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Integrated treatment of combined sewer wastewater and stormwater in a hybrid constructed wetland system in southern Spain and its further reuse

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ABSTRACT

An integrated pilot-scale treatment system consisting of a vertical subsurface flow (317 m^2), a horizontal subsurface flow (229 m^2) and a free water surface (240 m^2) constructed wetlands operating in series for the treatment of a combined sewer effluent was put into operation and monitored over a period of about 1.5 years. The goal of the treatment system was to provide effluents suitable for various water reuse applications. Moreover, the influence of pulses of high flow resulting from several rain events over the treatment performance of the system was evaluated. An intensive sampling campaign was also carried out following an intense storm (45 mm in one-hour span) to have a further insight into the characteristics of the inflowing water at the early part of it or so-called 'first-flush'. Results under dry weather conditions showed a good performance on the removal of BOD_5, COD and TSS taking place already in the vertical flow wetland (94, 85 and 90%, respectively). A high removal of total nitrogen occurred also in the vertical flow wetland (66%) suggesting both nitrification and denitrification to take place, presumably due to the existence of both aerobic and anoxic microenvironments within the bed. Removal of *Escherichia coli* along the treatment system was of almost 5 log units. To this respect, the horizontal flow and free water surface wetlands proved to be crucial treatment units to achieve a water quality suitable for further reuse (e.g. recharge of aquifers by percolation through the ground, silviculture and irrigation of green areas non accessible to the public). Although the occurrence of the storm event caused a prompt raise of COD and TSS within the first 30 min of rainfall (868 and 764 mg L^{-1}, respectively), it was soon followed by a dilution effect. In general the storm events did not jeopardize the correct functioning of the system, proving its robustness for the treatment of a combined sewer effluent.

1. Introduction

Nowadays, it is estimated that the load of wastewater receiving inappropriate treatment in Spain (mostly small communities with less than 2000 people equivalent (PE)) corresponds to 3–4 million PE. Although this load represents just a small percentage of the total load to be treated (6–8%), more than 6000 communities have been counted to contribute (CEDEX-CENTA, 2008). This fact highlights the complexity on the development of Sanitation Plans to be introduced.

The Spanish National Plan for Water Quality (2007–2015) was created to comply with the quality objectives and requirements of Directive 91/271/CEE concerning urban wastewater treatment (EC, 1991), as well as the EU Water Framework Directive (EC, 2000). Although no specific criteria or prescribed technologies for communities with less than 2000 PE have been specified, the plan aims at boosting the establishment and use of low-cost solutions to provide wastewater treatment to small communities.

To this regard, constructed wetlands constitute the most commonly used treatment technology in the last years (Vera et al., 2011). Numerous studies have shown their capability to maintain hydraulic, technical, economic, environmental and ecological benefits (Zhou et al., 2009; Dixon et al., 2003; Vymazal, 2002). Although the number of these systems is still not so large in Spain (Puigagut et al., 2007), it is important to note that this technology has a promising prospective in the coming years.

In Spain most of the sewer catchments are combined, collecting both urban wastewater and urban runoff (Diaz Fierros et al., 2002). The original aim of this is to prevent flooding in urban areas and to protect public health. Mediterranean weather, which is characteristic in south Spain, is distinguished by periods of low or no rainfall followed by stormy periods. It is now fully recognized that

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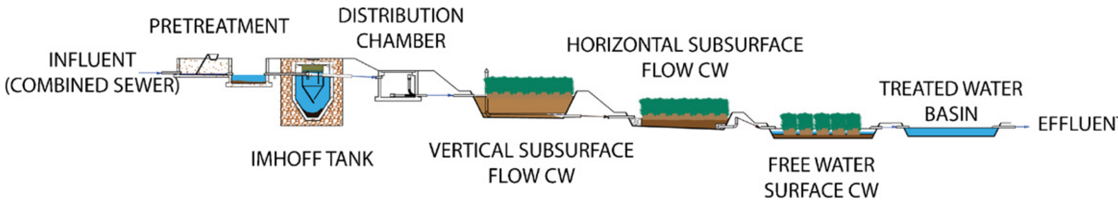

Fig. 1. Layout of the experimental treatment plant.

combined sewer overflows are themselves significant sources of pollution of receiving water systems (Lau et al., 2002).

Constructed wetlands (CWs) have been widely used for the treatment of wastewater but also for stormwater, separately (Carleton et al., 2001; Somes et al., 2000). In stormwater wetlands there is in many cases a need to compensate for evapotranspiration in dry periods. To that regard, the use of CWs for the treatment of combined sewer wastewaters as well as stormwaters could solve this problem. However, only a few examples of the influence of high rainfall events in this type of system have been assessed (Van de Moortel et al., 2009; Green et al., 1999).

In this context a collaborative project between the Universitat Politècnica de Catalunya (Barcelona) and the Foundation Centre for New Water Technologies (Seville) emerged in 2009, aiming at integrating the treatment of a combined sewer effluents containing wastewater and urban runoff in small communities through the use of constructed wetlands.

Hybrid systems are a combination of various types of CWs so as to balance out the strengths and weaknesses of each type of system (Vymazal, 2005). In this study, the performance of an integrated approach for the treatment of a combined sewer system based exclusively on CWs was assessed. A pilot-scale treatment system consisting of a series of different types of wetlands was put into operation and monitored over a period of about 1.5 years. An interpretation of the functioning of the system under dry weather, wet weather conditions and for the beginning of an intense storm event was made, so as to evaluate its performance on the treatment of a combined sewer effluent.

The influence of some intense storm events over the treatment performance was examined so as to evaluate the buffer capacity of the wetland system under extraordinary high flow conditions. Albeit characterizing contaminant loads in storm water is a complex issue due to spatial and temporal variations in weather conditions and rainfall pattern, we have proceeded to feature the composition of the early part of an intense storm event or so-called 'first-flush event', which has been identified as a relatively high proportion of the total storm pollution load, through the implementation of an intensive sampling campaign and assessment of the water quality. Moreover, the final goal of the treatment system was to provide effluents suitable for its reuse. For that purpose, the final effluent was contained in a water tank and its quality was monitored and compared to the Spanish guidelines' requirements so as to estimate its possible reuse in various environmental applications.

2. Materials and methods

2.1. Description of the treatment system

The constructed wetland treatment system was part of a larger pilot-scale treatment plant that received the wastewater from 2500 PE from the municipality of Carrión de los Céspedes (Seville) together with the runoff collected in a combined sewer system. Research activities of the Foundation Centre for New Water Technologies (CENTA) are developed within this 41,000-m^2 experimental plant, which contains a great variety of both extensive and intensive technologies for its analysis and validation, but also for knowledge dissemination and outreach (http://www.centa.es/). Pretreatment chambers are common to all technologies in the plant and its effluent is diverted towards each of them.

The constructed wetlands started operation in spring 2005, however the treatment line as it is now began its operation in July 2009. In particular, a hybrid system consisting of a combination of various types of constructed wetlands was set so as to balance out the strengths and weaknesses of each type of system. The raw wastewater is firstly screened through two sieves of 3 cm and 3 mm wide, followed by a pretreatment chamber for sand and grease removal. The water is then conveyed towards a pumping chamber, from which the water is conducted through submersible pumps into a distribution system. This last one consists of a chamber, equipped with electromagnetic flow meters (Sigma 950). The pretreated water is next led through gravity towards an Imhoff tank, with a treatment capacity of 40 $m^3\,d^{-1}$ (for the feeding of 3 different lines of wetlands, just one belonging to this study treatment system), a settling area volume of 3.5 m^3 and a digestion area volume of 25 m^3. The primary effluent is then pumped towards 3 lines of constructed wetlands of different configurations operating in series, including the studied hybrid constructed wetland system (Fig. 1). Each of the treatment lines is fed 20 times per day. Pumped flow was measured by means of an electromagnetic Sigma 950 flow meter of 50 mm of diameter. The hybrid wetland consisted of a vertical subsurface flow constructed wetland (VF), which was connected in series to a horizontal subsurface flow constructed wetland (HF) and finally to a free-water surface wetland (FWS). Both the VF and the HF were planted with *Phragmites australis* with a density of 5 plants m^{-2}. The VF had a surface area of 317 m^2 (23.5 × 13.5 m) and received an average flow of 14 $m^3\,d^{-1}$, an average organic loading rate (OLR) of about 9 g $BOD_5\,m^{-2}\,d^{-1}$ and an average hydraulic loading rate (HLR) of 44 mm d^{-1}. The bed consisted of a top layer of 0.05 m of sand (grain size = 1–2 mm), followed by a 0.6 m layer of gravel (grain size = 4–12 mm) and an underlying 0.15 m stone layer (grain size = 25–40 mm). Feeding of the VF was done through five lengthwise pipes of 32 mm of diameter, perforated with 1 cm diameter holes every 1.8 m distance. Five draining pipes (diameter = 125 mm) were installed lengthwise at the bottom of the wetland within the 15 cm-thick gravel layer. Every draining pipe had three 1 m-tall chimneys so as to provide oxygen transfer into the wetland beds.

The HF had a surface area of 229 m^2 (26 × 8.8 m) and consisted of a gravel bed of 0.4 m depth (grain size = 4–12 mm), with an inlet and outlet zone of stones of 40–80 mm of diameter. Feeding of the bed was done through 63 mm diameter polyethylene pipes perforated with 1 cm holes located every 1 m distance. The outlet of the wetland consisted in two 125 mm-diameter draining pipes buried at the bottom of the outlet stone layer and connected to a flexible pipe that held the water level 5 cm below the top of the gravel.

The FWS had a surface area of 240 m^2 (24 × 10 m) and a water depth ranging 10–50 cm. A mixture of *Typha* spp., *Scirpus* spp., *Iris pseudacorus*, *Carex flacca*, *Cyperus rutundus* and *Juncus* spp. were