

Analysis of the reclamation treatment capability of a constructed wetland for reuse

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Abstract

A research project was conducted during 2008-2009 in Portugal to evaluate the potential of reclaimed water from constructed wetlands for irrigation reuse. A 21 month monitoring campaign was set up in a Filtralite-based horizontal subsurface flow bed. Results showed a significant fluctuation of the hydraulic loading rate that has influenced the hydraulic retention time and the wastewater characteristics over time and, therefore, the removal efficiencies for BOD₅, COD, TSS, nitrogen and phosphorus were lower than the reported values for CW performance. If the hydraulic loading rate could be properly controlled the treatment performance, as well as the quality of the reclaimed water, can be improved considerably. The effluent concentrations of conductivity (EC), BOD₅, COD, TN, K, Ca, Mg and phytotoxic elements (Na, Cl and B), showed a suitable quality for irrigation reuse according to different international standards, although it is necessary to improve the removal of phosphorous and a final disinfection must be implemented to decrease the pathogenic content.

Keywords: constructed wetlands, irrigation, reclaimed water, reuse, treatment capability

INTRODUCTION

Water supply and sanitation will be one of the main future challenges in a world of growing population and industrialisation. The growing awareness of water resource scarcity, the competition for water resources and the negative impact of polluted water on human health and the environment, demand the development of adequate strategies for water management. Next to the development of new management strategies to supply fresh water, reclaimed water will play an important role in tackling the existing and occurring water problems (UNESCO, 2009).

Approximately half of the European countries, representing almost 70% of the population, are facing water stress issues today (AQUAREC, 2003). Portugal presents some features of Mediterranean climate, particularly in the half of the country located at south of river Tagus. Under a natural regime, according to Marecos do Monte (2007), 57.5% of the country mainland suffers a water deficit that may bring serious consequences to the economy.

Constructed wetlands (CW) is considered a low cost wastewater treatment process for small populations and rural areas (Kadlec *et al.*, 2000; Korkusu, 2005) and it seems a suitable system to deal with loads fluctuations (Albuquerque *et al.*, 2009) and to produce a final effluent for reuse (Masi and Martinuzzib, 2007; Marecos do Monte and Albuquerque, 2010). Rural areas in Portugal cover 85% of the territory and 32% of the population in mainland Portugal (INE, 2007). From 1999 to 2006 the percentage of the population served with wastewater treatment plants (WWTP) has increased from 55% to 70% (INE, 2007), in order to

fulfill the requirements of the 1991/271/EEC Directive. In rural areas, strongly investments have been made in low cost WWTP during the last decade, especially in CW treatment systems with horizontal subsurface flow (HSSF).

In southern Europe, reclaimed water is used predominantly for agricultural irrigation (44% of the projects) and for urban or environmental applications (37% of the projects) (Bixio *et al.*, 2006). Currently, the use of reclaimed water in Portugal is increasing, although is limited almost exclusively to agriculture irrigation and landscape irrigation. This practice may bring important advantages for the integrated water management in rural areas with water shortage such as the Cova da Beira region, where 60% of the population lives in agglomerates with less than 2000 inhabitants. These rural areas are covered by an irrigation plan to improve agriculture activities and have several golf courses projects and SPA resorts that need large amounts of water. Therefore, the reclaimed water produced in the almost 300 WWTP may be seen as an alternative source for those activities with important environmental and economics benefits.

Nevertheless, some reuse opportunities require a polished effluent since the content of nutrients, heavy metals, microorganism and organic residuals may be not suitable for application. Therefore, the selection of reuse options should be made taking into account a rational analysis on the reclaimed water quality over time, reuse guidelines, climatologically parameters, requirements for polishing treatment and reuse projects cost-effectiveness.

A research project (EVAWET) launched in 2007 aims to evaluate both the performance of CW located in rural areas of Portugal and the suitability of reclaimed water for irrigation results. The results of November 2007 to November 2009 are presented and discussed in this paper.

MATERIAL AND METHODS

A 21 month monitoring campaign (November 2007 to November 2009) was set up in a HSSF CW located at Vila Fernando (Portugal), that started 6 months after its start-up. The bed was colonized with *Phragmites australis*, filled with Filtralite MR 4-8 mm (a Leca that allows a void ratio of 0.45) and had 23x18 m (length x width), a water depth of 0.5 m and was designed for 800 p.e., maximum flow rate of 50 m³ d⁻¹, maximum hydraulic loading rate (HLR) of 12 cm d⁻¹, minimal hydraulic retention time (HRT) of 4 d, BOD₅ from 200 to 400 mg L⁻¹ and COD from 500 to 700 mg L⁻¹.

The campaign included the daily measurement of flow-rate (entrance of the HSSF bed) and the collection of monthly samples (a single sampling approximately at the same day and hour) at the influent and effluent of the bed to determine pH, temperature, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), ammonia nitrogen (NH₄-N), nitrate nitrogen (NO₃-N), total nitrogen (TN), total phosphorus (TP), electric conductivity (EC), sodium (Na), calcium (Ca), potassium (K), chloride (Cl), total coliforms (TC), fecal coliforms (FC), *E. Coli*, and helminths eggs (HE). In the last sampling month it was also measured magnesium (Mg), boro (B), cadmium (Cd), chromium (Cr), cooper (Co), nickel (Ni), plumb (Pb) and zinc (Zn). Mg was needed to estimate the Sodium Adsorption Ratio (SAR) and B and the heavy metals are fitotoxic parameters and were necessary evaluating their levels.

Temperature, pH and electrical conductivity (EC) were measured directly using a Tritilab TIM 900 (Radiometer, France). COD was determined with cuvette tests LCK 614 (50-300 mg L⁻¹) and a CADAS 100 Lange spectrometer (Hach-Lange, Germany) following the standard DIN 38409-4. TN, NH₄-N and TP were obtained using the cuvette tests LCK 138 (1-16 mg TN L⁻¹), LCK 238 (5-40 mg TN L⁻¹), LCK 303 (2-47 mg NH₄-N L⁻¹) and LCK 350 (2-20 mg TP L⁻¹) and the same

spectrometer, following the method 2,6-dimethylphenol (TN, APHA-AWWA-WEF (1999)), the standard DIN 38406-E 5-1 (NH₄-N) and the standard DIN 38405-D11-4 (TP), respectively. NO₃-N and Cl were analyzed using a Dionex-IX120 ion chromatography (Dionex, USA) according with the ISO 10304-1:2007 standard. BOD₅ and TSS were determined according to the 5210B, 2540D and 2540E standards, respectively, from APHA-AWWA-WEF (1999).

The heavy metals (Cd, Cr, Ni, Pb, Zn, e Cu) were determined by atomic absorption spectroscopy with electrotermic atomizer (GBC-906, Australia) following the standard ISO 15586:2003. The Na, Ca, K and Mg were analyzed with the same equipment, but using air-acetylene flame method as described in the standards ISO 9964-1:1993 (Na and K) and ISO 7980:1986 (Ca and Mg). B was determined using a spectrophotometer UV-Vis (GBC-Cintra 40, Australia) following the standard method 4500 B (APHA-AWWA-WEF, 1999).

The FC, TC and *E. Coli* were analyzed following the standard ISO 9308-1:2000 and the Standard Methods 9221 B e 9221 E (APHA-AWWA-WEF (1999)). EH was determined though a optic microscopy (Ceti, Belgium) according to the modified Bailenger method (Ayres and Mara, 1996).

RESULTS AND DISCUSSION

The results of the monitoring campaign are shown in Table 1.

The average removal efficiency (RE) for BOD₅ (74%), COD (68.3%), TSS (57.6%), NH₄-N (10%), TN (18.2%) and TP (27.4%) were close or lower than the minimum values suggested for good performance of Filtralite-based CW (Jensen e Krogstad, 2003; Adam *et al.*, 2006; Johansson, 2006; Adam *et al.*, 2007; van Deun and van Dyck, 2008): 70-95% (BOD₅), 60-90% (COD), 70-90% (TSS), 60-70% (NH₄-N), 50-70% (TN) and 60-90% (TP). The influent and effluent concentrations of BOD₅ and COD were unstable over time (maximum values of 203 mg BOD₅ L⁻¹ and 548 mg COD L⁻¹, for influent, and 71 mg BOD₅ L⁻¹ and 193 mg COD L⁻¹, for effluent). A more significant variation was observed for TN and NH₄-N concentrations (maximum values of 131 mg TN L⁻¹ and 73 mg NH₄-N L⁻¹, for influent, and 71 mg TN L⁻¹ and 62 mg NH₄-N L⁻¹, for effluent).

The lower performance of the bed is associated with the entrance of a high average flow rate (more 18% than the maximum value used to size the bed) during the 24 monitoring months due to stormwater infiltration, with values that ranged from 9.2 m³ d⁻¹ (October 2008, driest month) to 233 m³ d⁻¹ (March 2009, wettest month), which have caused a variation of both the HLR from 2.2 to 56.5 cm d⁻¹ and of the HRT from 2 to 45 d. Therefore, the average HLR (15 cm d⁻¹) was 25% higher than the respective project value. During the months with HLR lower than 12 cm d⁻¹ and HRT higher than 9 d the RE of COD, BOD₅, TSS and NH₄-N doubled in respect to the average values for the 24 months.

These results showed that the entrance of stormwater may negatively affect the performance of HSSF beds and the quality of the reclaimed water, but it also shows that this kind of bed presents a good response when the HLR is properly controlled. Therefore, the control of the HLR is a key factor to achieve a final effluent suitable for reuse.

The variation of the HLR and the HRT seems to have had a lower impact in TP removal (the RE ranged between 25 and 31%). The removal of phosphorous in Filtralite substrates occurs mainly through adsorption and precipitation of phosphates (Adam *et al.*, 2007), and a small part is taken by plants (Kadlec *et al.*, 2000; Vymazal and Kropfelova, 2008). Therefore, the fluctuation of the HLR in Filtralite-based HSSF beds seems to affect more the microbiological removal pathways than the physical-chemical removal pathways.

Table 1 | Characteristics of the wastewater in the CW of Vila Fernando (November 2007 to November 2009)

Parameters	Influent ¹⁾	Effluent (reclaimed water) ¹⁾
Flow rate (m ³ d ⁻¹)	58.9 ± 26.0	-
Temperature (°C)	15.6 - 3.8	15.3 - 3.9
pH	6.2 - 7.3	6.3 - 7.7
EC (dS m ⁻¹)	0.22 ± 0.02	0.22 ± 0.02
BOD ₅ (mg L ⁻¹)	105.7 ± 32.1	27.4 ± 7.2
COD (mg L ⁻¹)	265.2 ± 79.8	83.9 ± 13.0
TSS (mg L ⁻¹)	64.0 ± 19.2	27.1 ± 18.3
NH ₄ -N (mg L ⁻¹)	60.3 ± 5.8	54.4 ± 7.4
NO ₃ -N (mg L ⁻¹)	1.7 ± 1.5	0.8 ± 0.5
TN (mg L ⁻¹)	74.2 ± 16.1	60.7 ± 13.8
TP (mg L ⁻¹)	9.5 ± 2.2	6.9 ± 1.3
Na (mg L ⁻¹)	110.9 ± 14.4	118.7 ± 11.4
Mg (mg L ⁻¹) ²⁾	0.23	0.21
Ca (mg L ⁻¹)	19.5 ± 2.4	23.6 ± 3.1
K (mg L ⁻¹)	30.2 ± 4.6	28.4 ± 5.3
Cl (mg L ⁻¹)	83.7 ± 31.3	79.5 ± 32.5
B (mg L ⁻¹) ²⁾	< 0.02	< 0.02
Cd (mg L ⁻¹) ²⁾	0.03	0.02
Cr (mg L ⁻¹) ²⁾	1.38	0.1
Co (mg L ⁻¹) ²⁾	0.04	0.01
Ni (mg L ⁻¹) ²⁾	0.2	0.07
Pb (mg L ⁻¹) ²⁾	0.02	0.02
Zn (mg L ⁻¹) ²⁾	0.02	< 0.01
TC (NTU/100 mL)	1,79 x10 ⁷ ± 1120	1,95 x10 ⁶ ± 980
FC (NTU/100 mL)	3,78x10 ⁶ ± 458	6,91 x10 ⁵ ± 652
E.Coli (NTU/100 mL)	5,02 x10 ⁶ ± 879	1,05 x10 ⁴ ± 540
HE (eggs 10L ⁻¹)	< 10	< 10

¹⁾ Average and confidence interval (calculated for a confidence level of 95% and the following number of samples: 21 (flow rate, temperature, pH, BOD₅, COD, TSS, NH₄-N, NO₃-N, TN, TP, Na, Ca, K and Cl), 10 (EC and TC, FC), 6 (HE, E. Coli)).

²⁾ Only one measurement in the last sampling.

The organic loading rate (OLR), as BOD₅ and COD, the solids loading rate (SLR), as TSS, the nitrogen loading rate (NLR), as NH₄-N and TN, and the total phosphorous loading rate (PLR), as TP, and the areal mass removal rates (in g m⁻² d⁻¹) for BOD₅, COD, TSS, NH₄-N, TN and TP (defined as r_{BOD5}, r_{COD}, r_{TSS}, r_{NH4}, r_{TN} and r_{TP}) were calculated. A significant linear correlation was observed between OLR and r_{BOD5} and r_{COD} (R² of 0.93 and 0.69, respectively), SLR and r_{TSS} (R² of 0.75) and PLR and r_{TP} (R² of 0.73) as it can be seen in Figure 1, and low correlations were observed between NLR and r_{NH4} and r_{TN} (R² of 0.33 and 0.24, respectively). A good correlation between OLR and r_{BOD5} and r_{COD} was also observed in another study carried out by authors in a highly loaded HSSF bed (Albuquerque *et al.*, 2009).

The average r_{BOD5} (7.6 g BOD₅ m⁻² d⁻¹) and r_{COD} (15 g COD m⁻² d⁻¹) are higher than the values found by Vilpas *et al.* (2005) in Filtralite-based HSSF beds in Finland (maximum of 10 g COD m⁻² d⁻¹) and by Ghosh and Goal (2010) in a hotter climate in India (maximum values of 6.8 g BOD₅ m⁻² d⁻¹ and 11.6 g COD m⁻² d⁻¹). The average r_{TSS} (4.7 g TSS m⁻² d⁻¹) is much higher than the values observed by Ghosh and Goal (2010), up to 0.7 g TSS m⁻² d⁻¹. However, according to the German standard ATV-A 262E (1998), the

average values of OLR (30 g COD m⁻² d⁻¹) and SLR (12.1 g TSS m⁻² d⁻¹) are 1.8 and more than 2 times higher than the suggested values to prevent bed clogging (16 g COD m⁻² d⁻¹ and 6 g TSS m⁻² d⁻¹).

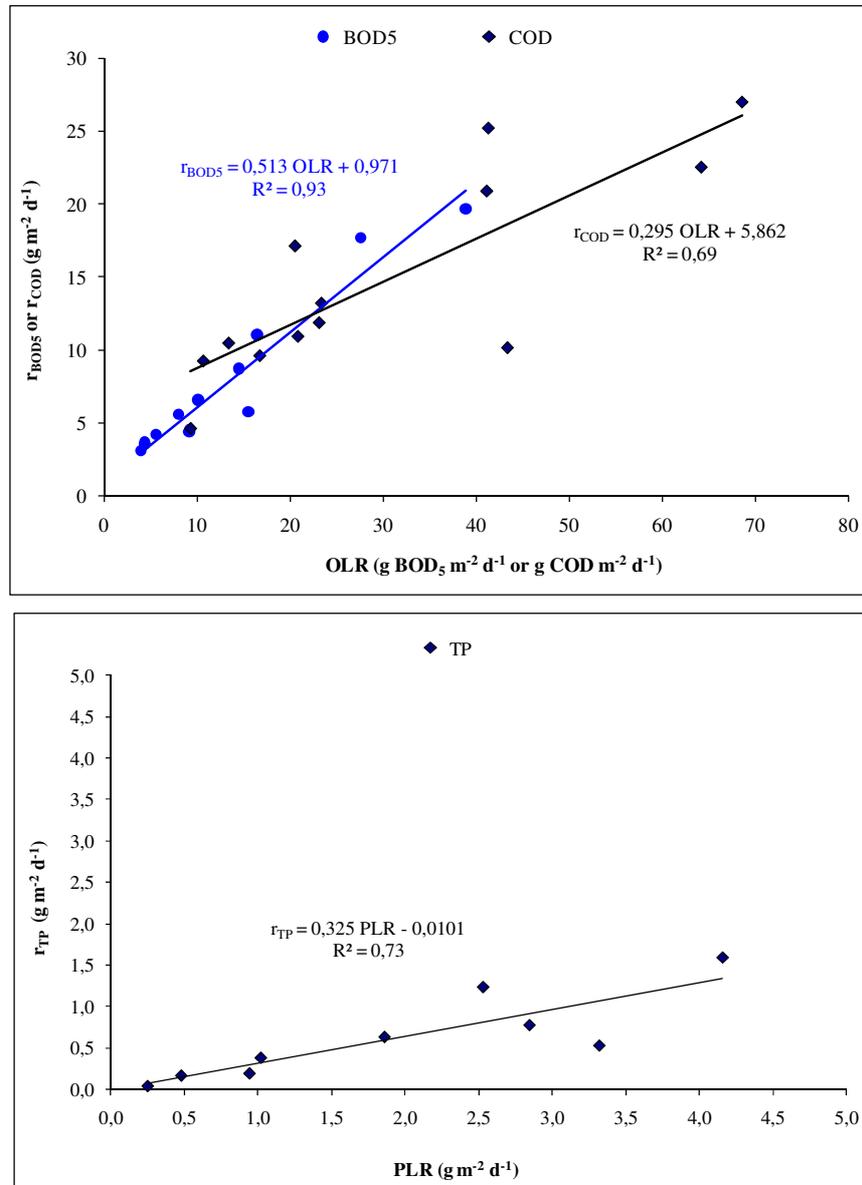


Figure 1 | Correlations between applied loading rates and removal loading rates for BOD₅, COD and TP.

The average value of r_{NH_4} (1.7 g NH₄-N m⁻² d⁻¹) is close the minimum observed by Vilpas *et al.* (2005) (1 to 6 g NH₄-N m⁻² d⁻¹), however these authors observed higher RE (90 to 94%). Ghosh and Goal (2010) also present higher values (3 to 7 g NH₄-N m⁻² d⁻¹) for HRT between 1 and 4 d (*i.e.* half of the average value found in this study). Therefore, if the variation of HLR could be controlled, the bed may reach a better performance and a better quality of reclaimed water may be achieved.

Non conventional wastewater treatments has several benefits in irrigation reuse, the two most important are, saving energy and to keep a part of the nutrients. However, for irrigation application, these nutrients can be beneficial and can supply a significant portion of plant needs (EPA, 2004). This can then reduce the amount of fertilizer that might be applied (Lazarova and Barhi, 2005; EPA, 2004). Supplemental fertilization with specific nutrients not provided by reclaimed water may still be required depending on plant species and the recommended rates for desired results.

As observed by Marecos do Monte and Albuquerque (2010), the physical-chemical characteristics of the final effluent suggest that it can be used for irrigation since it fulfill the goals set by several

authors and organizations (EPA, 2004; Bixio and Wintgens, 2006; Asano *et al.*, 2007): 6.5 to 8.4 (pH), 35 to 60 mg L⁻¹ (TSS), 5 mg L⁻¹ (NO₃-N) and 3 mg L⁻¹ (TP). However, the TP concentration and the pathogenic content (TC, FC and *E. Coli*) are not suitable for irrigation and an improvement in phosphorous removal and a final disinfection would be required for that purpose.

In accordance with Murcott (1995) the ideal characteristics of the reclaimed water to be used in crop irrigation are: (a) high organic content; (b) high nutrient content (N, P); (c) low pathogen content and (d) low metal and toxic organic compounds contents, so the effluent concentrations of BOD₅, COD, TN, TP, K, Ca, Mg and phytotoxic elements (Na, Cl and B) show a good potential for irrigation according to the standards presented in Bixio and Wintgens (2006), Asano *et al.* (2007) and UNESCO (2009).

The nutrient content may contribute to crop growth and to optimize fertilizers application, but periodic monitoring is needed to avoid imbalanced nutrient supply. Nitrate concentrations in the effluent constitute a very low risk for groundwater contamination. EC present no salinity and toxicity problems because phytotoxic ions (B, Cl, Na) are under restriction range (Westcot and Ayers, 1985) as well heavy metals (Cd, Cr, Co, Ni, Pb, Zn). Potential soil permeability problems are moderate in the long term if the leaching fraction is not applied. This problem is mainly related to a relatively high sodium concentration and low calcium and magnesium content (Westcot and Ayers, 1985).

Health and environmental aspects are particularly sensitive issues and important prerequisites, since wastewater effluent will not be used and/or be accepted to replace conventional or possibly other non-conventional water sources for irrigation, unless it is adequately treated and safely applied (Salgot *et al.*, 2003; Gerba and Rose, 2003). In irrigation reuse, different technologies and also different irrigation methods must be considered. Drip irrigation can reduce 2-log unit in low-growing crops, and 4-log unit in high growing crops (WHO, 2006). On surface and subsurface drip irrigation shows differences in soil moisture content, soil salinity, nitrogen, phosphorus and potassium content (Oron *et al.*, 2001).

CONCLUSIONS

During the 21 month monitoring campaign in the HSSF CW located at Vila Fernando (Portugal), the low removal efficiency reached, was associated to the fluctuation of HLR that influenced the HRT and the applied loads and, therefore, reduced the treatment capability of the bed. Nevertheless, the effluent concentrations of EC, BOD₅, COD, TN, TP, K, Ca, Mg and phytotoxic elements (Na, Cl and B), showed a suitable quality for irrigation reuse according to different international standards, although it is necessary to improve the removal of phosphorous and a final disinfection must be implemented to decrease the pathogenic content. The use of reclaimed water from constructed wetland systems may represent an important water source for irrigation reuse in rural areas of Portugal with water shortage, with important environmental and economics benefits.

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