmental restoration. **DOI:** 10.1061/(ASCE)EE.1943-7870.0001091.

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Introduction

Water and sanitation remain a worldwide problem that requires an immediate response. The lack of wastewater collection and treatment facilities results in serious quality deterioration of both surface and groundwater resources, hampering their exploitation. In Palestine, the deficiencies in sanitation services do not allow current and future demands to be adequately covered (ARIJ 2011). Palestine is located in Southwest Asia, in the heart of the Middle East, with an arid to semi-arid climate and very limited water resources. In addition to the excessive exploitation of these scarce water resources, the water quality is jeopardized by the disposal of untreated wastewater. Signals of groundwater pollution have already been reported, e.g., NO_3 more than 50 mg/L (PWA 2012). The yearly wastewater generation in the West Bank of Palestine is estimated at approximately 50 mcm. Of this amount, 30% is collected by sewage networks, whereas the other 70% is discharged primarily in unlined cesspits (facilitating infiltration into the soil), and a small fraction of the population depends on the on-site wastewater treatment at the household level. Sewage networks are rarely supported by treatment facilities; only 20% of the collected wastewater is treated in two wastewater treatment plants (WWTPs), and the rest is discharged untreated in the nearby wadis. The final effluent discharge requirements in Palestine are often very stringent because of the Karstic nature of the groundwater aquifer (PSI 2003, 2012). Therefore, effluents from even well-designed and operated plants might need further polishing to cope with stringent environmental requirements of reuse of treated effluent for agriculture and groundwater recharge.

Constructed wetlands (CWs) are engineered natural systems (marsh-like areas) that have been applied for wastewater treatment and reuse in many different developing countries, including India, Nepal, Iran, Thailand, and Egypt (Mburu et al. 2013). Horizontal subsurface-flow constructed wetlands (HSSF CWs) are natural low-cost treatment systems in which wastewater flows slowly across the gravel and the roots and rhizomes of the planted vegetation. The process involves the use of a planted root system of reeds so that the plants survive on the nutrients in the wastewater. In HSSF CW systems, oxygen supply is typically limited and restricted to a micro-oxygenated zone close to the plant roots (Williams et al. 2010). Allen et al. (2002) showed that all plants enhanced the treatment capacity of HSSF CWs, compared with unplanted systems. Reeds are popular plants in CWs. They can remove multiple aquatic pollutants by making use of physical, chemical, and biological processes of natural ecosystems driven by solar energy, requiring minimal maintenance and external energy inputs (Maltby et al. 2013).

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CWs are used commonly for on-site wastewater treatment. Some authors reported that CWs perform well in terms of organics and suspended solids, but the removal of total nitrogen is very limited, as horizontal flow systems do not oxidize ammonia (Vymazal 2011). The suitability and performance of such natural treatment systems depend on several factors such as source water quality, availability of electron acceptors, process conditions applied, and water-quality goals to be achieved by treatment (García et al. 2004). CWs are not recommended for the treatment of raw wastewater; ideally, effluent should be preceded by a pretreatment step (El-Khateeb et al. 2009). CWs could act as primary buffers between pollution sources and adjacent aquatic ecosystems (Mueller et al. 2014). CWs are more complex than conventional treatment processes because of the diffusive flow and the large number of processes involved in wastewater degradation. The various types of treated wastewater are expected to have a different size distribution of contaminants, which might be influential in the CW performance (Maltby et al. 2013). Consequently, removal efficiency is more unpredictable because of the influence of varying hydraulics and a dynamic internal environment (Mburu et al. 2013).

The main goal of this research is to investigate sustainable urban water management, focusing on the role of natural wastewater treatment options. Specifically, it aims to investigate the potential for CW treatment as a posttreatment, of already treated wastewater effluents, for aquifer recharge and agricultural reuse, by analyzing the removal performances of several pollutants in the semi-arid Palestine.

Material and Methods

Experimental Setup

Three microcosms of subsurface horizontal-flow CWs were installed in parallel outdoors, under prevailing arid environmental conditions, at the campus of Birzeit University in Palestine. The CWs were made of stainless steel (60 cm in length, 45 cm in width, and 40 cm gravel depth/35 cm wastewater depth). The CWs were filled with gravel sieved between 12.5 and 19 mm, with 40% porosity and planted with common reed (*Phragmites australis*). Ten reed plants were planted into each CW. Each of the CWs was equipped with a wastewater holding and feeding plastic tank. A valve to control the flow under gravity was installed at the inlet point. At the outflow of each unit there was a level control to keep the water at 35 cm from the base.

CWs' Startup, Operation, and Monitoring

The CWs were started up in spring, in mid-March, and lasted for 7 months. The CWs were fed with three types of wastewaters, namely: (1) secondary effluent of contact process–activated sludge from the community's on-site wastewater treatment plant (WWTP) serving the campus of Birzeit University (approximately 10,000 students and employees); (2) tertiary effluent of the municipal, centralized, extended aeration system serving Al Bireh City (treatment capacity of 50,000 PE); and (3) on-site septic tank effluent in a house in Al-Mazra'a village (47 persons). The source waters were collected twice weekly and stored at 4°C. The CWs were provided daily with influent wastewaters using the influent holding tanks, which were cleaned weekly. The CWs were operated for 46 days (approximately 6 weeks) without monitoring to let the reeds grow, and afterward the influent and effluent were sampled and analyzed over an additional 6-week period (for a total of 12 weeks of operation/3 months) for the selected parameters [NH_4^+, NO_3^-, PO_4^{3-}, COD, dissolved oxygen (DO), and pH]. During the 12-week period of operation, the reeds were fully grown. Afterward, the influents and effluents were analyzed for the same parameters, in addition to the total Kjeldahl nitrogen (TKN), BOD, DOC, SO_4^{2-}, TSS, TDS, DO, EC, pH, and FC, once weekly for an additional 4 months.

The flow rate was measured daily to ensure a hydraulic retention time (HRT) of 1.3 days. Oxic conditions were maintained by aeration of the influent. Composite samples from the inlet and outlet of the CWs were collected in sterile plastic bottles and stored in a refrigerator at 4°C for analysis. Each composite sample consisted of three subsamples collected between 7:30 and 11:00 a.m.

Water Balance Estimations

The water balance was assessed by measuring exactly the volume of wastewater in the influent collection tanks, and collecting overnight the effluent water in a bucket; then the actual influent and effluent volumes were measured. The water loss measured as the difference between the influent and effluent volumes was considered because of evapotranspiration. This process was repeated eight times.

Analytical Methods

BOD, COD, DOC, nitrogenous compounds (NH_4^+, TKN, NO_3^-), PO_4^{3-}-P, FC, TSS, and TDS were measured according to the standard methods of the American Public Health Association (APHA 2005). Nitrate-N (NO_3^--N) was analyzed using the capillary ion analyzer (CIA) method. The DOC was measured using the Aurora 1030W TOC analyzer (OI Analytical/Xylem, OI Analytical in College Station, Texas). The EC and temperature were measured with a conductivity meter. The DO was measured with the HQ10 oxygen meter (HACH, Loveland, Colorado). The pH was measured using the 691 pH meter (Metrohm, Herisau, Switzerland).

Calculations

The process performance and design parameters including the removal efficiency, the specific removal rate, and the BOD rate constant were calculated based on field measurements. The fallowing formulas were used for calculating these parameters.

Removal Efficiency

The mass removal of measured organic and inorganic parameters in each CW was calculated using influent and effluent concentrations, measured over the operating period, in addition to the influent and effluent flow rates. The removal efficiency based merely on influent and effluent concentrations, without considering the evapotranspiration that leads to increasing the effluent concentrations, is erroneous, and therefore will underestimate the actual potential of the CWs for pollutant removal. The following formula was used for calculating the average mass removal efficiency in percentage:

$$\text{Mass removal efficiency} = \frac{(\text{Qinf} \times \text{Cinf} - \text{Qeff} \times \text{Ceff})}{\text{Qinf} \times \text{Cin}} \times 100\% \tag{1}$$

where Qinf and Qeff = average influent and effluent flow rates (m^3/d); and C_{inf} and C_{eff} = influent and effluent concentrations (mg/L) measured over the whole operating period.

Specific Removal Rate

The following formula was used for calculating the annual specific removal rate in $kg/ha \cdot year$:

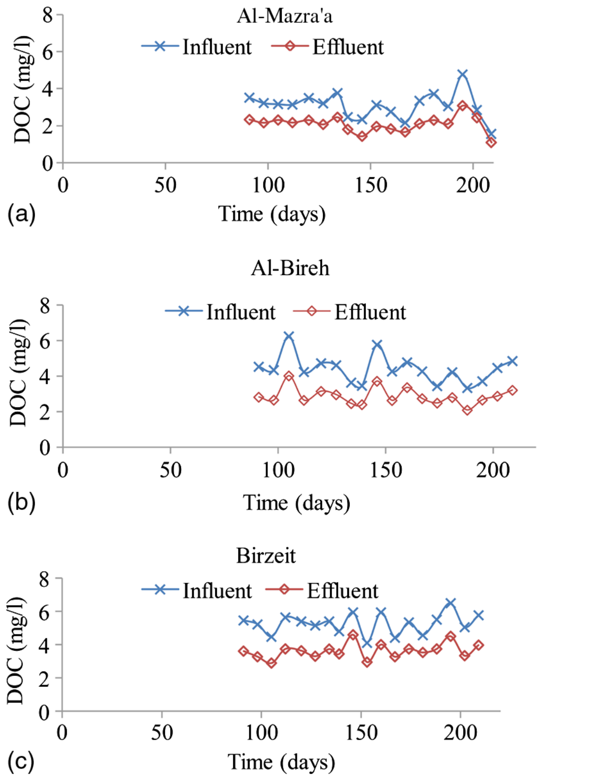

Fig. 1. Influent and effluent DOC concentrations in CW polishing-treated sewages

$$\text{Specific removal rate} = \frac{(\text{Qinf} \times \text{Cinf} - \text{Qeff} \times \text{Ceff}) \times 3{,}650}{A_h} \qquad (2)$$

where 3,650 = conversion factor to obtain the removal rate in the unit of kg/ha · year, given units of the other variables in the equation; and A_h = surface area of the CW (m^2).

BOD Rate Constant

The following formula, first proposed by Kichuth (1977), has been widely used for sizing HSSF CW for domestic sewage treatment (Vymazal 2005) and was used for calculating the average rate constants in m/d

$$K_{\text{BOD}} = \frac{\text{Qinf}(\ln\text{Cinf} - \ln\text{Ceff})}{A_h} \qquad (3)$$

Statistical Analysis

Statistical comparisons of means were followed by an analysis of variance (ANOVA) for the measured parameters of the three CW reactors using the *SPSS, version 20.0*, in which P value <0.05 was considered significantly different. For statistical comparisons of influent and effluent means of each CW, a paired-samples t-test ($P < 0.05$) was used.

Results and Discussion

The performances of the three investigated CWs are presented in the following sections. The presented average or mean data are overall mean values calculated over a 4-month period (monitored over the period of 91–210 days; number of samples 18), and the corresponding standard deviations are presented between parenthesis.

Removal of DOC and COD

The influent and effluent DOC concentrations and removal efficiencies are presented in Fig. 1 and Table 1. The effluent DOC concentrations were stable and relatively high of the three tested effluents.

The achieved COD removal efficiencies of the three investigated CWs are presented in Tables 1 and 2. The achieved removal efficiencies are in the range of the results reported in literature for horizontal flow wetlands, such as 42.7% (Ghrabi et al. 2011), 71.8% (Avsar et al. 2007) and 72–79% for a wetland-treating gray water (Niyonizima 2007), 93.6% for a wetland-treating dairy and agricultural wastewater (Pucci et al. 2000), and 77.8% for a wetland-treating domestic wastewater (Vipat et al. 2008).

Removal of BOD

The average effluent DO concentration was 4 mg/L, indicating that the CW beds were operating under aerobic conditions (Table 1). It is likely that the wastewater remained relatively oxygenated during the HRT of 1.3 days, as the beds used in this study are very small (short in length and much shallower than the typical field-scale system).

A stable period for BOD removal started after approximately 135 days of operation (Fig. 2). For the CW fed with Al-Bireh secondary treated wastewater, after 102 and until 210 days of operation, the overall mean BOD in the influent and effluent were 7.4 (1.2) mg/L and 6 (0.7) mg/L, respectively. The data presented in Fig. 2 reveal that, for the CW fed with Al-Bireh secondary treated wastewater, the BOD concentration was marginally improved. Indeed, the Al-Bireh effluent contained very low BOD concentration, most likely consisting of poorly biodegradable remains of exocellular polymeric substances. This is clear from the calculated field rate constant (KBOD) of 0.03 (0.02), as compared with the field rate constants of 0.1 (0.07) and 0.1 (0.03) for the Al-Mazra'a and Birzeit effluents. The rate constant is increased with the hydraulic loading rate and BOD_5 mass loading rate (Vymazal 2005). The KBOD values obtained in this study are in agreement with the values reported in literature. According to Vymazal (2005), the field measurements showed that the value of KBOD is usually lower than 0.19 m/day. Vymazal (2005) reported an average KBOD value of 0.118 (0.022) m/day for 66 village systems after 2 years of CW operation. Because the obtained KBOD values were different in the order of three times, and the KBOD value is a key design variable, the use of the Kickuth proposed design equation should be with care, especially when assuming values of KBOD. The KBOD values attained in this study confirm that the rate constants vary according to the influent concentrations (Rousseau et al. 2004). Moreover, the value of KBOD depends on temperature (Mara 2004), so the calculated values of KBOD are only valid at the operated process temperature of approximately 25°C, as presented in Table 1. Stefanakis and Tsihrintzis (2009) reported that the surface-area demand of constructed wetland depends on the climatic conditions of primarily temperature.

Unlike the CW fed with treated effluent from the wastewater treatment plant (WWTP) of Al Bireh city, the CW fed with Al-Mazra'a and Birzeit water had noticeably improved the BOD effluent quality (Fig. 2; Tables 1 and 2). Therefore, the results confirm that the performance of such natural treatment systems depend, among others, on source water quality as reported by García et al. (2004), because the BOD values of the three CWs were significantly different from each other.

The results show that the achieved effluent quality in this study is very high when compared with other studies based on effluent quality, not removal efficiency, because of the pretreated effluents.

Table 1. Average Influent and Effluent Concentrations and Removal Efficiencies in CWs

Parameter	Al-Mazra'a water Influent	Al-Mazra'a water Effluent	Al-Mazra'a water Removal efficiency	Al-Bireh water Influent	Al-Bireh water Effluent	Al-Bireh water Removal efficiency	Birzeit water Influent	Birzeit water Effluent	Birzeit water Removal efficiency
BOD	21(5)	$11^c(5)$	58(19)	7(1)	$5.7^a(1)$	38(8)	16(2)	$8.6^b(3)$	60(9)
COD	54(9)	$34^b(12)$	55(12)	33(7)	$24^a(5)$	45(11)	46(7)	$30^b(5)$	50(7)
DOC	3.1(0.7)	$2.1^a(0.4)$	32(6)	4.4(0.76)	$2.9^b(0.78)$	34(3.4)	5.3(0.61)	$3.7^c(0.45)$	31(4.1)
NO_4^+-N	7.06(1.33)	$0.4^a(0.3)$	96(2.7)	3.33(1.73)	$0.3^a(0.17)$	90(6)	6.23 (1.47)	$0.22^a(0.1)$	96(1.2)
NO_3^--N	11.86 (3.14)	$2.12^b(1.25)$	88(7)	14.65 (4.15)	$1.14^a(0.53))$	94(3)	11.7 (3.45)	$1.22^a(0.7))$	93(3)
TKN	29(7)	$13.4^a(4)$	53(11)	18.5(4)	$12.1^a(3.7)$	35(12)	27(9)	$13.7^a(4)$	50(12)
Organic N	22.3(7.06)	$13^a(4)$	53(15)	15.6(4.6)	$11.8^a(4.2)$	45(11)	21(9.6)	$13.4^a(4.4)$	53(12)
PO_4^{3-}-P	4.55(2.02)	$1.7^a(0.9)$	63(14)	6.22(1.63)	$2.8^b(0.9)$	61(14)	6.88(1.8)	$3.4^b(1.3)$	57(11)
SO_4^{2-}	135(32)	$115^c(30)$	15(8)	45(19)	$38^b(16)$	16(11)	27(9)	$22^a(8)$	19(13)
TSS	95(22)	$80^b(23)$	16.4(7.7)	33(7)	$26^a(7)$	22(11)	42(10)	$32^a(9)$	23(9)
TDS	337(67)	$366^b(64)$	−9.2(3.82)	327(23)	$351^b(23)$	−7.6(4.8)	299(52)	$325^a(37)$	−11(16)
EC	680(136)	$737^b(128)$	−8.9(3.64)	658(47)	$695^b(62)$	−5.6(5.8)	603(104)	$653^a(77)$	−10(15)
pH	8.1(0.21)	$7.5^a(0.2)$	—	8.3(0.26)	$7.8^a(0.3)$	—	8.2(0.32)	$7.8^a(0.3)$	—
Temperature	25.6(1.7)	25.6(1.7)	—	25.6(1.7)	25.6(1.7)	—	25.6(1.7)	25.6(1.7)	—
DO	5(0.3)	$4.0^a(0.4)$	—	5(0.35)	$4.2^a(0.34)$	—	5(0.37)	$4.3^a(0.5)$	—
FC	4.4×10^9 (8.7×10^9)	1.2×10^{8a} (1.7×10^8)	90(14)	1.6×10^8 (4.3×10^8)	5.7×10^{7a} (1.8×10^8)	85(19)	9.3×10^9 (1.8×10^{10})	2.6×10^{8a} (6.2×10^8)	95(5)

Note: All units are in mg/L, except FC in CFU/100 mL, EC in μs/cm, and removal efficiency (in %); the values in parenthesis represent the standard deviation; the number of samples is 18; and the a, b, and c letters indicate the significant difference at $\alpha = 0.05$ between the means of effluent values.

Table 2. Characteristics of the CWs' Influents and Effluents and Palestinian Discharge Standards

Parameter	Al-Mazra'a water Influent	Al-Mazra'a water Effluent	Al-Bireh water Influent	Al-Bireh water Effluent	Birzeit water Influent	Birzeit water Effluent	Treated wastewater standards (PSI, 2003, 2012): Aquifer recharge Class A	Agricultural reuse Class B	Agricultural reuse Class C	Agricultural reuse Class D
BOD_5	20(5)	$11^c(5)$	7(2)	$5.7^a(1)$	16(2)	$8.6^b(3)$	20	20	40	60
COD	54(9)	$34^b(12)$	33(7)	$24^a(5)$	46(7)	$30^b(5)$	50	50	100	150
NO_3^--N	13(3)	$2.12^b(1.25)$	15(5)	$1.14^a(0.53)$	13(4)	$1.22^a(0.7)$	20	20	30	40
NO_4^+-N	7(1)	$0.4^a(0.3)$	3(1.7)	$0.3^a(0.17)$	6(1.5)	$0.22^a(0.1)$	5	5	10	15
TN	41(5)	$15.5^a(4.1)$	33(4)	$13.2^a(3.6)$	39(6)	$15^a(4.6)$	30	30	45	60
TSS	95(22)	$80^b(23)$	33(7)	$26^a(7)$	42(10)	$32^a(9)$	30	30	50	90
FC	4.4×10^9 (8.68×10^9)	1.2×10^{8a} (1.69×10^8)	1.6×10^8 (4.29×10^8)	5.7×10^{7a} (1.75×10^8)	9.3×10^9 (1.8×10^{10})	2.6×10^{8a} (6.16×10^8)	200	1,000	1,000	1,000

Note: All units are in mg/L, except FC in CFU/100 mL. The values in parenthesis represent the standard deviation; the number of samples is 18; and the a, b, and c letters indicate the significant difference at $\alpha = 0.05$ between the means of effluent values.

A similar conclusion can be drawn from the COD results. Zurita et al. (2009) reported a 78.2% BOD removal for a HSSF CW planted with one species (*Zantedeschia aethiopica*) treating domestic wastewater, and a higher removal of 81.5% for the same system planted with three different species. BOD removal efficiency for a HSSF CW fed with gray water was in the range of 72–79%, as found by Niyonizima (2007) with influent and effluent concentrations of 250 and 71 mg/L, respectively. A BOD removal efficiency of 85.4% was achieved in a HSSF CW filled with gravel (Ghrabi et al. 2011). In addition, BOD removal efficiency of 65.7% was reported by Vipat et al. (2008) when treating the presettled sewage in HSSF CW, with 46.7 and 19.5 mg/L influent and effluent BOD concentrations, respectively.

Removal of Nitrogenous Compounds

The three investigated CWs achieved very high ammonia removal (Table 1; Fig. 3). The attained results are relatively higher than these reported in literature (53.3–63.8%) (Pucci et al. 2000; Avsar et al. 2007; Vipat et al. 2008). Yang et al. (2001) observed an average of approximately 50% NH_3-N removal in a CW, which increased up to 80%. The researched CWs consistently achieved near-complete NH_4^+-N removal for all three influents. The results revealed that NH_4^+-N was almost completely removed after 66, 34, and 44 days for Al-Mazra'a, Al-Bireh and Birzeit wastewaters, respectively (Fig. 3). The high removal of NH_4^+-N in the researched CWs is postulated to nitrification, as a result of aerobic status of the beds with relatively high effluent DO. The pH values were slightly reduced, probably caused by nitrification (Table 1), in the three CWs with no significant difference. In contrast, Vymazal (2011) reported that the removal of total nitrogen is very limited, as horizontal flow systems do not oxidize ammonia. In the past research, the poor nitrogen removal in horizontal flow CWs was caused by poor oxygen content (Zurita et al. 2009). It is well known that in horizontal subsurface-flow CW systems, the oxygen supply is typically limited and restricted to a micro-oxygenated zone close to the plant roots (Williams et al. 2010). The CW beds used in this study are very small (short in length and much shallower than the typical field scale systems reported in literature); therefore, the wastewater remained relatively oxygenated during the 1.3 days HRT. The influent DO concentrations were slightly reduced in the CWs ($P < 0.05$), but remained relatively high (Table 1).

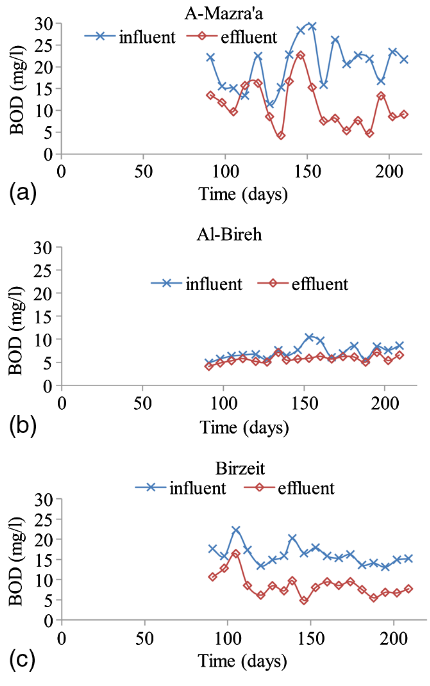

Fig. 2. Influent and effluent BOD concentrations in CW polishing-treated sewages

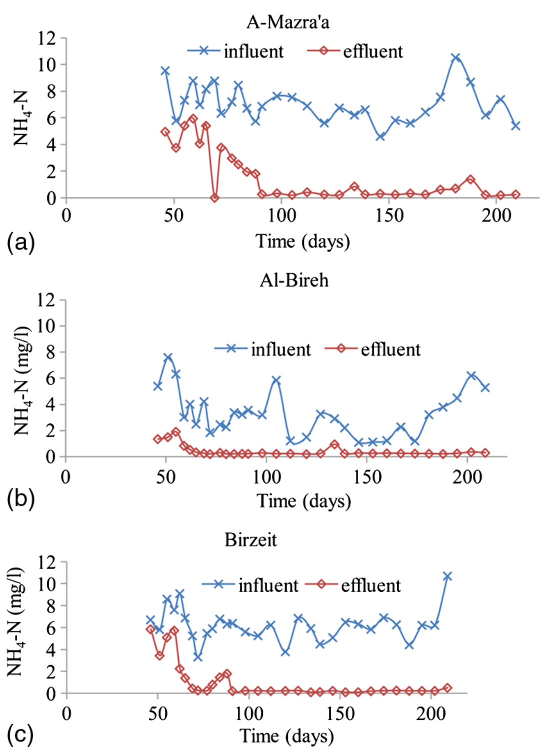

Fig. 3. Influent and effluent ammonia concentrations in CW polishing-treated sewages

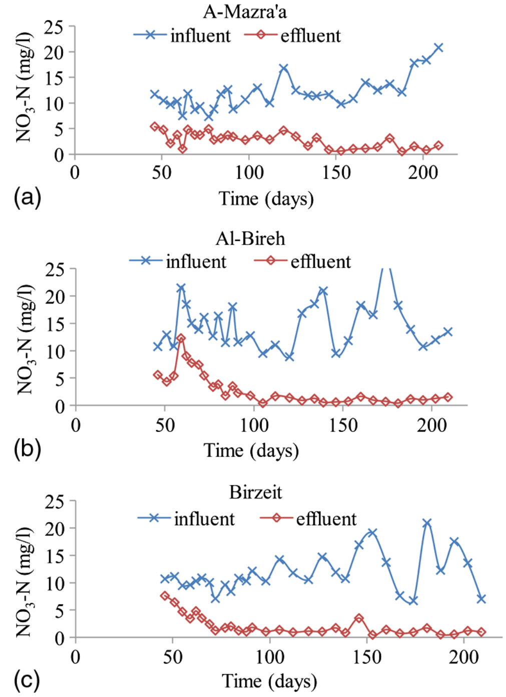

Fig. 4. Influent and effluent nitrate concentrations in a CW treating: (a) anaerobically/on-site land pretreated wastewater in Al-Mazra'a; (b) tertiary treated municipal wastewater in an extended aeration, Al-Bireh; (c) secondary treated wastewater in a contact process activated sludge, Birzeit University, Palestine

The nitrate results are presented in Fig. 4 and Table 1. The effluent NO_3^--N concentration for the CW fed with Al-Bireh water after approximately 100 days of operation was stable regardless of the influent fluctuations. Nitrate was almost completely removed from all wastewaters investigated, especially from Al Bireh and Birzeit wastewater that were slightly but significantly less than that of Al Mazra'a. The same result was reported by other researchers (Mantovi et al. 2003; Zhao et al. 2013). According to Mayo and Bigambo (2005), the major pathways leading to permanent removal of nitrogen in a HSSF CW system are denitrification (29.9%), plant uptake (10.2%), and net sedimentation (8.2%). The average removal efficiencies for nitrate were 88(7)%, 94(3)% and 9(3)% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. The overall removal efficiencies were higher than those reported by other authors of 40–62% (Pucci et al. 2000; Vipat et al. 2008; Zurita et al. 2009). The rather high nitrate removal from the three investigated source waters is most likely the result of plant uptake (Yang et al. 2001), considering the low COD/N ratio and the prevailing aerobic conditions. The mechanism of removal of nitrate from different types of wastewater effluents in HFCW should be studied further.

The results of influent and effluent concentrations and removal efficiencies of organic nitrogen in the three investigated CWs are presented in Table 1. These results are in agreement with those obtained by Zurita et al. (2009), who reported removal efficiencies in the range of 39–46%. Therefore, the Kjeldhal nitrogen removal was not only the result of free ammonia removal, but also organic nitrogen removal. Indeed, the total nitrogen in the effluents consists primarily of organic nitrogen, with no significant difference. This entails that under this research setup configuration, ammonification, and nitrification proceeded simultaneously, as the operation period was during summer months of high temperature, which favor these two processes (Ding et al. 2012). The three investigated CWs were equally efficient for total nitrogen removal (Table 1)

Removal of PO_4^{3-}, SO_4^{2-}, *TSS, TDS, EC, and FC*

The phosphate removal efficiencies in the three CWs presented in Table 1 support the general consensus that phosphate is generally found to be poorly removed in CWs (Ghrabi et al. 2011). However, the effluent phosphate concentrations were still low, bearing in mind that the influent concentrations were also low. The phosphate in the effluent of the CW fed with Al Mazra'a wastewater was significantly lower than those of Al Bireh and Birzeit because phosphate concentration was lowest in the first. The results obtained in this study for phosphate removal are close to that reported by Mantovi et al. (2003) of 60%. Several factors contribute to phosphorous removal, including vegetation, detritus, fauna, microorganisms, and substrate. However, because phosphorous adsorption to the substrate is the main removal mechanism (Yang et al. 2001), most wetland studies have shown that the soil compartment is the major long-term phosphorous storage pool (Chung et al. 2008). In the longer term, the removal of phosphorous might decrease because of the saturation of phosphorous adsorption in the substrate (Vymazal 2011). Temperature has little influence on phosphorous removal because the most important removal mechanisms are chemical precipitation and physicochemical sorption processes, which are not temperature dependent (Pucci et al. 2000; Yang et al. 2001). The reduction in sulphate content was low, most likely because of the prevailing aerobic conditions, and the effluent concentrations were significantly different from each other, according to the influents' concentrations.

The TSS removal in the three investigated CWs was less than expected as compared with literature (Table 1), with significantly higher TSS values in the CW fed with Al Mazra'a wastewater in comparison with the other two types of wastewaters. Zurita et al. (2009) reported higher TSS removals in a HSSF CW planted with one species and fed with domestic wastewater. They reported TSS removals in the range of 80–84% with 57 and 11 mg/L influent and effluent TSS concentrations. Niyonizima reported TSS removal efficiency in the range of 34–53% (Niyonizima 2007). In addition, high removal efficiencies ranging from 79.2 to 92.9% have been reported by other researchers (Pucci et al. 2000; Avsar et al. 2007; Vipat et al. 2008; Zurita et al. 2009). The lower TSS removal efficiencies achieved in this research is probably the result of the rather large diameter of 1.2–1.9 cm of the filling gravel, which could have induced the rapid seepage of wastewater through the wetlands as suggested by Zurita et al. (2009), especially when sand or smaller gravel zones were not provided at the inlet, as in a large-scale CW; and the low depth and length dimensions of the microcosms' CW. The preliminary results of the long-term operation of the researched microcosms' CW show improved TSS removal with an effluent quality of approximately 10 mg/L, probably the result of more root development and accumulation of litter, sediments, and soil. Bodin (2013) found that TSS removal was substantially improved as the macrophytes shoots grew and became older, and the TSS effluent standards were met when the macrophytes had been growing for at least 3–4 months. This strongly indicates that scaling up of this research on CW would surely result in better TSS removal based on numerous CW studies.

There was an increase in TDS concentrations and EC in the effluent of the three investigated CWs (Table 1), which is primarily the result of evapotranspiration.

The results of fecal coliform presented in Table 1 reveal low removal, most likely because the imposed HRT of 1.3 days was inadequate to create favorable environmental conditions for higher FC removal. However, these results are comparable to the findings of other researchers, e.g., 99.7% by Pucci et al. (2000), 99% by Mantovi et al. (2003), 72–79% by Niyonzima (2007), and 98.7% by Vipat et al. (2008). Also Avsar et al. (2007) reported 92.9% removal HRT of 5 days using volcanic tufa.

General Discussion

The findings of this research clearly indicate the high potential of CWs for enhancing the quality of various types of treated effluents (residential on site, community on site, and municipal treatment plants) in the semi-arid Palestine. The data obtained in this study are very important for the design of CWs in Palestine, because the existing design approaches based on rules of thumb and regression equations show large variation and uncertainty in the design; these approaches neglect important factors such as climate and bed material (Rousseau et al. 2004). The applied HRT of 1.3 days was sufficient to remove a substantial amount of organic matter (Tables 1 and 2). In addition, the CW was efficient in terms of total nitrogen removal and achieved the Palestinian requirements for using treated effluent for recharging the aquifers (Table 2). Treatment in the CW has shown tolerance to different influent concentrations of pollutants. This is in line with the findings of several authors (Mantovi et al. 2003; Mayo and Bigambo 2005; Landry et al. 2009). Reed (*Phragmites australis*) had been shown to survive and perform well in treating the three investigated wastewaters, whereas gravel material provided a suitable plant growth medium in constructed wetlands.

The systems operated with Al-Mazra'a and Birzeit wastewaters showed higher removal efficiencies for COD than that obtained for Al-Bireh, because of the already low concentration of different pollutants in the latter (Tables 1 and 2). Similar results were found for BOD and TKN. The TSS in the Birzeit and Al Bireh CW effluent achieved the Palestinian standards, but TSS in the CW fed with Al Mazra'a wastewater was significantly higher than the values of the other two systems, and did not not comply with the Palestinian standards. The calculated specific removal rates of phosphate, nitrogen, and BOD of the reed-planted CWs fed with Al-Mazra'a, Al-Bireh, and Birzeit were (1,471, 1,922, 2,211 kg P/ha/year), (15,329, 11,877, 14,692 kg N/ha/year), and (5,980, 1,371, 4,862 kg BOD/ha/year), respectively. However, the CWs were small-scale microcosms that have been run for several months, so the calculated specific annual removal rates (e.g., 2,211 kg P/ha/year) were somewhat arbitrary; therefore, systematic research should be done.

Based on the water mass balance, it was found that approximately 24% of the influent water was lost as a result of evapotranspiration. Glenn et al. (2013) reported over an annual cycle that 54% of inflows had supported evapotranspiration, and 10% in winter in an anthropogenic coastal desert wetland. This indicates that the actual effluent quality is even better than measured. Accordingly, the installation of CW in semi-arid regions like Palestine will surely help in protection of the scarce water resources, especially the precious groundwater. The application of CWs as a natural treatment will indeed reduce the technical requirements of sophisticated mechanical treatment methods, as the three source waters were all attenuated to an acceptable level, with particular improvement to TN and BOD. Therefore, CWs could act in Palestine as primary buffers between pollution and the adjacent aquatic ecosystems, as argued by Mueller et al. (2014). Additionally, installation of CWs in Palestine would increase the amount of green space in the arid landscape, which would contribute to habitats and ecosystems for many animals and birds; the disappearances of many indigenous birds are a national concern. Ecological restoration has been identified as one of the possible ways to replace biodiversity loss (Maltby et al. 2013).

Conclusions

The results of this study indicate that HSSF CWs are robust systems that can achieve multiple contaminant removal and offer an attractive treatment option for further polishing different types of effluents before agricultural or other reuse applications. The total nitrogen removal efficiencies of CWs were 72(6), 70(7) and 71(8)% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively, with effluent concentrations of less than 20 mg N/L. Effluent BOD concentrations were below 10 mg/L for the three wastewaters tested. The quality of CW effluents, in terms of BOD and total nitrogen, met the critical requirements of Class A of the Palestinian standards for reuse in irrigations or to recharge the aquifer.

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